SEA CHANGE

2015-2025 Decadal Survey of Ocean Sciences

Committee on Guidance for NSF on National Ocean Science Research Priorities:
Decadal Survey of Ocean Sciences

Ocean Studies Board

Division of Earth and Life Studies

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

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Funding for this study was provided by the National Science Foundation under grant number OCE-1341319. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the National Science Foundation.

International Standard Book Number-13: 978-0-309-36688-5
International Standard Book Number-10: 0-309-36688-7
Library of Congress Control Number: 2015937043

Additional copies of this report are available from the National Academies Press, 500 Fifth Street, NW, Keck 360, Washington, DC 20001; (800) 624-6242 or (202) 334-3313; http://www.nap.edu.

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Acknowledgments

This report was greatly enhanced by the efforts of those who participated in committee meetings, attended town halls, provided information to the committee, and assisted with successful meetings. The committee would like to acknowledge Art Allen (U.S. Coast Guard), Jon Alberts (University-National Oceanographic Laboratory System), Holly Bamford (National Oceanic and Atmospheric Administration [NOAA]), Anjuli Bamzai (National Science Foundation [NSF]), Jack Barth (Oregon State University), Jeff Bingham (congressional staff), Paula Bontempi (National Aeronautics and Space Administration [NASA]), Scott Borg (NSF), Natalie Bruso (University of Hawaii at Manoa), RADM Nevin Carr (retired, U.S. Navy), Charlie Chestnutt (U.S. Army Corps of Engineers), Tim Cowles (Ocean Leadership), Beth Curry (University of Washington Applied Physics Laboratory), Paul Cutler (NSF), John Delaney (University of Washington), Annette DeSilva (University-National Oceanographic Laboratory System), Tommy Dickey (University of California, Santa Barbara), Paul Digiacomo (NOAA's Satellite and Information Service), Tom Drake (Office of Naval Research [ONR]), John Farrell (U.S. Arctic Research Commission), Sarah Giddings (Scripps Institution of Oceanography [SIO]), Peter Girguis (Harvard University), Rebecca Green (Bureau of Ocean Energy Management [BOEM]), John Haines (U.S. Geological Survey), Frank Herr (ONR), Susan Humphris (Woods Hole Oceanographic Institution [WHOI]), Martin Jeffries (ONR), Walter Johnson (BOEM), Rebecca Lent (Marine Mammal Commission), Naomi Levine (University of Southern California), Eric Lindstrom (NASA), Kim Martini (University of Washington), Kathleen McNeil (NOAA/National Weather Service), Brian Melzian (U.S. Environmental Protection Agency), Richard Merrick (NOAA/National Marine Fisheries Service), Allison Miller (Schmidt Ocean Institute), Berrien Moore III (University of Oklahoma), John Orcutt (SIO), Peter Ortner (University of Miami), Leonard Pace (Schmidt Ocean Institute), Jamie Pierson (University of Maryland Center for Environmental Science), Al Plueddemann (WHOI), Helmut Portmann (NOAA National Data Buoy Center), David Score (NOAA), Simon Stephenson (NSF), Steven Squyres (Cornell University), Jason Sylvan (University of Southern California), Andrew Thompson (California Institute of Technology), Woody Turner (NASA), Jennifer Wade (NSF), Chuck Wilson (Gulf of Mexico Research Initiative), Carl Wunsch (Massachusetts Institute of Technology), Bill Zamer (NSF), and Victor Zykov (Schmidt Ocean Institute).

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 National Research Council'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 **David Karl,** University of Hawaii at Manoa, appointed by the Division on Earth and Life Studies, and **Michael Kavanaugh,** Geosyntec Consultants, 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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Summary

New observational and computational technologies are transforming the ability of scientists to study the global ocean with a more integrated and dynamic approach. This enhanced understanding of the ocean is becoming ever more important in our economically and geopolitically connected world, enabling informed decisions on vital ocean policy matters.

In the United States, the National Science Foundation (NSF) is the primary funder of the basic research that underlies advances in our understanding of the ocean. This study addresses the strategic investments necessary at NSF to ensure a robust ocean scientific enterprise over the next decade.

SCIENTIFIC ADVANCES FROM OCEAN RESEARCH

The ocean science community has undertaken the challenge of exploring the ocean domain and over the past few decades has produced a remarkable surge in understanding the physics, biology, and chemistry of the ocean, and the geology and geophysics at and beneath the seafloor. Technological advances have fueled much of the increase in knowledge, as ocean scientists have rapidly adopted, developed, and employed new computational and modeling capabilities, robotics, and technological innovations such as genomics. Satellites and autonomous sensor systems have revealed a dynamic global ocean system on unprecedented temporal and spatial scales; chemists have detected significant declines in ocean pH, and biologists have studied the impact of this change in ocean chemistry on marine species and ecosystems. Geologists have documented eruptions on the deep seafloor and discovered microbial communities beneath the seafloor. Also, ocean research has improved scientific understanding of global climate change, one of the defining issues of the 21st century.

These exciting developments in ocean science have been made possible by investments in a portfolio of funds for research, development and application of new technologies, and oceanographic infrastructure such as ships, gliders, and submersibles; in situ and remote observing systems; and other facilities such as marine laboratories, cyberinfrastructure, and sample and data repositories. In addition, substantial advances have arisen from programs that cut across traditional disciplinary boundaries, bringing together scientists from many fields, federal agencies, and other countries. Such programs have yielded insights into the global ocean and have informed policy makers, the private sector, and the general public about both the future opportunities and limits of the ocean as a resource.

OCEAN SCIENCES AT THE NATIONAL SCIENCE FOUNDATION

Although many other federal agencies contribute to ocean science and technology, the Division of Ocean Sciences (OCE) at NSF provides the broadest base of support for the field, including funding for research in physical, biological, and chemical oceanography and marine geology and geophysics, and the development, implementation, and operational support for ocean research infrastructure. Within NSF, OCE encompasses a broad portfolio of diverse interests and activities. Managing this enterprise has been made more challenging with the continued increase in operations and maintenance costs for the ocean research facilities, especially the academic research fleet, scientific ocean drilling through the International Ocean Discovery Program (IODP [2013-2018]), and the launch of the Ocean Observatories Initiative (OOI). Infrastructure expenses have risen over the past decade (about 18% in 2014 dollars) even as the total NSF OCE budget fell by more than 10%. With no significant budget increases anticipated by NSF in the near future, strategic decisions are required to ensure that key programmatic elements are supported to maintain the overall health of the ocean sciences community.

Traditionally, NSF seeks community input on long-range research priorities and strategies to optimize scientific investments. A decadal survey process that establishes research priorities, and then identifies the investments nec-

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essary to achieve those priorities, has been used by several scientific disciplines and science agencies to develop community-based plans. In 2013, OCE asked the National Research Council's (NRC's) Ocean Studies Board to undertake a decadal survey of ocean sciences to provide guidance from the ocean sciences community on research and facilities priorities for the coming decade. OCE requested this guidance to address the community's priorities in the context of funding constraints imposed by the current trend of flat or declining budgets. The research portfolio includes investments in infrastructure, individual investigator-based science, multi-investigator large research programs, and cross-directorate initiatives like NSF's Science, Engineering, and Education for Sustainability. The study committee was asked to place NSF's ocean science activities in the context of activities undertaken by other federal ocean agencies. The committee also examined the role of international cooperation and collaboration in advancing ocean science. The full statement of task for the study is provided in Box I-1.

PRIORITY SCIENCE QUESTIONS AND INFRASTRUCTURE FOR THE NEXT DECADE OF OCEAN RESEARCH

Selection of Priority Science Questions

The committee was asked to select no more than 10 ocean science priorities with the goal "to identify areas of strategic investment with the highest potential payoff" for the coming decade (2015-2025). NSF, the Ocean Studies Board, and this committee viewed community involvement as an essential element in the process of identifying priorities. To encourage participation, the committee held town hall meetings at the 2013 American Geophysical Union Fall Meeting (San Francisco, California) and the 2014 Ocean Sciences Meeting (Honolulu, Hawaii). In addition, the committee solicited input through a web-based Virtual Town Hall that collected over 400 responses from November 2013 to March 2014. The community responses were supplemented with research topics identified in more than 30 reports and publications, presentations by scientists from both academic and government institutions, letters from institutions, and discussions with colleagues. Additionally, the committee actively sought out opinions from early career scientists whose futures will be influenced by decisions made over the next decade.

The committee devoted a major effort to distill the many topics gathered through these sources down to 10 or fewer priorities. The process began with sorting the input into three dozen diverse, high-level, disciplinary and interdisciplinary scientific questions. Similar questions were then clustered to yield high-level scientific questions, to which four criteria—transformative research potential, societal impact, readiness, and partnership potential—were applied, listed in order of relative importance. These criteria were derived from previous NRC and interagency reports related to ocean science research priorities, and from suggestions by NSF program managers.

Eight priority science questions emerged from this process, each representing an integrative and strategic research area. The questions cover topics appropriate for OCE core programs, cross-cutting NSF programs, or in partnership with other federal agencies or international programs. A synopsis of the eight priorities is provided below, ordered from the ocean surface, through the water column, to the seafloor:

- **What are the rates, mechanisms, impacts, and geographic variability of sea level change?**
- **How are the coastal and estuarine ocean and their ecosystems influenced by the global hydrologic cycle, land use, and upwelling from the deep ocean?**
- **How have ocean biogeochemical and physical processes contributed to today's climate and its variability, and how will this system change over the next century?**
- **What is the role of biodiversity in the resilience of marine ecosystems and how will it be affected by natural and anthropogenic changes?**
- **How different will marine food webs be at mid-century? In the next 100 years?**
- **What are the processes that control the formation and evolution of ocean basins?**
- **How can risk be better characterized and the ability to forecast geohazards like mega-earthquakes, tsunamis, undersea landslides, and volcanic eruptions be improved?**
- **What is the geophysical, chemical, and biological character of the subseafloor environment and how does it affect global elemental cycles and understanding of the origin and evolution of life?**

Each of these high-level questions encompasses many subtopics that are described in much greater detail in the report. Most of the questions will require interdisciplinary research across the subdisciplines of ocean science as they are managed within OCE, within the disciplines of the Directorate for Geosciences, and across directorates. Because interdisciplinary research across the subfields of ocean science will be essential to achieve many of the decadal science priorities, it is particularly important that the ocean science community does not encounter or perceive barriers to obtaining funding for interdisciplinary research.

The OCE core programs will likely address many aspects of the scientific priorities identified above, but the committee recognizes that it would be counterproductive

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to constrain the core programs to fund only those proposals directly related to these priorities. To advance ocean science and technology, the core programs require a high degree of flexibility to fund basic research and promising new ideas and approaches, respond to infrequent events that present opportunities to understand key phenomena, incorporate advances from other areas of science and technology, and encourage the training and professional development of the next generation of scientists.

Because the eight priority questions have broad relevance to societal issues, other federal agencies may also be interested in devoting resources to addressing these research topics. Collaborations between U.S. basic research and mission agencies could hasten both research advancements and transition to operational products by taking advantage of complementary skills, resources, and expertise among organizations. Industry, foundations, international organizations, and nongovernmental organizations could also be engaged to assist in addressing these questions, due to their global reach.

Alignment of Infrastructure to the Priority Science Questions

One purpose of identifying priorities in this report is to ensure alignment between the next decade's foremost topics in ocean science and NSF's investments in ocean research infrastructure. The committee assessed how well the current portfolio of NSF-supported ocean research infrastructure matched the decadal science priorities and focused on three major infrastructure assets—the academic research fleet, IODP, and OOI—which together comprise over 50% of the total OCE budget and over 90% of the infrastructure budget. In addition, the committee evaluated a few smaller facilities and programs supported by OCE, such as the National Deep Submergence Facility (NDSF) and field stations.

The committee identified categories of alignment between infrastructure and each decadal science question. *Critical* refers to infrastructure assets without which the science priority question cannot be addressed effectively and *important* infrastructure is useful but not essential to address the question.

Academic Research Fleet

The strongest match between current infrastructure and the decadal science priorities is the academic research fleet. Research vessels, especially Global class ships, support a broad swath of oceanographic activities and are essential to achieve all of the science priorities. Global class ships have greater deck loading, berthing, and sea state capacities and are *critical* to or *important* for the multidisciplinary, multi-investigator types of research identified in all of the science priorities. Regional class ships strongly contribute to societally relevant questions in coastal environments, being *critical* to or *important* for topics such as sea level rise and biodiversity of marine ecosystems. Ice-capable ships are requisite for answering a number of questions related to understanding climate change, ocean-ice interactions, and polar marine food webs.

NSF is currently considering the acquisition of up to three new Regional class research vessels (RCRVs). Under current plans, the new RCRVs will have a length and berthing capacity comparable to the larger Intermediate class and are expected to have day rates that are substantially higher than the Regional ships that are being replaced. This expansion in capability and cost, combined with the restricted geographical range and days at sea associated with the RCRV's regional status, raises the question of whether the current design and estimated day rates of the RCRVs are well matched for expected future use.

Scientific Ocean Drilling

Based on the committee's analysis, scientific ocean drilling facilities and analysis of core collections are *critical* for the decadal science priorities related to subseafloor exploration, geohazards, and formation and evolution of the ocean basins. They are also *important* for issues related to climate and sea level variability. Scientific ocean drilling has also proven to be an effective vehicle for science diplomacy through building long-term international partnerships.

NSF has supported an ocean drilling program for over 45 years and, as part of IODP (2013-2018), currently covers the majority of costs for the *JOIDES Resolution* drill ship. Although scientific ocean drilling is necessarily an "infrastructure-heavy" undertaking, requiring a high proportion of funding for operations relative to research, IODP has implemented many cost-savings measures in recent years to decrease operating costs and improve efficiency. Nevertheless, the United States still carries a heavier financial burden than many of the other contributing countries to cover scientific ocean drilling facilities and operations costs. Moreover, the international community as a whole appears overextended in scientific ocean drilling facilities. NSF has the ability to renegotiate its contribution to the IODP consortium and is strongly urged to pursue a more cost-effective partnership. If additional revenue cannot be found, one budget solution could include a reduction in the total number of platforms operated by members of the consortium, which would allow more efficient utilization of the remaining assets. NSF plans to fund IODP (2013-2018) at a total of $250 million over the next 5 years, providing for four *JOIDES Resolution* expeditions annually.

Ocean Observatories Initiative

The different OOI components—global moorings, coastal arrays, and the regional cabled observatory—are not all at the same level of alignment with the science priorities. The coastal arrays are *important* for sea level rise, coastal processes, and climate variability; the global moorings are *important* for climate variability. The regional cabled obser-

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vatory is *important* for solid earth and subseafloor biosphere questions.

Because OOI has not yet entered full operation, it lacks both a robust user community and a record of research accomplishments. Therefore, the committee determined that it was premature to make strong statements about potential success, failure, or the possibility for transformational research. However, comments from the Virtual Town Hall and additional discussions with both early career and established scientists suggest a lack of broad community support for this initiative, exacerbated by an apparent absence of scientific oversight during the construction process. OOI is an expensive new piece of infrastructure; estimated operational costs are at least $55 to $59 million per year for the next 5 years.

COURSE CORRECTIONS

NSF asked the committee to "recommend a strategy to optimize investments that will advance knowledge in the most critical and/or opportune areas of investigation while also continuing to support core disciplinary science and infrastructure" and provide "guidance on the most effective portfolio of investments achievable at the current funding level that will support both the research infrastructure and programmatic science necessary to address the most significant priorities."

The committee undertook this assignment by first developing a vision for the ocean sciences in the next decade:

> *The ocean science community will undertake research and pursue discoveries that advance our understanding of the oceans, seafloor, coasts, and their ecosystems; foster stewardship of the ocean; reduce society's vulnerability to ocean hazards; and nurture and exploit the integration of the disciplines. A diverse and talented community of researchers will develop new technologies to study the ocean in novel and cost-effective ways and create innovative educational programs that will engage and inspire the next generation. Partnerships will be fostered across funding agencies, national borders, and the private sector to provide the greatest value for the nation's investment in ocean science.*

With this vision in mind, the committee considered the balance of investments in ocean science funding and the research infrastructure. Since 1970, the total budget at OCE has seen an annual growth rate of roughly $3 million per year (2014 dollars), punctuated by spurts of growth and shrinkage in spending power. Over the past decade the OCE budget has declined by more than 10% (inflation-adjusted,[1] see Figure S-1). During times of budget increases, OCE was able to initiate new technologies and sustain research facilities in addition to maintaining a diverse research portfolio that took advantage of the new capabilities.

Since 2000, there has been a shift in investment from the core research programs to the operations and maintenance costs of infrastructure (Figure S-1). In the past 4 years (2011-2014) the overall budget has not grown; as a consequence, the continued increase in infrastructure costs (about 18% in 2014 dollars) has resulted in a substantial decline (about 25% in 2014 dollars) in the amount of funding available for the core research programs and therefore less support for investigator proposals. The funding for Oceanographic Technology and Interdisciplinary Coordination (OTIC), the main source of support for technology development within OCE, has been particularly hard hit by this decline.

Since the committee was asked to assume that the OCE budget is unlikely to grow significantly over the next decade, and given that cost inflation will continue at recent historical rates (~2% per year), the only way to recover funding for core science and OTIC is to reduce the amount of money spent on infrastructure. Such reductions are not easy and will cause disruptions for parts of the ocean science community. However, restoring the core science budget and investing prudently in new technology will promote the vision presented above—a diverse community of scientists able to undertake research and pursue discoveries that will advance ocean science. During the next 5 years, the goal is to carry out necessary programmatic changes to prepare for full implementation of the vision during the second half of the decade.

Recommendation 1: In order to sustain a robust ocean science community, holistic fiscal planning is necessary to maintain a balance of investments between core research programs and infrastructure. To maintain a resolute focus on sustaining core research programs during flat or declining budgets, infrastructure expenses should not be allowed to escalate at the expense of core research programs.

The committee identified two models to achieve balance: (1) maintaining a *fixed ratio* for infrastructure costs relative to the total budget and (2) maintaining a consistent *long-term funding trajectory* for core science. The applicability of these two approaches depends on the fiscal outlook. In periods of flat or declining budgets, using a fixed ratio as a target for guiding expenditures would ensure that one part of the budget does not increase at the expense of the other. In times of increasing budgets, maintaining a consistent long-term funding trajectory for core science, rather than a fixed ratio, may provide a better approach to achieve balance. This approach accommodates adjustments in the budget fraction dedicated to infrastructure costs to reflect short-term needs or long-term changes in the use of existing infrastructure assets, as well as development of new technologies and facilities.

[1] Inflation adjustments were based on the U.S. Bureau of Labor Statistics Consumer Price Index annual average, with the exception of 2014, which was based on an average of January-November values.

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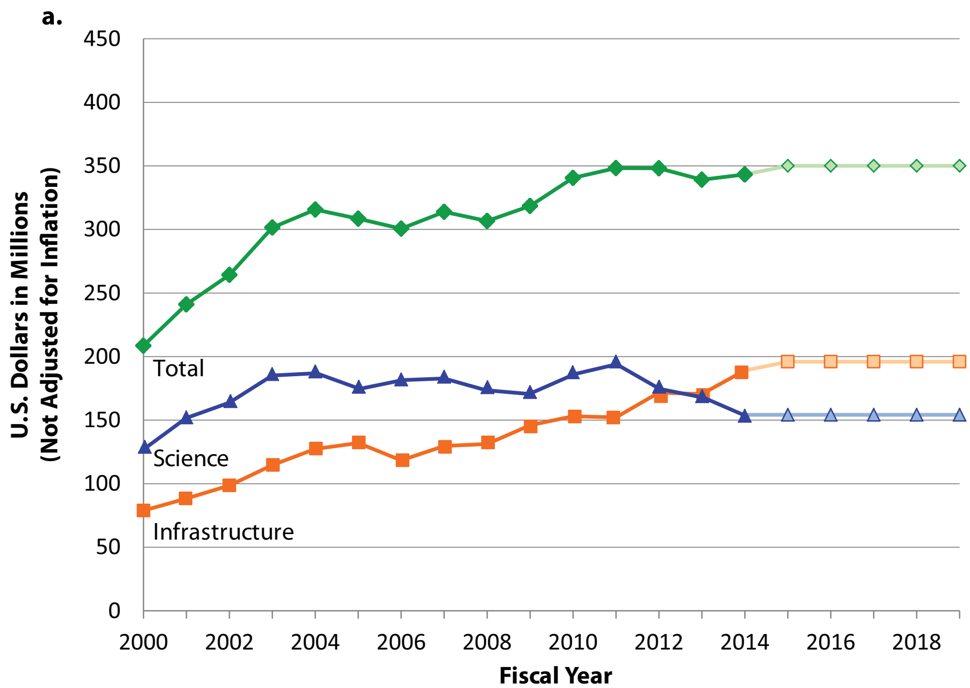

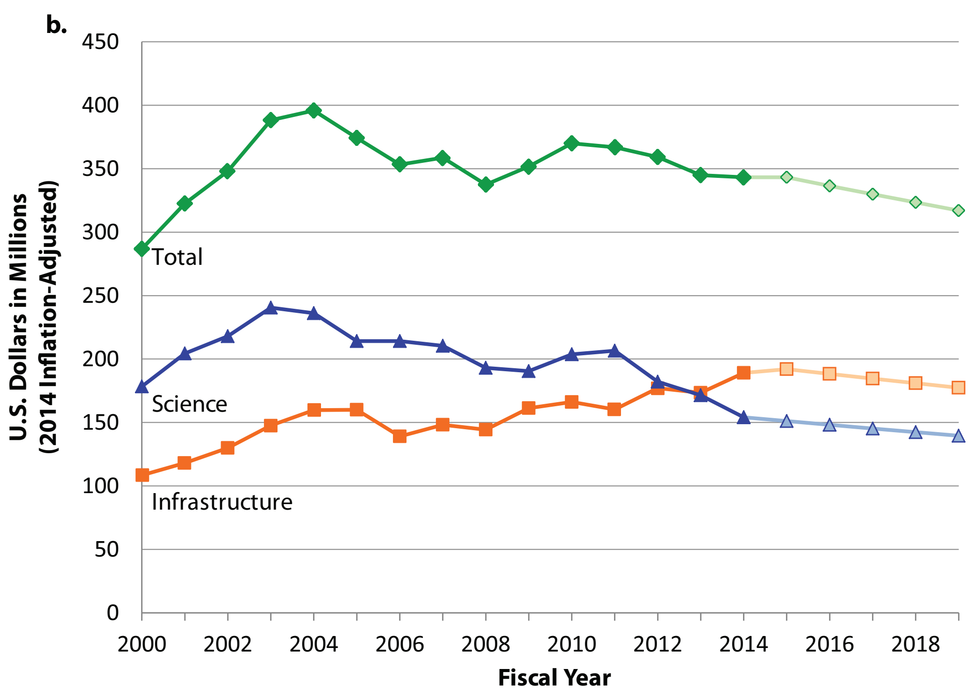

FIGURE S-1 NSF investments in core ocean science (blue) and infrastructure (orange) since 2000, shown in (a) current dollars and (b) 2014 inflation-adjusted dollars. Total funding for OCE is shown in green. Projections for fiscal years 2015-2019 (lighter colors) are based on the following assumptions provided by OCE—total future budgets are flat with no inflationary increases and operations and maintenance costs for the academic research fleet, IODP, and OOI are held constant. OCE defines "infrastructure" as the academic research fleet, OOI, IODP, field stations and marine laboratories, the accelerator mass spectrometer facility, and miscellaneous smaller facilities. Facilities held in the core programs (shown in Table 3-1) are included in core science, not in infrastructure. Data from NSF, December 2014.

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The committee developed a strategy for improving the balance of the OCE budget over the next decade. To restore core science funding during these lean budget times, the immediate goal is to reverse the trend of increasing infrastructure spending at the expense of core science in the OCE budget. Assuming that OCE has a flat budget over the next 10 years, roughly 20% (about $40 million in 2014 dollars) of the infrastructure operations and maintenance (O&M) budget would need to be reallocated to core science (including OTIC) to meet this goal. This would return core science funding to approximately the budget level in 2011, the last year before funding for core science began to decrease (Figure S-1).

Recommendation 2: OCE should strive to reduce the O&M costs of its major infrastructure (OOI, IODP, and the academic research fleet) and restore funding to core science and OTIC within the next 5 years. If budgets remain flat or have only inflationary increases, OCE should adjust its major infrastructure programs to comprise no more than 40-50% of the total annual program budget.

Recommendation 3: To implement Recommendation 2, OCE should initiate an immediate 10% reduction in major infrastructure costs in its next budget, followed by an additional 10-20% decrease over the following 5 years. Cost savings should be applied directly to strengthening the core science programs, investing in technology development, and funding substantive partnerships to address the decadal science priorities, with the ultimate goal of achieving a rebalancing of major infrastructure costs to core science funding within the next 5 years.

There are several options available to reduce infrastructure costs while sustaining research capabilities. These options include descoping or terminating activities, lengthening the time horizon of programs, delaying the start of new or planned programs or facilities, and finding ways to lower costs. Based on the analysis of the infrastructure investment alignments with the scientific priorities, costs of operation, efficiencies that could be gained, and likelihood of community support, the committee determined that the distribution of initial cost reductions between OOI, IODP (2013-2018), and the academic research fleet should be weighted.

Recommendation 4: The immediate initial 10% cost reduction in major infrastructure should be distributed, with the greatest reduction applied to OOI, a moderate reduction to IODP (2013-2018), and the smallest reduction to the academic research fleet.

A suggested weighting is to initially and immediately reduce OOI by 20%, IODP by 10%, and the University-National Oceanographic Laboratory System fleet by 5%. OOI is recommended for the greatest cost reduction because fewer of its components align strongly with the science priorities, operation of the program can be scaled to fit the available budget, and the separate components of the OOI structure provide flexibility to retain those components that align more strongly with the decadal science priorities and broad OCE research goals. For example, OOI might focus attention on one or two of the four global sites to minimize logistic costs and to demonstrate proof of concept. A moderate weighted cut recommended for the NSF-supported portion of IODP (2013-2018) reflects that IODP is important or critical for over half of the decadal science priorities. However, the *JOIDES Resolution* is an expensive facility and cost-sharing agreements within the consortium are not evenly distributed. The smallest cost reduction is recommended for the academic research fleet, because essentially all of the science priorities require ship-based access to the sea. Even a modest cut will require finding efficiencies to reduce the costs of the current fleet and to prevent an increase in overall O&M expenses with future ship acquisitions.

Recommendation 5: NSF should reconsider whether the current RCRV design is aligned with scientific needs and is cost effective in terms of long-term O&M, and should plan to build no more than two RCRVs.

Decision Rules for the Future

The committee established the following strategic principles to guide decision making in an uncertain budget climate, which when combined with open communication and consistent actions will assist NSF in maintaining a balanced portfolio:

Promote a Decadal Budget Planning Outlook

A 10-year budget planning outlook can take into account both inflation and anticipated increased costs of doing business, while accounting for risks associated with unexpected costs.

Maintain Conservative Infrastructure Investment Strategies

Given the uncertain budget environment, it is prudent to assume budget cuts are permanent and increases are temporary. Strategies for controlling the overall costs of infrastructure have to be identified prior to the addition of any new asset. Assumptions that prove to be too conservative can be corrected in future budget cycles.

Involve the Community in Setting Goals

Involving the scientific community in the development of strategic goals and objectives provides a broad base for identifying priorities and building community support for

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the enterprise into the future. The NSF Advisory Committee for Geosciences (AC-GEO) could serve as a link with the broader community. Involvement of AC-GEO could bolster support for difficult decisions that need to be made by OCE to adhere to the strategic plans.

Although NSF has undertaken reviews of individual programs and has established committees advising OOI, IODP, the fleet, and NDSF, at present there is no advisory body with broad oversight of major OCE infrastructure that can provide advice on the construction, maintenance, and operations of facilities in relation to the science priorities.

Recommendation 6: Program reviews for OOI, IODP, the academic research fleet, and NDSF should occur periodically (nominally every 3-5 years, with a 10-year outlook) and should be considered within the context of the broader OCE budget environment, rather than independently. OCE should consider exit strategies for major acquisitions if funding is insufficient. OCE should seek periodic community input to help ensure infrastructure investments align with the science priorities.

Recommendation 7: OCE should initiate a high-level standing infrastructure oversight committee to evaluate the entire portfolio of OCE-supported infrastructure and facilities and to recommend proposed changes. The outlook should be for at least 10 years and should include discussion of the entire life cycle of construction, operations and maintenance, decommissioning, and recapitalization. Committee membership should include professionals experienced in long-range budgeting and strategic planning.

Ocean research inevitably transcends national boundaries, with numerous opportunities for interagency and international collaboration. Such partnerships can leverage resources and maximize progress and are expected to play an increasingly strong role for support of large, multidisciplinary programs to address complex, high-priority, ocean science questions.

Recommendation 8: The committee encourages OCE to expand its partnership capabilities with other federal agencies, international programs, and other sectors. Such partnerships can maximize the value of both research and infrastructure investments and may help spread the costs of major ocean research infrastructure beyond OCE.

Although the contributions of the ocean sciences community have been invaluable in guiding the work of the committee, the conclusions represent the deliberations of its members, who recognize the difficulty of the task and the reality that resolving current budget issues will impact existing programs. The committee focused on the long-term health of the ocean sciences with the goal of restoring a healthy balance among OCE's funding profiles and portfolios, while preserving the essential elements to sustain the research enterprise into the next decade. These strategic issues need to be examined regularly to make continued course corrections as necessary to steer ocean sciences toward a vibrant future.

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Introduction

We envision a future in which our understanding of the world ocean, national coasts, coastal watersheds, and Great Lakes protects lives, enriches livelihoods, and enhances quality of life. At the same time, the research we undertake will help ensure the health and sustainability of our ocean ecosystem for years to come.

—Charting the Course for Ocean Science for the United States for the Next Decade: An Ocean Research Priorities Plan and Implementation Strategy (NSTC Joint Subcommitte on Ocean Science and Technology, 2007)

The ocean has been integral to the history of the United States—its national security, its economic strength, and the well-being and intellectual growth of its people. The nation has a long sea-faring history, from early European explorers, generations of fishermen, and sailors of the merchant marine and Navy. Ocean science has underlain the success of ocean-going enterprises, such as enhancing the speed and efficiency of trans-Atlantic trade through mapping ocean currents (work begun by Benjamin Franklin); supporting expeditions to Antarctica and the Arctic; observing and modeling water column properties to outmaneuver Soviet submarines during the Cold War; and assessing the abundance and dynamics of fish stocks to manage the nation's living marine resources. In addition to these practical applications, students, poets, and artists have been inspired by the mystery, the beauty, and the bounty of the sea. With the past as prologue, this report outlines strategic directions to ensure a strong future for the ocean sciences and, thus, for the nation and its people. Like a ship maneuvering through a narrow channel, the field of ocean science requires careful course adjustments to be well positioned for the next decade. With fiscal discipline and wise research investments now, the next decade and beyond could be a time of opportunity and progress in ocean science, with advances that benefit the social and economic goals of not only the nation, but also the world.

BACKGROUND

Starting with the International Geophysical Year of 1957-1958, and maturing during the International Decade of Ocean Exploration (1970s), the National Science Foundation (NSF) has become the principal federal agency funding basic ocean science research at academic institutions (NRC, 2000). Until the late 1960s, the U.S. Navy's Office of Naval Research (ONR) had been the main source of funding for academic oceanographers; the exception was biological oceanography, which has long received support from NSF and the Department of Energy. ONR still plays a vital role in oceanographic research, particularly in the development of new technologies and funding for academic research vessels. However, in the past few decades NSF has assumed a larger role both in the support of basic oceanographic research and in the provision of oceanographic facilities and support for new technologies. While other federal agencies such as the National Oceanic and Atmospheric Administration and the National Aeronautics and Space Administration play essential roles in ocean science advances, especially in support for monitoring and remote sensing facilities, NSF has become the primary funding agency for the U.S. academic oceanography research community.

The emergence of NSF as the prime funder of academic oceanographic research has been accompanied by an impressive expansion in the capabilities of sea-based platforms ranging from ships to autonomous sensors. These innovations have advanced our understanding of the ocean in unforeseen ways. Some examples of the advances achieved during just the past decade are highlighted in the next chapter.

Ocean science relies on infrastructure and technology to provide access to the ocean and to enable essential observations of key phenomena. While operating infrastructure is part of the cost of doing business in oceanography, it needs to be balanced against the cost of supporting scientists, their

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research, and training of their students and technical staff. For the purpose of this report, a "healthy balance" between the two is qualitatively defined as supporting sufficient infrastructure to provide access to the ocean and advance the science while maintaining sufficient funds for scientists and trainees to conduct research and provide value for the infrastructure investment.

The issue today—and a strong motivation for this report—is the growing community and agency concern that these two portfolio elements are not in balance and that the facilities are disproportionately consuming funds and leaving insufficient funding for scientists and research activities. How to determine, achieve, and maintain the correct balance between infrastructure and research is a great challenge and needs to be periodically evaluated as the community and technologies evolve. This will enable us to make the course corrections necessary for steering ocean sciences toward a vibrant future.

To help guide future investments in ocean sciences, NSF has sought community input on long-range research priorities and strategies for optimizing investments. Other disciplines within NSF and other federal agencies have conducted decadal surveys for strategic guidance on research priorities to maximize the effective use of limited resources. Although previous community-based efforts developed priorities for various segments of the ocean sciences, they were not explicitly constrained by resource availability or trade-offs among competing investments and hence did not address the broader issue of how to balance the full portfolio of NSF's ocean research investments when constrained by realistic budget scenarios and funding uncertainties.

In 2013, NSF's Division of Ocean Sciences (OCE) asked the National Research Council's (NRC's) Ocean Studies Board to undertake a decadal survey of ocean sciences to provide guidance from the ocean sciences community on research and infrastructure priorities for the coming decade. The request was preceded by extensive discussions between OCE and the Ocean Studies Board and consultation with members of the ocean sciences community, including other federal agencies.

As stipulated by NSF, the goal for this decadal survey is to provide a community-based, regularly recurring approach to the visioning and setting of NSF-funded research priorities in the ocean sciences within the context of likely available resources. The research portfolio includes investments in infrastructure, individual investigator-based science, multi-investigator large research programs, and cross-directorate initiatives like NSF's Science, Engineering, and Education for Sustainability (SEES). Infrastructure includes the academic fleet (surface and submersible platforms), ocean drilling platforms, ocean observing sensors and platforms, major shared-use instrumentation, cyberinfrastructure, and the development of new technological innovations. The geographic context includes all oceans of the world including polar regions, the seafloor, estuaries, the coastal zone, and the Great Lakes. Although this report focused primarily on OCE, other directorates as well as other divisions within the Directorate for Geosciences that support ocean sciences research were included. To place the NSF portfolio in the context of the full federal investment in ocean science, NSF asked for a consideration of the priorities and investments of other federal agencies in ocean sciences to identify potential areas for cooperation and collaboration. The full statement of task is provided in Box I-1.

COMMITTEE PROCESS

The Committee on Guidance for NSF on National Ocean Science Research Priorities: Decadal Survey for Ocean Sciences was convened by the NRC at the request of NSF. Committee members brought to this task a broad spectrum of knowledge and expertise related to ocean sciences; member biographies are provided in Appendix A. During the study, the committee convened five meetings that included information-gathering public sessions and two additional meetings in closed session to develop this report; public meeting agendas are listed in Appendix B. The committee actively sought participation from the ocean sciences community through town halls organized at the 2013 American Geophysical Union Fall Meeting (San Francisco, California) and 2014 Ocean Sciences Meeting (Honolulu, Hawaii), roundtables with early career scientists, and a Virtual Town Hall (see Appendix C for the online questionnaire) that provided opportunities for individuals to submit their ideas on ocean priorities for NSF in 2015-2025. In addition, the committee reviewed past reports regarding ocean science priorities and infrastructure, heard presentations from NSF leadership and staff, interviewed representatives of other ocean-related federal agencies, and listened to presentations by scientists involved in infrastructure programs.

Although the contributions of the ocean sciences community have been invaluable in guiding the work of the committee, the conclusions represent the deliberations of its members, who recognize the difficulty of the task and the reality that resolving current budget issues will impact existing programs. The committee focused on the long-term health of the ocean sciences with the goal of restoring a healthy balance to OCE's funding portfolio to sustain the ocean research enterprise into the future. Looking ahead, the committee developed the following vision for the ocean sciences in the next decade:

> *The ocean science community will undertake research and pursue discoveries that advance our understanding of the oceans, seafloor, coasts, and their ecosystems; foster stewardship of the ocean; reduce society's vulnerability to ocean hazards; and nurture and exploit the integration of the disciplines. A diverse and talented community of researchers will develop new technologies to study the ocean in novel and cost-effective*

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BOX I-1
Statement of Task

The committee for the Decadal Survey of Ocean Sciences 2015 (DSOS) will develop a list of the top ocean science priorities for the next decade in the context of the current state of knowledge, ongoing research activities, and resource availability. The DSOS committee's report will present a compelling research strategy for increased understanding of the oceans over the decade 2015-2025.

The report will include the following elements:

1. A review of the current state of knowledge that highlights findings and technologies over the past decade that have advanced our basic understanding of the oceans, driven new discoveries, created new paradigms, or established new societal imperatives. The review should also consider new science and technologies emerging from other disciplines that could be applied to the ocean sciences.
2. A concise set of compelling, high-level scientific questions that will be central to the ocean sciences over the coming decade and, if answered, could transform our scientific knowledge of the oceans. Prioritization may be derived from relevance to societal benefits, new technological breakthroughs, emerging or underdeveloped yet vital subjects poised for rapid development, or other drivers. The scientific questions and related priorities need not be all inclusive and should be limited to 10 or fewer. The goal is to identify areas of strategic investment with the highest potential payoff.
3. An analysis of the research infrastructure needed to address the priority research topics or questions. This will include an assessment of the current portfolio of multi-user facilities investments funded by NSF and their operational costs (information to be provided by NSF) as well as proposed new facilities. If new facilities are proposed, the committee will provide a range of estimates for the cost (upper and lower bounds) and include not only construction but also the full life-cycle costs for operations and maintenance. The analysis should also consider capacity to respond to unexpected events.
4. An analysis of the current portfolio of investments in ocean science programs at NSF with recommendations for changes necessary, if any, to align resources so as to achieve the priorities established in #2. The current portfolio includes programs within the Division of Ocean Sciences and allied program areas (e.g., Polar Programs, Biodiversity) as well as NSF-wide cross-divisional/cross-directorate initiatives that target highly interdisciplinary themes involving the ocean (e.g., SEES).
5. An identification of opportunities for NSF to complement the capabilities, expertise, and strategic plans of other federal agencies so as to avoid duplication of effort, encourage collaboration and shared use of research assets where appropriate, and maximize the value of NSF investments in the ocean sciences. This will be based on a brief survey of major ocean research programs funded by other federal agencies.

The final report will recommend a strategy to optimize investments that will advance knowledge in the most critical and/or opportune areas of investigation while also continuing to support core disciplinary science and infrastructure. The recommendations of the committee should include guidance on the most effective portfolio of investments achievable at the current funding level that will support both the research infrastructure (#3) and programmatic science (#4) necessary to address the most significant priorities. This should include assessing trade-offs among options and identifying potential cost-saving mechanisms; assessing the impact of new initiatives and/or modification of existing programs on the overall portfolio; as well as identifying opportunities for collaboration among the federal agencies that would leverage investments, optimize use of infrastructure assets, and foster multidisciplinary research. The report will include decision rules on how the program could be adjusted if future funding levels increase or decrease relative to the current level.

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Sea Change: 2015-2025 Decadal Survey of Ocean Sciences

ways and create innovative educational programs that will engage and inspire the next generation. Partnerships will be fostered across funding agencies, national borders, and the private sector to provide the greatest value for the nation's investment in ocean science.

The committee's approach and recommendations are guided by this vision, and although the words are from the committee, the content and focus derive from those with whom the committee spoke, from the Virtual Town Hall, from discussions at major ocean science conferences, and from presentations at committee meetings. The report begins with a retrospective of some of the major accomplishments in the field since the release of the last OCE decadal planning document, *Ocean Sciences in the New Millennium* (NSF, 2001). These accomplishments (Chapter 1) illustrate many of the strengths of the field that the committee highlights in the vision statement as being vital for future success. This analysis helped to inform the committee's approach to identifying science priorities for the next decade (Chapter 2). This chapter includes a description of the committee's strategy for developing research priorities, provides a short explanation of the importance of each priority, and lists examples of specific research questions that fall within them. Next, the report provides an overview of the current circumstances of OCE's budget, describes the major research infrastructure and facilities, and assesses the alignment of major infrastructure with the identified science priorities (Chapter 3). In Chapter 4, the committee provides a path forward, addresses the current fiscal challenges facing OCE, recommends guidance for OCE's budget decisions over the next decade, and discusses strategies to ensure a dynamic and productive research enterprise in the decades to come.

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1

21st-Century Achievements in Ocean Science

The remarkable thing is that although basic research does not begin with a particular practical goal, when you look at the results over the years, it ends up being one of the most practical things government does.
—President Ronald Reagan, Radio Address to the Nation on the Federal Role in Scientific Research, April 2, 1988

The 15 years since the turn of the millennium have brought dramatic changes in the collection, analysis, and distribution of information across many sectors of society, creating tremendous new opportunities in the sciences. In the ocean sciences, advances in observational and computational capabilities have led to rapid increases in understanding—from the minutest organisms to the vast expanse of the ocean basins. Ocean biologists and biogeochemists applied molecular biology techniques to understand the diversity and function of marine life, while satellites and autonomous sensor systems have revealed a dynamic global ocean on unprecedented temporal and spatial scales. Precise measurements of ocean chemistry have shown a decline in ocean pH, prompting studies on its potential impact on marine organisms and ecosystems. Advances in seafloor exploration have documented eruptions on the deep seafloor, discovered new morphologic features, and uncovered active subseafloor microbial communities. Predictability of the dynamic variability of ocean and climate systems at all scales has been enhanced by new observing technologies and analytical strategies, including improved models.

The accomplishments summarized below represent significant advancements in ocean research and reflect support and innovations from federal agencies, some foundations, and many nations. They were selected from government, international, National Research Council, and academic reports from roughly the past 15 years; from Division of Ocean Science (OCE) highlights provided by National Science Foundation (NSF) program officers; from the primary literature; and from discussions within the committee. While no such list can be truly comprehensive, this chapter captures some of the most exciting developments in ocean science that have yielded rapid increases in knowledge and major advances in understanding of the ocean over the past decade.

THE OCEAN COMPONENT OF CLIMATE VARIABILITY AND CHANGE

Sea level rise varies greatly across geographic regions. If the ocean were simply a giant bathtub, sea level rise from increasing ocean temperature and additional water from melting land ice would occur uniformly. However, a variety of physical and geological processes cause water levels to increase dramatically in some regions while others see little to no change or even declines. Sea level along the U.S. eastern seaboard is a striking example—sea level is rising faster between Cape Hatteras, North Carolina, and Cape Cod, Massachusetts, than anywhere else along the East Coast (Figure 1-1). This is vital information for coastal engineers, planners, and communities.

Arctic summer sea ice volume over the past decade has decreased on a trajectory that is steeper than other indicators of global change. Unlike many climate change signals, the loss of Arctic sea ice has been remarkably persistent—its volume has decreased by a factor of 5 in the September minimum between 1979 and 2014 (Figure 1-2). This ice loss has geopolitical and ecological consequences. Increased opportunities for shipping, cruise ship tourism, hydrocarbon resource exploitation, and fishing heighten the potential for large-scale search-and-rescue missions, oil spill response, and international disputes that can increase national security concerns. The effect of an ice-free Arctic on the global climate system, and in particular mid-latitude weather patterns, is still unclear. However, the decreased reflectivity of sunlight (albedo) in an ice-free Arctic points

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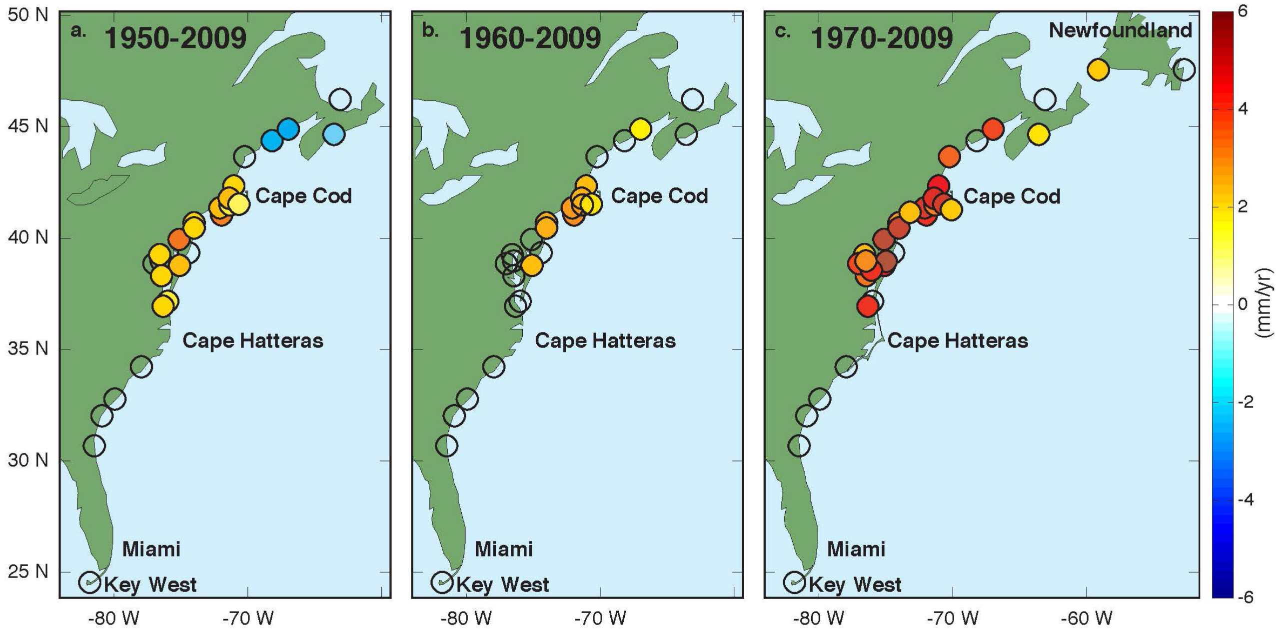

FIGURE 1-1 Sea-level rise rate differences for a 60-year time series at tide gauge locations across the East Coast of North America. SOURCE: Sallenger et al., 2012.

to further amplification of regional warming, suggesting that loss of sea ice could be irreversible.

The first seafloor drilling in the perennially ice-bound central Arctic showed a transition from a warmer "greenhouse" climate ~55 million years ago to a colder environment ~45 million years ago that continues to the present. Seafloor sediment cores indicated that surface temperatures ~55 million years ago were significantly warmer, supporting the hypothesis that the earliest Arctic cooling occurred at the same time as cooling in Antarctica and that climate change was symmetric at the poles. Additionally, the cores documented a transition from poorly to fully oxygenated sediments in the Arctic, attributed to the opening of the Fram Strait, which permitted deep-water exchange between the Arctic and North Atlantic Oceans. The effects of albedo, temperature, and oxygen variations determined from these cores helped illuminate the history of the Arctic circulation regime, which is key to successfully modeling global thermohaline circulation and the global climate system.

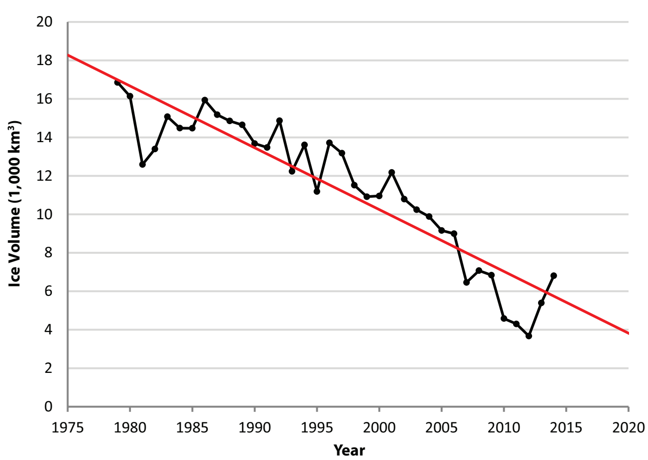

FIGURE 1-2 Yearly minimums of Arctic ice volume from 1980 to 2014 calculated using the Pan-Arctic Ice Ocean Modeling and Assimilation System (Zhang and Rothrock, 2003). The red line shows the linear trend. Data from the Polar Science Center, Applied Physics Laboratory, University of Washington.

Reconstruction of climate patterns from the geologic past reveals causes and effects of climate change that are relevant for interpreting modern climate patterns. Methodological improvements have increased the chronological precision for accelerator mass spectrometry measurements and radiocarbon calibration; uranium-series dating of corals, speleothems, and lake carbonates; layer counting in sediments and ice cores; trace gas, O_2/N_2, and isotopic measurements in ice cores; and zircon U/Pb and $^{40}Ar/^{39}Ar$ dating. This new information reveals event sequences and helps to diagnose causes and effects of the dynamically changing Earth system and resolves an apparent paradox in climate patterns and elevated atmospheric CO_2 in the Northern and Southern Hemispheres.

Based on more accurate chronologies, the global-scale paleotemperature compilation shows that increases in global and Northern Hemisphere temperature lag behind the rise in

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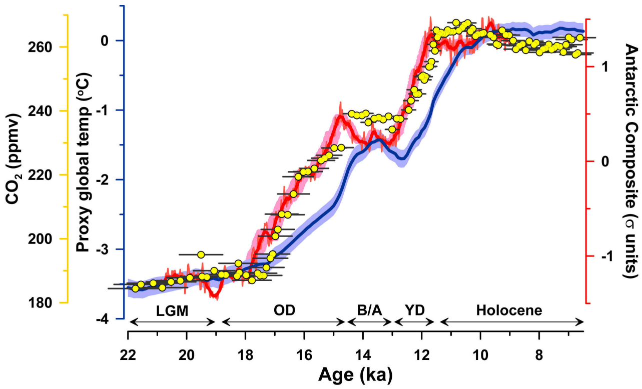

FIGURE 1-3 Global proxy temperature (blue) and Antarctic ice-core composite temperature (red) during the last deglacial transition, compared to atmospheric CO_2 concentration (yellow circles). Abbreviations are as follows: LGM, Last Glacial Maximum; OD, Oldest Dryas; B/A, Bølling-Allerød; and YD, Younger Dryas. SOURCE: Shakun et al., 2012.

atmospheric CO_2 by an amount consistent with the thermal inertia of the global ocean-ice system (Figure 1-3). Paradoxically, high-latitude Southern Hemisphere climate records show warming prior to the increase in CO_2. New findings indicate that natural sources and sinks of carbon and dynamic controls of regional warming are linked to ocean circulation, providing an explanation for the apparent paradox from Southern Hemisphere ice core data. This synthesis of information provides compelling evidence from the geologic record that greenhouse gases are a powerful force for global climate change.

The ocean's overturning circulation varies in both space and time, with significant variability on time scales less than a year and with spatially non-uniform upwelling. Recent observations and modeling results have challenged the "great ocean conveyor belt" paradigm. For decades oceanographers assumed that the overturning circulation changed gradually, that its strength was coherent across the entire Atlantic, and that the deep currents were concentrated along the western boundaries of the basins. Instead, it is now understood that the overturning circulation is marked by strong temporal and spatial variability and that the deep waters' equatorward pathways include the ocean interior. The Southern Ocean plays a key role in returning deep waters to the surface via wind-driven upwelling. This more sophisticated view of ocean circulation, which is the result of the international observational programs as well as the novel use of Lagrangian floats, opens new avenues for understanding ocean heat, freshwater, and carbon transport.

More comprehensive data from the Argo array augments 50 years of historical data to measure with high certainty the multi-decadal warming of the global oceans and changes in ocean salinity patterns. Heating rates have been estimated at 0.45 ± 0.15 W/m^2, averaged over the surface area of the Earth. The increase in ocean heat content represents about 90% of the net energy imbalance in the total climate system. Most of the present ocean heat content increase is in the extratropical Southern Hemisphere. Compared with the relatively steady and continuing increase in ocean heat content (or vertically averaged temperature), the mean surface temperature of the ocean and of the base of the marine atmosphere is more variable. For example, data [significantly augmented by the Argo program (Box 1-1)] show that the recent much-discussed "pause" in warming is confined to surface temperature data and that upper ocean heat content (to 2,000 m depth) has increased unabated. Multi-decadal trends in upper ocean salinity indicate that the relatively fresh regions of the oceans have become fresher and the salty regions saltier, consistent with enhancement of the mean patterns of evaporation minus precipitation. Argo is a case study of how transformational discoveries result from a good alignment of infrastructure with science priorities.

BIOGEOCHEMICAL AND ECOLOGICAL DIMENSIONS OF A CHANGING OCEAN

About one-third of the CO_2 released to the atmosphere by human activities has been absorbed by the ocean, causing a decline in the pH of upper ocean waters (often called "ocean acidification"). Changing ocean pH can affect the physiology, behavior, growth, and reproduction of marine organisms. The deleterious effect of this altered chemistry on the success of organisms that make calcium carbonate skeletal material or shells (e.g., corals, mollusks) has already been documented. This can have lethal impacts; for example, molluscan larvae that fail to produce a sufficiently calcified first shell that is needed to attach to hard substrate for maturation. In some regions, this is causing massive hatchery failures for coastal oyster aquaculture. Planktonic mollusks that have delicate shells, such as pteropods, are important components of oceanic food webs, and significant changes in their abundance could impact valuable fisheries (e.g., the Pacific Northwest salmon).

The prevalence of oxygen-depleted waters is increasing in many coastal and deeper ocean areas. Rivers carrying nitrogen and phosphorus from urban waste systems and from agricultural application of fertilizers have fundamentally altered many coastal ecosystems, stimulating phytoplankton blooms (Figure 1-4). When phytoplankton growth exceeds the capacity of zooplankton grazers, the excess production sinks and is biodegraded by bacteria that consume oxygen. In extreme cases, the bottom waters become hypoxic or even anoxic, often referred to as "dead zones" because most fish and other marine life cannot survive there. Excess algal growth also reduces the clarity of water in shallow coastal areas, blocking sunlight that is necessary for maintaining sea grasses and coral reefs, which provide essential habitat for fish and invertebrates. In some areas on the U.S. Pacific Coast, influxes of low-oxygen water have been

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BOX 1-1
The Argo Program

As the first observing system for the global subsurface ocean, the international global Argo array of over 3,000 profiling floats has transformed how large-scale ocean processes are studied and has blazed organizational trails that may guide developers of future oceanographic observing infrastructure. Argo is based on technology developed under NSF and the Office of Naval Research (ONR), specifically designed to study ocean properties on basin scales as part of the World Ocean Circulation Experiment. Buoyancy engines were added to neutrally buoyant Swallow floats so they could repetitively profile from the subsurface to the surface, where they could obtain satellite navigation and relay data. Argo uses improved versions of these floats to report, in real time, subsurface velocity and profiles of temperature and salinity to 2,000 m depth from across the ice-free global ocean.

Arguably more innovative than its technology was the way the Argo program was developed. In the 1990s, the World Ocean Circulation Experiment and the Tropical Ocean Global Atmosphere program accelerated scientific and operational interest in the ocean's role in climate and in predicting climate variability. By 1999, satellite altimetry had revolutionized oceanography by showing that sea surface height was dominated by variability patterns like El Niño and by slower global trends. To meet the operational and scientific needs for complementary subsurface ocean observations, Argo was established by what may be oceanography's most effective international collaboration. U.S. Argo (initially a National Oceanic and Atmospheric Administration [NOAA]/ONR National Oceanographic Partnership Program program, now NOAA-funded) and many national partners agreed to build Argo as an international collaboration dedicated to providing publicly available, real-time data for joint scientific and operational use.

Technical improvements to float reliability and lifespan, aggressive use of ships of opportunity, and an innovative internationally coordinated data quality control system led to the program surpassing its goals for float lifespan, data quality, and speed of data delivery. Today 11,000 profiles are collected from a uniformly distributed global array every month at a cost of $170 per profile. In comparison to the 1.2 million profiles obtained by Argo, only about 500,000 temperature/salinity profiles were collected by ships, mostly in the Northern Hemisphere, since the late 1800s. Figure a shows how Argo has supplanted other methods of profiling, increasing the rate of acquisition of upper ocean temperature and salinity profiles. Moreover, the Argo program has achieved almost uniform geographic coverage of the ice-free ocean, shown in Figure b. Its greatest scientific impact is in temperature/salinity profiles in the Southern Hemisphere, where Argo has contributed over an order of magnitude more samples than have ships.

Argo users include operational centers that typically use near-real-time data for ocean state estimation and prediction and researchers that use quality-controlled data (delayed ~1 year) to publish over 1,700 scientific papers (www.argo.ucsd.edu/Bibliography.html). These systematic ocean observations have proven essential to studies of climate and air-sea phenomena including rapid weather events, interannual-to-decadal climate variability, water mass formation, and key processes of air-sea exchange and oceanic transport in the global hydrologic and heat cycles.

Argo continues to evolve, with a broader observational scope to better describe a range of large-scale phenomena. New floats will extend Argo coverage to 4,000-6,000 m depth and carry Argo to seasonal ice coverage in high latitudes, while coverage in marginal seas and enhanced sampling in western boundary current regions is planned. Technologists around the world are working to extend working lifetimes and reduce energy use of a wide range of biogeochemical sensors and improve biological sampling methods. This effort will transform areas of oceanography that need long-term global water-column observations. Many of these observations will be made independently by small groups, but a coordinated effort will be needed to achieve sustained global coverage. This new effort should benefit from what made Argo successful:

- narrow, well-defined observational goals aimed at widely appreciated scientific and operational issues;
- broad international and multi-agency support based on meeting societal needs as well as science;
- tenacious championship within academia, industry, and government agencies;
- commitment to publicly available data, which demands careful open data-quality control;
- sensors that are well matched to float capabilities and the demands of low-cost deployment; and
- freedom for methods and technology to evolve, subject to clear performance requirements.

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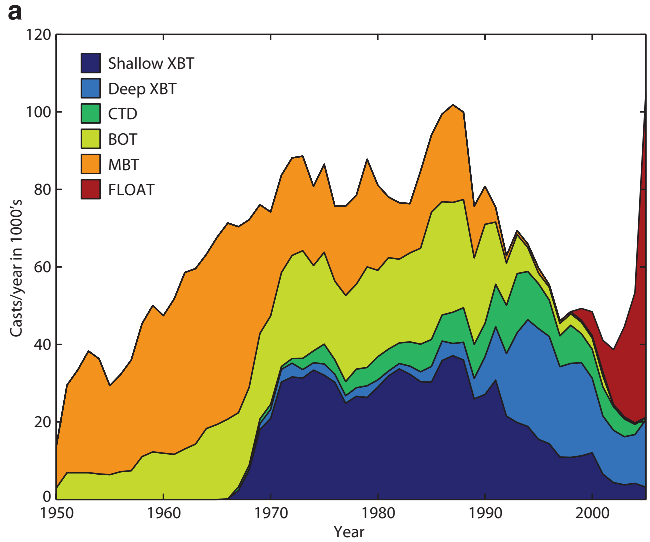
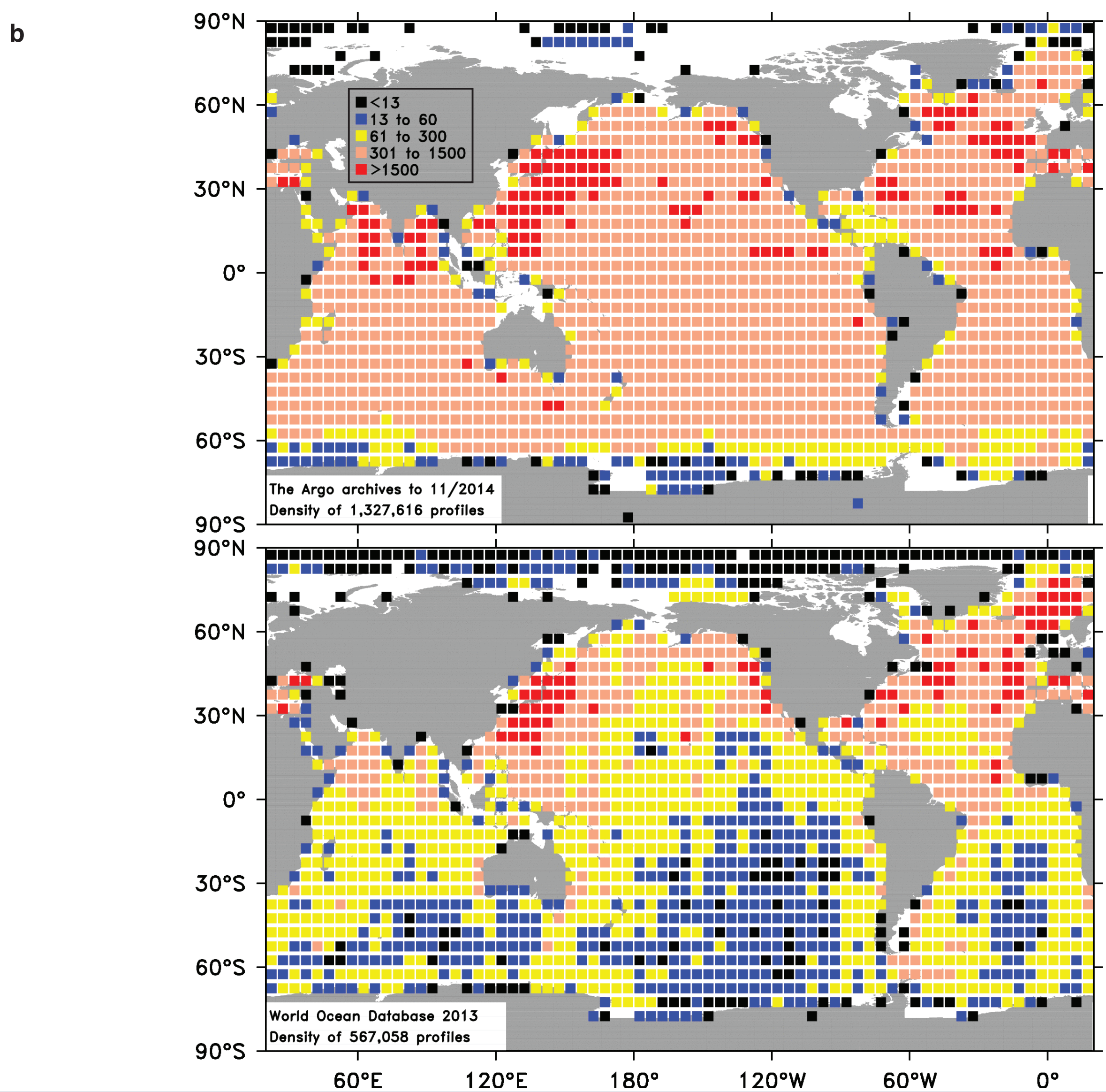


FIGURE a The mix of ocean observation platforms from 1950 to the present. The number of ocean profiles taken per year in historical archives is charted by instrument type: XBT, expendable bathythermographs; MBT, mechanical bathythermographs; CTD, conductivity-temperature-depth instruments deployed from ships; BOT, Nansen and Niskin bottle casts; and FLOAT, CTD-equipped profiling floats. SOURCE: Johnson and Wijffels, 2011.

FIGURE b Number of temperature/salinity profiles to at least 1 km depth per 5° × 5° square collected by (top) Argo through 2014 and (bottom) all years from the World Ocean Database of ship-based profiling. SOURCE: Used with permission from Dean Roemmich.



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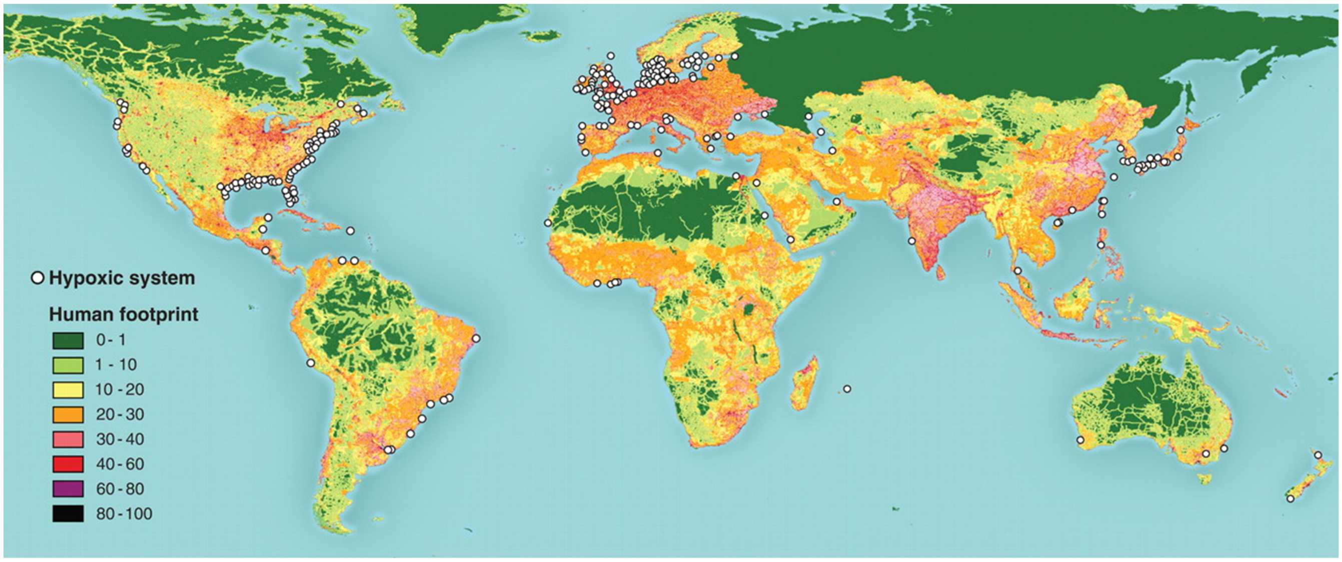

FIGURE 1-4 Incidences of dead zones from hypoxic systems in coastal regions, as well as the "human footprint" on land. The human footprint is a measure of potential human influence on the land surface, determined by population density, land transformation, access, and electrical power infrastructure (Sanderson et al., 2002). SOURCE: Diaz and Rosenberg, 2008.

associated with shoaling of deeper water rather than runoff of nutrients from land-based sources. The North Pacific has experienced oxygen declines for the past 50 years, possibly due to changes in ventilation from increased freshening of surface waters and atmospheric warming. Because the hypoxic zone in the North Pacific is the most extensive and the shallowest of the major oceans, relatively small oxygen decreases in deep water will impact the essential habitat of many species in the food web. A decline in the oxygenation of the deeper waters may be a result of a warmer, more strati-

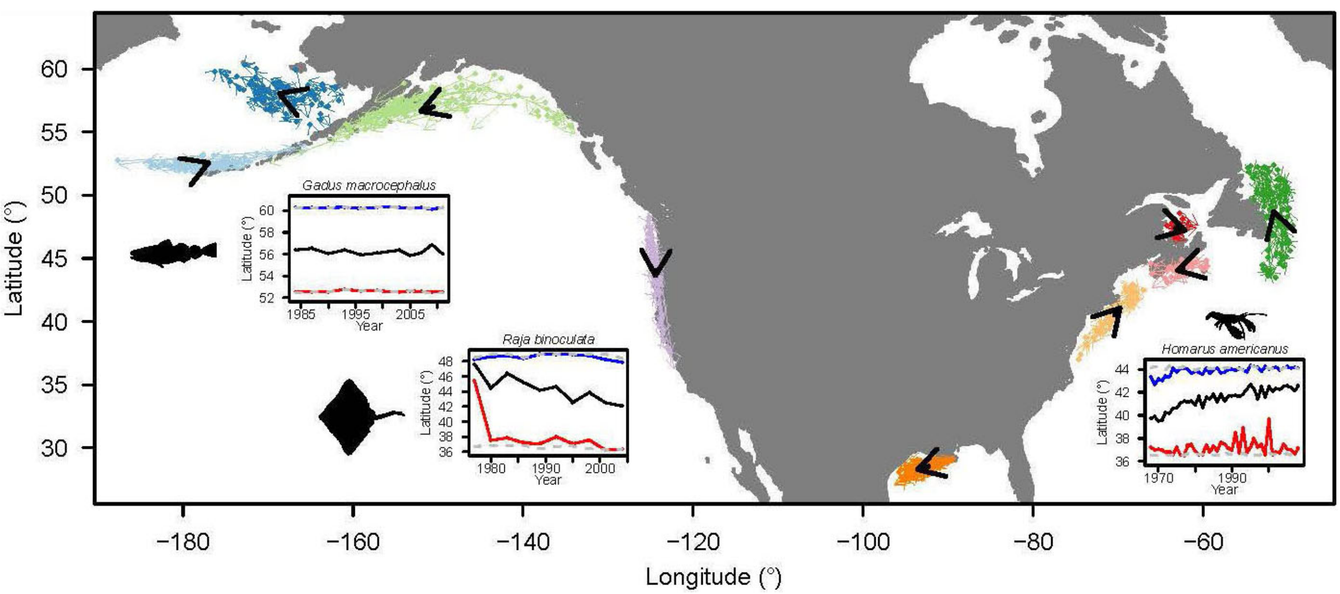

FIGURE 1-5 Shifts in the distribution of marine taxa. Black arrows show the mean shift of surveyed taxa in each region. Inset graphs show the mean (black), maximum (blue), and minimum (red) latitude of detection for Pacific cod (*Gadus macrocephalus*) in the Gulf of Alaska, big skate (*Raja binoculata*) on the U.S. West Coast, and American lobster (*Homarus americanus*) in the Northeast as examples. Gray dashed lines in insets indicate the range of surveyed latitudes. SOURCE: Pinsky et al., 2013.

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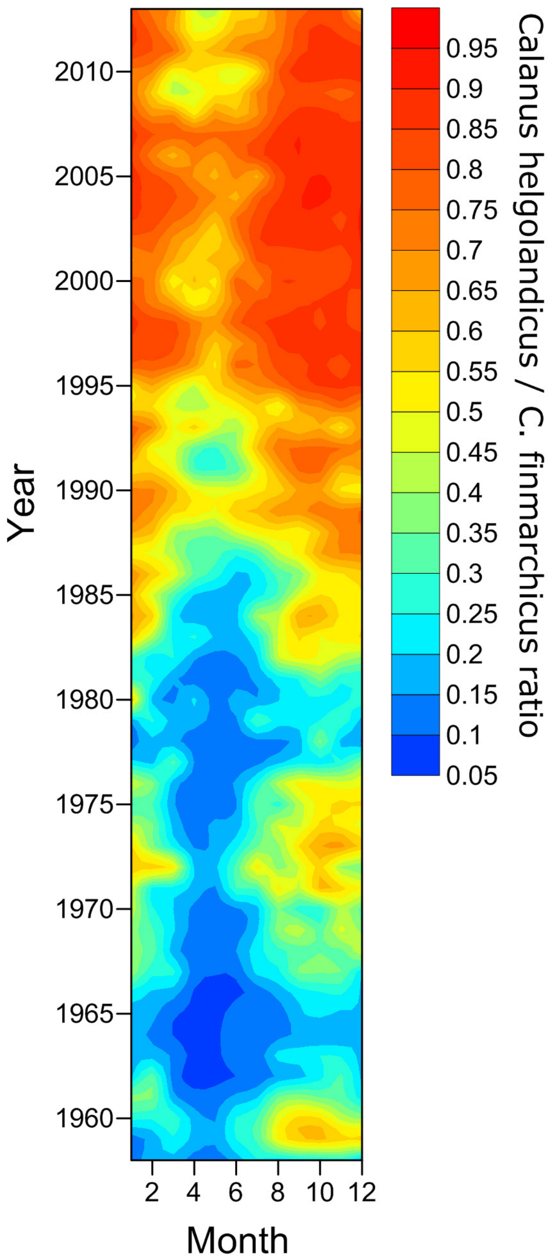

FIGURE 1-6 Monthly ratio of a warm-water copepod species (*Calanus helgolandicus*) to a cold-water species (*Calanus finmarchicus*) from 1958 to 2012 as averaged over the North Atlantic. Red values indicate dominance of the warm-water species and blue values indicate dominance of the cold-water species (0, total *C. finmarchicus* dominance; 1, total *C. helgolandicus* dominance). SOURCE: Used with permission from David Johns, Sir Alister Hardy Foundation for Ocean Science.

fied surface layer and, therefore, could be an early manifestation of climate change. A multiple-stressors approach will be needed to tackle the effect of concurrent stressors such as lower pH and oxygen.

The geographic distribution of ocean life—including phytoplankton, zooplankton, fish, and marine mammals—is shifting, affecting the structure of marine food webs. The ecological effects of global warming include poleward shifts in some species distributions (Figures 1-5 and 1-6) and/or changes in the timing of species migrations. These shifts did not occur as a linear effect of ocean warming; rather they are due to complex interactions of the biota with physical oceanographic properties such as currents, fronts, and eddies (e.g., some species seek greater depths instead of poleward migration to maintain optimal temperature conditions, especially in semi-enclosed seas). The shift of species distributions occurs at different rates, suggesting that large-scale population shifts may create new ecosystem associations over time. These changes are expected to have profound impacts on marine ecosystem productivity, with consequences for human communities that depend upon them.

BIODIVERSITY, COMPLEXITY, AND DYNAMICS OF OCEAN ECOSYSTEMS

Direct sequencing of DNA from the environment revealed the vast complexity, physiological capabilities, novel biogeochemical pathways, and species interactions of the microbial ocean. Analysis of DNA in seawater samples has revealed that the great majority of the microorganisms in the ocean have yet to be cultured or characterized. Viruses have been shown to influence marine microbial populations, from triggering the end of an algal phytoplankton bloom to changing the composition of bacterial communities. DNA sequencing technology has also contributed to efforts to catalog the diversity of larger, multicellular marine life through an international program known as the Census of Marine Life (Box 1-2).

Overfishing has had profound effects on marine species and ecosystems. Marine species are dynamically connected, directly and indirectly, such that human interventions—from extractive activities such as fishing to conservation efforts such as habitat restoration—have the potential to affect the ocean's trophic structure. Research and management actions have revealed the deep interdependencies among ecological, economic, and social systems. Data from long-term monitoring programs in large marine ecosystems have documented the profound effects of overfishing and sequential depletion on the productivity and species compositions of marine ecosystems, including cascading impacts throughout the ecosystem due to the removal of top predators. Regionally based ecosystem monitoring, such as the international program Global Ocean Ecosystem Dynamics (GLOBEC) and the California Cooperative Oceanic Fisheries Investigations (CalCOFI), clearly demonstrated the impacts of overfishing, including the functional replacement of high-value stocks with less valuable fish species (Figure 1-7). Increased public awareness of the vulnerability of marine

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BOX 1-2
A Decade of Discovery of Marine Life

The Census of Marine Life (CoML) was a decade-long global effort dedicated to discovering new species and habitats in all marine realms. Harnessing the efforts of over 2,700 scientists in more than 80 countries, over 500 expeditions were undertaken (http://www.coml.org/about-census). Results of the CoML documented at least 1,200 new species, potentially increasing to over 6,000 new species once all the data are fully analyzed. Not since the *Challenger* expeditions of the 1870s was there such a comprehensive effort to discover marine life in the global ocean. The CoML employed modern sampling and genetic techniques to identify species from microbes to mammals and established baseline information regarding the abundance, distribution, and diversity of marine life. One legacy of the program is the Ocean Biogeographic Information System, an online repository of georeferenced data that can be used to study how marine species distribution and abundance may be influenced by global climate change. The program was spearheaded by the Sloan Foundation, which provided the initial funding and helped to leverage a total of over $650 million for the program.

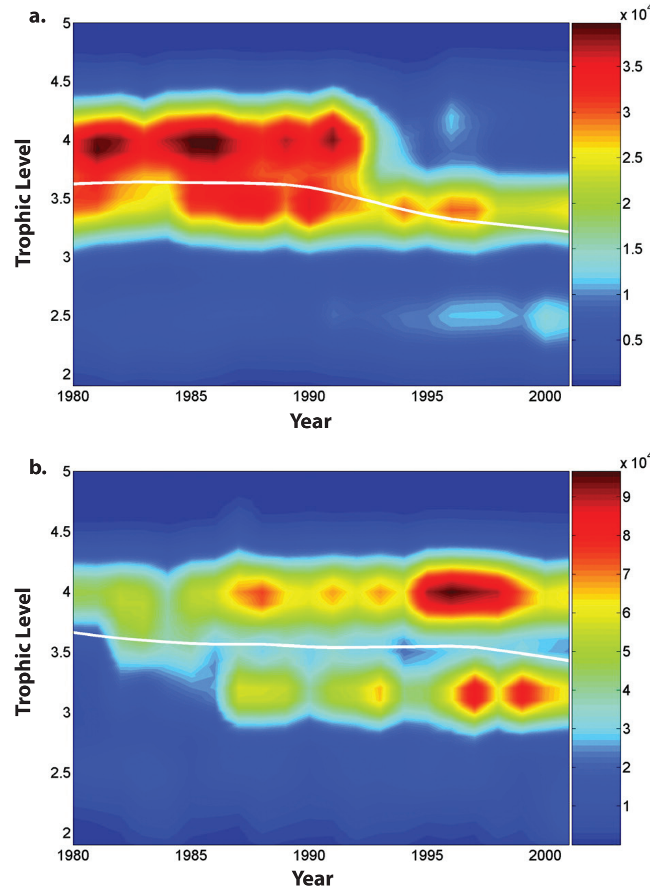

FIGURE 1-7 Illustrative examples of fishing down the food web characterized by (a) sequential collapse followed by replacement mode and (b) sequential addition mode. Total yearly catch for each 0.1 trophic-level increment is indicated by the color bar on the right (104 kg/year). The mean trophic level (white line) was created by using a locally weighted regression smoother. (a) The Scotian Shelf ecosystem exhibited a sharp decline in mean trophic level from 1990 to 2001 owing to the collapse of the cod fishery followed by a decline in the herring fishery and then the growth of the northern prawn fishery. (b) The mean trophic level of the Patagonian Shelf declined from 1980 to 2001, during which time catches for upper-trophic-level species (Argentinean hake) grew substantially while new fisheries for shortfin squid developed. SOURCE: Essington et al., 2006.

ecosystems to human activities has led to new national and international management policies and some successes with ecosystem recovery.

THE SEAFLOOR IS GEOLOGICALLY, PHYSICALLY, AND BIOLOGICALLY DYNAMIC

The Hawaiian hotspot is created by mantle upwelling beginning more than 1,000 km beneath Earth's surface. The largest ocean bottom seismometer deployment of the past decade, the Plume-Lithosphere Undersea Mantle Experiment (PLUME), demonstrated that upwelling beneath Hawaii begins in the lower mantle, refuting a hypothesis that all volcanic hotspots originate within the upper mantle. Combined with petrological studies and geodynamical modeling, experiments like PLUME reveal the pattern of mantle convection beneath the plates. Paleomagnetic and age-dating studies using samples from the Louisville and Hawaiian seamount chains (obtained by scientific ocean drilling) have shown that mantle convection has caused the two hotspots to migrate independently.

Anomalous ridge features and hydrothermal activity reveal the flow of fluids and magma through the ocean floor. Seafloor mapping demonstrated the existence of hydrothermal activity and pyroclastic volcanic materials at super-slow-spreading mid-ocean ridges, while other parts of these ridges appear to be completely lacking in volcanic activity (Figure 1-8). These observations challenge the existing plate tectonic paradigm and indicate that mantle melting is not

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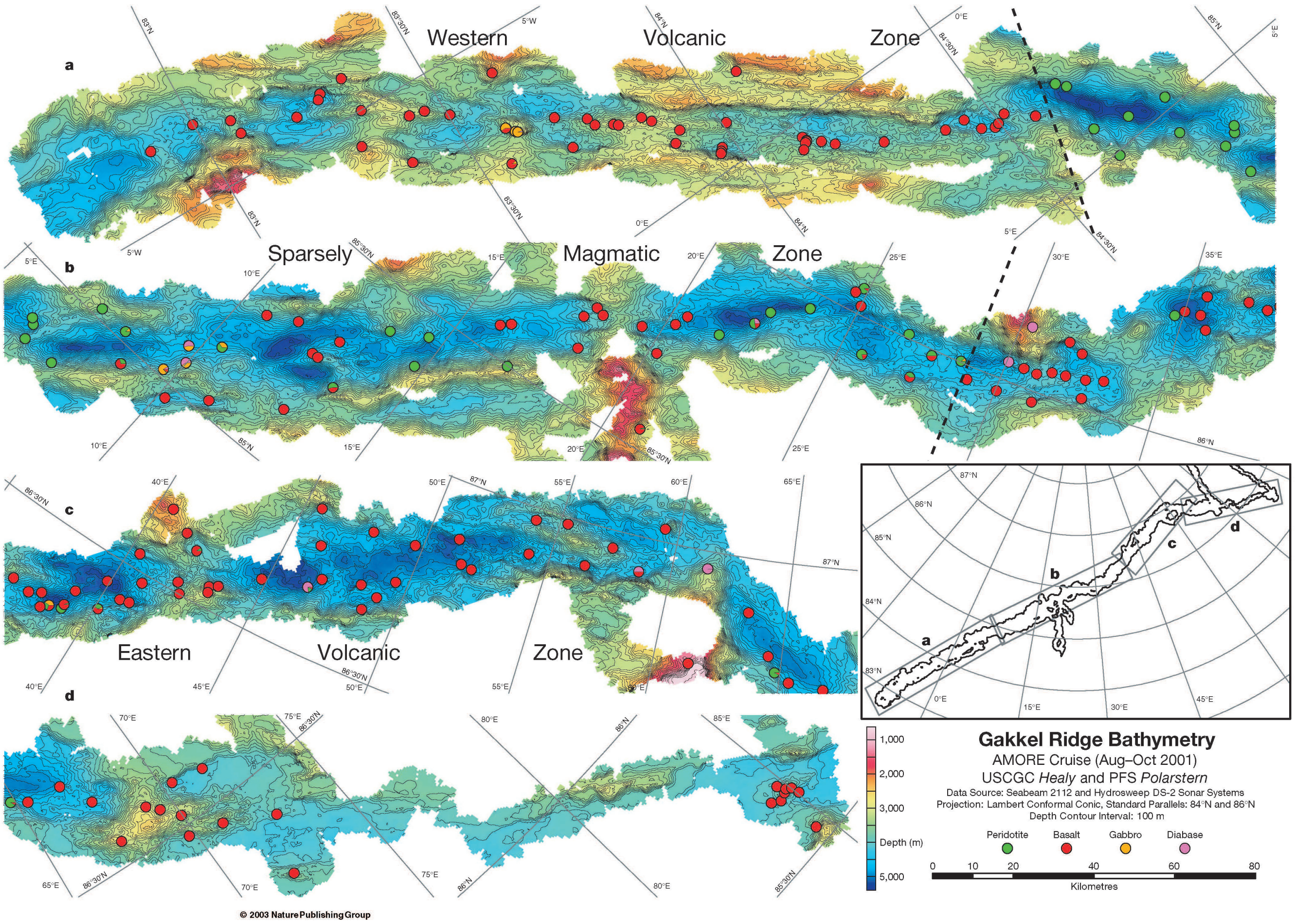

FIGURE 1-8 Bathymetry of the Gakkel Ridge overlaid with a range of lithologies recovered by dredge (basalt [red], peridotite [green], gabbro [orange], diabase [blue]). The western volcanic zone terminates at the eastern end of panel a. The sparsely magmatic zone continues to the eastern end of panel b. The eastern volcanic zone includes the eastern end of panel b as well as panels c and d. SOURCE: Michael et al., 2003.

simply a function of spreading rate but rather has a complex, poorly understood relationship. Hydrothermal processes in the ridge system influence ocean chemistry, contribute to mineral deposits, and provide habitats that support novel biological communities.

Surprising slip behavior is observed in fault zones. In some subduction zones, slow magnitude 7 earthquakes regularly occur at depths just beyond the zone that produces great earthquakes. These events last approximately 2 weeks, rather than slipping in a few seconds like typical earthquakes, and may be involved in triggering the occasional shallower earthquakes. In the great Tōhoku earthquake seaward of Japan in 2011, the huge tsunami was generated in part by as much as 50 m of slip on the fault at the trench axis in a portion of the subduction zone that was previously expected to slip gradually and quietly rather than suddenly. Using the *Chikyu* drillship, an Integrated Ocean Drilling Program expedition drilled into the toe of the Tōhoku fault zone and demonstrated that the unusual amount of slip was facilitated by a thin, very weak layer of clay. Understanding the controls on the nature of the slip along subduction zones could lead to better earthquake and tsunami forecasting and reduce the lag between event detection and response to major earthquake events.

A widespread and diverse microbial biosphere has been encountered beneath the ocean floor, and each new discovery produces new implications for global energy and carbon cycles. This subseafloor biosphere derives energy, in part, from the weathering products of oceanic crust and the availability of oxidants through subsurface circulation. The deep biosphere may represent a significant fraction of the total living biosphere on Earth, but it remains the least explored. Research on the subseafloor biosphere may have the potential for identifying new species, metabolic properties, and unique biochemical pathways that could be of value for biotechnology applications.

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NEW TECHNOLOGIES ENABLE EFFICIENT COLLECTION OF GLOBAL OCEAN DATA

New sensor, vehicle, and laboratory technologies have revolutionized ocean observing by decreasing the cost of many observations; increasing resolution and accuracy in support of discovery, quantitative studies, and modeling; and enabling physical, chemical, and biological observations that were previously impossible. Great progress has been made with sensors to characterize acidification, the carbon and nutrient cycles, and the planktonic food web.

Miniaturized satellite-tracking tags on a variety of marine animals have disclosed migration paths, such as the trans-Pacific trek of leatherback turtles and the white shark aggregations midway between Baja California and Hawaii. Migratory paths and aggregations indicate behavioral strategies and the degree of interconnectivity of populations—vital information for fisheries management and conservation.

Genomics, the study of an organism's DNA, has expanded over the past decade into "omics," a collection of technologies to explore the relationships and actions of genes, proteins, and small metabolites. This is one example of how transformational discoveries in another discipline—biomedical science—have been applied to significant questions in ocean science. Two key advances made this possible: rapid high-throughput sequencing and mass spectrometric analysis of macromolecules, and bioinformatics to manage and analyze the vast data volumes generated. As speed, versatility, and affordability have increased, "omics" has moved from national facilities to individual laboratories and research ships, fostering discovery and experimentation. Metagenomics can be used to assess and quantify microbial diversity and functions, while metatranscriptomics and metabolomics can provide information on metabolic activities and may even lead to the discovery of novel biogeochemical pathways.

Robotic sensing is also revolutionizing physical measurements in the ocean. A collaboration of many nations established the Argo array of more than 3,000 profiling floats to measure changes of temperature and salinity in the ocean's upper 2,000 m (Box 1-1). These variables directly address the global heat budget, the water cycle, and the ocean dynamics affecting them. Argo data accurately determine upper ocean heat content and have shown that subsurface ocean warming has been relentless, even as surface temperature increases slowed over the past 15 years. Expanding the global float array to full ocean depth and adding chemical and biological sensors is under way.

The widespread use of unmanned research vehicles is transforming oceanographic infrastructure. Large, powerful, and fast autonomous underwater vehicles (AUVs) are increasingly used in research and exploration. High stored energy and payload enable large sensor suites, water sampling, operations under ice, and high-resolution mapping to reveal geological features and processes (in addition to high-resolution mapping from ships [Box 1-3]). Easier handling and long ranges free some AUVs and buoyancy-driven gliders from ship support, enabling operations under ice or in remote locations and making sustained sampling feasible, particularly near coasts. Small, low-power sensors are now regularly monitoring physical, chemical, and biological indicators of dynamical variability and ecosystem variations in coastal and island settings.

Sustaining very long-term observations at low cost by harvesting energy from the environment is also a theme of recent, compelling technological advances. Particularly at the ocean surface, where wind, solar radiation, and surface waves are high-intensity energy sources, vehicles and moored sensor suites are becoming environmentally powered. Small surface vehicles and moored wire-walking profilers harvest wave energy for propulsion, increasingly affordable solar panels and improved methods of keeping them clean make solar power ever more useful, and modernized

BOX 1-3
Advances in Bathymetric Mapping

Multibeam and sidescan sonars, used to map seafloor bathymetry and reflectivity, were first installed on research vessels and towed vehicles in the 1960s. By the 1980s, these systems played an integral role in most seagoing research programs, documenting the shape and texture of terrain with ever-increasing levels of resolution and precision. The resultant maps were essential to seafloor sampling operations and provided fundamental base maps for integration with other geophysical data such as gravity, magnetics, and subseafloor structure. Acquisition of acoustic data from the ocean surface, however, could only advance so far—physical processes such as the attenuation of sound waves in water; the effects of temperature, pressure, and salinity variations; as well as noise from waves, wind, fauna, and ships ultimately limit the ability of an ocean surface system to map the ocean bottom. Since the 1990s, seafloor mapping has instead advanced through technological innovations that include migration of acoustic systems to unmanned vehicles; integration of precise, high-sample-rate orientation information provided by sophisticated, high-precision referential motion sensors; and increased capacity and speed of data acquisition and processing. These advances have enabled changes in the seafloor to be quantified through repeated surveys.

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forms of the sailboat and windmill abound. Energy has also been harvested from the ocean's thermal stratification by vertically profiling vehicles, but the small ocean temperature difference from surface to depth has hindered their efficiency.

COLLABORATIONS ADVANCE OCEANOGRAPHY ACHIEVEMENTS

Federal Partnerships

In addition to the accomplishments highlighted above, there have been many contributions arising from cooperatively funded programs and partnerships, both federal and international. A few examples to illustrate how these joint activities can foster advances in scientific knowledge and support the missions of the federal ocean agencies are provided.

ONR's major collaborations with NSF have been in the provision of ships, tools, and sensors. NSF has greatly benefited from ONR's sustained investments in infrastructure and sensors such as *Alvin*, moorings, current meters, conductivity-temperature-depth and microstructure sensors, bioacoustics, autonomous underwater vehicles, Argo development, and gliders.

NSF, NOAA, the Environmental Protection Agency, ONR, and the National Aeronautics and Space Administration have cooperatively funded programs on the ecology of harmful algal blooms for over a decade. These projects have led to breakthroughs in understanding the mechanisms that underlie development of harmful algal blooms and their impacts on ecosystems, fisheries, and local economies, as well as potential management strategies.

NOAA and NSF cooperated on international GLOBEC studies in the Northwest Atlantic, the Northeast Pacific and Gulf of Alaska, and the Southern Ocean over the course of a decade. The studies were a successful interdisciplinary effort to assess the impact of global change on physical and biological oceanographic processes with a focus on economically valuable fisheries.

The National Institute of Environmental Health Sciences worked with NSF and NOAA on an interagency effort on oceans and human health, which established new centers and forged new research directions on marine toxins and disease and led to discoveries of natural products with potential pharmacologic value.

International Partnerships

The United States (through NSF and ONR), has often played a major role in large, international ocean science programs. Although internationally planned and coordinated oceanography involves some upfront costs in terms of efficiency and management, these programs have often demonstrated that significant achievements can be gained that otherwise would not have occurred. Some examples of past successes in international ocean science research are described below. These examples are illustrative and not exhaustive, chosen to demonstrate the scope and high value of activities.

The World Ocean Circulation Experiment Hydrographic Survey was the first attempt to measure and map the global ocean's physical properties, using a common measurement protocol. Many nations contributed their research vessels to the multiple legs that comprised the survey. The ongoing international Argo program (Box 1-1) can be viewed as a continuation of the survey.

The Integrated Ocean Drilling Program (IODP [2003-2013]) and the current International Ocean Discovery Program (IODP [2013-2018]) have the objective to advance the understanding of the subseafloor environment by utilizing specialized drilling platforms to sample, install instrumentation, and monitor conditions. IODP (2013-2018) involves partnerships among 26 nations.

The Joint Global Ocean Flux Study international program pooled oceanographic resources of several nations to mount a major study of biogeochemical processes contributing to the fluxes of organic matter at several locations. It brought together not only scientists of many nations but also a wide range of disciplines to work together, often for the first time. Iron fertilization experiments were conducted to test the role of iron in stimulating biological productivity in the open ocean. The results not only contributed to the scientific understanding of ocean productivity, but also informed debates on proposals to use iron fertilization for carbon capture and sequestration.

The ongoing International Study of Marine Biogeochemical Cycles of Trace Elements and their Isotopes (GEOTRACES) surveys are measuring trace chemical, isotopic, and biogeochemical properties of the global ocean to increase understanding of biogeochemical cycles. GEOTRACES is designed to provide a globally consistent view of tracer distributions to develop a more accurate understanding of their behavior. These tracers are often invoked as regulators of key biogeochemical processes, for their utility in decoding past environmental changes, and as a measure of the human impact on the global environment.

ANALYSIS OF THE SCIENTIFIC ACCOMPLISHMENTS

In the late 1990s, OCE undertook a community-based assessment of research opportunities that would define the next decade of ocean science (*Ocean Sciences at the New Millennium* [NSF, 2001]). Each ocean science discipline prepared a report on what it saw as the major research opportunities, which were used to identify seven interdisciplinary topics that were ripe for advancement. In addition, the summary highlighted key findings, new science trends, and interdisciplinary fields of interest to the ocean sciences.

There is good concordance between those seven topics identified in 2001 and the major advances identified above, demonstrating that forward planning was indeed successful

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BOX 1-4
Contributions of Long-Term Monitoring Programs

Monitoring refers to the recurring documentation of biological, chemical, or physical environmental factors. Notable examples include the monitoring of atmospheric CO_2 concentrations at Mauna Loa, Hawaii (see Figure a) (Keeling, 1998); observations of biological, physical, and chemical processes in marine and terrestrial biomes through the Long Term Ecological Research Program; and tracking commercial fish abundances in the California current ecosystem through the CalCOFI program (MacCall, 1996). Specific NSF-supported long-term time-series studies include the Bermuda Atlantic Time-series Study (BATS), the Hawaii Ocean Time-series (HOT) program (Figure b), and Carbon Retention in a Colored Ocean. Information on spatial or temporal variation, with sampling at appropriate intervals of sufficient duration that yield time series, provides essential data to help identify trends—for instance, in fish or marine mammal populations—and distinguishes unique outliers that represent novel events from sampling problems or equipment failure.

Numerous challenges characterize monitoring endeavors. Since it is impractical to monitor everything, strategic decisions need to be made on key parameters for measurement. Depending on the parameter, geographic coverage may be limited by the sampling technology. Monitoring can be expensive, requiring sustained commitments of resources that are counter to typical federal agency funding models and peer-review panels. Last, scientific rewards from monitoring are long term, conflicting with the short-term reward structure of the typical career trajectory.

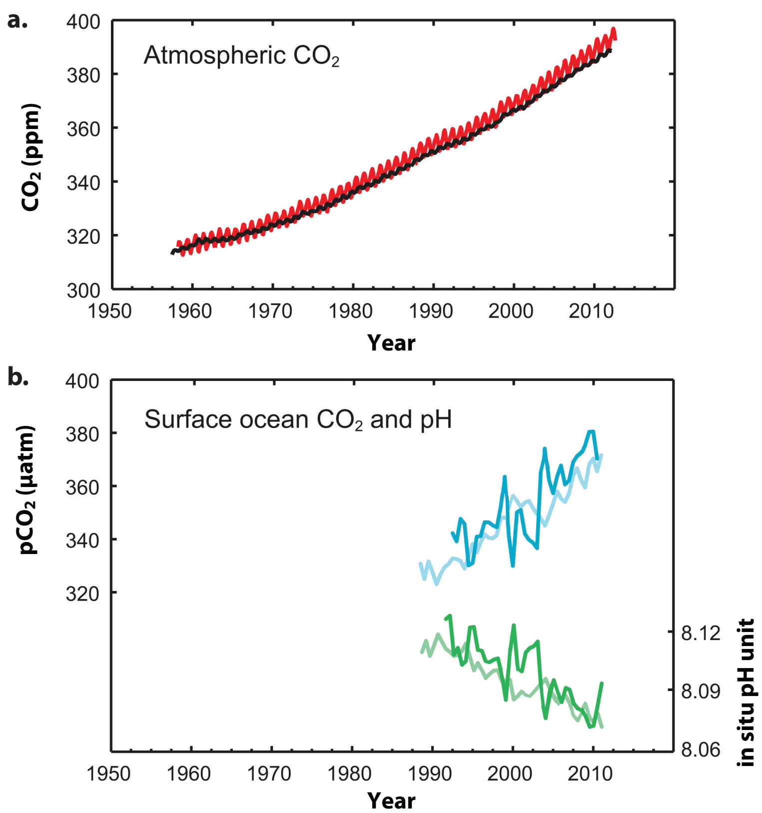

FIGURE (a) Observations of increasing CO_2 in the atmosphere (red, Mauna Loa 19°32'N, 155°34'W; black, South Pole Station); and (b) surface ocean CO_2 (blue) and decreasing surface pH (green) (darker colors, BATS 31°40'N, 64°10'W; lighter colors, HOT 22°45'N, 158°00'W). The oceanic stations have been occupied at monthly intervals since the late 1980s/early 1990s and include a host of physical and biogeochemical measurements. SOURCE: IPCC (2013) and references therein; Dore et al., 2008.

in fostering meaningful scientific accomplishment. However, not every research theme was anticipated. For example, the *New Millennium* report did not highlight sea level rise or ocean acidification as major research topics. The subsequent shift to research on these themes argues for providing flexibility to the research program to allow for changes in direction as new issues or priorities emerge.

In addition, the rapid rate of new discoveries and increases in understanding of fundamental ocean properties indicates that during the first decade of the millennium there was a productive balance of investment in core research, major research infrastructure assets, technology development, and multidisciplinary and internationally coordinated research programs. The success of the past decade and a half also demonstrates the invaluable contributions of long-term monitoring programs (Box 1-4).

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OCE has an enviable track record of past success, based on strategic basic research investments and partnering with other organizations to enhance research opportunities for the scientific community. In many cases, these accomplishments have led to practical applications with direct societal benefits. Basic research in the ocean sciences provides a strong foundation for mission agencies to build upon, for international collaborations, and for public welfare.

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2

Ocean Science Priorities for 2015-2025

Nothing is less predictable than the development of an active scientific field.

—Charles Francis Richter

OBJECTIVES

The committee was charged to develop "compelling, high level scientific questions that will be central to the ocean sciences over the coming decade and, if answered, could transform our scientific knowledge of the oceans." The goal of these questions is to "identify areas of strategic investment with the highest potential payoff." Instead of attempting to include all topics of interest in oceanography, the committee sought questions that are likely to be transformative, are of broad interest, offer significant impact to society, and can conceivably be initiated or addressed in the next decade.

The purpose of identifying priorities in this report is to ensure alignment between key topics in ocean science over the next decade and the National Science Foundation's (NSF's) investments in ocean research infrastructure. The committee spoke at length with NSF about the relationship between these science priorities and the Division of Ocean Science's (OCE's) core programs,[1] which seek to advance fundamental scientific understanding of the ocean by supporting high-quality research proposals. Future core program funding is likely to address many aspects of the scientific priorities identified in this report, but it will also support a broad range of work not directly related to these priorities—for example, addressing long-standing issues that may not be transformative but where making progress remains vital, or laying the groundwork for new or unanticipated topics through support for basic research. As noted in Chapter 1, topics such as sea level rise variability and ocean acidification were advanced by fundamental research even though they were not highlighted in reports a decade ago. The NSF Directorate for Geosciences (GEO) recently released a plan, *Dynamic Earth: GEO Imperatives & Frontiers 2015-2020*, which recognizes that "basic research [is] at the heart of GEO's mission" (NSF Advisory Committee for Geosciences, 2014). To make significant progress in ocean science and technology, the core programs require a high degree of flexibility to fund promising new ideas and approaches, respond to infrequent events that present opportunities to understand important phenomena, incorporate discoveries in other areas of science and technology, and encourage the training and professional development of the next generation of scientists.

APPROACH

To identify the set of science priorities, the committee obtained input and suggestions from town hall meetings at the 2013 AGU Fall Meeting (San Francisco, California) and the 2014 Ocean Sciences Meeting (Honolulu, Hawaii); from over 400 responses on a web-based Virtual Town Hall that was open from November 2013 to March 2014; from ~300 challenging ocean science topics embedded in more than 30 NSF, federal agency, research community, National Research Council (NRC), and international reports over the last 10 years;[2] from presentations to the committee by NSF program managers and others (see Appendix B); from presentations, interviews, and material provided by personnel in other federal agencies and other programs; and from

[1] Core science refers to the grants resulting from unsolicited proposals submitted to and supported by NSF OCE research and education programs. NSF includes Biological Oceanography, Chemical Oceanography, Physical Oceanography, Marine Geology and Geophysics, Oceanographic Technology and Interdisciplinary Coordination, Ocean Education, and IODP Science as part of core science.

[2] All of the reports considered by the committee are listed at the end of the chapter under "References and Bibliography."

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additional suggestions provided by letters received from research institutions and individuals.[3]

The input was first sorted and consolidated into about three dozen diverse, high-level, disciplinary and interdisciplinary scientific questions. The committee used methods focused on the diversity of the input rather than its popularity, an approach that is consistent with the Nominal Group Technique (Delbecq and Van de Ven, 1971). The sorting scheme was organized around four unifying themes—oceans, climate, ecosystems, and subsea Earth—that encompass the diverse topics in ocean sciences. All of the input was sorted into "bins" that encompassed one or more themes (for example, three bins were ecosystems, subsea Earth-ocean, and climate-ocean ecosystems) that captured both disciplinary and integrative aspects of ocean science.

Following published and tested research on the methods for prioritization of science programs (e.g., Sutherland et al., 2006), similar questions were clustered to produce approximately 20 distinct, high-level questions, with subquestions that articulated the focus of the original input at a consistent level of detail. For example, the importance of place-based research such as in the polar regions was a theme expressed in comments received from the Virtual Town Hall. During the process of synthesizing the input, the committee incorporated place-based research questions into the subquestions, while recognizing that other parts of NSF and other agencies also support ocean research and collaborate with OCE.

The Analytical Hierarchical Process (Forman and Gass, 2001) was then used to narrow the list to fewer than 10, as directed by the statement of task. The basis of the analytical hierarchical process is the use of selection criteria that are weighted in importance and then applied one at a time to the working list. These criteria were derived from suggestions by NSF program managers and previous NRC and interagency reports related to ocean science research priorities. There were four criteria used—*transformative potential*, *societal impact*, *readiness*, and *partnership potential*—listed in order of relative importance and discussed below:

- Research with *transformative potential*, as defined by NSF, "involves ideas, discoveries, or tools that radically change our understanding of an important existing scientific or engineering concept or educational practice or leads to the creation of a new paradigm or field of science, engineering, or education. Such research challenges current understanding or provides pathways to new frontiers."[4] Examples might include investigating a previously unexplored question or researching a long-standing question with new insights, improved instrumentation, or a novel perspective, with either path leading to major revisions in current knowledge.
- An increasing emphasis at NSF and other federal agencies is to focus funding on areas with significant *societal impact*,[5] as noted in the "Broader Impacts" requirement for NSF proposals. Federal ocean science themes with societal relevance are outlined in *An Ocean Blueprint for the 21st Century* (USCOP, 2004), *Charting the Course for Ocean Science in the United States for the Next Decade* and *Science for an Ocean Nation* (NSTC, 2013; NSTC Joint Subcommittee on Ocean Science and Technology, 2007), and the *National Ocean Policy Implementation Plan* (NOC, 2013), and include topics such as increasing resilience to natural or anthropogenic hazards, improving human and ecosystem health, and maintaining a sustainable and secure food supply.
- Some topical areas have high *readiness*: the questions are clearly articulated, tools and infrastructure exist to address them, there is an energized and/or growing community equipped to address them, and partners are available. Research could begin quickly, even if results may be slow to materialize.
- Although NSF is the dominant funder of basic ocean science research, other federal and state agencies, private foundations, industries, and international organizations also have basic and applied interests. Topics of interest outside NSF have *partnership potential*. They could attract cooperative interest and support increased research funding, additional technical tools or infrastructure, added research expertise or in-kind resources, access to different geographic regions, or advice on societal impacts and private-sector applications.

These four weighted criteria were applied qualitatively to the list of about 20 questions, using the committee's informed judgment. Transformative science potential was given the most weight, followed by societal impact, readiness, and partnership potential. Because transformative research potential was the first and highest ranked criterion, research that was deemed scientifically important but low in its transformative potential was not ranked highly. However, as a reality check, each question's scientific importance was also qualitatively ranked; the committee found relatively high correlation to those questions with high transformative potential. A few questions with lower scientific importance were balanced by relatively high societal relevance and/or readiness. This application of the analytical hierarchical process winnowed the questions to a final set of eight science priorities.

[3] There have been other attempts to suggest priority research questions in the ocean, for example most recently a survey from York University, United Kingdom (Rudd, 2014). This survey was not aimed at the same community, and purpose and methodology differed from the efforts described in this report.

[4] See http://www.nsf.gov/about/transformative_research/definition.jsp.

[5] See http://www.nsf.gov/pubs/2007/nsf07046/nsf07046.jsp.

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PRIORITY SCIENCE QUESTIONS FOR 2015-2025

The following eight science priorities are considered by the committee to be integrative, interdisciplinary, strategic research areas that are presented as high-level themes. Specific research questions can be posed within these areas. The committee envisions these questions as foci to be addressed within OCE core programs or within cross-cutting NSF programs, or in partnership with other federal agencies or international programs. The committee did not prioritize among the eight questions. Rather, they are ordered from the ocean surface, through the water column, to the seafloor:

- **What are the rates, mechanisms, impacts, and geographic variability of sea level change?**
- **How are the coastal and estuarine ocean and their ecosystems influenced by the global hydrologic cycle, land use, and upwelling from the deep ocean?**
- **How have ocean biogeochemical and physical processes contributed to today's climate and its variability, and how will this system change over the next century?**
- **What is the role of biodiversity in the resilience of marine ecosystems and how will it be affected by natural and anthropogenic changes?**
- **How different will marine food webs be at mid-century? In the next 100 years?**
- **What are the processes that control the formation and evolution of ocean basins?**
- **How can risk be better characterized and the ability to forecast geohazards like mega-earthquakes, tsunamis, undersea landslides, and volcanic eruptions be improved?**
- **What is the geophysical, chemical, and biological character of the subseafloor environment and how does it affect global elemental cycles and understanding of the origin and evolution of life?**

Because of their broad relevance to societal issues, federal agencies in addition to OCE may have interest in devoting resources to fields related to the science priorities. These partnership potentials are discussed in detail under each question. Collaborations between basic research and mission agencies may hasten both research advancements and transition to operational products by taking advantage of complementary skills, resources, and expertise among organizations. For example, understanding the mechanisms that control biodiversity and food web structure also has relevance for managing marine ecosystems and tracking environmental contaminants. In addition, there is potential for useful partnerships with industry, foundations, international organizations, and nongovernmental organizations.

What are the rates, mechanisms, impacts, and geographic variability of sea level change?

The population of coastal communities has expanded rapidly over the past few decades. Small increases in local sea level expose this population to inundation by storm surge, cyclones, and extreme waves. In the past half million years, global mean sea level has fluctuated between 140 m lower and perhaps as much as 10 m higher than its present level. Understanding the mechanisms and rates of change behind global and regional variability on all scales, and projecting future changes in sea level, is an interdisciplinary challenge to oceanographers. The immediate cause of today's global mean sea level rise is global warming, which acts through thermal expansion of ocean waters and loss of water mass from major land reservoirs such as glaciers and ice sheets. Significant regional patterns of sea level change result from uneven rates of ocean warming, the net transport of seawater in ocean currents, regional tectonics, isostatic adjustments, shoreline subsidence, and regional gravitational anomalies. Understanding and anticipating sea-level change will require answers to the following:

- How does the ocean gain, lose, transport, and store heat and what is the temporal and spatial variability of these processes?
- How does regional sea level respond to ocean circulation driven by changes in heat and salt budgets, winds, and the hydrologic cycle?
- How does a warming ocean affect sea ice and glacier melt in polar regions? How is ocean circulation influenced by sea ice and glacier melt?
- Are there thresholds that will trigger loss of oceanic ice shelves and grounded ice, and how will these effects change the distribution of sea ice and accelerate long-term sea level rise?
- How and on what temporal and spatial scales will flooding, storm surge, and large wind waves impact shorelines?
- What is the coupling between sea level rise and increasing vulnerability to storms?

Opportunities exist for NSF to partner with the U.S. Navy, the U.S. Coast Guard, the U.S. Geological Survey (USGS) and other organizations within the Department of the Interior, the U.S. Army Corps of Engineers (USACE), the National Aeronautics and Space Administration (NASA), and the National Oceanic and Atmospheric Administration (NOAA; particularly the National Ocean Service and the Office of Oceanic and Atmospheric Research [OAR]) on in situ and satellite measurements of rates of sea level change, predictive models, and policies for mitigation and adaptation. Collaborations within NSF, for example, with the Division of Polar Programs, could address the impacts of ice sheet, glacier, and sea ice melt on sea level and circulation. The

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Interagency Arctic Research and Policy Committee could also have interest in this science priority. Several of these topics were highlighted as NSF research frontiers in *Dynamic Earth* (NSF Advisory Committee for Geosciences, 2014).

How are the coastal and estuarine ocean and their ecosystems influenced by the global hydrologic cycle, land use, and upwelling from the deep ocean?

The land adjacent to the coastal oceans and estuaries is experiencing increasing pressures from residential, industrial, agricultural, extractive, and recreational uses. The effects of human activities are heavily focused on the coastal and estuarine ocean, in part because runoff and associated sediment, nutrients, and pollutant fluxes can dramatically alter marine ecosystems and result in habitat loss. Many human activities (e.g., commerce and associated dredging, fishing, sewage disposal, and hydrocarbon exploration and resource extraction) are altering coastal ecosystems and their habitats. Anthropogenic pressures, such as thermal or chemical contaminants that change ocean properties, have stronger impacts in shallow waters. Changes in the ocean also have poorly understood feedbacks that affect adjacent land by increasing the vulnerability of coastal areas to storms, altering coastal aquifers, and changing global rainfall patterns. Understanding how the inherently dynamic marine environments on the edges of the ocean respond to ongoing changes has significant societal importance. For example:

- How will changes in river runoff volumes associated with shifting hydrologic patterns affect the dynamics and ecology of nearshore areas?
- How is the boundary between freshwater and saltwater in coastal aquifers changing due to both aquifer withdrawal and sea level rise?
- How will the pathways and processes that redistribute or concentrate pollutants change with altered sediment inputs?
- Will changes in nutrients in coastal waters alter the export of organic carbon to the deep sea and seafloor? Will the increased oxygen demand significantly expand continental margin dead zones?
- What are the impacts of pollutants and perturbations on coastal ecosystems, including pesticides and other chemicals, acoustic signatures from resource extraction and shipping, and human alterations to the ocean floor?
- What constitutes sustainable use of the coastal zones, and how will projections of long-term change influence planning and management of human activities in these areas?

Several operational agencies (e.g., USGS, NOAA, and the U.S. Navy) have mission-specific responsibilities that would benefit from collaborative coastal research products. NASA, USACE, and the Environmental Protection Agency (EPA) also sponsor research that connects terrestrial inputs to coastal and estuarine impacts and creates public literacy on coastal planning and methods to mitigate risk. There are significant opportunities for linking ocean and satellite observations from research and monitoring programs with ocean observatory capabilities. In some instances, basic ocean research done by NSF could have mission applications by other federal agencies. NSF's Division of Earth Science and Directorate for Social, Behavioral, and Economic Sciences could also have interest in this topic.

How have ocean biogeochemical and physical processes contributed to today's climate and its variability, and how will this system change over the next century?

Ocean processes are a crucial component of both climate and carbon cycles. Over the past century, the ocean has absorbed about one-third of the excess CO_2 emitted from fossil fuel combustion and over 90% of the excess energy of global warming. Attendant effects include changes in the distribution of temperature and salinity in the oceans, in ocean circulation and heat transport, in decreasing pH of seawater, and in the expansion of low-oxygen zones. Impacts of these physical and chemical changes on organisms, ecosystems, and resources are the subject of current research. Whether biological and chemical effects will amplify or mitigate changes remains unknown. In the coming century, rates of these and other related changes are expected to increase; the near-term buffering capacity of the ocean may be less effective as the upper ocean seeks dynamic equilibrium with a warmer, high-CO_2 atmosphere. Over many millennia, the ocean is expected to neutralize the human additions of carbon by dissolution of seafloor carbonate minerals. On shorter time scales, warmer, fresher surface waters could decrease the convective mixing and overturning circulation that carries heat into the deep ocean. Climate change could also be exacerbated by loss of sea ice and increased albedo feedback or from methane and carbon dioxide venting from subseafloor hydrates or permafrost. How these complex and dynamic changes will play out, at what rates and with what impacts, remains poorly known. Answering these questions in the near future will be of high priority, as policy decisions made in the coming decade will set the course of changes in climate, the ocean, and its biogeochemical cycles not just for the next few decades, but for centuries and millennia to come; some possible changes, such as substantial loss of glaciers and polar ice caps, may be essentially irreversible. In particular the following aspects of the linked climate and biogeochemical system will require focused attention over the next decade:

- What is the ocean's role in regulating the carbon cycle? How might the ocean's uptake or release of radiatively and biologically active gases, and the ef-

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ficiency of carbon export to the deep ocean, be better quantified?
- What are the consequences of ocean acidification and the impact of decreasing pH on marine organisms and ocean biogeochemistry?
- What is the ocean's role, through CO_2 uptake and transport, on transient and equilibrium climate sensitivity?
- What is the role of the polar oceans on global and regional circulation?
- What are the natural and anthropogenic drivers of coastal and open ocean deoxygenation, and how can the two drivers be distinguished?
- What are the impacts of changes in the ocean's physical properties and circulation on the frequency and amplitude of catastrophic events such as hurricanes and floods?
- How do changes in mixing and circulation affect nutrient availability and ocean productivity?
- What is the spatial and temporal distribution of ocean mixing, turbulence, and stirring, and how might these processes be represented in climate-scale ocean models?

This topic covers mission interests at many federal agencies (e.g., Department of Energy, NASA, NOAA, and the Federal Emergency Management Agency [FEMA]). In addition, the global nature of this question could be advanced by international collaborations such as Future Earth (Box 2-1), Horizon 2020 (a European Commission research program), and other complementary programs.

BOX 2-1
Future Earth

Future Earth is a 10-year international research program that seeks to provide scientific knowledge that can be used to help societies address current and future environmental problems. It aims to answer fundamental questions about the changing global environment and implications of human development for the diversity of marine and terrestrial life. Future Earth also seeks to identify opportunities to mitigate risk, improve resilience, increase innovation, and demonstrate how science can aid progress toward the societal goal of a sustainable planet. To do this, the program will integrate disciplines from physical science, social science, engineering, and humanities, encompass bottom-up ideas, and be inclusive of existing global change research programs. Ocean science has a clear role in Future Earth, not only due to human impacts on the marine environment but also because of ecosystem services the oceans provide (e.g., the ocean's role in food from the sea, uptake of carbon dioxide, and its stabilizing effect on global temperature).

What is the role of biodiversity in the resilience of marine ecosystems and how will it be affected by natural and anthropogenic changes?

One of the grand challenges of marine ecology is to understand the extent to which biodiversity enhances productivity and influences recovery from perturbations. While it is often assumed that more diverse ecosystems are more resilient to change, there is considerable debate in the contemporary literature; thus, the importance of protecting marine diversity as a primary ecosystem conservation objective is yet unresolved. Some marine ecosystems are subject to rapid ecological shifts, due to changing oceanographic conditions, natural or imposed shifts in the abundance of apex predators, or some combination of both. The details of these shifts, however, are poorly understood.

Resolving the interplay between biodiversity and ecosystem resilience, while a daunting task, is essential for understanding the cumulative and individual effects of changes in ocean physical and chemical processes, species abundances, and the related dynamics of both natural variability and human impacts. Overfishing and increasing eutrophication exacerbate the effects on individual species and on ecosystems, further complicating analyses. The broad range of marine ecosystem settings (e.g., salt marshes, coral reefs, continental shelf, and undersampled ecosystems like the deep ocean and mid-water column) presents a continuum of opportunities to test theory, to obtain valuable data, and to generate models for better understanding of the roles that biodiversity—species, genetic, functional—may play in a changing ocean. Understanding the roles of biodiversity in the resilience and productivity of marine ecosystems is fundamental to answering a number of practical questions, including, but not limited to:

- How do multiple and cumulative anthropogenic and natural stressors affect productivity, stability, connectivity, and recovery dynamics of marine species and ecosystems?
- Can we identify and predict triggers for ecological regime shifts?
- How diverse, resilient, and productive are vast and underexplored ecosystems (e.g., bathypelagic and abyssal realms)?

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- Does increased resilience to perturbations make it more or less difficult to recover individual species or species groups?
- To what extent will species, genetic, or functional biodiversity be affected by acidification, warming, sea level rise, freshwater dynamics, hypoxia, and exploitation? Which organisms have the ability to adapt to change and how will ecosystems shift as a function of these responses?
- How will marine and coastal ecosystem services be impacted by natural and anthropogenically driven change?

Opportunities to enhance understanding of biodiversity and resilience exist within many federal agencies (e.g., EPA, NASA, NOAA/National Marine Fisheries Service [NMFS], the Bureau of Ocean Energy Management [BOEM], and the U.S. Fish and Wildlife Service [USFWS]), and within NSF through the Directorate for Biological Sciences (BIO) and the Directorate for Social, Behavioral, and Economic Sciences. This includes work on cumulative impacts and the potential for regime changes in relation to climate and anthropogenic effects and provides an opportunity to link modeling and field research programs. Private research entities are also capable of supporting partnerships in this arena; one example of a successful, international, public-private partnership was the Census of Marine Life (which was established by a private foundation and supported by over 80 countries, including U.S. federal agencies; see Box 1-2).

How different will marine food webs be at mid-century? In the next 100 years?

Food web configuration integrates a number of key aspects of marine ecosystems including predator-prey dynamics, coupling of benthic and pelagic components, climate forcing, physical and biogeochemical impacts on the base of the food web (primary production), "top-down" cascading effects of overharvesting, and the population dynamics of constituent species. Food web stability and structure are influenced by the number and strength of interactions among both internal and external components. Large-scale changes in marine food webs have been documented in a number of ecosystems, including the eastern Pacific, the northwest Atlantic, and along the Aleutian chain. Creative combinations of data from commercial fish and shellfish fisheries with multi-species monitoring have increasingly shown that large marine ecosystems are dynamic and subject to abrupt changes.

There is already evidence that marine ecosystems are responding to climate-related changes in ocean physics and biogeochemistry, potentially changing the spatial patterns and overall levels of productivity of the oceans. At the same time, harvesting patterns will transform in response to requirements for sustainable human uses of the ocean and its margins. The evidence suggests marine food webs may transition to different food web configurations and interactions that involve both bottom-up and top-down control, with implications for ecosystem stability and future human use. Understanding how food web dynamics respond to changing climate and human use patterns could shed light on how productivity may change under multiple simultaneous controls. Some of the relevant questions include the following:

- How will the effects of climate change in the ocean, superimposed on other natural and anthropogenic stressors, alter the carrying capacity and recovery potential of marine ecosystems?
- Will changes in biogeochemical processes related to the availability of essential macronutrients (such as nitrogen) and micronutrients (such as iron) alter patterns of global primary productivity?
- How will changes in apex predator exploitation with accompanying population increases or decreases affect the organization and dynamics of ecosystems?
- What determines the resilience of marine assemblages, the structure of their food webs, and rates of recovery of species to overharvesting? What are the key criteria for sustainable fishing and aquaculture practices?

Dynamic Earth (NSF Advisory Committee for Geosciences, 2014) mentions the response of marine ecosystems to climate and anthropogenic impacts as an important basic research area for the emerging research frontier topic about Earth systems processes that cross the land-ocean interface. Opportunities exist to bring together agencies responsible for management (e.g., NOAA/NMFS, EPA, USFWS, the Marine Mammal Commission [MMC]) with research (e.g., NASA, NOAA OAR, NSF BIO) and with international initiatives such as Future Earth. Cross-agency collaborations, such as the Global Ocean Ecosystem Dynamics International Programme (GLOBEC), demonstrate that bringing agencies together with academic communities is a powerful model for moving research forward.

What are the processes that control the formation and evolution of ocean basins?

Plate tectonic processes have been studied since the 1960s, but only recently has sufficient infrastructure existed to collect the data necessary to evaluate this paradigm on a basin-wide scale and to image structures in the deep crust and mantle that reveal plate tectonic mechanisms. Tectonic processes control the regional shape of the ocean basins and the roughness of the seafloor, exerting influence on the circulation of the overlying water column and the distribution of ecosystems that inhabit it. Many tectonic plate boundaries also are the loci of geologic hazards, potentially linking the safety of human populations onshore to conditions and

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events that are tens of kilometers beneath the seafloor or thousands of kilometers across the planet. Heat from cooling plate and cooling magma bodies drives hydrothermal circulation, which alters seawater composition and provides nutrients for deep ecosystems. Understanding the processes that control the formation and evolution of the ocean basins is contingent upon answering the following questions, but it is important to note that the systems are all interrelated and coupled to varying degrees as part of the overall manifestation of convection within the Earth:

- Beneath mid-ocean ridge spreading centers, where does magma form and what are its pathways to the surface to form the oceanic crust? How do spreading rate and proximity to subduction zones and transform faults affect this process?
- What are the interactions between the plates and convection in the deeper, underlying, convecting mantle?
- How does a heterogeneous mantle contribute to dynamic changes in topography at the Earth's surface?
- What is the sequence of tectonic processes that cause continents to split apart and new ocean basins to form? How do new subduction zones form?
- What is the role of fluids in localizing plate boundaries, triggering volcanic eruptions, and controlling slip distribution in earthquakes?
- To what extent do faults control hydrothermal circulation in the crust and thus the distribution of vent communities and microbial populations in the deep biosphere?
- What causes massive volcanic outpourings that have formed oceanic plateaus, seamounts, and islands, and how are they related to continental analogs?

OCE could partner with NSF's Division of Earth Sciences (EAR) to fund opportunities that cross land-ocean boundaries and could work with USGS on monitoring. Permitting issues related to seismic and acoustic research are also of interest to NOAA, BOEM, the Office of Naval Research, and MMC.

How can risk be better characterized and the ability to forecast geohazards like mega-earthquakes, tsunamis, undersea landslides, and volcanic eruptions be improved?

Earthquakes, tsunamis, and volcanic eruptions have caused hundreds of billions of dollars in damage and hundreds of thousands of fatalities over the past decade. At the same time, development and expanded deployment of new technologies has improved understanding of the processes that generate geohazards, refined probabilistic estimates of the dangers, and reduced the lag between event detection and response. Improved understanding and forecasting of geohazards is listed as a potential area for basic research inquiry in *Dynamic Earth* (NSF Advisory Committee for Geosciences, 2014). Necessary improvements in understanding and forecasting geohazards, and thus reducing risks, depend on answering the following questions:

- Are there recognizable precursors to volcanic eruptions and mega-earthquakes? Do the episodic periods of slow slip in deep parts of fault zones represent times of increased earthquake hazard?
- Why do some earthquakes generate damaging tsunamis and others do not?
- Why do some earthquakes generated at oceanic transform boundaries reoccur at predictable intervals?
- What is the role of water in controlling fault slip and triggering volcanic eruptions?
- What controls and triggers submarine slides? What controls slope stability? Does climate change play a role in slope stability through sea level changes? How do methane seeps influence slope stability and what are the likely effects of resource extraction?
- What parts of the interface between the subducting and overriding plates are locked, accumulating strain that will be released in earthquakes, and which parts are stably sliding? What are the physical processes controlling the pattern of locked and slipping fault zones?
- To what extent can we decipher the history of infrequent, dangerous events from the sediment record, the morphology of the seafloor, and the stratigraphy of the subseafloor?
- How does volcanism impact weather and contribute to climate change?

Opportunities exist to collaborate on prediction and rapid response to geohazards with agencies (e.g., USGS, NOAA OAR and National Weather Service, NSF EAR, FEMA, and the Federal Aviation Administration) and private sectors ranging from transportation and logistics to insurance.

What is the geophysical, chemical, and biological character of the subseafloor environment and how does it affect global elemental cycles and understanding of the origin and evolution of life?

The ocean is underlain by a dynamic seafloor in which fluids circulate and viable microbial communities exist at great depths, in both sediments and in rock. This largely uncharacterized environment is metabolically active, showing evidence of nitrogen, iron, and sulfur cycling, as well as unusual oxidation-reduction reactions. Some of this life is supported by organic carbon generated in the photic zone, but evidence from both terrestrial and oceanic subseafloor realms suggests the possibility of lithoautotrophy and creation of organic carbon independent of light ("dark organic carbon"). Exploration of the deep biosphere has revealed that

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novel microbial physiologies and diverse life forms may exist and that these novel forms may be linked to metabolic processes in Earth's early history or on other planets (Box 2-2). In addition to understanding genetic diversity, exploration of the deep biosphere may lead to possible human health applications—for example, discovery of novel chemicals and/or processes that could be used to prevent or treat diseases or metabolic disorders.

The magnitude and metabolic activity of this unique biosphere affects the character of subseafloor fluids and raises the possibility that the microbes themselves may be transported in crustal fluid flows. While there is some disagreement regarding the size of the organic carbon reservoir and microbial activity in subseafloor sediments and igneous rocks, the presence of a vast metabolizing community beneath the seafloor raises the possibility that current estimates of global carbon biomass and cycling may require substantial revision and that global biogeochemical fluxes and cycles may be significantly affected by subseafloor processes throughout the global ocean. These possibilities give rise to the following questions:

- What are the mechanisms and rates of fluid circulation in this crustal environment, and to what extent does it fuel the diversity and composition of microbial life under the seafloor?
- How have these microbial forms evolved, how are their ecosystems organized and interconnected, and what do these organisms reveal about the origin and evolution of new life forms on and beyond Earth?
- What is the biogeochemical and organismal flux within and across the seafloor and how does it contribute to global biogeochemical cycles? How are these ecosystems sustained over long spatial and temporal scales?
- To what extent is new organic carbon formed in the subseafloor biosphere? Is it a vast unexplored and active reservoir that has the potential to transform our understanding of carbon storage and burial?
- How can subseafloor processes and products be used for societal benefit (e.g., novel enzymes for industrial and biomedical applications, or new chemicals for human health applications)?

In addition to support from OCE, other potential partners at NSF include BIO and EAR. Several of the topics for this priority question would contribute to the GEO research frontier on Early Earth in *Dynamic Earth* (NSF Advisory Committee for Geosciences, 2014). Programs within NOAA (such as Ocean Exploration), NASA programs addressing interplanetary life, and the National Institutes of Health programs focused on the discovery and development of marine-derived products with human health applications also present collaboration opportunities.

BOX 2-2
Exploration: Key to Paradigm Shifts

Prior to 1977, a student reading a biology textbook would have learned that the process of photosynthesis, by which the sun's energy is converted into food for plants, is essential for life on Earth. That same textbook likely would not have contained a discussion of chemosynthesis, the process by which organisms derive energy from inorganic compounds in the absence of light and obtain carbon in the form of carbon dioxide, despite the discovery of chemosynthesis by Winogradsky 90 years previously.

In the late 1970s, the paradigm for the basis of life on Earth was fundamentally changed when scientists from several collaborating oceanographic institutions went searching for evidence of "hot springs" (hydrothermal vents) on the ocean floor and first discovered plumes of warm water, then evidence of chemosynthetic life on the deep seafloor (2,500 m), and, finally, actual vents. The scientific expeditions to the Galapagos Rift did not set out in search of biological communities; rather, researchers identified the site as a likely location to find hydrothermal vents, which were hypothesized to exist based on measured deep water temperature anomalies, chemically altered rocks and metal-rich ocean sediments recovered from the seafloor, remnants of hydrothermal systems preserved on the continents, and surprisingly low measurements of heat flowing through seafloor sediments near mid-ocean ridges. Using *Alvin*, the Deep-Tow geophysical instrument, and the Acoustically Navigated Geophysical Underwater System, scientists discovered and mapped dense fields of clams, mussels, worms, and fish surrounding hydrothermal vents. Their discoveries amazed the world and convincingly established the importance of chemosynthesis in supporting life.

Hydrothermal vent communities are not independent of photosynthesis; they require oxidants such as dissolved oxygen that would not exist at the seafloor in the absence of atmospheric oxygen. However, recently attention has focused on methanogens that create organic matter from rock-derived hydrogen and inorganic carbon dioxide, an energy source that is truly independent of photosynthesis.

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INTERDISCIPLINARY SCIENCE AND FUNDING WITHIN NSF AND OCE

Most of the priority questions will require interdisciplinary[6] research across the subdisciplines of ocean science as they are managed within OCE, within the GEO disciplines, and across Directorates. In recent years, GEO Directorate-level Integrative and Collaborative Education and Research (ICER) funds (which did not exist a decade ago) have been the main source of interdisciplinary initiatives such as the Science, Engineering, and Education for Sustainability (SEES) program ($68 million in fiscal year 2014). SEES supports a portfolio of research that highlights NSF's unique role in helping society address the challenge of achieving sustainability and includes ocean-related themes such as Ocean Acidification, Coastal SEES, and Hazard SEES. Other GEO-level and NSF-wide interdisciplinary programs include Cooperative Studies of the Earth's Deep Interior, Earth Cube, and Decadal and Regional Climate Prediction using Earth System Models.

In the past, programs like the World Ocean Circulation Experiment, the Joint Global Ocean Flux Study (JGOFS), the Ridge Interdisciplinary Global Experiments (RIDGE), MARGINS, and others originated with new funding that came into OCE via, for example, the Global Change Research Program. Once those programs ended, funds remained in the core research budgets; for example, JGOFS funds were split evenly between the Biological and Chemical Oceanography programs. This was an opportunity for OCE program officers to continue similarly themed programs or begin new interdisciplinary programs without an impact on the core budgets. However, at present ICER funds remain within GEO, are not added to core research budgets, and are subsequently not under the direct control of OCE program officers.

OCE funds interdisciplinary work at two levels: the moderate- to large-scale initiatives discussed above, and individual-investigator or small-team proposals directed to one or more core programs. The larger efforts (e.g., RIDGE, GLOBEC) are considered to be handled well within NSF, although they take considerable time to develop and are generally initiated by established community members that have the energy and stature to lead such efforts.

Obtaining funding for smaller interdisciplinary programs is often viewed as more problematic by the scientific community. As a result of this perception, the 2012 OCE Committee of Visitors looked at the funding record for peer-reviewed interdisciplinary proposals within OCE, excluding those in named initiatives such as the International Study of Marine Biogeochemical Cycles of Trace Elements and their Isotopes (GEOTRACES), and concluded that their success rate does not differ significantly from those submitted to the core programs (NSF Committee of Visitors, 2012). Nevertheless, the impression within the community is different. Respondents to the Virtual Town Hall and young researchers (postdoctoral and assistant professor levels) who spoke during committee meeting open sessions believe that it is more difficult to get interdisciplinary work funded and that such proposals are not encouraged by NSF. A contributing factor is the near absence of guidance on the OCE webpage as to how to submit an unsolicited interdisciplinary proposal. It is unclear whether such proposals are welcomed and, if so, how to optimize the proposal for success. Furthermore, when proposal success rates are lower, there is a perception that OCE program officers are more likely to protect their core programs and less likely to work across disciplines.

Because interdisciplinary research across the subfields of ocean science is of increasing interest, particularly among younger scientists, and because such research will be essential to achieve many of the decadal science priorities, it is vital that the ocean science community is encouraged to work across fields and does not experience barriers in finding funding for interdisciplinary work.

TECHNOLOGY DEVELOPMENT FOR THE NEXT DECADE

Many research advances depend on new technologies that provide opportunities to measure or collect previously unattainable information. Long-duration moorings, global float arrays, high-resolution bathymetric mapping, genomics, high-performance computing, wireless communications, satellite sensing and locating, sensitive and accurate chemical sensors for the water column and subseafloor, and advanced remotely operated and autonomous platforms are all technologies that have opened new intellectual vistas, enabled new kinds of research, and described new aspects of the ocean. For the next decade's priority science questions, new technology will be needed to foster and support innovative research.

New research tools, from sustained arrays for geochemical and biological observations to animal-borne sensing, will use sensors based on new approaches like "labs on a chip" and miniaturized wet-chemistry systems, as well as conventional sensing approaches improved with new technologies like nanotechnology and microelectronics. Extended and accurate lifetimes, reduced power requirements, and miniaturization can expand the suite of sensors available for long-term unattended measurements to address issues of ocean change on a global scale. Similarly, recent advances in the use of video and image processing techniques, originally adopted for military and homeland security applications, offer the possibility for more accurate and cost-effective applications such as fishery stock assessment. An area ripe

[6] "Interdisciplinary research is a mode of research by teams or individuals that integrates information, data, techniques, tools, perspectives, concepts, and/or theories from two or more disciplines or bodies of specialized knowledge to advance fundamental understanding or to solve problems whose solutions are beyond the scope of a single discipline or area of research practice" (NRC, 2004).

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for technology development is seafloor geodesy. Very-high-precision, persistent geodetic measurements of the seafloor, especially in conjunction with measurements of the water from buoys and tide gauges, could allow for quicker detection of and response to geohazards such as local (near-field) tsunamis.

Unmanned sensor platforms are expanding the feasibility of spatially and temporally extensive ocean observation. Unmanned aerial vehicles and autonomous underwater vehicles carry sensors to vantage points from above the ocean surface to the deep ocean, even under ice; floats, gliders, and unattended surface platforms extend affordable spatial and temporal coverage of low-power sensors. Development of new low-cost and low-power sensors with long accurate lives for these platforms promises another decade of dramatic advances in ocean measurement. New vehicle capabilities are targets of research, including vehicles powered by energy harvested from the environment and development of methods for onboard analysis and/or preservation of water column and seafloor samples.

Social media and wireless communications also offer an entirely new way to advance research and obtain data otherwise not available. For example, *Sikuliaq* and other new research vessels are equipped to enable telepresence, which can facilitate virtual participation of researchers and students and can also provide outreach and education opportunities. Jellywatch[7] uses cell phones as sensors for citizen-science measurements to determine the distribution and abundance of jellyfish washing up onshore. Our Radioactive Ocean[8] uses crowdsourcing to fund monitoring of radioactivity in the Pacific Ocean related to the Fukushima Dai-ichi nuclear accident. It also provides citizen scientists the opportunity to propose a location for monitoring and provide samples for analysis.

Finally, high-performance computing, big data, and software development across disciplines are all high-impact activities that, although not part of ocean science, are nonetheless necessary to advance the field. OCE will need to take a proactive approach to foster relationships within other directorates at NSF and with other agencies to ensure that new technologies contribute to the advancement of ocean science.

WOULD A DIFFERENT COMMITTEE HAVE CHOSEN DIFFERENT PRIORITY SCIENCE QUESTIONS?

The themes and specific questions presented above were coalesced from a large amount of input, using formal methods to aggregate and differentiate information. However, the eight selected science priorities are still similar in scope and focus to those in many prior reports. As such, the committee is not breaking totally new ground but rather is providing a synthesis of the input, based on the committee members' collective insights and perspectives. Because the next chapters of this report draw conclusions and make recommendations based on these eight priorities, it is fair to ask how different the conclusions and recommendations might be if the decadal science questions were different.

As stated above, given the broad community, agency, and international input on which the assessment was based, it is unlikely that a different group would have arrived at eight completely different questions. Although a few of the science questions might have had a different emphasis, the more detailed descriptions of the questions would be expected to contain substantial overlap. Furthermore, many of the committee's conclusions and recommendations are based on the alignment of the eight science questions to NSF-supported infrastructure in the next chapter. In that discussion, it is shown that much of the infrastructure is multi-use and of high relevance for many of the priorities. Hence, changes of a few science questions would have had little effect on the infrastructure assessment. It is possible that, for those infrastructure assets with moderate to high relevance for only a few of the questions, a change in the focus of those questions could influence their alignment with infrastructure.

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[7] See http://www.jellywatch.org/.
[8] See ourradioactiveocean.com.

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3

The Current Landscape: Alignment of Current Ocean Research Infrastructure with the Decadal Science Priorities

We need to stop thinking about infrastructure as an economic stimulant and start thinking about it as a strategy. Economic stimulants produce Bridges to Nowhere. Strategic investment in infrastructure produces a foundation for long-term growth.
—Roger McNamee

During times of increasing federal support, the Division of Ocean Sciences (OCE) has been able to initiate new technologies and sustain research facilities, in addition to maintaining a diverse research portfolio that took advantage of the new capabilities. Since 1970, the total budget at OCE has grown by roughly 75% in 2014 dollars (Figure 3-1). When looking at the overall budget, there has been an almost linear long-term increase, punctuated by a few periods of greater growth (such as 2000-2004). However, when these data are parsed by the proportion of funds spent on core science versus those spent on infrastructure and facilities, the recent trends are quite different (Figure 3-2). Since 2000, the operations and maintenance (O&M) costs of OCE's research infrastructure generally have increased at a rate faster than inflation.[1]

The proportion of the OCE budget spent on infrastructure has grown at the expense of core programs. In 2000, 62% of the budget was available to support core research[2] programs (Figure 3-2). By 2014, core programs received only 46% of the funding. Budget projections from the National Science Foundation (NSF) show that this high proportion of the budget being dedicated to major infrastructure is expected to continue through at least 2019. The rising expense of supporting major infrastructure during a period of flat budgets has reduced the amount of funding available to support OCE core science programs because most infrastructure expenditures represent "fixed costs" in terms of O&M and multi-year contractual obligations.

Within the category of "infrastructure" in Figure 3-2, NSF includes the academic research fleet, the National Deep Submergence Facility (NDSF), scientific ocean drilling, the Ocean Observatories Initiative (OOI), and field stations and marine laboratories. There are many smaller facilities that are funded out of the core programs, shown in Table 3-1. The cost of infrastructure includes O&M for a number of programs but does not include most capital costs of construction or major refits.[3]

For fiscal year (FY) 2014-2017, the Directorate for Geosciences (GEO) is planning to provide $42 million in Integrative and Collaborative Education and Research (ICER) funds to help OCE cover O&M costs for OOI as it comes online. Although this short-term supplement could ease the pressure on the core research budget for a few years, it is not a permanent solution; starting in FY2018, the cost of infrastructure would again consume more of the OCE total budget at the expense of core science.

The current imbalance of infrastructure and core research funding drives much of the interest in evaluating the existing portfolio of NSF-funded multi-user ocean research facilities as part of the analysis of the research infrastructure needed to address the decadal science priorities identified in Chapter 2. A more detailed discussion of OCE's current budget situation is presented in Chapter 4.

NSF provided background and budget information on its investments in ocean research infrastructure, which the committee categorized as "major" facilities and infrastructure (annual budgets of $5 million/yr and higher) or "minor"

[1] Inflation adjustments were based on the U.S. Bureau of Labor Statistics Consumer Price Index annual average, with the exception of 2014; data from 2014 were based on an average of values from January to November.

[2] See Chapter 2 for a discussion of the term "core research."

[3] Whereas some mid-sized infrastructure construction or recapitalization is included in the OCE budget (e.g., an upgrade of the human-occupied vehicle *Alvin*), large-scale construction (e.g., new research vessels, the *JOIDES Resolution* refit, OOI) is sourced from an NSF-wide Major Research Equipment and Facilities Construction (MREFC) account.

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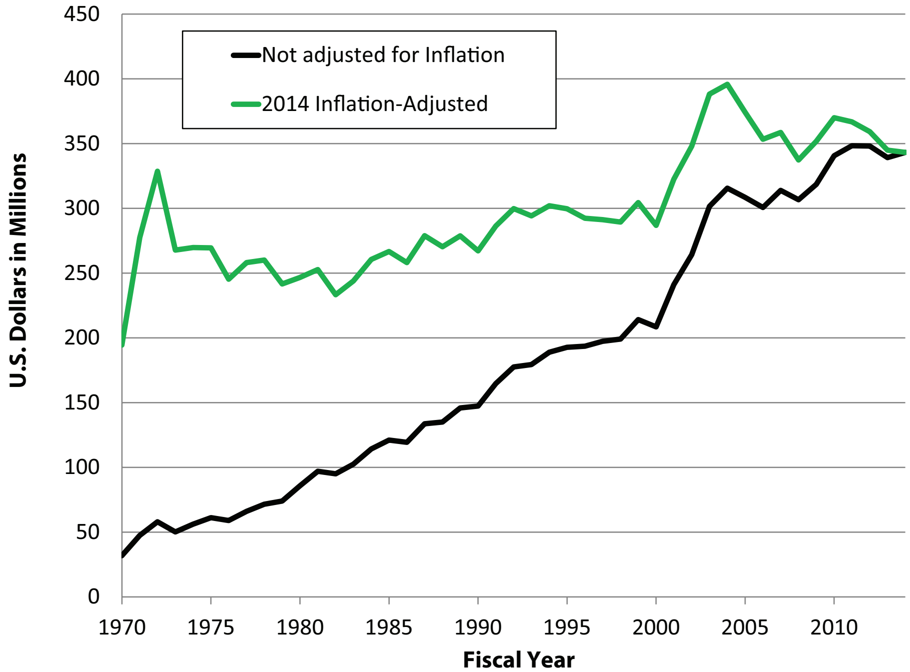

FIGURE 3-1 OCE annual budget from 1970 to 2014. Annual budget data in current dollars was obtained from NSF, July and December 2014. 2014 inflation-adjusted values were calculated based on the U.S. Bureau of Labor Statistics Consumer Price Index annual average except for 2014, which was based on an average of values from January to November.

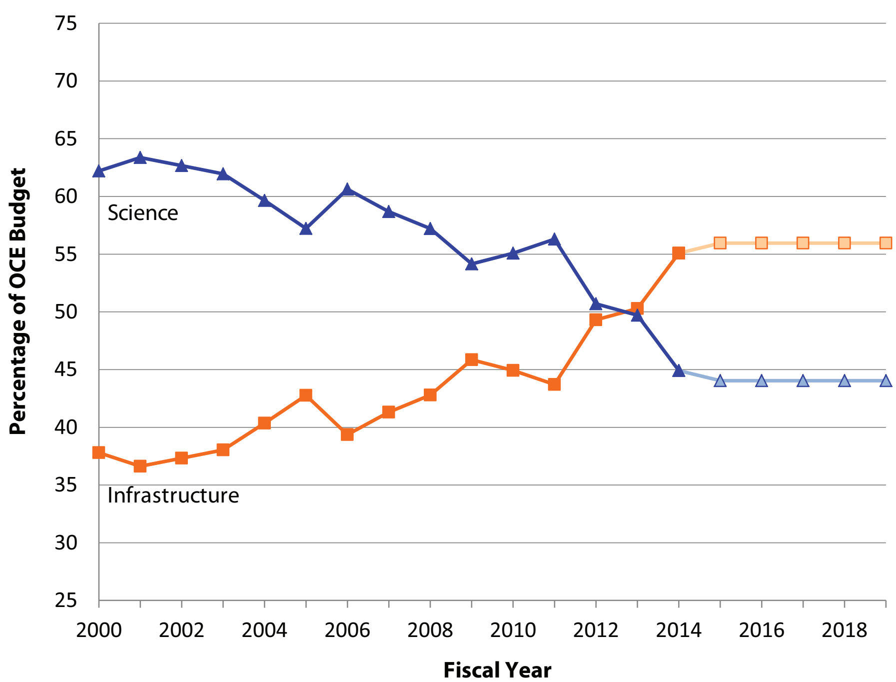

FIGURE 3-2 NSF investments in core ocean science (blue) and infrastructure (orange) since 2000, as a percentage of the total OCE budget. These percentages were calculated based on OCE data presented in the following chapter (Figure 4-1). Fiscal year (FY) 2015-2019 projections assume flat budgets with no inflationary increases. OCE defines "infrastructure" as the academic research fleet, OOI, scientific ocean drilling, field stations and marine laboratories, the accelerator mass spectrometer facility, and miscellaneous smaller facilities. Facilities held in the core programs (shown in Table 3-1) are included in core science, not in infrastructure. Data from NSF, December 2014.

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TABLE 3-1 Small Facilities and Infrastructure Funded by NSF OCE Core Programs. Data from NSF, November 2013.

Type of Infrastructure	Program	Date Started	Funding Support	O&M (per year)
Platforms and Instruments	POOL - mooring equipment	2000	PO	None; periodic upgrades are made using mid-sized infrastructure funds and program funds
	Ocean Bottom Seismograph Instrument Pool (OBSIP)	1999	MGG/ODP	~$3.5 million, with additional experiment costs
	AUV/Glider Pool	2013?	BO/CO/PO	To be determined; may rely on mid-sized infrastructure funds
	Monterey Accelerated Research System (MARS) deep cabled node	2002	OTIC	$285,000-600,000 (2007-2013)
	ALOHA Cabled Observatory deep cabled node	2002	MRI/OI/ OTIC	$390,000-440,000 (2012-2014)
Shore-Based Facilities	National Ocean Sciences Accelerator Mass Spectrometry Facility	1991	AMS/IPS	$2.5 million
Databases and Repositories	CLIVAR and Carbon Hydrographic Data Office	2004	PO	$400,000-500,000
	Biological and Chemical Oceanography Data Management Office	2006	BO/CO	$1.6 million
	Scientific Ocean Drilling Core Repository		MGG	~$800,000
	Geoinformatics Facilities Support	2010	EAR/MGG	~$1.3 million for MGG; $0.7 million for EAR
	Community Surface Dynamics Modeling System	2006	EAR/MGG	~$500,000 for MGG; ~$500,000 for EAR
Time Series	Hawaii Ocean Time-Series (HOT)	1988	BO/CO/PO	~$1.6 million
	Bermuda Atlantic Time-Series (BATS)	1988	BO/CO	~$1 million
	Station S	1954	PO	~$200,000
	Carbon Retention in a Colored Ocean (CARIACO)	1998	CO	~$600,000
	Ocean Flux Program	1978	CO	~$500,000

NOTE: Abbreviations as follows: Accelerator Mass Spectrometry (MAS), Biological Oceanography (BO), Chemical Oceanography (CO), Integrative Programs Section (IPS), Major Research Instrumentation (MRI), Marine Geology and Geophysics (MGG), Ocean Drilling Program (ODP), Ocean Technology and Interdisciplinary Coordination(OTIC), Oceanographic Instrumentation (OI), Physical Oceanography (PO).

infrastructure (less than $5 million/yr). These investments include large programs such as the International Ocean Discovery Program (IODP [2013-2018]), mid-scale facilities such as NDSF, and smaller instrumentation such as the ocean bottom seismograph instrument pool. The committee analyzed the current infrastructure portfolio against the science priorities in order to determine which facilities and infrastructure were indispensable or could strongly contribute to addressing the science priority questions. Table 3-2 summarizes the committee's determination of the alignment between infrastructure and the decadal science priorities.

APPROACH

The committee's assessment of how the current infrastructure matched to the science priorities was approached from two directions. First, the committee examined each question, including its sub-bullets and any geographic

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TABLE 3-2 Alignment of Current NSF-Funded Major Ocean Research Infrastructure to the Eight Decadal Science Priorities.

		Sea level change	Coastal and estuarine oceans	Ocean and climate variability	Biodiversity and marine ecosystems	Marine food webs	Ocean basins	Geohazards	Subseafloor environment
Fleet and Other Ships	Global/Ocean	C	I	C	C/I	C/I	C	C	C
	Regional/Coastal	I	C	C/I	C	C			
	3-D Seismic Ship						C/I	C	I
	Ice-Capable	C/I	I	C	C/I	C/I	I		
IODP	*JOIDES Resolution*	I		I			C	C	C
OOI	Coastal	I	I	I					
	Global			I					
	Cabled						I	I	I
Vehicles	*Alvin*				I	I			I
	ROVs						I	I	C
	AUVs		I		I	I	I		
	Gliders	I	I	I	I				
Other	OBSs						I	C	
	Field Stations / Marine Labs	I	C	I	C	C/I			
Other Critical or Important Infrastructure Assets		Argo, tide gauges, satellites, ice-ocean models, coring facilities and core repositories, mission-specific drilling platforms (MSPs)	River gauges, hydrologic models, satellites, coring facilities and core repositories	Argo, modeling, surface weather analyses, satellites, coring facilities and core repositories, acoustic tomography, MSPs	Fisheries surveys and vessels, sequencing facilities, manned/unmanned vehicles, satellites	Fisheries surveys and vessels, taxonomy, isotope facilities, manned/unmanned vehicles, satellites	Global seismograph arrays, magnetotellurics, manned/unmanned vehicles, *Chikyu* , MSPs	Interferometric synthetic aperture radar, seafloor geodesy, satellites, magnetotellurics, coring, manned/unmanned vehicles, *Chikyu* , MSPs	Sequencing facilities, manned/unmanned vehicles, *Chikyu* , MSPs

NOTE: A “C” indicates a critical asset, while “I” indicates an important asset. The approach taken to reach this alignment is discussed in the text. A list of other critical or important infrastructure is also included.

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constraints (if applicable), and matched those with NSF-supported ocean research infrastructure. This also served to identify infrastructure gaps and needs that were not available through OCE or elsewhere in NSF and led to discussions about whether such facilities could be obtained through other avenues (e.g., other federal agencies, international programs, and private-sector organizations). Second, the committee examined each component of the infrastructure portfolio and matched its specifications and stated goals with the science priorities. This approach emphasized those facilities and infrastructure that served many science priorities, but it also highlighted those that did not. Both approaches are qualitative—informed by program goals, science plans, earlier reports of science and infrastructure needs, and community input from the Virtual Town Hall. Overall infrastructure cost and cost-effectiveness were not discussed at this stage, but they are discussed in detail in later sections of this chapter.

The committee identified four categories of alignment between infrastructure and the decadal science questions: *critical*, *important*, *supportive*, or *not relevant*. The science priority question cannot be addressed effectively without *critical* infrastructure assets, while *important* infrastructure is useful but not essential to address the question. *Supportive* infrastructure assets can provide useful information, but there are other options that may address the research question more directly, completely, or cost-effectively. An example of critical alignment (discussed in detail later) is the use of remotely operated vehicles to study the subseafloor environment; this science priority cannot be addressed without this specific infrastructure asset.

To focus on highest-priority issues, only the committee's assessment of critical and important assets is shown in Table 3-2. Although the committee recognizes that not every member of the ocean science community will agree with each detail of the assessment presented in Table 3-2, the table presents a general overview of the alignments between infrastructure and the science priority questions. The assessment shows that infrastructure assets may be critical or important for some questions and supportive or not relevant for others. During the committee's analysis, the infrastructure components that could be operated independently (for example, the fleet is composed of individual ships of varying sizes and capabilities) were considered separately with regard to their utility for the various science priorities. This segregation is reflected in Table 3-2.

Table 3-2 is followed by a detailed discussion of the major NSF-supported facilities and programs that have significant impacts on the OCE budget—the academic research fleet, IODP (2013-2018), OOI, and NDSF. Icebreakers, although not part of OCE's portfolio, are discussed in association with the fleet, and other types of unmanned vehicles are discussed in conjunction with NDSF. As mentioned previously and shown in Table 3-1, there are a number of smaller, targeted infrastructure facilities and programs funded within OCE's core programs, at an annual cost of about $16 million total. These are not discussed in detail, given their minor impact on budget decisions.

THE ACADEMIC RESEARCH FLEET AND ICEBREAKERS

The UNOLS Fleet

Objectives and Background

Ships provide invaluable access to the sea and are an essential component of the ocean research infrastructure. Evolving science needs, cost pressures, and newer technologies—such as autonomous underwater vehicles (AUVs) and remotely operated vehicles (ROVs) incentivized by development for military and commercial applications (e.g., oil and gas, search and rescue)—have changed the oceanographic research toolbox. However, they have not lessened the reliance on highly capable ships. For example, the Argo drifter array is dependent on global repeat hydrography, taken from ships, to provide independent validation and calibration of temperature and salinity measurements. The committee determined that the University-National Oceanographic Laboratory System (UNOLS) fleet (Figure 3-3), especially the largest (Global class) general-purpose research vessels, is critical and indispensable for addressing the majority of the science priorities (Table 3-2).

UNOLS is widely recognized as providing effective oversight of the fleet (e.g., NRC, 2009), including efforts to determine how to right-size the fleet (the appropriate number of vessels, capabilities for scientific research, and geographic distribution) in times of constrained budgets and increased costs, such as fuel and crew. Frequent interactions between NSF and UNOLS contribute strongly to continued oversight and right-sizing. Concern about reducing the fleet due to limited budgets is not a new phenomenon (e.g., Malakoff, 2005; Mervis, 1996). Right-sizing the fleet is a crucial and continuing effort to manage costs, to match seagoing capabilities with research demands, and to maintain or replace current capabilities. The fleet has already been reduced from 27 vessels in 2005 to 20 vessels in 2014, and it is expected to shrink to 14 or fewer vessels by 2025, depending on whether one or more of the up to three planned Regional class research vessels (RCRVs) are built (discussed below).

The academic research fleet, especially the largest vessels, reflects the strong collaboration and shared needs of NSF and the U.S. Navy from the 1960s through the present. Of the 14 Global, Ocean, and Intermediate ships in the UNOLS fleet, more than half were built by the Navy. However, over the past two decades NSF and Navy missions have diverged, and federal funding for civilian oceanographic Navy ships has been reduced. While Navy has recently built two new Ocean class vessels (*Armstrong* and *Ride*), NSF has taken the lead on design, construction, and/or purchase

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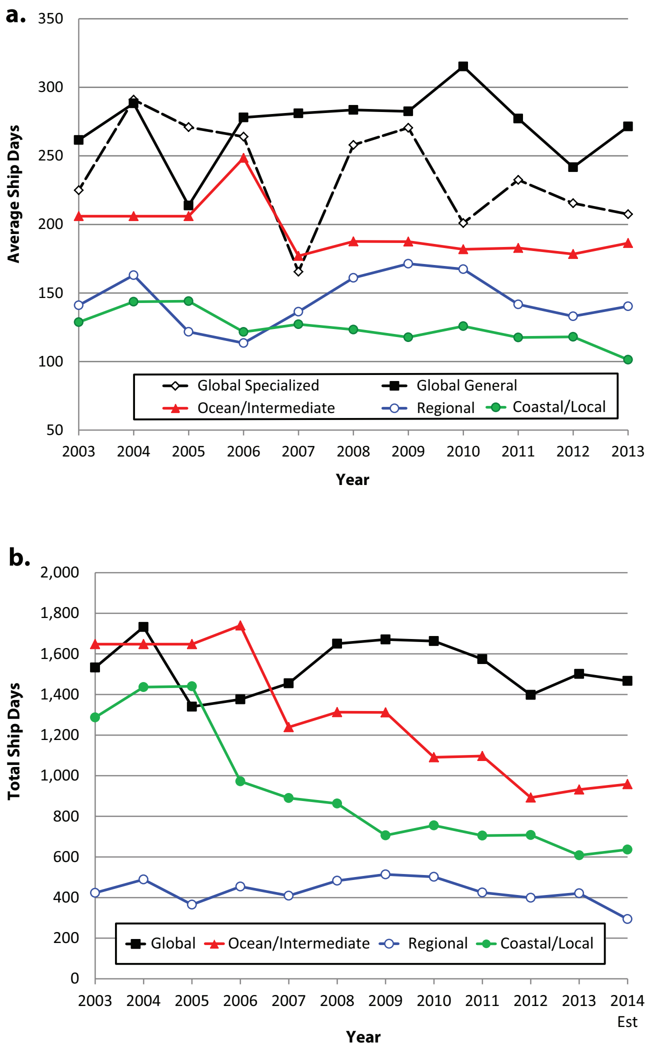

FIGURE 3-3 Ship usage for the UNOLS fleet, broken out by class. (a) Average number of ship days per year (total number of days for each class, divided by the number of ships). In this graph, the Global class is divided into general purpose and specialized ships (*Langseth*, *Sikuliaq*, *Atlantis*). (b) Total number of ship days for each class. Data from NSF and UNOLS, October 2014.

of some of the new vessels for the academic fleet (e.g., *Sikuliaq*, RCRVs). Although it has long been familiar with the challenging process of operating and maintaining a fleet, NSF has recently taken on a greater role in managing fleet modernization, life cycles, and replacement.

Global Class

The Global class ships (and especially the general-purpose ships *Melville*, *Knorr*, *Thompson*, and *Revelle*) are the most heavily scheduled vessels in the UNOLS fleet (Figures 3-3 and 3-4) and have larger capacities at approximately the same day rate as the new Ocean class ships *Ride* and *Armstrong* (Figure 3-4). High demand for the Global ships in part reflects the growth of complex multi-investigator projects that require relatively large science parties. However, both Global class ships *Knorr* and *Melville* were retired in 2014. The *Thompson* will be re-engined, which will increase its service life to the 40-plus-year range. This is likely to occur at the end of 2015 (written response from Rose Dufour, NSF, January 5, 2015). The *Atlantis* is primarily committed as the tender of *Alvin*. The *Langseth*, specialized for three-dimensional seismic operations, has much lower usage than the rest of the Global class (Figure 3-4). It is typically available as a general-purpose platform only ~40% of the time (Houtman, 2014) and has limited capabilities as a general-purpose Global ship. *Sikuliaq*, with its ice-strengthened hull, is best suited for work in polar regions.

No additional general-purpose Global class vessels are currently planned. The Ocean class ships *Ride* and *Armstrong*—with shorter lengths, smaller numbers of berths, and day rates comparable to or higher than existing Globals—were planned as the next generation of large general-purpose vessels. Their completion is coinciding with the retirement of two Global class vessels (*Melville* and *Knorr*). However, they do not have sufficient capabilities for larger coring and seismic survey operations, unlike the retiring Global vessels. Assuming that *Atlantis*, *Langseth*, and *Sikuliaq* remain mostly committed to special purposes or specific regions, only *Revelle* will be available to meet the oceanographic community's need for a general Global class ship by 2022 (if *Thompson* does not undergo a refit). Of particular concern for the marine geology and geophysics community, the fleet stands to lose some of its capacity for larger expeditionary operations such as long sediment coring—*Knorr* was the only UNOLS vessel capable of handling the NSF-funded long coring facility, which was put into caretaker status when the ship was retired. Because of limited over-the-side lifting capabilities, smaller coring operations are also compromised on the Ocean class ships, at least in their current configuration. In addition, programs that need to sample in high seas and work in rough weather regions like the Southern Ocean; highly interdisciplinary, multi-principal investigator, extended sampling programs like the International Study of Marine Biogeochemical Cycles of Trace Elements and their Isotopes (GEOTRACES); and those with large deck space requirements for deploying moorings and other instrumentation all need to use Global vessels. The anticipated shortage of Global class ship resources could be mitigated by exploring innovative exchange or leasing arrangements, either domestically or internationally (a possible example is the National Oceanic and Atmospheric Administration's [NOAA's] *Ronald H. Brown*). Leasing international ships could, however, further limit utilization of the UNOLS fleet.

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SHIP/CLASS	BUILT	Owner	LOA m (ft)	Science Berths	Total Ship Days Used (2013)	Ship Operation + Tech Day Rates	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	End Year
Global Class																								
Melville	1969	NAVY	85 (279)	38	307	28,930																		
Knorr	1970	NAVY	85 (279)	34	253	38,192																		
Thomas G. Thompson	1991	NAVY	84 (274)	36	260	35,702		M																
Roger Revelle	1996	NAVY	84 (274)	37	266	39,121																		
Atlantis	1997	NAVY	84 (274)	37	229	41,202																		
Marcus G. Langseth	1991	NSF	71 (235)	35	186	53,338																		2030
Sikuliaq	2013	NSF	80 (261)	26		**(45-50k)**																		2044
Total in Class							6	5	5	5	5	5	5	5	4	4	4	4	4	3	2	2	2	
Ocean/Intermediate Class																								
Kilo Moana	2002	NAVY	57 (186)	29	241	39,319																		2032
Endeavor	1976	NSF	56 (184)	18	214	19,252																		
Oceanus	1976	NSF	56 (184)	19	162	23,951																		
Atlantic Explorer	1982	BIOS	51 (168)	20	152	23,249																		
New Horizon	1978	SIO	52 (170)	19	163	18,984																		
Neil Armstrong	2015	NAVY	73 (238)	24		**(40-45k)**																		2045
Sally Ride	2015	NAVY	73 (238)	24		**(40-45k)**																		2045
Total in Class							5	7	7	7	7	6	6	4	4	4	4	4	4	3	3	3	3	
Regional Class																								
Point Sur	1981	NSF	41 (135)	12	196	13,896																		
Hugh R. Sharp	2005	UD	44 (146)	14	210	11,725								M										2035
RCRV1	2021	NSF	58 (191)	**(18)**		**(22-23k)**																		2051
RCRV2	2022	NSF	58 (191)	**(18)**		**(22-23k)**																		2052
RCRV3	2023	NSF	58 (191)	**(18)**		**(22-23k)**																		2053
Total in Class							2	1	1	1	1	1	1	2	3	4	4	4	4	4	4	4	4	
Coastal/Local Class																								
Robert Gordon Sproul	1981	SIO	38 (125)	12	31	13,400																		
Pelican	1985	LUMCON	32 (105)	14	194	9,340																		
Walton Smith	2000	Miami	30 (96)	16	115	15,071			M															2030
Savannah	2001	SKID/UG	28 (92)	19	111	9,511				M														2031
Blue Heron	1985	UMINN	26 (86)	6	62	10,020																		
Clifford Barnes	1966	NSF	20 (66)	6	95	4,441																		
Total in Class							6	6	6	5	5	4	4	3	3	3	3	3	2	2	2	2	2	
Total Number of Vessels							19	19	19	18	18	16	16	14	14	15	15	15	14	12	11	11	11	

FIGURE 3-4 Service life projections for the UNOLS fleet. The "M" shown on some ships' expected service life stands for the approximate year of a mid-life refit, if one were to be scheduled. For the category "Ship Operation and Tech Day Rates," numbers shown in black reflect 2013 rates, while numbers in red are operating estimates for future years (RCRV day rate estimate has been deflated to 2014 dollars). Anticipated berthing capacity for proposed Regional class ships are also shown in red. Day rates for all ships vary annually as a result of the actual number of funded operational days on each ship's schedule. New Horizon will be withdrawn from service in February 2015 (personal communication, M. Leinen, October 2014). Modified from UNOLS, with additional data from NSF. NOTE: Abbreviations as follows: Bermuda Institute of Ocean Sciences (BIOS), Scripps Institution of Oceanography (SIO), University of Delaware (UD), Louisiana Universities Marine Consortium (LUMCON), Skidaway Institute of Oceanography/ The University of Georgia (SKID/UG), University of Minnesota Duluth (UMINN).

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Regional Class

NSF is currently considering building between one and three new RCRVs. The planning process for the RCRVs extends back to at least 2001, when the idea of three new Regional vessels was advanced in the Federal Oceanographic Facilities Committee report *Charting the Future for the National Academic Research Fleet* (FOFC, 2001). The Science Mission Requirements for these vessels date back to 2002 (UNOLS, 2003), based on a community workshop and input. GEO has proposed the RCRVs as a potential Major Research Equipment and Facilities Construction (MREFC) project (NSF, 2014). OCE funded Oregon State University to be the lead institution for designing the RCRVs, which recently passed the preliminary design review phase (August 2014). The earliest RCRV could begin construction is 2017. As currently planned, NSF estimates the RCRV day rate (including marine technicians) at about $27,000 in 2021 ($22,000-23,000 in 2014 dollars[4]), based on a 200-day schedule, which is the lower bound of the 200- to 230-day operating year for the UNOLS Regional class (written response from Bauke Houtman, NSF, October 28 and December 10, 2014).

The new RCRVs are likely to be significantly more capable than existing Regional vessels, with length and berthing capabilities that are more similar to the Intermediates *Oceanus* and *Endeavor*, and the Ocean class *Kilo Moana* (Figure 3-4). These features reflect the ocean sciences community's desire to address more complex, multidisciplinary science questions in coastal regions.

Usage and Budget

Figure 3-3 shows steady use of the Global and Regional classes and declining use of the Coastal/Local class. In addition, there is a disturbing trend of substantially higher day rates for the *Ride*, *Armstrong*, *Sikuliaq*, and the planned RCRVs when compared to vessels that have been recently retired (Figure 3-4). In the case of the Regional vessels, "capability creep" (discussed further below) is likely to be responsible for the higher estimated day rates. Because of these higher day rates, the retirement of the same number of lower-cost ships will not be enough to maintain a level budget. Therefore, additional pressure on the budget can only be avoided through overall reductions in the number of vessels.

For FY2014, the provisional NSF contribution to the UNOLS fleet operating budget was $83 million (written response from NSF OCE, June 1, 2014). NSF funded a significant percentage of total fleet costs in FY2014—67% of the Global class, 65% of the Ocean class, 51% of the Regional class, and 30% of the Local class (Houtman, 2014). These percentages could increase in future years if other agencies experience budget decreases, which would put additional fiscal pressure on OCE. UNOLS has been exploring alternatives to meet budget and usage shortfalls. These include strategies such as partnering with industry to use UNOLS ships as test platforms for new products and occasional commercial charters on UNOLS vessels, thereby reducing the day rate to federal agencies. An additional approach may be to remove some of the Coastal/Local ships from the UNOLS pool, given their relatively low utilization and ease of replacement through short-term charters of private-sector vessels.

Ice-Capable Ships

Ice-capable ships provide access to polar regions, necessary for many emerging and existing science fields. The newly commissioned *Sikuliaq*, the only ice-strengthened ship in the UNOLS fleet, can operate in 2.5 ft of ice. Through the Division of Polar Programs, NSF operates two other ice-capable research vessels—*Nathaniel B. Palmer*, a 308-ft-long icebreaker capable of moving through 3 ft of ice, and *Laurence M. Gould*, a 230-ft-long ice-strengthened vessel capable of breaking through 1 ft of ice. These vessels are under charter and their costs, capabilities, and longevity are evaluated by NSF as contracts are considered for renewal. NSF also has access to U.S. Coast Guard vessels for heavy icebreaking (*Polar Star*) and medium icebreaking (*Healy*) that support both science and logistical missions, such as breaking the channel into the Antarctic McMurdo Station for annual resupply and science operations in the high Arctic. There has recently been discussion among Congress, the U.S. Coast Guard, and other federal agencies about the rationale and cost to maintain U.S. capabilities for heavy icebreaking[5] as well as the viability of chartering non-U.S. icebreakers for some operations. The polar ships occasionally support lower-latitude research cruises, which can help to avoid long and costly transits for UNOLS vessels and provide cost efficiencies for both the polar ships and the academic research fleet.

Alignment with the Science Priorities

Some of the strongest alignments between current infrastructure and the decadal science priorities are seen when assessing the fleet. This is supported by conclusions from many previous reports, which state that the ocean sciences will continue to be a strong user of ships now and in the future. The Global class vessels are either critical or important for all decadal science priorities (Table 3-2), which is consistent with the *Science at Sea* report (NRC, 2009). That committee concluded that current trajectories in ocean science will increase demand for the Global class, with their greater deck loading, berthing, and sea state capacities, and that new technologies are likely to increase the need for research ships capable of supporting multidisciplinary, multi-investigator

[4] This calculation uses an integrated inflation rate for fuel (2.9% or 4.0%) and nonfuel (2.2%) costs and rounds off to the nearest thousand dollars.

[5] See, for example, http://transportation.house.gov/calendar/eventsingle.aspx?EventID=386881, a July 2014 House hearing on "Implementing U.S. Policy in the Arctic."

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science. The science priorities point to a continuing need for ships capable of long-leg hydrographic cruises measuring the full suite of physical and biogeochemical variables at high precision, and for deployment of the large tools typically used by the marine geology and geophysics communities.

The *Science at Sea* report also discusses the need for larger, more capable Regional ships to explore coastal processes and to collect sediment, water, and biological samples from nearshore areas. In addition, OCE program managers identified potential uses for the planned RCRVs, including utility as support ships for OOI and for deployment of instruments along coastal margins (Houtman, 2014).

Ice-capable ships are important for answering a number of the priority research questions in polar oceans and will continue to be critical for understanding climate change, ocean-ice interactions, and polar marine food webs.

Additional Comments

In the UNOLS lexicon, ships are categorized into Global, Ocean/Intermediate, Regional, or Coastal/Local classes (Figures 3-3 and 3-4). These designations have evolved over time and do not necessarily reflect each vessel's capabilities. For instance, Ocean and Intermediate class ships are listed together but have varying capabilities and capacities that will affect their usage. Because *Ride* and *Armstrong* will not be available until 2015, it is difficult to predict their use at this time or their ability to approach the capabilities of retiring Global class vessels. In addition, specialized ships (such as *Langseth* or *Atlantis*) confound simple analyses of ship class and usage.

To increase the availability of general-purpose Global research vessels, NSF could look for cost-effective ways for such ships to be made more readily available. For example, NSF could ask NOAA and UNOLS to determine whether the *Ronald H. Brown* could be used by UNOLS through mutual scheduling or even inclusion into the UNOLS fleet proper. Discussions could also be held with other large research vessel operators to see if any excess capacity could be used to support NSF needs. Examples to consider might be the Schmidt Ocean Institute's *R/V Falkor* or the acoustically quiet *NRV Alliance*, operated by the North Atlantic Treaty Organization's Centre for Research and Maritime Experimentation. This type of discussion could explore how collaborations between agencies and nonfederal entities could be mutually beneficial and fiscally attractive.

Over a decade has been spent planning for the new RCRVs. The current design approaches the capabilities of the Intermediate class—the next larger class of ship—which results in substantially higher expected day rates than the current Regional class vessels. This expansion in capability and cost, combined with the restricted geographical range associated with the RCRV's regional status (Figure 3-4), raises the question of whether the current design is well matched for expected future use. Additionally, budget realities raise the question of whether three new RCRVs are appropriate and affordable. The committee notes that RCRV planning began when the OCE budget was rising (Figure 3-1) and the ratio of infrastructure to science was more balanced than at present.

SCIENTIFIC OCEAN DRILLING

Objectives and Budget

NSF has supported an ocean drilling program for many decades: the Deep Sea Drilling Program (1968-1983), the Ocean Drilling Program (ODP [1983-2003]), the Integrated Ocean Drilling Program (IODP [2003-2013]), and the International Ocean Discovery Program (IODP [2013-2018]), which will operate until 2018 in its initial 5-year phase. The 2011 NRC report *Scientific Ocean Drilling: Accomplishments and Challenges* found that "the U.S.-supported scientific ocean drilling programs . . . have been very successful, contributing significantly to a broad range of scientific accomplishments in a number of Earth science disciplines" (NRC, 2011b). The high-level science themes of IODP (2003-2013) and IODP (2013-2018) are similar to one another, involving studies of past climate and environmental change, microbial life in the deep subseafloor, geohazards, and solid earth processes.

The scientific ocean drilling programs have generally been regarded as "infrastructure heavy." By design, most direct IODP funding is allocated for facilities and operations. The smaller amount for science support has primarily been associated with the U.S. Science Support Program, with the majority of the funding going toward travel and salary support for U.S. scientist participation in shipboard operations and required post-cruise meetings. Although most pre-drilling site survey activities have been funded by core programs and peer reviewed on their independent scientific merits, a small portion of NSF's IODP funds were in the past allocated to site surveys that were considered necessary to maximize the success or safety of drilling operations. Prior to FY2015, a smaller portion of funds from NSF-IODP were allocated for initial post-expedition research, but most post-expedition analyses were funded through core programs. Starting in FY2015, all site surveys and post-expedition research will be funded through the core science programs.

Figure 3-5 shows the distribution of NSF funding for the *JOIDES Resolution* facility and for science support (external to core programs) during IODP (2003-2013) and IODP (2013-2018). Although the data do not reflect the full time period, in part because of the 2006-2009 *JOIDES Resolution* refit, science as a percentage of the total budget was higher (32%) in 2003 (the final year of ODP) than in the later years of IODP (2003-2013) (14-18%). The science percentages estimated for FY2015-2019 (12-13%) are even lower than in previous years. These changes in the percentage of science relative to infrastructure support show a long-term trend of treating IODP more as a facility than as a science program,

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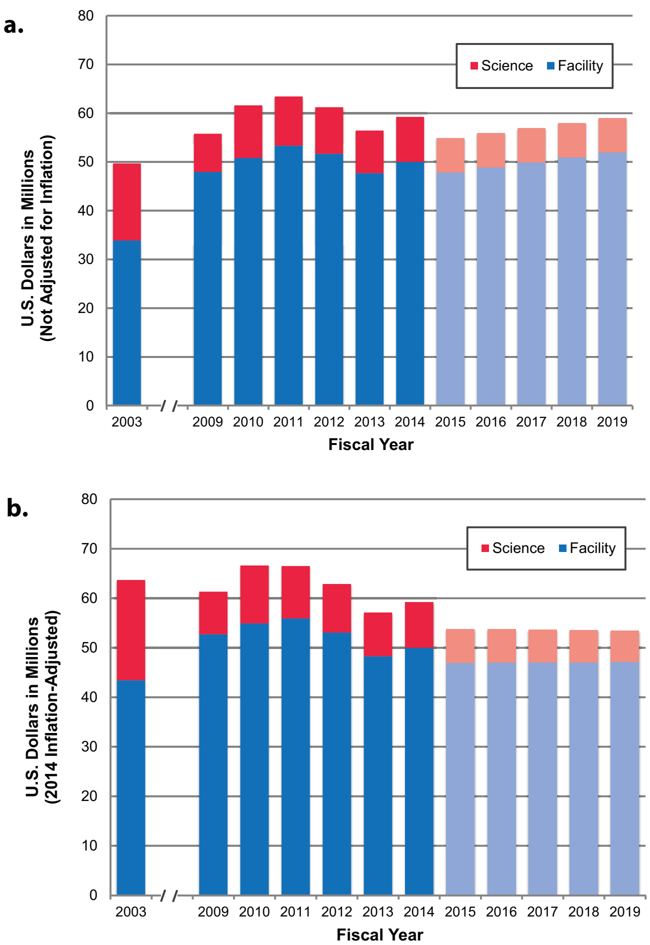

FIGURE 3-5 NSF funding for the *JOIDES Resolution* facility and for science during IODP (2003-2013) and IODP (2013-2018). For FY2003 and FY2009-2014, science funding includes individual grants from NSF, the U.S. Science Support Program, and a 2013 cooperative agreement with Scripps Institution of Oceanography for an IODP Support Office during the transition between programs. It does not include individual science grants related to IODP that originate from core programs. Data from FY2004-2008 are not included because the available information is a mix of program and facilities costs that were associated with an interim operating contract, the 2006-2009 *JOIDES Resolution* refit, and decreasing usage in 2004-2006. Values for FY2015-2019 are estimated budgets; the science estimate in future years does not include the grants moved to core programs in FY2015. (a) Values in current dollars. Data from NSF, January and July 2014. (b) Values in 2014 inflation-adjusted dollars.

with a shift of science activities mostly into the Marine Geology and Geophysics core program.

There was a major change in how international scientific ocean drilling was funded at the transition between ODP and IODP in 2003, which resulted in significantly higher total costs associated with operating multiple drilling platforms. IODP (2003-2013) was co-led by the United States and Japan, with substantial contributions from the European Consortium for Ocean Research Drilling (ECORD) and the involvement of other countries. During this phase of the program, NSF operated the drillship *JOIDES Resolution*; the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) operated the *Chikyu* drillship; and ECORD leased mission-specific platforms depending on the type of operations needed. Management costs were shared.

The complexity of working with multiple partners, and an assumption of growth in the NSF and international science budgets that was not realized, led to funding shortfalls and delays in implementation. Given these shortfalls, both the *JOIDES Resolution* and *Chikyu* were kept in port for extended periods of time. Some high-priority science programs were deferred, even though substantial daily lease costs for the *JOIDES Resolution* continued. Program operations in this phase were also disrupted by a 3-year, $115 million refit of the *JOIDES Resolution* funded by NSF's MREFC account, which was descoped due to budget overruns (Allen and Walters, 2009). During this hiatus, a portion of the program funds helped to retain essential staff that assisted with the refit process. Cost pressure during IODP (2003-2013), driven by complex management arrangements, rapidly increasing fuel costs, generally flat budgets, and decisions to invest in other programs, led to a need to decrease IODP operating costs and improve efficiency in the next phase.

In an effort to address budget reductions, IODP (2013-2018) initiated a new program model, in which each platform provider (NSF, ECORD, and MEXT) is now funding and managing its own infrastructure. As the primary funder of the U.S. platform *JOIDES Resolution*, NSF's FY2015 contribution to operating costs is $47.9 million; this constitutes 74% of the ship's total operating budget (Figure 3-5). Other countries will contribute an additional $16.5 million for FY2015 *JOIDES Resolution* operations (Brazil and China, $3 million each; Australia and New Zealand, $1.5 million combined; India and Korea, $1 million each; and ECORD, $7 million). Each country or consortium supports its own scientists and their research costs separately. All contributions are expected to remain steady (with inflationary increases) through FY2019 (Figure 3-5). The current *JOIDES Resolution* funding scenario supports approximately four expeditions per year (approximately 2 months per expedition, with 8 months of total operation), with about 6-10 high-priority proposals expected to be forwarded to the *JOIDES Resolution* Facility Board each year. Under that scenario, about half of the high-priority proposals would be supported.

An additional funding mechanism—Complementary Project Proposals (CPPs)—has been implemented, in which an interested country or private entity can provide extra funds on top of any continuing contribution for specific expeditions on the *JOIDES Resolution* beyond the nominal four expeditions per year funded by the consortium. CPPs are still vetted through the normal IODP (2013-2018) peer-review process. For example, in FY2014, China contributed $6 mil-

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lion for the South China Sea CPP, and in FY2015, India will contribute $6 million for the Arabian Sea CPP. In addition, the *JOIDES Resolution* is available for externally funded industry work during the 4 months per year that it is not used for academic research. For example, in FY2012-2013 industry provided an estimated $11 million of cost avoidance for NSF, including day rate avoidance and savings from fuel, insurance, and salary avoidance. Although some industry objectives were proprietary, the academic community was given access to the drill cores.

Alignment with the Science Priorities

Based on the committee's analysis, scientific ocean drilling capabilities are critical to decadal science priorities related to the formation of ocean basins, characterization of geohazards, and attaining a better understanding of the global significance of the subseafloor ocean biosphere (Table 3-2). Ocean drilling, through its ability to explore past climate, is important for the decadal science priorities related to sea level rise and climate variability. Addressing these priorities requires long-term commitments to sampling the subseafloor and analysis and archiving of cores. Community input from the Virtual Town Hall was supportive of scientific ocean drilling as a valuable tool for the ocean sciences. Scientific ocean drilling has also proven to be an effective vehicle for science diplomacy, with its sustained focus on international partnerships.

Additional Comments

The total planned NSF contribution to the *JOIDES Resolution* facility over the next 5 years is estimated at $250 million (Figure 3-5), which provides ~$50 million annually for the four *JOIDES Resolution* expeditions and a number of berths on the other platforms. For 2015, there are berths for 32 U.S. scientists to sail on the *JOIDES Resolution* (8 per expedition), 16 berths on *Chikyu*, and 8 berths on ECORD's mission-specific platform operations. MEXT and ECORD receive an equivalent annual number of berths on the *JOIDES Resolution*, and ECORD contributes $7 million/yr to *JOIDES Resolution* operations. However, when examining the FY2015 *JOIDES Resolution* funding as a proxy for cost allocations, NSF appears to pay significantly more for a U.S. scientist to sail annually than the IODP (2013-2018) contributor countries that do not manage their own infrastructure. The committee notes that *Chikyu* has no planned expeditions for 2015. Furthermore, the frequency of ECORD mission-specific platform operations, originally intended to average one per year according to the past two IODP science plans,[6] has not been realized. In contrast to these optimistic plans, between 2004 and 2014 just five mission-specific platform operations occurred. None occurred in 2011, 2012, or 2014, and one is planned for late 2015.

Given the berth agreements, the reductions in missions by international partners, and the increasing fraction of NSF expenditures on IODP infrastructure relative to science, it is unclear if U.S. scientists have obtained the scientific benefits proportional to the program costs that were intended by the original international agreements. If three drilling platforms are maintained, the committee urges NSF to evaluate whether the subscription costs for international partners to sail on the *JOIDES Resolution* are appropriately priced. In addition, private entities or nations purchasing expeditions through the CPP mechanism appear to mainly be paying the incremental cost of operations instead of the full O&M and transit costs of the facility.

The committee recognizes that IODP and the drilling community have made significant efforts to address budget shortfalls. The development of mechanisms to enhance revenue through CPP and industry contracts provides welcome cost avoidance, but the need for those mechanisms and the lower-than-anticipated use of non-U.S. drilling platforms suggests that the international community is overextended in the area of scientific ocean drilling. It appears that the United States is shouldering an excessive burden for ocean drilling compared to other contributing countries. The committee urges NSF to strongly consider an alternative financial arrangement within IODP and/or a reduction in the number of platforms in the consortium, including the possibility of terminating the *JOIDES Resolution* if additional operating revenues cannot be found from non-NSF sources. However, the committee recognizes that the greatest proposal pressure within IODP is associated with use of the *JOIDES Resolution*, and its broad utility needs to be a driving force in these discussions.

In the context of a level budget, a successful strategy for IODP (2013-2018) might be to reduce the proportion of funding spent on infrastructure and to increase the proportion used for analysis of existing materials. A consideration of cost-effective ways to collect cores that are most relevant to high-priority science themes is needed. In particular, less costly approaches might be used to address some issues of climate and sea level variability on the subcentury scale, as well as to understand some of the processes occurring within the subseafloor biosphere.

OCEAN OBSERVATORIES INITIATIVE

Objectives and Budget

The objective of the OOI is to provide sustained measurements from the seafloor to the air-sea interface across specific sites in the coastal, regional, and global domains, with a planned 25-year operational life (OOI, 2007). OOI's concept is that of a shared facility for use by the entire sci-

[6] "One mission-specific platform (MSP) operation (two months average) per year is expected" (IODP-MI, 2011, p. 70) and "[w]e anticipate that mobilization of one mission-specific drilling platform per year will be standard operating procedure in IODP" (IODP, 2001, p. 74).

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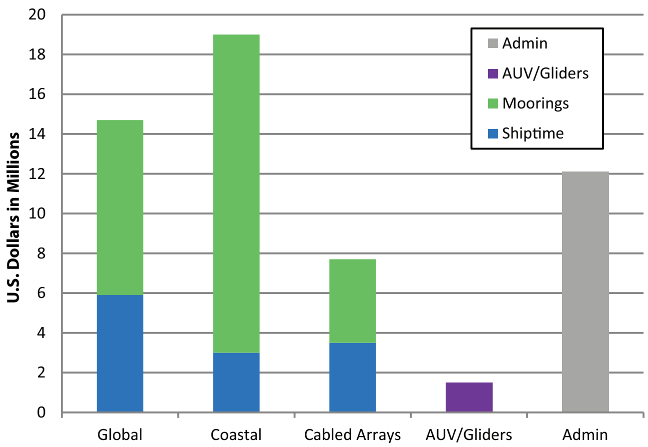

FIGURE 3-6 NSF estimate of annual O&M costs for the global, coastal, and cabled observatory components of OOI, as well as administrative costs for scientists, engineering, and management. Data from NSF, December 2014.

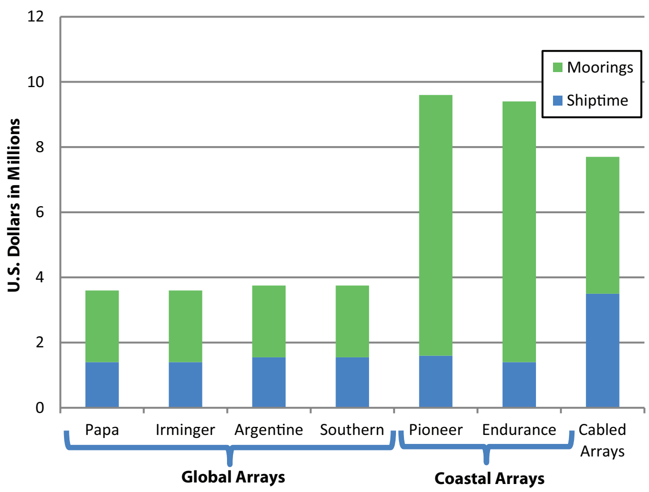

FIGURE 3-7 NSF estimate of OOI annual O&M costs (also shown in Figure 3-6) of the individual components of the global mooring and coastal arrays. Data from NSF, December 2014.

ence community, which is a new model for providing access to ocean data. This concept began to take shape in the late 1990s and was refined through the next decade. An early vision of the ocean observatory initiative consisted of the cable-connected Northeast Pacific Time-Series Undersea Networked Experiments (NEPTUNE) array, spanning the Juan de Fuca plate and its boundaries with three neighboring plates, motivated by a need to understand plate-scale tectonic and volcanic processes. Beyond the clear geophysical and geologic value of this array, a compelling case was made that the power and bandwidth supplied by the seafloor cable could enable a wide variety of additional multidisciplinary sensors. Community outreach at meetings expanded the concept to include long-duration and coastal moorings that addressed a variety of scientific topics in geographic locations beyond NEPTUNE.

OOI construction was enabled by funding from the American Recovery and Reinvestment Act of 2009 through the MREFC account within NSF. Total construction costs are estimated at ~$386 million (written response from Jean McGovern, NSF, March 1, 2014). The 25-year O&M costs of OOI are to be supported by the OCE budget and are estimated to be capped at $55 million for FY2015, increasing by $1 million/yr through FY2019 (written response by Debbie Bronk, NSF, January 29, 2014). Estimated annual O&M costs by site are summarized in Figures 3-6 and 3-7. Administration costs of $11.1 million annually support 38 scientists, engineers, managers, and technicians (written response from Debbie Bronk, June 23, 2014). The project is currently in the construction and deployment phase and is expected to be operational by March 2015.

The $55 million to $59 million per year currently estimated by NSF to be allocated to OOI operations for FY2015-2019 is for O&M only and does not include any support for research projects proposed by the scientific community, or for sensors beyond the basic array. Research projects and any other equipment to be added to the array will compete within core science budgets or relevant initiatives through a peer-review process.

OOI Components

OOI has four major components (Figure 3-8): a cabled observatory, two coastal arrays, four global-scale high-latitude moorings, and cyberinfrastructure. Although NSF views OOI as a "networked ocean research observatory," the committee noted that, although there are common specifications and sensors, the components are geographically separated and have distinct research functions. Therefore, this report examines the potential contributions of the major components (excluding cyberinfrastructure) for their expected alignment to the science priorities, rather than assessing the OOI as a single system. These are summarized in Table 3-2 and discussed in detail below.

Global Moorings

The *global component* is composed of assets deployed in four high-latitude sites: the Southern Ocean southwest of Chile (55°S, 90°W), the Irminger Sea southeast of Greenland (60°N, 39°W), the Argentine Basin in the South Atlantic (42°S, 42°W), and Station Papa in the North Pacific (50°N, 145°W). Each site has a local array composed of surface and subsurface moorings with sensors to measure air-sea fluxes, biochemical sensors, and acoustic Doppler current profilers; gliders to sample between the moorings at given sites; and telemetry for providing data in near real time. Vertical profiling moorings will allow adaptive sampling of episodic features.

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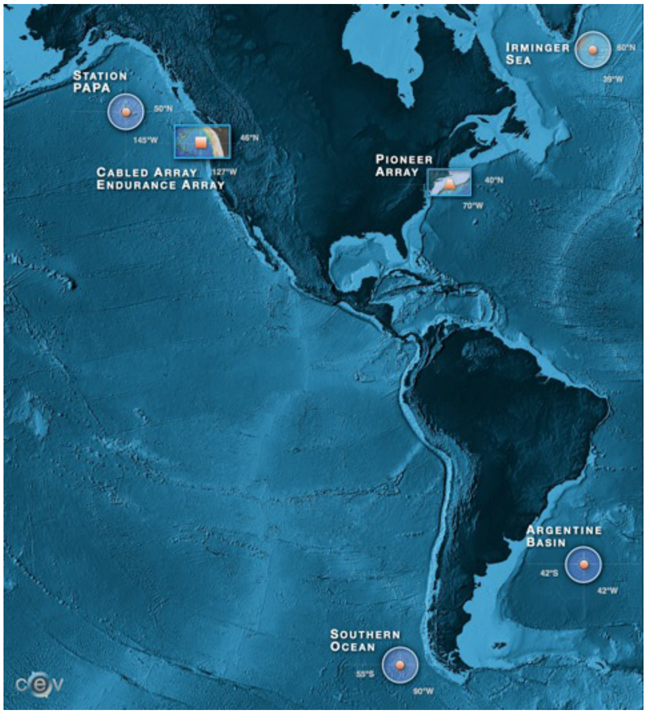

FIGURE 3-8 Location of OOI components. SOURCE: OOI Cabled Array program and the Center for Environmental Visualization, University of Washington.

Regional Cabled Observatory

The *regional component* is composed of a high-power, high-bandwidth fiber optic cable observatory on the Juan de Fuca tectonic plate, west of Newport, Oregon. There are three main study sites: Hydrate Ridge (methane seeps), Axial Seamount (active volcanism), and the Newport Line (moorings and gliders) connecting to the Endurance Array of the coastal component. Site sensors include mass spectrometers, seismometers, and temperature and chemical probes. In evaluating the alignment of the cabled observatory with science priorities, the Newport Line was included as part of the coastal component.

Coastal Arrays

The *coastal component* comprises the Pioneer Array, currently located south of Martha's Vineyard in the Atlantic Ocean, and the Endurance Array off Oregon and Washington. The Pioneer Array is intended to study shelf-break frontal dynamics and impacts on ecosystem and climate for a 5-year period, after which the array O&M will be recompeted and could be moved elsewhere. The Endurance Array will support research on wind-driven cross-shelf transport and freshwater-driven transport in an eastern boundary current system across the Cascadia continental margin for the planned life of the project (25 years). Part of the array is connected to the regional cabled observatory, which will provide power and high-bandwidth data transfer; the other part of the Endurance Array—off Grays Harbor, Washington—is stand-alone. The two sites on the Endurance Array are connected by patrolling gliders. The Pioneer Array will have AUVs and seafloor-mounted docking stations for recharging and data transfer.

Cyberinfrastructure

The *cyberinfrastructure* component comprises a common operating infrastructure and database scheme for the other three components of the OOI, with the goals of supporting data management and making data freely available for educational and scientific pursuits.

Alignment to the Science Questions

The committee considered the priority questions in relation to the capabilities of the OOI components. Because the OOI infrastructure is yet to be fully deployed or operated (as of November 2014), the committee based its assessment on the most recent documentation of OOI science themes, which were outlined in the 2007 report *Ocean Observatories Initiative (OOI) Scientific Objectives and Network Design: A Closer Look* (OOI, 2007). The coastal arrays are important for the decadal science priorities related to sea level rise, coastal processes, and climate variability and impacts; the global moorings were also found to be important for climate variability. The regional cabled observatory is important for exploring the evolution of ocean basins, characterization of geohazards, and life in the subseafloor biosphere, although the committee notes that the final design of the cabled observatory is much reduced from the 2007 plan. As noted above, in evaluating the alignment of the cabled observatory with science priorities in Table 3-2, the Newport Line was included as part of the coastal component.

The global moorings are least well aligned to the decadal science priorities. For example, the committee noted that the high-latitude moorings of the global array do quite well in addressing air-sea interaction during extreme events, a long-standing issue for the improvement of climate models. However, the committee is unconvinced that 25 years of measurements will be required to address that topic. Observations collected over a 2- to 3-year time frame (or long enough to achieve a variety of conditions, including extreme events) would likely provide sufficient information to better characterize air-sea interactions for climate models.

In addition, the committee thought that fewer than four sites would be required, and that the Northern Hemisphere moorings were of more potential value in addressing the decadal science priorities. The Irminger Sea mooring has potential for European collaboration and is the site of documented deep water formation. It is likely to advance the goal of quantifying the energy and gas exchange between the surface and deep ocean, improving storm forecasting and climate change models. The Station Papa site has a long history

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of interdisciplinary studies. Given current cost constraints, the Northern Hemisphere sites also have the advantage of being somewhat less expensive to maintain.

Additional Comments

Assessing the value of infrastructure that is not fully operational was a difficult task for the committee. Without a track record or a significant user base, it is premature to make strong statements about potential success, failure, or the possibility for transformational research. OCE has not yet provided information to the scientific community on the process for combining the use of OOI assets with more traditional infrastructure (e.g., ship-based programs) to study ocean processes, or for adding instrumentation once the platforms are operational. In theory, access to freely available data from OOI could enable the development of lower-cost proposals that utilize these data, expanding the pool of scientists that will use the facility.

However, a review of comments from the Virtual Town Hall and additional discussions with both early-career and established scientists suggest a widespread lack of community support—OOI is an expensive project that appears to have limited appeal and is coming online at a time when budgets are highly constrained. The lack of community-wide support may be due to the MREFC process itself, which requires a final plan for construction and does not have a process for responding to input received from the community during implementation. The MREFC process also precluded adoption of a staged approach of testing, modification, and phased array deployment, which could have incorporated lessons learned and user feedback. The shift of OOI's focus from a broad-based science project discussed at community meetings to a construction project (as stipulated by the MREFC process) appears to have limited community engagement and created an impression that the project lacked transparency.

The lack of broad community support has been exacerbated by an apparent lack of scientific oversight during the construction process. For example, the OOI Program Advisory Committee was established in 2008, but it appears to be inactive—there is no publicly available information on their website.[7] UNOLS does have an Ocean Observing Science Committee that provided a number of recommendations to NSF regarding data management, deployment of infrastructure, and engagement with the broader ocean sciences community (OOSC, 2012).

Other models exist for the management of GEO MREFC projects that include greater community engagement and scientific oversight. For example, EarthScope, funded by NSF's Division of Earth Science (also in the GEO Directorate), is a land-based observation system that uses geophysical instruments to explore the evolution of the North American continent. The construction phase included commercially available instruments, strong scientific oversight through annual reports from the EarthScope Facilities Executive Committee (members included the project director and representatives and principal investigators for the three facilities) and NSF program and project managers, and, perhaps most importantly, strong community engagement through EarthScope Project Advisory committees (EarthScope Facilities Executive Committee, 2006). These community-based advisory committees met at least twice per year and provided scientific and technical advice as the project developed. There was a formal process for considering change requests "that weighs scope, schedule, cost, risk, and gain against the project's scientific objectives" (EarthScope Facilities Executive Committee, 2006). Furthermore, data were made available to the research community as instrumentation was installed, providing an opportunity for new scientific results even before the construction phase was complete. In the post-construction phase, NSF established an EarthScope National Office and an EarthScope Steering Committee to motivate broad community participation and develop a science plan. Funds were specifically set aside to support science, not just facility O&M; this included an NSF program officer to manage EarthScope science. The separate funding scheme recognized that observatory-related science is different from traditional science and was considered essential to the program's success. Although the OOI construction phase is nearing completion, there is still an opportunity to apply lessons learned from projects such as EarthScope to help build support.

In addition, there do not appear to be many plans to engage international partners in OOI. Especially for the global moorings, this seems to be an area that is ripe for opportunities to collaborate and share costs. The committee also has concern that the O&M costs for OOI will exceed the cost ceiling designated by NSF. Ocean Networks Canada has dealt with the issue of anticipated maintenance and unanticipated failures by planning not only for annual costs of maintenance for instruments and other equipment but also for extraordinary maintenance investments to replace cables and nodes, and self-insurance to cover accidents on the system. NSF might consider this type of contingency planning for OOI, if it has not already. Finally, the committee notes that, as with the RCRVs, long-term planning and costing for OOI was initiated at a time when the overall costs of infrastructure were lower and budget outlooks were brighter.

However, it is encouraging that several new initiatives are planning process studies that leverage OOI infrastructure and data. These initiatives include the National Aeronautics and Space Administration–supported EXport Processes in the Ocean from RemoTe Sensing (EXPORTS Science Plan Writing Team, 2014) and a proposed Global Biogeochemical Flux Observatory (Honjo et al., 2014).

[7] See http://oceanobservatories.org/about/ooi-program-management/program-advisory-committee/ (accessed October 2014).

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THE NATIONAL DEEP SUBMERGENCE FACILITY

Objectives and Background

The NDSF is a federally funded center that coordinates the use of the human-occupied vehicle (HOV) *Alvin*, the ROV *Jason*, and the AUV *Sentry.* It is operated and maintained by Woods Hole Oceanographic Institution (WHOI). The UNOLS Deep Submergence Science Committee provides oversight in the use of NDSF vehicles and promotes technological innovations and increased capabilities for the vehicles. There are other unmanned vehicles (AUVs and gliders) that are supported by NSF but are funded individually or through other initiatives (e.g., gliders associated with OOI) and are not associated with NDSF.

Alvin

The U.S. Navy–owned *Alvin*[8] has been in operation since 1964, with numerous cycles of technical upgrades to increase its capabilities over the decades. *Alvin* has a dedicated Global class tender, also U.S. Navy owned, the *R/V Atlantis*. *Alvin* use declined by approximately 20% between 1990-1999 and 2000-2009, although it still averaged about 200 dives per year in the last decade (NRC, 2011a).

In 2004, during a time of NSF budget growth, NSF awarded $22.9 million to WHOI to upgrade *Alvin* to enable it to operate at depths down to 6,500 m. After construction of a new, larger titanium personnel sphere, the revised cost estimates to complete the *Alvin* upgrade were significantly higher than the original amount budgeted. NSF decided to proceed with a staged approach to the remaining *Alvin* improvements and provided an additional $13 million. WHOI also provided an additional $5 million (personal communication, Brian Midson, December 30, 2014). Total cost of the overhaul was $40.9 million. Phase 1 upgrades included the new personnel sphere, additional viewports, better navigation, new syntactic foam, and hardware improvements, but not an overall increased depth capability. All of the hardware improvements made in Phase 1 are rated to 6,500 m. The A-frame on *Atlantis* was also upgraded. The Phase 1 upgrade began in 2011 and *Alvin* returned to full service in 2014. Its current depth certification is for 3,800 m, but it is expected to be certified for depths down to 4,500 m in January 2015.

The next stage of upgrading *Alvin* requires new batteries with increased capacity; a new battery system would need to be approved by the Naval Sea Systems Command, which certifies *Alvin* for use. In addition to batteries capable of supporting 6,500-m operations, implementation of a Phase 2 upgrade would be predicated on persistent science demand for humans to reach those depths and the availability of funds to support its upgrade, maintenance, and operation.

There are currently no other deep-diving U.S. manned submersibles in the oceanographic research community. *Johnson Sea-Link I* and *II* (914-m depth capability), owned by Harbor Branch Oceanographic Institute-Florida Atlantic University, were taken out of service in 2011 due to lack of agency support. *Pisces IV* and *V* (2,000-m depth capability), owned by the University of Hawaii, were recently recertified but are not currently operating, also due to lack of agency support. Several other nations currently operate HOVs that reach at least 6,000 m,[9] and there are also privately owned and operated research submersibles, most of which have shallower maximum depth capabilities.

Jason

The present-generation 6,500-m-depth *Jason* ROV has been in service since 2002 (the first-generation ROV was launched in 1988). It is equipped to collect samples, take imagery, and navigate the seafloor, with dives lasting up to about a week (although typically 1-2 days). *Jason* is deployed with *Medea*, which provides tether management and decouples the motion of the ROV from its surface ship. *Jason* can be deployed from Ocean or Global class vessels. Following the general trend of increased ROV use, *Jason* dives increased threefold between 1990-1999 and 2000-2009 (NRC, 2011a). Since 2011, there has been consistently high demand and use of *Jason* (approximately 170 days/year; NSF Committee of Visitors, 2014).

Jason is one of several large, capable ROVs available for use in the oceanographic community, but it is the only one associated with and subsidized by the NDSF. There are similar ROVs funded by NOAA, other countries, private institutions, and industry.[10]

Sentry

Sentry is a 2.9-m-long AUV that is capable of carrying a sensor suite that can operate in the water column or near the seabed. As *Sentry* is a smaller platform than *Jason* and does not require dynamic positioning, it can be used on a broad range of UNOLS vessels. It is one of many types of autonomous vehicles that are now currently operating in more than 1-km-depth water (see Chapter 2 for a description of other autonomous vehicles; also see NRC [2011a] for more discussion of AUVs). *Sentry* became an NDSF asset in 2010,

[8] See http://www.whoi.edu/main/hov-alvin.

[9] These are *Nautile* (6,000 m; France), *Mir 1 and 2* (6,000 m; Russia), *Shinkai* (6,500 m; Japan), and *Jiaolong* (7,000 m; China).

[10] These include *Deep Discoverer* (6,000 m), operated by NOAA's Office of Ocean Exploration and Research; *Kaiko 7000II* (7,000 m) and *Hyper Dolphin* (3,000 m), operated by the Japan Agency for Marine-Earth Science and Technology; *ISIS* (6,000 m), operated by the National Oceanography Centre and owned by the United Kingdom's Natural Environment Research Council; *ROPOS* (5,000 m), operated by the Canadian Scientific Submersible Facility; *Doc Ricketts* (4,000 m), *Ventana* (1,850 m), and the high-latitude *miniROV* (1,500 m) operated by the Monterey Bay Aquarium Research Institute; and *Global Explorer* (3,000 m), operated by Deep Sea Systems Inc.

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after the loss of the AUV *ABE*, which had also been operated as part of NDSF. AUVs with similar depths and capabilities are operated by many other U.S. and international research groups.[11] Similar vehicles are also available from commercial vendors[12] and are extensively used by the oil and gas and submarine cable industries and for military applications.

Budget and Organization

NSF is the primary NDSF sponsor (providing $7.3 million in FY2014), although the Office of Naval Research (ONR) and NOAA contribute to operational costs. NDSF funding provides support for vehicle operation, maintenance, and routine upgrades and maintains a staff of experienced employees. The 2014 provisional day rates for the vehicles are $16,000 for *Alvin*, $23,000 for *Jason*, and $14,000 for *Sentry*.[13] Operations and maintenance are continual for *Jason* and *Sentry*, with costs that are included in the vehicle day rates. *Alvin*'s periodic overhauls have previously been split between NSF, ONR, and NOAA, but in the future they will be amortized and included in the day rate (written response from Brian Midson, NSF, December 31, 2014).

An advantage of the NDSF facility structure is that it enables diverse groups of scientists to have access to, and OCE funding for, NDSF assets, using a formal request process. In much the same way that UNOLS ship time is not included as an expense in NSF proposals, scientists requesting use of NDSF vehicles do not have to include vehicle operations expenses in their proposal budgets. This is an incentive for use of the NDSF vehicles and, conversely, a disincentive for use of other, non-NDSF deep submergence assets that have to be included in NSF science program budgets.

Alignment with the Science Priorities

Unlike the other categories of infrastructure, the committee considered the broader categories of underwater vehicles, not just NDSF assets, when evaluating their alignment to the decadal science priorities (Table 3-2). Although the committee recognizes the value of HOVs to conduct real-time observations and sampling, manned vehicles are limited in their alignment to the decadal science priorities. HOVs are important for studying the subseafloor ocean environment, marine food webs, and biodiversity and marine ecosystems, but *Alvin* is not critical to any priority (Table 3-2). This is due to the greatly increased capabilities and availability of ROVs, AUVs, and gliders, most of which are not associated with, or subsidized through, the NDSF.

Unmanned vehicles (ROVs, AUVs, and gliders) are important to almost all decadal science priorities, demonstrating a broad utility across many scientific disciplines. Unmanned vehicles continue to play a major role in providing detailed observations and enabling precise sampling, manipulative experiments, and installation of scientific equipment on the seafloor. ROVs are important for studying the formation of ocean basins and for geohazards, and critical for understanding the subseafloor environment. AUVs are important for studying coastal oceans, biodiversity, marine food webs, and ocean basins. Gliders are important for addressing questions related to sea level change, the coastal ocean environment, climate variability, and biodiversity.

Additional Comments

There has been increased interest in using NDSF assets outside their normal environments, including use in higher latitudes, under ice, and in littoral zones (presentation by Peter Girguis, December 6, 2013). This expansion in operating capability could currently be limited by the geographic restrictions that occur due to scheduling. Because NDSF assets are scheduled like UNOLS vessels, there is a need to maximize operational days while minimizing days in transit, which can lead to geographic restrictions related to scheduling and use of the NDSF vehicles.

There is concern about the importance of and costs associated with *Alvin*, including its need to use *Atlantis* as a dedicated tender at a time when more general-purpose Global class ships are needed. Another consideration is the planned Phase 2 upgrade to increase *Alvin*'s depth capability to 6,500 m, which needs to be framed in the context of both its alignment to the decadal science priorities and overall OCE infrastructure costs.

In addition, an increasing number of research ROVs, AUVs, and gliders are operated by private foundations, industry, and other federal agencies. Commercial vendors provide a variety of systems, and although the primary commercial market is focused on military and oil industry applications, use within the academic oceanographic community is expanding rapidly. The most capable, efficient, and economical platforms for the decadal science priorities may not be NDSF assets, and the NDSF model may need to be reevaluated to broaden its scope. Instead of three vehicles that are expensive to operate and maintain, a mix of unique platforms and smaller, less expensive assets may be a possibility for the future. The 2004 NRC study *Future Needs in Deep Submergence Science* identified a similar concern and stated, "It is apparent that realizing the vision of deep ocean research . . . will require access to a broader mix of

[11] These include WHOI (e.g., *Nereid*, *SeaBED*), MBARI (mapping AUV), National Oceanographic Center (*Autosub*), Australian Centre for Field Robotics (*SeaBed*), and *Explorer* class AUVs provided by International Submarine Engineering at University of Bremen, Memorial University of Newfoundland, National Resources Canada, and University of Southern Mississippi.

[12] These include Bluefin Robotic, Hydroid, Kongsberg Maritime, Daewoo, Boeing, ECA SA, Saab, and L'Institut Français de Recherche pour l'Exploitation de la Mer (data from http://auvac.org/explore-database/advanced-search/results_purpose).

[13] Final rates may be slightly lower for *Alvin* and *Jason* due to increased actual days of operation, whereas *Sentry*'s final rate may be slightly higher due to decreased actual days.

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more capable vehicles than are currently available through the NDSF."

The 2014 NSF Committee of Visitors recommended a center of excellence or pool be established for the use of gliders and small AUVs. A common pool approach toward O&M for both NDSF and non-NDSF unmanned vehicles (including skilled technical support) could deliver increased value and utilization for NSF-supported infrastructure and could also provide opportunities to include other agencies in pooling equipment and sharing costs.

OTHER FACILITIES AND INFRASTRUCTURE

Field Stations and Marine Laboratories

Marine field stations and laboratories[14] provide access to a range of environments, including coral reefs, estuaries, kelp forests, marshes, mangroves, and urban coastlines. Often affiliated with universities, marine field laboratories are valuable research platforms that support faculty research and graduate and undergraduate learning and provide opportunities for educational outreach focused on immersive learning (NRC, 2014). Many marine laboratories support long-term observational studies that provide vital baseline data for understanding natural systems, such as natural variations and human impacts on ecosystem processes, and enable comparative studies that provide broad insights into ecological processes.

Field stations and marine laboratories play a vital role in the decadal science priority themes. They are critical or important for several of the questions, including studies of coastal food webs, ecosystem biodiversity, and human impacts on coastal environments. NSF support of field stations and marine laboratories has provided much-needed infrastructure and capital improvements that have enhanced the quality of scientific research and engagement with the public. Recent efforts by NSF to promote networking and data sharing among field laboratories will provide further opportunities for research and education.

Ocean Bottom Seismograph Instrument Pool

The Ocean Bottom Seismograph Instrument Pool (OBSIP) is the largest of the smaller facilities supported through core science funding (Table 3-1) and is included in Table 3-2 as an example of these smaller facilities. Typically, these facilities provide necessary capabilities for particular disciplines and undergo regular review within the core programs. OBSIP supplies and services instruments for long-term deployments (approximately 1 year), recording waveforms from globally distributed earthquakes and local seismicity, as well as for short-term deployments in conjunction with active source surveys using *Langseth* or other ships. OBSIP is a resource used both by marine seismologists and by land-based seismologists that are interested in deep Earth structure beneath the oceans and in earthquake hazards. As shown in Table 3-2, ocean bottom seismometers are important to understand the formation and evolution of ocean basins, and are critical for characterizing geohazards.

[14] See www.naml.org for more information about marine laboratories.

COST VERSUS RELEVANCE FOR NSF-SUPPORTED INFRASTRUCTURE

This chapter evaluated the alignment of current NSF-supported ocean research infrastructure to the eight priority decadal science questions, with high-relevance infrastructure labeled as critical or important to achieving the science priorities. In addition, the costs of operating each of those infrastructure assets have been presented. These two dimensions—relevance and cost—need to be looked at simultaneously, as both are significant for strategic planning and decision making.

Table 3-2 can be surveyed along each row to suggest an overall impact for each infrastructure asset across the eight questions. Every infrastructure component is supportive to at least one question; no asset is without relevance. Each piece of infrastructure can then be looked at in terms of its relative cost to operate and maintain. Figure 3-9 presents a

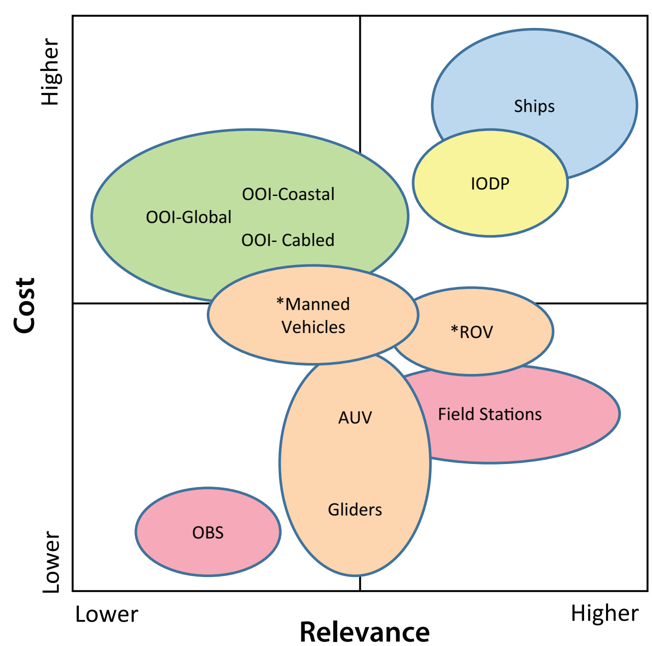

FIGURE 3-9 Conceptual diagram of relative operation and maintenance costs versus relevance of infrastructure assets presented in Table 3-2. The academic research fleet is clustered into one category. The asterisk (*) for manned vehicles and ROVs indicates that inclusion of necessary support vessels would increase costs. Each category is color-coded as in Table 3-2.

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conceptual diagram of relevance versus costs for each of the infrastructure assets presented in Table 3-2.

From this figure, the infrastructure can be roughly divided into quadrants. In a budget-constrained environment, higher-relevance assets can justify higher costs; lower-relevance, lower-cost infrastructure is also acceptable. Infrastructure assets that are higher cost but of lower relevance are of the greatest concern and are candidates for lowering their costs or refocusing their efforts to be of greater relevance for the decadal science priorities. The dimensions of cost and relevance are further explored in the next chapter, as part of the context for OCE's future strategic planning and budgeting decisions.

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4

The Path Forward: Maintaining Ocean Science in a Constrained Budget Environment

We can afford all that we need; but we cannot afford all that we want.
—Franklin D. Roosevelt, Veto of the Bonus Bill (May 22, 1935)

THE IMPACT OF RISING INFRASTRUCTURE COSTS ON THE OCE BUDGET

Over the past 15 years the cost of infrastructure has steadily increased, consuming a larger fraction of the total budget for the National Science Foundation (NSF) Division of Ocean Sciences (OCE) (Figure 4-1). The rise in infrastructure expenditures has been driven by the addition of new infrastructure such as the Ocean Observatories Initiative (OOI), and by continuing support for operations and maintenance (O&M) costs for other facilities, including the *JOIDES Resolution* for the International Ocean Discovery Program (IODP [2013-2018]) and the ships in the academic research fleet. Some of the cost increase has been driven by higher fuel costs; such price fluctuations are difficult to avoid or to compensate for in the future. In the absence of top-line budget growth, an over-reliance on infrastructure consumes funds that otherwise could support the core science program. Since 2003, there has been a ~37% decline in the funding available for the core science program (based on inflation-adjusted values), which has had pervasive negative impacts on the research community through a reduction in the number of funded proposals and declining programmatic flexibility to fund new initiatives. For example, infrastructure costs rose by about $10 million/yr between 2011 and 2014, using inflation-adjusted values. Taking $173,000 as a typical funding level for a single principal investigator proposal,[1] the infrastructure increase is roughly equivalent to reducing funding for OCE core science programs by over 50 proposals each year.

In addition to a reduction of core science funding, there has been a precipitous drop in funding for Oceanographic Technology and Interdisciplinary Coordination (OTIC) (Figure 4-2). OTIC is the main source of support for technology development within OCE. In prior years, OCE benefited from other agencies' investments in technology development (often the Office of Naval Research [ONR]). However, ONR and other agency funding for ocean technology has become more restricted, more scrutinized for relevance to agency missions, and less flexible in terms of cost sharing.

In the statement of task, the committee is charged with recommending "the most effective portfolio of investments achievable at the current funding level." Assuming that the OCE budget is unlikely to grow significantly over the next decade, and that cost inflation will continue at recent historical rates, the only way to restore core science and OTIC is to reduce the amount spent on infrastructure.

As mentioned in the previous chapter, the NSF Directorate for Geosciences (GEO) plans to provide $42 million over the next 4 budget years through Integrative and Collaborative Education and Research (ICER) funds. These funds would be available to help OCE manage the onset of O&M costs for OOI and devote more of its budget to the core science programs. Although this would provide OCE with some short-term relief, the ICER funds would only temporarily reduce the rate of decline in core science funding, with severe cuts becoming necessary in FY2018 if OCE fails to reduce infrastructure O&M costs. This reduction will not be easy, is unlikely to be done quickly, and will cause disruptions for parts of the ocean science community. However, the committee felt strongly that restoring the core science budget and investing in technological innovation is essential and will promote the vision presented at the beginning of this report—that of a diverse community of researchers able to

[1] $173,000 has been the average funding level per OCE proposal per year over the past 10 years (written response from Kandace Binkley, NSF, December 10, 2014).

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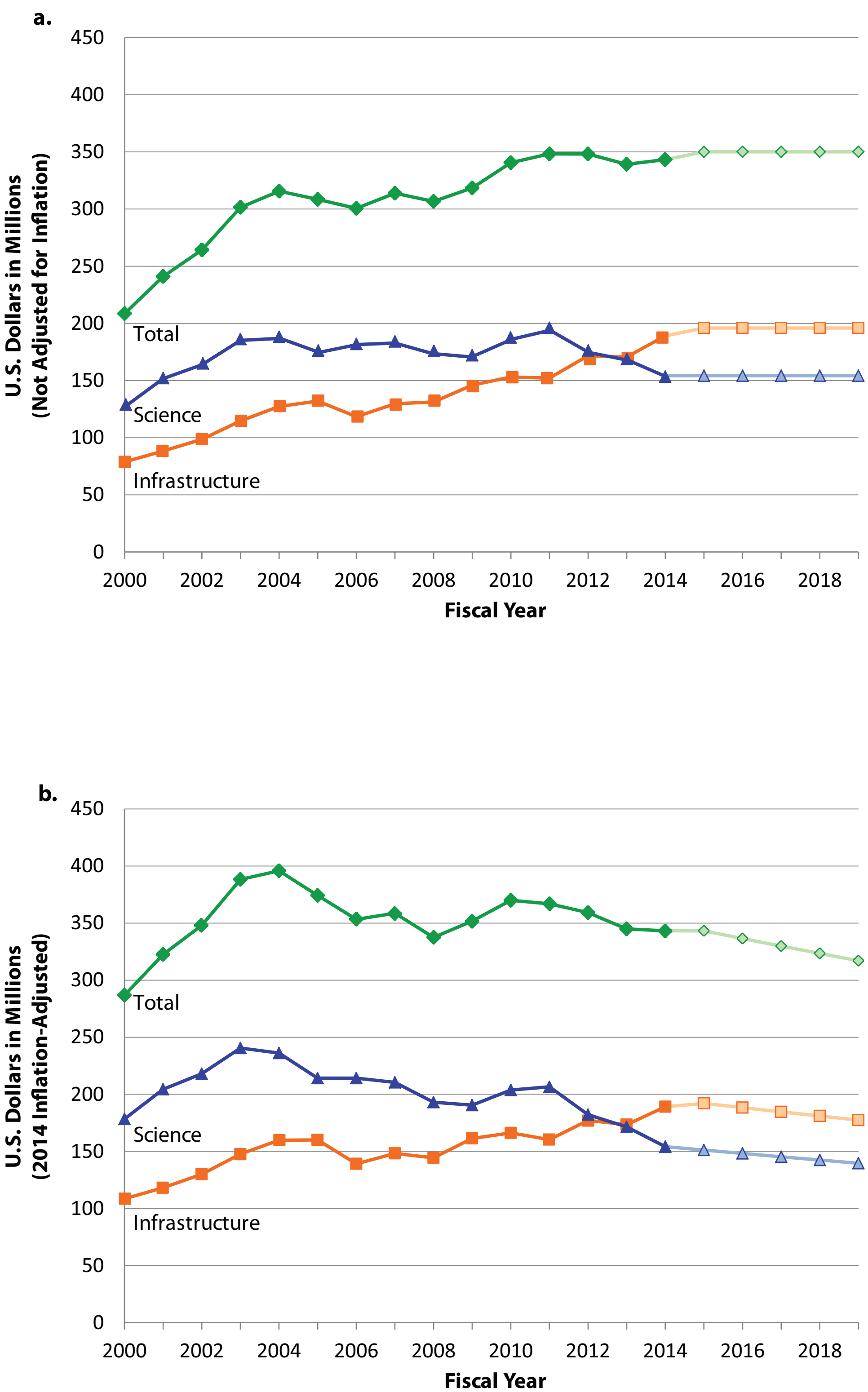

FIGURE 4-1 NSF investments in core ocean science (blue) and infrastructure (orange) since 2000, shown in (a) current dollars and (b) 2014 inflation-adjusted dollars. Total funding for OCE is shown in green. Projections for fiscal years 2015-2019 (lighter colors) are based on the following assumptions provided by OCE—total future budgets are flat with no inflationary increases and operations and maintenance costs for the academic research fleet, IODP, and OOI are held constant. OCE defines “infrastructure” as the academic research fleet, OOI, IODP, field stations and marine laboratories, the accelerator mass spectrometer facility, and miscellaneous smaller facilities. Facilities held in the core programs (shown in Table 3-1) are included in core science, not in infrastructure. Data from NSF, December 2014.

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undertake research and pursue discoveries that will advance ocean science understanding.

ACHIEVING BALANCE

Oceanography requires specialized, often expensive infrastructure to observe and access the ocean. Ocean science will continue to need investment in both infrastructure and research, but sustained and conscious management is needed to ensure an appropriate balance for the overall health of the field. As defined in the report's Introduction, a "healthy balance" means supporting sufficient infrastructure to efficiently advance the science while maintaining research funds for scientists and trainees.

The OCE budget has drifted out of balance. Due to relatively flat budgets, inflation, and increasing costs of O&M for OCE major infrastructure, funding for OCE's core programs has decreased by 25% (inflation-adjusted dollars) over the past 4 years (2011-2014). Consequently, the balance of OCE's budget has shifted such that the fraction dedicated to core science has declined from about 55% in 2011 to about 45% in 2014 (Figure 4-2). Assuming that the budget remains level (adjusted for inflation) or flat (no increase to offset inflation), restoring core science will require difficult decisions to reduce the costs of O&M.

The committee identified two ways to achieve balance: (1) maintain a *fixed ratio* for infrastructure costs relative to the total budget and (2) maintain a consistent *long-term funding trajectory* for core science. The applicability of these two approaches depends on the fiscal outlook.

In periods of flat or declining budgets, using a fixed ratio as a target for guiding expenditures would ensure that one part of the budget does not increase at the expense of the other. As an example, recent OCE practice has been to cover infrastructure costs first and then distribute remaining funds to other programs, thereby increasing the ratio of infrastructure expenditures relative to core science. This practice risks long-term damage to the core programs if funding remains stagnant through many budget cycles. Maintaining a fixed ratio would prevent the infrastructure costs from taking priority, but it would require active management of O&M costs by implementing efficiencies and making targeted cuts if expenses exceed budgets. In practice, a fixed ratio may be difficult to manage if there are long-term facility contracts that need to be considered.

In times of increasing budgets, maintaining a consistent long-term funding trajectory for core science may provide a better approach to achieve balance than a fixed ratio. This alternative strategy accommodates adjustments in the fraction of funds dedicated to infrastructure to reflect short-term needs or long-term changes in the use of existing infrastructure assets, as well as development of new technologies and facilities.

DECISION RULES

When dealing with a constrained budget, there are several options available to manage programs effectively while minimizing impacts on core science budgets. These options—not all of which are applicable to all types of infrastructure—include descoping or terminating activities, lengthening program time horizons, delaying the start of new or planned programs or facilities, and finding efficiencies to lower cost. The choice of action if there is a budget cut, and acceptance of the ensuing consequences, depends strongly on whether the reduction is temporary or permanent. For a temporary cut it may be sufficient to delay the start of a planned activity or it may be possible to identify sufficient efficiencies to avoid programmatic cuts. However, for a longer-term or permanent budget loss, stronger actions may be required such as the descoping or termination of a program. These actions will yield immediate savings but over the long term may be unpopular and irreversible. Alternatively, a program could be stretched such that the annual budget is lower, but the program continues for a longer period of time. Lengthening the time period assumes that the program end date can be extended or that the program can operate at a reduced level, either of which may not be possible or desirable. Finally, lowering costs of ongoing activities may yield suboptimal results, or may require up-front investment in technology that may be unfeasible. Given these choices, the committee established three strategic principles to guide decision making in an uncertain budget climate: promote a decadal budget planning outlook, maintain conservative infrastructure strategies, and involve the community in setting goals. When combined with open communication and consistent actions, these principles (described below) will allow NSF to achieve a reasonable balance between investigator-driven science and the ongoing costs of infrastructure while maintaining support of the community as a whole.

Promote a Decadal Budget Planning Outlook

A10-year budget planning outlook can take into account both inflation and anticipated increased costs of doing business, while accounting for risks associated with unpredictable cost fluctuations. When budgets are increasing, strategic investments need to be made in activities that increase capabilities and reduce long-term costs—for instance, new technology development. Given the federal government's reliance on annual budgets, creative and disciplined fiscal management is necessary to manage long-term programs and life-cycle costs. Although a 10-year plan will require adjustments to address evolving circumstances, the exercise of decadal-scale budget planning enhances fiscal discipline, enables balance, and informs strategic choices before they become crises.

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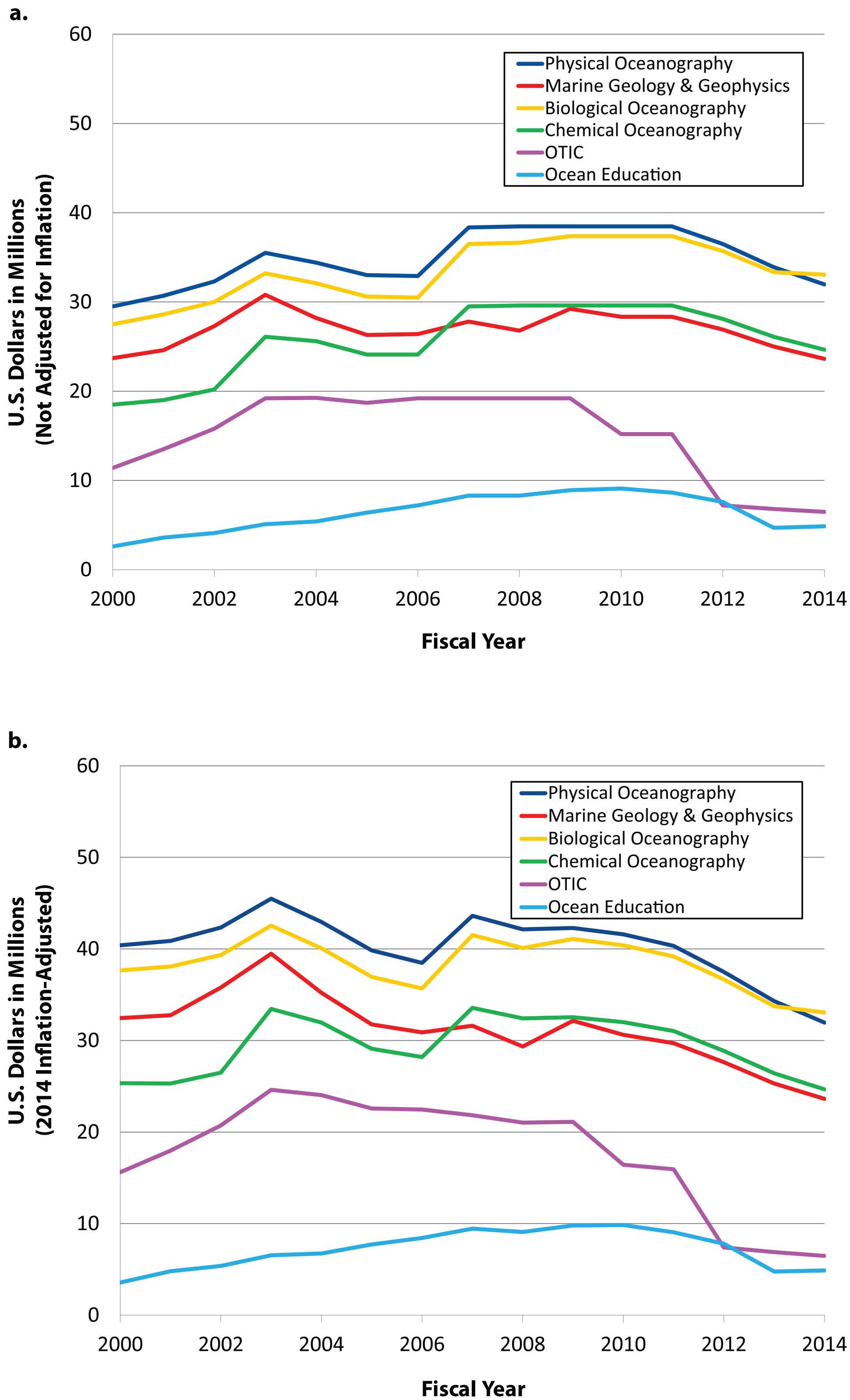

FIGURE 4-2 Annual budgets for OCE core research and education programs in (a) current dollars and (b) 2014 inflation-adjusted dollars. The Biological Oceanography budget includes funding for Long-Term Ecological Research. Since FY2004, the Chemical Oceanography budget has included funding for Oceans and Human Health. Data from NSF, July 2014.

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Maintain Conservative Infrastructure Investment Strategies

Given the uncertain budget environment, it is prudent to assume budget cuts are permanent and increases are temporary (see Box 4-1). Strategies for controlling the full life-cycle costs of infrastructure have to be identified prior to the addition of any new asset. Assumptions that prove to be too conservative can be corrected in future budget cycles.

Involve the Community in Setting Goals

Involving the scientific community in the development of strategic goals and objectives provides a broad base for identifying priorities and building community support for the enterprise into the future. The NSF Advisory Committee for Geosciences[2] (AC-GEO) is composed of established members of the scientific community and hence could serve as a link between the broader community and NSF. When tough decisions need to be made, the involvement of AC-GEO could bolster support for adhering to strategic plans. Community-developed strategies could help make difficult decisions defensible and reduce the pressure and criticism borne by OCE program managers and leadership.

Recommendation 1: In order to sustain a robust ocean science community, holistic fiscal planning is necessary to maintain a balance of investments between core research programs and infrastructure. To maintain a resolute focus on sustaining core research programs during flat or declining budgets, infrastructure expenses should not be allowed to escalate at the expense of core research programs.

A STRATEGY TO REDUCE INFRASTRUCTURE COSTS

The committee developed a strategy for restoring balance to the OCE budget over the next decade. Because core funding has been decreasing over the past 4 years of flat budgets (Figure 4-1), the immediate goal is to reverse the decline in core science funding. This is consistent with the strategy described above to maintain the ratio of core science and infrastructure funding when the program is level funded or declining. Assuming that OCE has a flat budget over the next 10 years, at least 20% (about $40 million in 2014 dollars) of the major infrastructure O&M budget would need to be reallocated to core science and the OTIC program to meet this goal. This would restore core science funding to approximately the 2011 budget amount. A greater reduction of 30% (about $60 million) would provide future flexibility for new programs and for investments in technology development that could help reduce infrastructure O&M.

[2] See http://www.nsf.gov/geo/advisory.jsp.

BOX 4-1
Decadal Planning in Uncertain Budget Environments

The following scenarios illustrate how managers could maintain programmatic balance for increasing, level, or decreasing budgets.

The Good: A Doubling of the NSF Budget over 10 Years

Programs receive a 7%/yr increase (about 4% with inflation taken into account) for a 48% increase over 10 years (constant dollars). Under this scenario, the strategy would be to maintain the consistent *long-term funding trajectory* for core science. New projects would be screened to ensure that they could be phased in or scaled up or down to accommodate potential surprises in future budgets. Ongoing efforts would be reviewed for possible increases; investments in technologies that might increase efficiency or productivity would be encouraged.

The Bad: A Level 10-Year Budget for NSF, Just Keeping Up with Inflation

Because programs would see no change in their budgets over the decade, the strategy would be to maintain a *fixed ratio* of core science to infrastructure costs. This would provide stability to the science program as a whole, while providing some flexibility to exploit new science or technology developments. If infrastructure O&M costs rise faster than the rate of inflation, then adjustments would be made in activities that could be phased or in activities with sufficient budget flexibility to be temporarily (or permanently) descoped.

The Ugly: A Budget for NSF That Does Not Keep Up with Inflation over 10 Years

Because programs would see a decline in their budgets in terms of spending power, the strategy would again be to maintain a *fixed ratio* of core science to infrastructure costs. Management would delay new starts, consider potential terminations, and implement overall descoping and slowdowns. A transition plan would be developed, with defined end points upon which management has sought and developed broad community agreement.

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Recommendation 2: OCE should strive to reduce the O&M costs of its major infrastructure (OOI, IODP, and the academic research fleet) and restore funding to core science and OTIC within the next 5 years. If budgets remain flat or have only inflationary increases, OCE should adjust its major infrastructure programs to comprise no more than 40-50% of the total annual program budget.

Recommendation 3: To implement Recommendation 2, OCE should initiate an immediate 10% reduction in major infrastructure costs in its next budget, followed by an additional 10-20% decrease over the following 5 years. Cost savings should be applied directly to strengthening the core science programs, investing in technology development, and funding substantive partnerships to address the decadal science priorities, with the ultimate goal of achieving a rebalancing of major infrastructure costs to core science funding within the next 5 years.

These recommendations are predicated on the assumption of flat or level budgets over the next five budget cycles. If this projection proves too pessimistic, the priority would still be on restoring the core science budget but would be likely to have fewer negative impacts on the infrastructure budget.

Maintaining Technology Development Investments

Technology development is essential to enable research on many of the decadal priority questions and on emerging research from the core programs. However, funding for OTIC has dropped precipitously, from $19.2 million in 2009 ($21.2 million in 2014 dollars) to $6.5 million in 2014. The committee supports a three-pronged approach: (1) revitalize and grow the OTIC program, (2) incentivize the core research programs to cost-share with OTIC on needed technology development, and (3) emphasize interagency technology development and co-funding through the National Oceanographic Partnership Program.[3] These approaches strengthen OCE's ability to address its own technology development needs, give program managers an incentive to support emerging technologies, and allow interagency cooperation to foster technology development of broad oceanographic interest.

ACHIEVING AN INITIAL 10% REDUCTION IN INFRASTRUCTURE COSTS

There are two main advantages to an immediate cut. First, it emphasizes the restoration of the core science budget, which the committee believes is the most fundamental element of the research enterprise. Second, it makes a strong statement to the community that the current budget situation is unacceptable and that decisions can no longer be postponed. Because the committee was tasked to recommend a portfolio of investments that aligned with the decadal science priorities and were achievable at the current funding level, it evaluated three scenarios of cost reduction that could be used to achieve an immediate 10% cost savings (at a minimum) upon implementation:

- **Scenario 1**—Immediate termination of NSF support for either OOI or IODP;
- **Scenario 2**—A 10% across-the-board cut applied equally to each of the major NSF-supported infrastructure assets (OOI, IODP, fleet); and
- **Scenario 3**—A 10% "weighted cut" divided among the major infrastructure assets, weighted by their alignment with the science priorities (described in Chapter 3) and the broader OCE science portfolio.

The committee's decisions are based on (1) information provided by NSF on its investments in ocean research infrastructure, (2) the committee's evaluation of the major infrastructure that is critical or important to the decadal science priorities (Table 3-2), (3) the recognition that infrastructure and facilities are vital in the support of OCE core programs, (4) the annual O&M costs of each of the facilities, (5) the committee's expectation that new technologies will be developed to address both the decadal priorities and core science research (recognizing that the capabilities and costs of those technologies are not yet known), and (6) input from the ocean science community via town hall discussions and Virtual Town Hall submissions. These follow the spirit of the prioritization framework described in the National Research Council (NRC) report, *Critical Infrastructure for Ocean Research and Societal Needs in 2030* (NRC, 2011), which suggests first determining the ability of infrastructure to address the science, then examining its affordability, efficiency, and longevity.

Depending on the option chosen, these scenarios would achieve an immediate 10-30% cut in major infrastructure. The committee considered whether to discuss termination of the academic fleet but dismissed it because ships support a broad swath of oceanographic activities and are essential to achieve all of the science priorities. However, as noted in future sections, the committee undertook a thorough examination of issues related to the fleet, such as the mix of ship capabilities and right-sizing in the future.

Scenario 1: Immediate Termination of Either OOI or IODP

Pros: Terminating NSF support for either IODP or OOI would provide immediate budget flexibility for OCE and would obviate the need for future incremental cuts. OOI does not yet have a strongly developed user community and its global components do not align well with the decadal science priorities. Terminating IODP would make room for new opportunities in the ocean sciences, rather than continual funding of a decades-long program. Restored core science

[3] See http://www.nopp.org/.

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funding could potentially expand analysis of archived data from IODP or could be reinvested in less-expensive options for recovery of shorter cores. The absence of NSF support for IODP could also spur innovation and may prompt other nations to develop or expand their own drilling capabilities.

Cons: Termination of NSF support for either OOI or IODP would be a loss of recent investments ("sunk costs" that are not recoverable) and future opportunity. The community has not yet assessed the impacts that OOI will have on provision of data (e.g., time series, coastal observations, air-sea flux calibrations), especially with further development or expansion. In addition, terminating all of OOI would be an inefficient use of the costs of construction and installation, because it disallows strategies based on the relative scientific merits of different OOI components (see below). IODP has an impressive record of past scientific accomplishments, has been responsive to recent restructuring and cost cutting, and has strong support from a multidisciplinary, multinational user community. Without NSF support for IODP, there is lost opportunity to study deep cores and to understand new forms of life in the subseafloor. Terminating NSF support for IODP would also damage the international collaborative efforts and leveraging that have been hallmarks of the program.

Scenario 2: Across-the-Board Cuts

Pros: An across-the-board cut is commonly perceived as equitable and unbiased, as it "spreads the pain" and may lead to broader community acceptance. It stimulates efficiencies across all of the programs and preserves all the tools that could support the decadal science priorities for continued community use, although there may be some diminished capacity.

Cons: It could be perceived as unfair because some programs (e.g., IODP) have recently restructured to achieve greater efficiencies. Other programs such as OOI are viewed as less essential for the broad oceanographic community (in part because they are not yet operating) or are less aligned with the identified science priorities. On a practical level, contracts that are already in place for some assets—for example, OOI or *JOIDES Resolution* operations—may make immediate across-the-board reductions unfeasible.

Scenario 3: Weighted Cuts

Pros: Cuts that are divided based on a weighting scheme can be better aligned with identified science priorities, with OCE core programs, and with community interest and demand. Weighting different programs also acknowledges recent efficiencies in program management. Finally, weighted cuts provide greater flexibility to accommodate existing agreements and to achieve efficiencies with the least disruption to ongoing science activities.

Cons: It is likely to be perceived as unfair because some parts of the ocean science community will bear a heavier burden than others. Programs with heavy up-front costs that take a heavier share of the cut may become so constrained that they cannot effectively support their science, while programs with a lesser share of the cut have less incentive to look closely for efficiencies.

Of the three scenarios, the option of immediately terminating NSF support for either IODP or OOI (an extreme version of the weighted cuts) was rejected as failing to reflect an appropriate consideration of balance. Instead, the committee considered across-the-board and weighted-cut scenarios, including examples of how such reductions might be achieved, and determined that weighted cuts, which take into account the alignment of infrastructure reductions with scientific priorities, was the most compelling argument among those put forward.

Determining the Weighted Cuts

To apply the strategy of weighted cost reductions, the committee returned to the alignment of science priorities with the major infrastructure (Chapter 3) but also evaluated costs of operation, efficiencies that could be gained, and likelihood of community support. Based on this assessment, the committee determined the following distribution of initial cost reductions among OOI, IODP (2013-2018), and the academic research fleet.

Recommendation 4: The immediate initial 10% cost reduction in major infrastructure should be distributed, with the greatest reduction applied to OOI, a moderate reduction to IODP (2013-2018), and the smallest reduction to the academic research fleet.

A suggested weighting is to initially and immediately reduce operational costs for OOI by 20%, for IODP by 10%, and for the academic research fleet by 5%. OOI is targeted for the greatest cost reduction because none of its components are critical for the decadal science priorities, the program has considerably less community support than either IODP (2013-2018) or the fleet, and there are areas where rephased operations (like longer deployment periods for moorings or somewhat reduced arrays) might provide efficiencies. The component structure of OOI provides flexibility to favor retention of those components that align more strongly with the decadal science priorities (such as the coastal arrays or the cabled observatory) and the broader OCE science program, or to focus attention on one or two global sites to minimize logistics costs and to demonstrate proof of concept. The 20% cut to OOI does not necessarily need to be applied evenly across its components, as the same considerations used to weight cuts among facilities should also be used to distribute cost reductions among the components.

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Applying a moderate weighted cut to IODP is a reflection that, although it fulfills some science priorities that cannot be met with any other infrastructure, IODP is an expensive facility and serves a smaller community than is served by the academic research fleet. However, it has had a long history of support from NSF and has produced transformative science.

All of the identified science priorities need access to the sea, which justifies the committee's suggestion that the smallest cost reduction be applied to the academic research fleet. In addition, research vessels are fundamental infrastructure that is shared across the broad ocean sciences community (other agencies and other parts of NSF share in the cost), and the University-National Oceanographic Laboratory System (UNOLS) and NSF constantly review the fleet for further program efficiencies.

In the next section, the committee provides some specific examples that NSF might pursue to achieve these cost reductions. These are not meant to be prescriptive; rather they illustrate the difficult decisions that must be made to achieve balance with funding for core science. The committee leaves it to NSF, in consultation with the ocean science community, to make the determinations as to which reductions would provide the greatest efficiency.

ACHIEVING ADDITIONAL COST REDUCTIONS

To achieve a rebalance over the following 5 years, infrastructure costs will need to be cut an additional 10-20%. These sustained cuts are just as difficult as the immediate cost reductions and in some instances may lead to discussions about how much can be cut from an individual program without damaging its intrinsic ability to function.

EXAMPLES OF POSSIBLE COST REDUCTIONS

OOI

Immediate Cuts

An immediate 20% (~$10 million) cut to OOI is likely to be difficult or impossible to accomplish without eliminating some of the array components. Both of these options below would be needed to reach the suggested cost reduction:

1. **Cut two of the global moorings.** When determining which moorings to cut, NSF needs to consider long-term costs for operations and maintenance (slightly higher for the Southern Hemisphere moorings) and scientific rationale. As noted in Chapter 3, the Irminger Sea mooring has the strongest science justification and is likely to advance the goal of improving storm forecasting and climate change models. The committee was not presented with a persuasive case for the Argentine Basin array.

   Consequences: Cutting two global moorings would provide cost savings of ~$7.2-7.5 million/yr in O&M costs, but would remove some observing capabilities and reduce UNOLS fleet use, as part of the cost savings is in ship time. Operating two moorings could provide "proof of concept," while the descoped moorings could be used for repairs to other OOI moorings, further reducing future O&M costs. As an alternative to cutting one or both moorings, NSF could potentially recruit partners, in the United States and internationally, to share long-term O&M costs.

2. **Reduce the costs of the coastal and cabled components and administration by 10%**, which would provide ~$4 million in savings.

   Consequences: It is likely that some functionality (such as data collection or turnaround maintenance time) would be sacrificed for each affected component. If data streams break down or there are inoperable subsystems for sustained periods of time (weeks to months), it could reduce the potential user base.

Sustained Cuts over 5 Years

Further cost reductions over 5 years could be achieved by a continued 10%/yr cut to the cabled observatory and coastal array O&M (~$9 million, averaging $1.8 million per year) and by a reduction in administration costs by 5%/yr ($3 million, averaging $0.6 million/year). In addition, rather than moving the Pioneer Array in 2020, the component could be eliminated for a costs savings of $9.9 million. It may be possible to manage the elimination of the Pioneer Array by awarding use of the array via an open competition (possibly including funding partners other than or in addition to NSF) that could encourage research groups to propose ocean process studies in other continental shelf locations.

Overall Consequences for OOI

The consequences of these example cuts to a new program are likely to be severe, as the initial reductions would take place just as scientists are beginning to consider OOI assets for proposed research. If OOI management chooses to reduce costs without downscoping the current operational plan, the risk to all components will be high. Eliminating some OOI components may also provide much-needed flexibility if O&M frequency and/or costs for remaining components increase.

The potential applications of OOI may be of scientific interest to other nations and other U.S. federal agencies. As mentioned previously, OOI may want to consider broadening international participation. Adding international partners could relieve NSF of some of the long-term costs for O&M, especially the ship time needed for maintenance of the global

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moorings. As discussed in Chapter 3, recruiting international partners for cost sharing has been a successful strategy for IODP. However, it takes dedicated time and sustained effort to build international collaboration and funding support.

If other U.S. federal agencies express an interest in using OOI as a national asset, then cost-sharing arrangements with these agencies would be appropriate and reasonable to cover the ongoing O&M costs. Foreseeably, some components of OOI could become part of an ocean observing system maintained over the long term by an operational agency. An interagency model similar to UNOLS could be developed to manage the facility.

IODP (2013-2018)

Immediate Cuts

Four options to immediately cut ~$6 million from IODP (about 10% of the FY2014 budget for IODP science and infrastructure) were considered. Because of the "componentless" structure of NSF's contributions to IODP (2013-2023)—the *JOIDES Resolution*, rather than multiple ships or moorings that can be considered separately—and because of recent organizational changes and cost-cutting measures, the committee found it difficult to suggest examples of how cuts might be achieved. As a result, the committee also considered options that increased external revenue in addition to making cuts from NSF. The committee notes that there is an overarching concern that the international scientific ocean drilling community as a whole is overextended in terms of the number of platforms.

1. **Raise more revenue from international partners.**

   Consequences: Raising the subscription price, the cost of complementary proposals, and/or increasing the number of international partners in IODP has the potential for revenue enhancement, but the potential loss of some members could negate these gains. Increasing the proportional membership of existing partners or the number of members could be based on a more stringent cost-benefit calculation, such that no partners receive subsidies. It is possible that a lower NSF contribution would reduce the number of berths available to U.S. scientists, implying a loss of cost efficiency for the NSF-supported part of the program, but this might be mitigated by enhanced shore-based participation due to more flexibility in core program funding.

2. **Increase external funding for operations.** Additional support for the *JOIDES Resolution* could come from non-U.S. national science programs or from the private sector.

   Consequences: There is potential for substantial cost savings, if the support provided by industry or non-U.S. national entities accounts for the costs of developing the program and its infrastructure, not just the incremental costs of operating another expedition. For example, this could mean increasing the cost of Complementary Project Proposals to accurately reflect the full cost of an expedition.

3. **Reduce costs for operations by reducing program-funded science services.** On-ship laboratories, downhole tools, and instrumented boreholes (among other instruments and facilities) could be funded by external grants or other sources.

   Consequences: The cost savings are likely to be small, and dependent on the complexity of particular expeditions. However, it would signal a shift from providing science services through infrastructure costs to providing it through science programs funded by NSF or other agencies. It could encourage technological innovation, but it could also lead to a loss of consistency among science services. There is also potential for serious mismatch between investigators' ability to get ship time and also to get external funding for science, which could compromise an expedition's scientific goals and achievements.

4. **Reduce the number of expeditions per year.**

   Consequences: Because of the standing costs of operating the *JOIDES Resolution*, removing an expedition would save on the order of $2-4 million but would reduce cost efficiency. The risk of reducing operations is dropping below a level that can sustain experienced staff and/or operations. Reducing operations to 6 months per year (from 8) may be below this threshold and risks collapse of the program through loss of staff. It could also jeopardize the long-term lease from the ship operator/owner.

Sustained Cuts over 5 Years

Additional cost reductions to cut another 10% of the IODP budget will likely follow the same options as the immediate cuts: raising revenues from international partners, finding new funding streams from other agencies or the private sector, or by further reducing the number of expeditions.

The Academic Research Fleet

Immediate Cuts

As part of the overall strategy to reduce infrastructure costs, an initial cut of approximately $3 million would be

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needed, representing a ~4% reduction in FY2014 UNOLS operating costs. Given the magnitude of the immediate cut and the uneven utilization rates (sea days per vessel) by various classes of vessels, the committee explored the option of laying up one of the 19 vessels in the fleet. This strategy is complicated by the spatial distribution of the current fleet and by the presence of purpose-built assets versus general-purpose ships. Three separate options for a fleet lay-up were considered, each of which would meet the requirement for an approximate $3 million savings in the near term. The third option occurred in October 2014, as this report was being prepared for review.

1. **Immediate lay-up of the R/V *Langseth*.** *Langseth* is operated less and has a higher day rate than the other general-purpose Global class vessels and *Atlantis.*

   Consequences: This option would lead to a reduced capability for subseafloor research due to the loss of access to specialized seismic tools. It would also lead to the loss of a Global class vessel, although its use as a general-purpose platform is questionable. Commercial seismic ships could be chartered as an alternative, which would require an analysis of charter rates and mission requirements.

2. **Consolidation of Atlantic Ocean/Intermediate class ships.** *Endeavor* and *Atlantic Explorer* operated a total of 366 ship days at a cost of $7.6 million in 2013. Laying up the less-capable *Atlantic Explorer* is more cost effective and would shift operating days to *Endeavor*.

   Consequences: *Atlantic Explorer* is the dedicated ship for the Bermuda Atlantic Time-series Study (BATS), and it would be inefficient to transit *Endeavor* to Bermuda for frequent BATS sampling while also maintaining a schedule of general-purpose oceanography on the East and Gulf Coasts. This could have impacts on the continuation of the BATS data and its scale of operation.

3. **Consolidation of Pacific Ocean/Intermediate class ships.** In October 2014, Scripps Institution of Oceanography decided to withdraw *New Horizon* from service in February 2015. Together, *New Horizon* and *Oceanus* (Oregon State University) totaled 325 ship days in 2013, at an operating cost of $7 million. Laying up *New Horizon* is likely to shift operating days to *Oceanus*.

   Consequences: Withdrawing *New Horizon* from service leads to a ~40% capacity loss for this class on the West Coast but will increase the use of *Oceanus* and likely reduce its day rate.

Sustained Cuts over 5 Years

Lowering fleet costs could be achieved by delaying or canceling the planned construction of the third Regional class research vessel (RCRV). The business case for this vessel needs to be carefully considered, as the RCRV O&M costs are considerably higher than the vessels they are intended to replace. Operating two, rather than three, RCRVs at 200 days/yr (the lower end of the anticipated full operating year) saves at least $4.4 million/yr in operating costs. Alternatively, cost savings could be achieved by constructing and operating a Gulf of Mexico RCRV in conjunction with partner organizations that are likely to need Regional class ship time (e.g., the National Oceanic and Atmospheric Administration [NOAA], Gulf states).

In addition, cost savings could be achieved by declining to fund the Phase 2 *Alvin* upgrade. Because scientific demand is high for access to Global class ships, NSF needs to consider the option of taking *Alvin* out of service and using *Atlantis* as a general-purpose vessel, if there is sufficient demand.

Right-Sizing the Fleet

In Chapter 3, Global class ships were among the infrastructure that was aligned most strongly to the decadal science priorities. Regional class ships were also found to be critical or important for many of the priorities. However, the planned fleet replacement of three Regional vessels and no Global vessels results in a mismatch between the future makeup of the fleet and likely research needs. The committee is concerned by the lack of an articulated plan to replace the Global class ships, especially because they appear to have the greatest demand signal into the next decade. If the *Langseth* is laid up, only *Revelle* and the ice-capable *Sikuliaq* will be available for use by 2022 (unless the *Thompson* receives its mid-life refit). The new Ocean class ships approach the Global class in size and endurance, but they are more limited in berthing and deck space and will likely not be capable of some larger expeditionary operations.

Similarly, the planned RCRVs are much larger than the existing Regional vessels, with capabilities that approach the existing Ocean/Intermediate class except in duration and range. Alternatively, NSF may reconsider the current design of the RCRVs and determine if smaller, less-expensive vessels would better meet regional needs.

Recommendation 5: NSF should reconsider whether the current RCRV design is aligned with scientific needs and is cost effective in terms of long-term O&M, and should plan to build no more than two RCRVs.

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STRATEGIC PLANNING

Periodic Reviews

The committee notes that both OOI and IODP (2013-2018) are scheduled for reviews at the time of key milestones in the 2017/2018 timeframe. Management of OOI operations is to be recompeted in 2017 and IODP (2013-2018) will have completed the first 5 years of its 10-year program. Additionally, the current National Deep Submergence Facility (NDSF) award expires June 2015 and a proposal to renew is expected this year. The results of these proposals and reviews could inform the distribution of additional infrastructure cuts for cost reduction, both between and within programs. For example, this might modify the balance of initial cost reductions affecting OOI. The committee endorses the recommendation from *Critical Infrastructure for Ocean Research and Societal Needs in 2030* (NRC, 2011) that major ocean research infrastructure "be reviewed on a regular basis for responsiveness to evolving scientific needs [and] cost effectiveness." However, these periodic reviews are not a reason to delay immediate and sustained cuts, which are needed to rebalance the portfolio.

There are a number of issues that could be considered in the IODP (2013-2018) review. These include

- Evaluating the U.S.-supported IODP business model to determine if the program can be operated efficiently yet productively at current or lower budgets;
- Determining the progress of acquiring other funding sources (e.g., additional international partners, industry) to supplement NSF operational costs for the *JOIDES Resolution*;
- Evaluating the major and/or transformative scientific accomplishments of the program, and recommending changes to program priorities for the next 5 years; and
- Determining if there is an appropriate time to sunset NSF support for the program.

Issues that could be considered in the OOI review include

- Restructuring operations and management to better engage the broader science community and provide greater cost efficiency, such as possibly decentralizing management and having components report directly to NSF;
- Assessing the effectiveness of existing oversight committees;
- Evaluating which components align most strongly with the interests of the science community;
- Assessing early scientific results that seem particularly significant and/or have the potential for transformative science;
- Evaluating whether components of the program are working as intended and are within their predicted operational budget;
- Discussing the possibility of descoping or eliminating lesser-performing components to strengthen financial support for components with the highest scientific potential; and
- Determining if the Pioneer Array should be relocated and, if so, its next location.

Taking the Broader View

OCE's working model for infrastructure and major facilities does not tend to consider impacts on the overall budget until it reaches Division leadership. For example, the UNOLS RCRV subcommittee is advocating construction of all three vessels (RCRV Subcommittee of the Fleet Improvement Committee, 2014), but the subcommittee was not tasked with weighing possible impacts on the other major infrastructure or on core science. The current system, where each major infrastructure asset is evaluated individually (sometimes with the apparent goal of advocating for particular assets), discourages an integrated assessment. This can be compounded by overly optimistic assumptions about future budgets and a lack of realistic infrastructure cost projections.

OCE program officers, section heads, division directors, and assistant directors are often rotators. Rotators have an invaluable connection to the science community, including the community's aspirations and their essential role in the peer-review process. However, they may not be fully aware of the long-term history and future uncertainties of the federal budget cycle, and they may not be present at NSF for the consequences of their decisions. Additional training on NSF budget and planning processes, including the history of major programs, could assist rotators in senior management positions.

Infrastructure Planning

OCE would benefit from external oversight of its infrastructure by a committee whose function would be to recommend overall priorities in an integrated manner. The committee could function under AC-GEO or be separate; however, it would need expertise from professionals versed in budgeting and strategic planning, not just from ocean sciences and academia. This group of experts could also assist in ensuring that initial cost estimates for new infrastructure or those for refits or expansions of existing facilities are realistic with projected requirements in order to keep operational costs in check over a project's lifetime.

This idea echoes the need for coordinated strategic planning set forth in *Critical Infrastructure for Ocean Research and Societal Needs in 2030* (NRC, 2011), which notes that "[i]n order to establish and continuously adapt a strategic plan for ocean infrastructure planning, funding agencies need to ensure that the resources and expertise are in place

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to carry out a systematic prioritization process. Expertise that is required for this type of planning includes both scientists and people trained in economics of information, valuation, and investment analysis under uncertainty."

Recommendation 6: Program reviews for OOI, IODP, the academic research fleet, and NDSF should occur periodically (nominally every 3-5 years, with a 10-year outlook) and should be considered within the context of the broader OCE budget environment, rather than independently. OCE should consider exit strategies for major acquisitions if funding is insufficient. OCE should seek periodic community input to help ensure infrastructure investments align with the science priorities.

Recommendation 7: OCE should initiate a high-level standing infrastructure oversight committee to evaluate the entire portfolio of OCE-supported infrastructure and facilities and to recommend proposed changes. The outlook should be for at least 10 years and should include discussion of the entire life cycle of construction, operations and maintenance, decommissioning, and recapitalization. Committee membership should include professionals experienced in long-range budgeting and strategic planning.

The intent of the above recommendation is not to duplicate functions of the individual committees advising OOI, IODP, the fleet, and NDSF, but rather to provide broad oversight of the full portfolio of major infrastructure with a particular focus on the costs of construction, maintenance, and operations in relation to the science priorities.

Opportunities for Collaboration and Partnerships

As noted throughout this report, OCE does not and cannot sustain exciting and innovative ocean research on its own. Sustained and effective partnerships within and between NSF divisions, between NSF and other federal agencies, with public and private sectors, and as part of international programs are needed to fully realize the range of opportunities in the next decade and beyond. Ocean science research accomplishments in the past depended strongly on the capabilities of multiple federal agencies (particularly the U.S. Navy) and international initiatives, as well as NSF's continued funding and interest. Pursuit of the decadal science questions will continue to require collaborations that can reach beyond annual funding cycles to achieve transformative research and scientific breakthroughs, even as the priorities of individual agency missions evolve. History has shown that these partnerships work best when they are based on trust, have credibility among agency staff (working level and senior management) and the community, and are seen to be in the interest of all parties.

NSF's participation in the Subcommittee on Ocean Science and Technology (SOST), especially the Interagency Working Group on Facilities and Infrastructure (IWG-FI) and the Interagency Working Group on Ocean Partnerships (IWG-OP), is an excellent vehicle to drive effective infrastructure partnerships among the agencies. OCE program managers can be tasked with implementation of recommendations from the SOST. Through IWG-FI, agencies can avoid duplication of effort and encourage the shared use of assets; through IWG-OP, agencies can find and be supportive of mutual research interests. Additionally, just as UNOLS provides effective cost-sharing strategies to manage the academic research fleet, perhaps a similar management structure could maximize the use of OOI, IODP, and other NSF-supported infrastructure across agencies, academic institutions, internationally, and potentially with the private sector.

An outstanding example of interagency and international cooperation is the Argo program (described in Box 1-1), in terms of both how the program was developed and how the data are used for both research and operations. Another is the Climate Variability & Predictability (CLIVAR) program, which began in 1997 and had initial support from U.S. agencies including NOAA, NSF, ONR, the National Aeronautics and Space Administration, and the Department of Energy. U.S. CLIVAR emphasizes themes of decadal variability, climate extremes, polar climate, and ocean carbon/biogeochemistry and contributes to the international CLIVAR project that is organized under the World Climate Research Program. Finally, there is the opportunity provided by Future Earth, described in Box 2-1. OCE might consider how it can best contribute to programs like Future Earth, which will need coordination across NSF Directorates, including its International Science and Engineering Section.

Recommendation 8: The committee encourages OCE to expand its partnership capabilities with other federal agencies, international programs, and other sectors. Such partnerships can maximize the value of both research and infrastructure investments and may help spread the costs of major ocean research infrastructure beyond OCE.

LOOKING AHEAD

The current focus on budget constraints faced by NSF and OCE does not preclude a bright future for the ocean sciences. There remain many compelling science questions to be answered, a need for new knowledge to solve important societal problems, and the promise of groundbreaking discoveries that inspire future generations. Research in ocean sciences is crucial to addressing some of the greatest challenges of our time. It is a national imperative to determine how the ocean and climate system will respond to increasing atmospheric carbon dioxide and how coastal communities will respond to sea level rise and pollutants. The public is becoming more aware of the ocean's role in their lives as an

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economic force and a cultural asset, and the desire for ocean stewardship will undoubtedly encourage additional interest and possible investment in ocean research over time.

The past decade has also seen remarkable advances in the field. Research that transcends the divides of traditional disciplines has led to some of the most significant emerging questions in ocean sciences today. Technological innovations have transformed the ocean sciences, revealing the promise of groundbreaking new technologies that enable observation and measurement in novel, cost-effective, and energy-efficient ways. Our ability to answer complex questions has grown tremendously with these developments and will continue to expand in the decades to come.

Attaining the visionary goals presented at the beginning of this report will require a diverse and talented group of researchers; rapid adoption of new technologies to measure the ocean in novel and cost-effective ways; elimination of the barriers to interdisciplinary and interagency research; enhancement of cost-shared partnerships across funding agencies, national borders, and sectors; and innovative educational programs that are aligned with this vision. The committee strongly believes that the ocean sciences community (including researchers and program managers) are prepared to strategically meet these challenges and emerge with an even more innovative and compelling future for the ocean sciences.

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Appendix A

Committee and Staff Biographies

COMMITTEE

Shirley Pomponi *(Co-Chair)* is research professor and Executive Director of the National Oceanic and Atmospheric Administration (NOAA) Cooperative Institute for Ocean Exploration, Research, and Technology at Harbor Branch Oceanographic Institute at Florida Atlantic University, and professor of marine biotechnology at Wageningen University, Netherlands. Her research focuses on evolutionary biology, systematics, and ecology of sponges, and marine biotechnology approaches to sustainable use of marine resources. Dr. Pomponi was a member of the Ocean Studies Board from 2003 to 2009, serving as the chair from 2005 to 2008. She participated in multiple National Research Council (NRC) committees, including as vice-chair of the Committee on Exploration of the Seas, and as a member of the Committees on Future Needs in Deep Submergence Science, Marine Biotechnology: Development of Marine Natural Products, and the Ocean's Role in Human Health. She also served on the U.S. National Scientific Committee on Oceanic Research, the Science Advisory Board for the U.S. Commission on Ocean Policy, and the Ocean Research Advisory Panel. She was the President of the Southern Association of Marine Laboratories in 2010 and 2011, and Chair, Board of Trustees, Consortium for Ocean Leadership from 2008 to 2010. Dr. Pomponi received her Ph.D. in biological oceanography from the University of Miami.

Dave Titley *(Co-Chair)* is a professor of practice in meteorology and Director of the Center for Solutions to Weather and Climate Risk at Pennsylvania State University. Dr. Titley's career included duties as Oceanographer and Navigator of the Navy and Deputy Assistant Chief of Naval Operations for Information Dominance. Dr. Titley initiated and led the U.S. Navy's Task Force on Climate Change and also served on the staff of the U.S. Commission on Ocean Policy. After retiring from the Navy, Dr. Titley served as the Deputy Undersecretary of Commerce for Operations, the Chief Operating Officer position at NOAA. He was invited to present on behalf of the Department of Defense at both congressional hearings and the Intergovernmental Panel on Climate Change meetings from 2009 to 2011. He speaks regularly on the topic of climate at universities across the country. He currently serves on the Advisory Board of the Center of Climate and Security based in Washington, D.C., is a member of the NRC Committee on Geoengineering Climate: Technical Evaluation and Discussion Impacts, and is a Fellow of the American Meteorological Society. He earned a Ph.D. in meteorology from the Naval Postgraduate School.

Edward Boyle is a professor of ocean geochemistry at the Massachusetts Institute of Technology (MIT) and MIT Director of the MIT-Woods Hole Oceanographic Institution Joint Program in Oceanography. His research interests include a focus on ocean trace-metal chemistry in relation to biogeochemical cycling, anthropogenic inputs, and as a tool for understanding the geological history of the ocean. He has worked on lead and other anthropogenic trace metals in Greenland ice cores and on trace metals in estuaries. Dr. Boyle discovered that iron in the deep southwest Pacific derives from distant hydrothermal vents. Additionally, he has shown that cadmium in some species of benthic foraminifera tracks the cadmium content of the bottom water they grow in, and he has applied this finding to sediment cores to trace past changes in ocean deep water chemistry which are influenced by changing ocean circulation patterns and changes in biogeochemical cycling within the ocean, including mechanisms that influence atmospheric carbon dioxide levels. He is a member of the National Academy of Sciences. He has served on the NRC's Ocean Studies Board, the Alexander Agassiz Medal Selection Committee, the Committee on an Ocean Infrastructure Strategy for U.S. Ocean Research, and the Marine Chemistry Study Panel. Dr. Boyle received his Ph.D. from the MIT/Woods Hole Oceanographic Institution Joint Program in chemical oceanography.

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Melbourne Briscoe is the President of OceanGeeks, LLC, an environmental consulting company and information provider specializing in information on ocean policy issues, advice on forming and maintaining ocean partnerships and collaborations, and best practices in the translation of ocean research results to practical applications. Prior to his consulting work, Dr. Briscoe was Director, Ocean, Atmosphere, and Space Research Division with the Office of Naval Research; Director, U.S. Global Ocean Observing System with NOAA; and Vice President and Director, Research and Education with the Consortium for Ocean Leadership. He is a member of multiple professional associations: the American Geophysical Union, The Oceanography Society, and the American Meteorological Society. His NRC experience includes membership on the Panel on Peer Review of the Army Corps of Engineers. Dr. Briscoe received his Ph.D. in mechanical engineering (fluid dynamics) from Northwestern University, and holds certifications in aspects of group dynamics and meeting facilitation.

Russ Davis is a research professor at the Scripps Institution of Oceanography. Dr. Davis' contribution to oceanography is a balance between observation and theory. Using current meters, and surface and deep drifters, he has studied ocean circulation, mixed-layer dynamics, and the diffusion of particles. He has applied methods of objective analysis to such diverse problems as the design of the MODE array, and the predictability of climate from observations of ocean surface temperature. He is a member of the National Academy of Sciences and chaired the Ocean Studies Board from 1988 to 1991. He has served on multiple committees including the 1992, 2001, and 2013 Alexander Agassiz Medal Selection Committees, the Climate Research Committee, and the Committee to Review the Global Ocean Observing System. He received the 2007 Prince Albert I Gold Medal from the International Association for the Physical Sciences of the Oceans. Dr. Davis received his Ph.D. in chemical engineering from Stanford University.

Margo Edwards is a senior research scientist and former Director of the National Center for Island, Maritime, and Extreme Environment Security at the University of Hawaii at Manoa. Her current scientific research focuses on using mapping skills to search for disposed military munitions south of Pearl Harbor, Hawaii, in water depths from 300 to 550 m to determine whether they pose a threat to people and the environment. Dr. Edwards was part of the Scientific Ice Expedition Science Advisory Committee, a collaborative project between the U.S. Navy and civilian scientists for environmental research in the Arctic Ocean. She has served on NRC committees including the Committee on an Ocean Infrastructure Strategy for U.S. Ocean Research in 2030, the Committee on Evolution of the National Oceanographic Research Fleet, and the Committee on Designing an Arctic Observing Network. Dr. Edwards earned her Ph.D. in marine geology and geophysics from Columbia University.

Mary Feeley retired as Chief Geoscientist from ExxonMobil Exploration Company in 2014. While with ExxonMobil, she was involved in oil and gas exploration activities in Africa, Asia, and Europe. Her responsibilities included advising senior ExxonMobil Upstream management on strategic geoscience matters and identifying global geoscience opportunities for ExxonMobil. Dr. Feeley is a member of the American Association of Petroleum Geologists, the Society of Exploration Geophysicists, and the American Geophysical Union. Her NRC experience includes membership on the Ocean Studies Board from 2005 to 2010 and serving on committees including the U.S. National Scientific Committee on Oceanic Research and the Committee on International Capacity Building for the Protection and Sustainable Use of Oceans and Coasts. Dr. Feeley earned her Ph.D. in oceanography from Texas A&M University.

Donald Forsyth is the James L. Manning Professor of Geological Sciences at Brown University. He is interested in the physical properties of the Earth's tectonic plates, the nature of convection in the upper mantle, and the processes that form new oceanic crust at mid-ocean ridges. Using arrays of seismometers on the seafloor and on land, he studies the seismic velocity structure and anisotropy of the lithosphere and asthenosphere as a means of revealing variations in temperature, composition, and flow patterns associated with convection and the aging of the plates. In the oceans, he has concentrated on mapping out variations in crustal thickness and the structure of the underlying mantle in order to understand the pattern of melt generation and migration that supplies the magma that forms new crust. He is a member of the National Academy of Sciences, a Fellow of the American Geophysical Union, and was the recipient of the Arthur L. Day Medal from the Geological Society of America. Dr. Forsyth earned a Ph.D. in marine geology and geophysics from the Massachusetts Institute of Technology and Woods Hole Oceanographic Institution.

Peter Liss is a Professorial Fellow at the University of East Anglia in the School of Environmental Sciences, and in 2013-2014 was a Faculty Fellow at the Texas A&M University Institute for Advanced Study. His research has focused on the biogeochemical interactions between the ocean and the atmosphere, specializing in the processes of air-sea gas exchange, the mechanisms of trace-gas formation in the oceans, and their reactivity and role in the atmosphere. Dr. Liss is a Fellow of the Royal Society, and other recognitions received include the Challenger Society Medal, the Plymouth Marine Sciences Medal, and the John Jeyes Medal of the Royal Society of Chemistry. He served on the Natural Environment Research Council, was Chair of the Scientific Committee of the International Geosphere-Biosphere Programme, and

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was Chair of the Scientific Steering Committee for the International Surface Ocean-Lower Atmosphere Study. He is a member of the Department for Environment, Food and Rural Affairs Science Advisory Council and chairs the U.K. Marine Environmental and Data Information Network, the International Advisory Board for the Marine Alliance for Science and Technology in Scotland, and the U.K. National Oceanography Centre's Association Board and is a member of its Science Advisory Council. He is currently Interim Executive Director of the International Council for Science. Dr. Liss received his Ph.D. from the University of Wales.

Susan Lozier is the Ronie-Richele Garcia-Johnson Professor of Physical Oceanography and Bass Fellow in the Nicholas School of the Environment at Duke University. Her research focuses on the ocean's role in climate variability and climate change. She is interested in the large-scale meridional overturning circulation of the ocean and how that circulation impacts the transfer of heat, salt, and anthropogenic carbon dioxide from one part of the ocean to another. Dr. Lozier was the recipient of a National Science Foundation Early Career Award in 1996 and is a Fellow of the American Meteorological Society and a Fellow of the American Geophysical Union. She recently served on the NRC Committee on Understanding and Monitoring Abrupt Climate Change and its Impacts and is currently the international lead on the OSNAP (Overturning in the Subpolar North Atlantic Program) ocean observing system. She also currently serves as the president of The Oceanography Society.

Roberta Marinelli is the Executive Director of the University of Southern California (USC), Wrigley Institute for Environmental Studies. She plays a leadership role in planning and implementing an expansion of academic and research programs in environmental studies at USC's University Park Campus and at the Philip K. Wrigley Marine Science Center on Santa Catalina Island. Her research interests include the ecology and geochemistry of seafloor communities, and coupled human-natural interactions in marine environments. Dr. Marinelli was a program officer in the National Science Foundation's Antarctic Sciences section, where she contributed to building collaborative programs across the Foundation, including the International Polar Year, Climate Research Investments, and Science, Engineering and Education for Sustainability. She was previously on the faculty of the University of Maryland's Center for Environmental Science and the Skidaway Institute of Oceanography, where she received a National Science Foundation Early Career Award. She is a member of the American Geophysical Union and the American Society for Limnology and Oceanography. Dr. Marinelli received her Ph.D. in marine science from the University of South Carolina.

James McCarthy is the Alexander Agassiz Professor of Biological Oceanography and acting Curator of the Malacology Department in the Museum of Comparative Zoology at Harvard University. His research interests focus on the regulation of plankton productivity in the sea, and the upper ocean nitrogen cycle, especially in mixing processes, monsoonal cycles, and the El Niño–Southern Oscillation system. He participated in the early planning phases of the International Geosphere-Biosphere Programme and served as its chair for the first 6 years of the program. He was involved in the first Intergovernmental Panel on Climate Change assessment, co-authoring the concluding chapter of Working Group I. In the third Intergovernmental Panel on Climate Change assessment he co-chaired Working Group II, whose task it was to assess impacts of and vulnerabilities to global climate change, with an intensified focus on adaptation. Dr. McCarthy has served on numerous scientific advisory boards and committees, including the NRC Ecosystems Panel to review the U.S. Global Change Research Program, the Committee on Global Change Research, and the Committee to Review the Global Ocean Observing System, and was a member of the Ocean Studies Board from 1980 to 1988. Dr. McCarthy received his Ph.D. from the Scripps Institution of Oceanography.

Alan Mix is a professor of oceanography in the Ocean Ecology and Biogeochemistry Division of the College of Earth, Ocean, and Atmospheric Sciences (COAS) at Oregon State University (OSU), where he has also served as Associate Dean. His research includes paleoceanography, paleoclimatology, paleoecology, and geochemistry. He is the director of the COAS/OSU Stable Isotope Laboratory and the OSU Mass Spectrometry Consortium. His many national and international projects include the Climate Long Range Mapping and Prediction project, the Mapping Spectral Variability in Global Climate project, the Joint Global Ocean Flux Studies, Environmental Processes of the Ice Age: Land, Oceans, and Glaciers, and Paleoclimate Variability. He currently co-chairs the Past Global Change project of the International Geosphere-Biosphere Program. Some recent honors include Joint Oceanographic Institutions/U.S. Science Advisory Committee Distinguished Lecturer, and Chapman Lectureship, University of Alaska, Fairbanks. He is a Fellow of the American Geophysical Union, and a member of the Geological Society of America, The Oceanography Society, and the European Geosciences Union. Dr. Mix received his Ph.D. in geology from Columbia University.

Steven Murawski is professor and Peter Betzer Endowed Chair of Biological Oceanography at the University of South Florida. He is a fisheries biologist and marine ecologist involved in understanding the impacts of human activities on the sustainability of ocean ecosystems. He is the Director of the Center for Integrated Analysis and Modeling of Gulf Ecosystems, a consortium funded by the Gulf of Mexico Research Initiative. He has developed approaches for understanding the impacts of fishing on marine fish complexes

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exploited in mixed-species aggregations. Additionally, his work on impacts of marine protected areas and other management options has formed the scientific basis for regulation. In addition to his science activities, Dr. Murawski is a USA Delegate and past vice-president of the International Council for the Exploration of the Sea. As former chief fisheries scientist with NOAA, Dr. Murawski was responsible for overseeing all fisheries research supported by NOAA. He is a current Ocean Studies Board member and a member of the U.S. National Committee for the International Institute for Advanced Systems Analysis. Dr. Murawski received his Ph.D. in wildlife and fisheries biology from the University of Massachusetts, Amherst.

Robert Paine is an emeritus professor of biology at the University of Washington. His research includes investigating the ecological processes producing structure in marine communities. His primary study system is the biologically diverse assemblage characterizing rocky shores exposed to heavy wave action along western North America. Basic questions involve the factors promoting coexistence and biodiversity, especially predation and disturbance. Dr. Paine is a member of the National Academy of Sciences and received the 2013 International Cosmos Prize. He was a member of the Ocean Studies Board from 2004 to 2006 and served on the NRC's Committee on Best Practices for Shellfish Mariculture and the Effects of Commercial Activities in Drake's Estero and Committee on Ecosystem Effects of Fishing: Phase II—Assessments of the Extent of Ecosystem Change and the Implications for Policy. Dr. Paine received his Ph.D. from the University of Michigan.

Charles Paull is a senior scientist at the Monterey Bay Aquarium Research Institute. His research interests include the frequency, distribution, and environmental significance of continental margin pore water seeps; the establishment of in situ characteristics of marine gas hydrates; and understanding of the diverse processes that form and subsequently erode continental margins. He is a member of the American Association of Petroleum Geologists, the American Geophysical Union, and the Society of Economic Paleontologists and Mineralogists. He was the Chair of the NRC Committee on the Assessment of DOE's Methane Hydrate Research and Development Program. Dr. Paull received his Ph.D. in oceanography from the Scripps Institution of Oceanography.

Don Walsh is the President of International Maritime Incorporated. He has worked on a wide variety of marine-related projects, ranging from ocean remote sensing from spacecraft to deep seafloor explorations by submersible, as well as from urban coastlines to remote polar regions. Some examples of his work are ocean remote sensing from aircraft and Earth-orbiting satellites, research ship development and operations, ocean law and policy questions related to national and international uses of the World Ocean, and non-nuclear military submarine development. Notably, he made a record maximum descent to the Mariana Trench in 1960 to a depth of 35,798 ft. Dr. Walsh is a member of the National Academy of Engineering, is a current Ocean Studies Board member, and has been on NRC committees including the NAE's Special Fields and Interdisciplinary Engineering Peer Committee, the Committee on the Arctic Research Vessel, and the Committee on the Review of NOAA's Fleet Replacement and Modernization Plan. Dr. Walsh received his Ph.D. in physical oceanography from Texas A&M University.

Bess Ward is the William J. Sinclair Professor of Geosciences, and chair of the Department of Geosciences, at Princeton University. Her main areas of research are the marine and global nitrogen cycle, using stable isotopes and molecular biological methods to study marine bacteria/archaea and microbial processes (especially nitrification and denitrification), and nitrogen utilization by phytoplankton. She has been honored in multiple science advisory positions, as a Fellow of the American Academy of Microbiology, as a Fellow of the American Geophysical Union, and as a Fellow of the American Academy of Arts and Sciences. Dr. Ward received her Ph.D. in biological oceanography from the University of Washington.

James Yoder is the Vice President for Academic Programs and Dean at the Woods Hole Oceanographic Institution. He was a professor at the Graduate School of Oceanography, University of Rhode Island, where he conducted research, taught graduate courses, and advised M.S. and Ph.D. students. He served 5 years as Graduate School of Oceanography Associate Dean in charge of the graduate program in oceanography and 1.5 years as Interim Dean of the School. Dr. Yoder has also held temporary positions in the federal government as a program manager at National Aeronautics and Space Administration Headquarters from 1986 to 1988 and 1996 to 1997 and as Director of the National Science Foundation's Division of Ocean Sciences from 2001 to 2004. Dr. Yoder has served on several NRC committees. He was the chair of the Committee on Assessing Requirements for Sustained Ocean Color Research and Operations, was a member of the Committee on Scientific Accomplishments of Earth Observations from Space, and is a current member of the Ocean Studies Board. Dr. Yoder received his Ph.D. in oceanography from the University of Rhode Island.

William Young is a professor of physical oceanography at the Scripps Institution of Oceanography. His research on geophysical fluid dynamics and dynamical oceanography has led to broad advances in understanding oceanic mixing, eddy generation, and other key features of oceanic dynamics with strong implications for the Earth's climate system. Young has recently been working on the generation of ocean surface waves and atmospheric water vapor distributions. He is a member of the National Academy of Sciences and a Fellow

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of the American Meteorological Society and the American Geophysical Union. Dr. Young received his Ph.D. in physical oceanography from the Woods Hole Oceanographic Institution and the Massachusetts Institute of Technology.

STAFF

Deborah Glickson is a Senior Program Officer with the Ocean Studies Board at the NRC. She received an M.S. in geology from Vanderbilt University in 1999 and a Ph.D. in oceanography from the University of Washington in 2007. Her doctoral research focused on magmatic and tectonic contributions to mid-ocean ridge evolution and hydrothermal activity at the Endeavour Segment of the Juan de Fuca Ridge. In 2008, she participated in the Dean John A. Knauss Marine Policy Fellowship and worked on coastal and ocean policy and legislation in the U.S. Senate. Prior to her Ph.D. work, she was a research associate in physical oceanography at Woods Hole Oceanographic Institution. Since joining the NRC staff in 2008, she has worked on a number of ocean and Earth science studies, including such topics as scientific ocean drilling, critical ocean science research needs and infrastructure, the academic research fleet, marine hydrokinetic energy, methane hydrates, and geoscience education.

Susan Roberts began her career with the Ocean Studies Board at the NRC in April 1998 and became the Board Director in April 2004. As Board Director, she oversees the work of the staff and manages the Board's portfolio of activities. In 2013, she also served as the Acting Director for the Polar Research Board and the Board on Atmospheric Sciences and Climate. Dr. Roberts received her Ph.D. in marine biology from the Scripps Institution of Oceanography. Prior to her position at the Ocean Studies Board, she worked as a postdoctoral researcher at the University of California, Berkeley, and as a senior staff fellow at the National Institutes of Health. Dr. Roberts' research experience has included fish muscle physiology and biochemistry, marine bacterial symbioses, and developmental cell biology. She has served as study director for 17 reports produced by the NRC on topics covering a broad range of ocean science, marine resource management, and science policy issues. She is a member of the U.S. National Committee for the Intergovernmental Oceanographic Commission (IOC) and served on the IOC panel for the Global Ocean Science Report. Dr. Roberts is a member of the American Association for the Advancement of Science, the American Geophysical Union, and the Association for the Sciences of Limnology and Oceanography. She is an elected Fellow of the Washington Academy of Sciences.

Stacee Karras joined the NRC in September 2012 as a fellow on the Ocean Studies Board, and is currently a Research Associate. She received her B.A. in marine affairs and policy with concentrations in biology and political science from the University of Miami in 2007. The following year she received an M.A. in marine affairs and policy from the University of Miami's Rosenstiel School of Marine and Atmospheric Science. Most recently, she earned her J.D. from the University of Virginia, School of Law.

Payton Kulina joined the Ocean Studies Board at the NRC in June 2013 and is currently a Senior Program Assistant. He graduated from Dickinson College receiving a B.A. in policy management, focusing on the Arctic National Wildlife Refuge and Rails-to-Trails projects. Prior to this position, Payton worked as a coordinator with BP Alternative Energy, also in Washington, D.C.

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Appendix B

Presentations at DSOS Committee Meetings

COMMITTEE MEETING 1
October 1-2, 2013, Washington, DC

Lessons Learned from Other Decadal Surveys

The Decadal Study Process
- Art Charo, NRC Space Studies Board

Earth Observations from Space: A Community Assessment and Strategy for the Future
- Berrien Moore III, University of Oklahoma

Vision and Voyages for Planetary Science in the Decade 2013-2022
- Steven Squyres, Cornell University

Congressional Perspective on Decadal Surveys
- Jeff Bingham, retired Senate Commerce Committee staff

Oceanography in the Next Decade
- Carl Wunsch, Massachusetts Institute of Technology

COMMITTEE MEETING 2
December 5-6, 2013, San Francisco, CA

Portfolio Planning—An Example from the Office of Naval Research
- RADM Nevin Carr, retired

NSF-Supported Infrastructure Panel

Ocean Observatories Initiative
- Tim Cowles, Oregon State University

Deep Submergence
- Peter Girguis, Harvard University

University-National Oceanographic Laboratory System
- Peter Ortner, University of Miami, and Jon Alberts, University-National Oceanographic Laboratory System

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International Ocean Discovery Program
- Susan Humphris, Woods Hole Oceanographic Institution

Discussion with National Science Foundation Division of Ocean Sciences

Study Origin, Expectation and Needs, Recent Budgets
- David Conover, former Division of Ocean Sciences Director

How DSOS Fits into Directorate for Geosciences Strategic Plans
- Roger Wakimoto, Directorate for Geosciences Assistant Director
- Marge Cavanaugh, Directorate for Geosciences Deputy Assistant Director

COMMITTEE MEETING 3
January 23-24, 2014, Washington, DC

Agency Panel I—NOAA and ONR

- Bob Detrick, NOAA Office of Oceanic and Administration Research
- Holly Bamford, NOAA National Ocean Service
- David Score, NOAA Director of Office of Marine and Aviation Operation
- Frank Herr, Office of Naval Research

Agency Panel II—NASA, USGS, BOEM, and EPA

- Eric Lindstrom and Paula Bontempi, NASA
- John Haines, USGS
- Walter Johnson, BOEM
- Brian Melzian, EPA

NSF Panel—Ocean-Relevant Divisions and Directorates

- Bill Zamer, Directorate for Biological Sciences
- Simon Stephenson and Scott Borg, Division of Polar Programs
- Anjuli Bamzai, Division of Atmospheric and Geospace Sciences
- Paul Cutler and Jennifer Wade, Division of Earth Sciences
- Deborah Bronk, Division of Ocean Sciences

COMMITTEE MEETING 4
March 1-2, 2014, Honolulu, HI

OOI Science Presentations

Regional Cabled Observatory
- John Delaney, University of Washington

Global Array
- Tommy Dickey, University of California, Santa Barbara

Pioneer Array
- Al Plueddemann, Woods Hole Oceanographic Institution

Endurance Array
- Jack Barth, Oregon State University

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Cyberinfrastructure
- John Orcutt, Scripps Institution of Oceanography

Lunch Roundtable with Early Career Scientists
- Kim Martini, University of Washington Joint Institute for the Study of the Atmosphere and Ocean
- Beth Curry, University of Washington Applied Physics Lab
- Jamie Pierson, University of Maryland Center for Environmental Science

COMMITTEE MEETING 5
June 11-13, 2014, Irvine, CA

Lunch Roundtable with Early Career Scientists
- Naomi Levine, University of Southern California
- Jason Sylvan, University of Southern California
- Sarah Giddings, Scripps Institution of Oceanography
- Andrew Thompson, California Institute of Technology

Discussion with Division of Ocean Sciences
- Deborah Bronk, National Science Foundation

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Appendix C

Virtual Town Hall Questionnaire

The Virtual Town Hall website (http://nas-sites.org/dsos2015/) was active from November 8, 2013, to March 15, 2014, and generated 416 comments. The questions below were posed to the ocean science community, to be used as input to the committee. All responses have been archived, and the website will remain live until the end of 2015. The website was advertised through numerous professional society, special interest, and National Science Foundation websites and/or listservs and was disseminated at the 2013 AGU Fall Meeting and the 2014 Ocean Sciences Meeting.

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1. Your affiliation

2. Your discipline

3. Across all ocean science disciplines, please list 3 important scientific questions that you believe will drive ocean research over the decade.

4. Within your own discipline, please list 3 important scientific questions that you believe will drive ocean research over the next decade.

5. Please list 3 ideas for programs, technology, infrastructure, or facilities that you believe will play a major role in addressing the above questions over the next decade. Please consider both existing and new technology/facilities/infrastructure/programs that could be deployed in this timeframe. What mechanisms might be identified to best leverage these investments (interagency collaborations, international partnerships, etc.)?

6. Other comments pertinent to the committee's charge.

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Appendix D

Glossary of Terms

Abrupt Change: Change that occurs more quickly than anticipated; often associated with "thresholds" and "tipping points."

Anthropogenic: Caused by people and their activities.

Biodiversity, Marine: The variety of life found in the ocean and on or within the sea floor, especially related to species and genetic variation.

Biogeochemical: The nexus of biological, geological, and chemical processes; may be used to refer to just two of the three components.

Biosphere: That part of the planet that harbors life; used here in reference to "deep biosphere" or "subseafloor biosphere" to denote the microbial communities beneath the seafloor.

Carbon Cycle: The biogeochemical processes by which carbon is exchanged among the ocean, atmosphere, land and subseafloor, and biosphere. It is often used together with the nitrogen, water, and other cycles to describe those global cycles that allow the Earth to sustain life.

Climate: The slowly varying aspects of the atmosphere-ocean-land surface system. Typically characterized in terms of averages over a month or more, climate includes both the temporal and spatial variability of these averages.

Connectivity (biological context): How different species and trophic levels are connected; dispersion or dispersal of organisms from place to place.

Decision Rules: Advance planning on how to deal with unanticipated budgetary changes to allow more effective strategic planning and response to near-term budgetary adjustments.

Ecosystem Services: The benefits to humans accruing from ecosystems; often parsed into provisioning, regulating, supporting, and cultural services.

Extreme Events: Events that are outside average experience and expectation, used in relation to natural occurances such as hurricanes.

Fluids: In this report, used to denote liquids (especially seawater) and gases (especially from the atmosphere); does not include magma.

Ocean Acidification: A term used to describe significant changes to the chemistry of the ocean. It occurs when carbon dioxide gas (or CO_2) is absorbed by the ocean and reacts with seawater to produce acid. The change in ocean chemistry caused by absorption of excess CO_2 from the atmosphere. The reaction of CO_2 with seawater causes a decrease in pH and an increase in the solubility of calcium carbonate, in the primary structural component of many marine species including clams, oysters, reef-building corals and calcareous plankton..

Ocean Circulation: The large-scale movement of water, created by horizontal currents and vertical motion such as upwelling and overturning, and driven by winds and the exchange of heat and freshwater at the air-sea interface.

Predictability: Used in a nontechnical sense to mean the extent to which natural phenomena can be forecast by existing models and data. Improved understanding of the phenomena can usually contribute to its predictability. We also distinguish between efforts to enhance predictability and efforts to make forecasts; the former are the focus of research activities, whereas the latter are often the province of operational agencies.

Primary Productivity: The rate at which energy is converted by photosynthetic and chemosynthetic processes and living organisms to organic substances; making new biomass from inorganic substances.

Readiness: Some topical areas are ready to be worked on: the tools and infrastructure exist, the money is possibly available, the questions are clear, the community interested in it is energized and perhaps growing, and the partners are ready and willing. It is "low-hanging fruit" in the sense that one does not need for it to ripen further. This does NOT imply that results will come quickly, only that the research can begin quickly.

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Resilience: The capacity of an ecosystem to respond to a perturbation or disturbance by resisting damage and recovering quickly. Some research suggests resilience is degraded if biodiversity is decreased.

Sea Level: In this report, used as the longer-term changes associated with land subsidence/uplift, and especially those changes associated with climate change, specifically glacier melt and ocean warming, not the daily/short-term variations associated with tides and winds.

Societal Impact: An increasing emphasis at NSF and in government-funded programs in general is to focus funding on areas of societal relevance. The federal themes of ocean-related societal relevance are stewardship of natural and cultural ocean resources, increasing resilience to natural hazards and environmental disasters, maritime operations and the marine environment, the ocean's role in climate, improving ecosystem health, and enhancing human health.

Transformative: The potential for radically changing the understanding of—and how one thinks about—the topic being investigated, if the research is successful.

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Appendix E

Acronyms Used in the Report

AC-GEO	NSF Advisory Committee for Geosciences
AUV	autonomous underwater vehicle
BATS	Bermuda Atlantic Time-series Study
BIO	Directorate for Biological Sciences
BOEM	Bureau of Ocean Energy Management
CalCOFI	California Cooperative Oceanic Fisheries Investigations
CLIVAR	Climate Variability & Predictability
CoML	Census of Marine Life
CPP	Complementary Project Proposal
DOE	Department of Energy
DSOS	Decadal Survey of Ocean Sciences 2015
EAR	NSF Division of Earth Sciences
ECORD	European Consortium for Ocean Research Drilling
EPA	Environmental Protection Agency
FEMA	Federal Emergency Management Agency
FY	fiscal year
GEO	NSF Geosciences Directorate
GEOTRACES	International Study of Marine Biogeochemical Cycles of Trace Elements and their Isotopes
GLOBEC	Global Ocean Ecosystem Dynamics
HOT	Hawaii Ocean Time-series
HOV	human-occupied vehicle
ICER	Integrative and Collaborative Education and Research
IODP (2003-2013)	Integrated Ocean Drilling Program
IODP (2013-2018)	International Ocean Discovery Program
IWG-FI	Interagency Working Group on Facilities and Infrastructure
IWG-OP	Interagency Working Group on Ocean Partnerships
JGOFS	Joint Global Ocean Flux Study

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MEXT	Ministry of Education, Culture, Sports, Science and Technology (Japan)
MMC	Marine Mammal Commission
MREFC	Major Research Equipment and Facilities Construction
MSP	mission-specific platform
NASA	National Aeronautics and Space Administration
NDSF	National Deep Submergence Facility
NEPTUNE	Northeast Pacific Time-Series Undersea Networked Experiments
NIEHS	National Institute of Environmental Health Sciences
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NOPP	National Oceanographic Partnership Program
NRC	National Research Council
NSF	National Science Foundation
O&M	operations and maintenance
OAR	Office of Oceanic and Atmospheric Research
OBSIP	Ocean Bottom Seismograph Instrument Pool
OCE	NSF Division of Ocean Sciences
ODP	Ocean Drilling Program
ONR	Office of Naval Research
OOI	Ocean Observatories Initiative
OTIC	Oceanographic Technology and Interdisciplinary Coordination
PLUME	Plume-Lithosphere Undersea Mantle Experiment
RCRV	Regional Class Research Vessel
RIDGE	Ridge Interdisciplinary Global Experiments
ROV	remotely operated vehicle
SEES	Science, Engineering, and Education for Sustainability (NSF)
SOST	Subcommittee on Ocean Science and Technology
UAV	unmanned aerial vehicle
UNOLS	University-National Oceanographic Laboratory System
USACE	U.S. Army Corps of Engineers
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
WOCE	World Ocean Circulation Experiment

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