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Critical Infrastructure for Ocean Research and Societal Needs in 2030

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Critical Infrastructure for Ocean Research and Societal Needs in 2030

Committee on an Ocean Infrastructure Strategy for U.S. Ocean Research in 2030

Ocean Studies Board

Division on Earth and Life Studies

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

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Cover: Artist's rendering of possible technological innovations and ocean infrastructure assets that will be deployed in support of U.S. ocean research by 2030, based on presentations from the February 2-3, 2010, Ocean Infrastructure Strategy Workshop (illustration by E. Paul Oberlander, Woods Hole Oceanographic Institution).

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This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the 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 Christine Henderson, appointed by the Divison on Earth and Life Studies, and J. Brad Mooney, 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

The United States has jurisdiction over 3.4 million square miles of ocean in its exclusive economic zone, a size exceeding the combined land area of the 50 states. This expansive marine area represents a prime national domain for activities such as maritime transportation, national security, energy and mineral extraction, fisheries and aquaculture, and tourism and recreation. However, it also carries with it the threat of damaging tsunamis and hurricanes, industrial accidents, and outbreaks of waterborne pathogens. The 2010 Gulf of Mexico *Deepwater Horizon* oil spill and the 2011 Japanese earthquake and tsunami are vivid reminders that ocean activities and processes have direct human implications both nationally and worldwide, understanding of the ocean system is still incomplete, and ocean research infrastructure is needed to support both fundamental research and societal priorities.

In 2004, the U.S. Commission on Ocean Policy report, *An Ocean Blueprint for the 21st Century,* called for "a renewed commitment to ocean science and technology" to realize the benefits of the ocean while ensuring its sustainability for future generations. Since the release of the Commission's report, federal agencies have been working together through the National Science and Technology Council's Subcommittee on Ocean Science and Technology (SOST), which has the mandate to identify research priorities, facilitate coordination of ocean research, and develop ocean technology and infrastructure. This study was initiated to assist SOST in planning for the nation's ocean research infrastructure needs in 2030 by identifying major research questions anticipated to be at the forefront of ocean science in 2030, defining categories of infrastructure that should be included in next-generation planning, providing advice on criteria that could be used to set priorities for asset development or replacement, recommending ways in which the federal agencies could maximize the value of ocean infrastructure investments, and addressing societal issues. It is also intended to complement efforts in support of the National Ocean Council, which was established to implement the National Ocean Policy outlined in the *Final Recommendations of the Interagency Ocean Policy Task Force* (Executive Order 13547, July 19, 2010).

Ocean research infrastructure supports both fundamental and applied scientific research that addresses urgent societal concerns such as climate change, human health, domestic offshore energy production, national security, marine shipping, tsunami detection and severe storm tracking, sustainable fisheries and aquaculture growth, and changes in marine ecosystem services. However, significant components of national infrastructure are aged, obsolete, or insufficient to meet growing societal demand for scientific information to enable safe, efficient, and environmentally sustainable use of the ocean. **A comprehensive range of ocean research infrastructure will be needed to overcome these challenges, and more interdisciplinary and multidisciplinary research will require a growing suite of infrastructure.** Current institutional barriers have inhibited collaborative efforts among federal agencies to plan for the operation and maintenance of major, high-cost, critical infrastructure assets such as ships, satellites, and global observing systems.

Recommendation: Federal ocean agencies should establish and maintain a coordinated national strategic plan for critical shared ocean infrastructure investment, maintenance, and retirement. Such a plan should focus on trends in scientific needs and advances in technology, while taking into consideration life-cycle costs, efficient use, surge capacity for

unforeseen events, and new opportunities or national needs. The plan should be based upon a set of known priorities and updated through periodic reviews.

Setting Priorities and Maximizing Investments

Prioritization of ocean infrastructure investments involves choosing optimal combinations of assets within certain budget constraints to maximize benefits. The committee devised criteria that could be used to help federal agencies and others develop a prioritization scheme. These criteria encompass a wide range of issues, including whether specific infrastructure can help address multiple scientific questions or needs; data quality and continuity; future technology trends; balance between risk and benefit; and national strategic or economic importance. From an economic viewpoint, this type of prioritization needs to acknowledge uncertainties regarding the ability of future ocean science research to produce information relevant to critical ocean-related societal issues.

Recommendation: Development, maintenance, or replacement of ocean research infrastructure assets should be prioritized based on (1) usefulness for addressing important science questions; (2) affordability, efficiency, and longevity; and (3) ability to contribute to other missions or applications. Such prioritization will maximize societal benefit for the nation.

Federal agencies can optimize investments in ocean research infrastructure by following a number of best practices: effectively and efficiently managing existing resources; providing broad access to data, information, and facilities; fostering collaboration at multiple organizational levels; facilitating the successful transition of infrastructure from research to operational use; and ensuring the next generation of ocean science infrastructure. A coordinated, adaptable, long-term strategy for usage of shared, federally funded infrastructure assets, with possibilities to include locally and state-funded infrastructure, and periodic reviews of ocean infrastructure are needed to fully capitalize on investments made by individual agencies.

Recommendation: National shared ocean research infrastructure should be reviewed on a regular basis (every 5-10 years) for responsiveness to evolving scientific needs, cost effectiveness, data accessibility and quality, timely delivery of services, and ease of use in order to ensure optimal federal investment across a full range of ocean science research and societal needs.

Major Research Questions in 2030

The committee identified four major themes that are of compelling interest to society and that will drive scientific research for the next two decades: **enabling stewardship of the environment, protecting life and property, promoting economic vitality, and increasing fundamental scientific understanding.** Utilizing strategic planning documents, current literature, and community input, the committee converged upon 32 major research questions that they anticipate will be at the forefront of scientific and societal importance in 2030. **The scientific questions that will drive research in 2030 are rich and diverse and are of compelling interest to society. The importance of these questions demands continued investment in ocean research infrastructure. In order to address the most important and societally relevant questions, U.S. ocean research infrastructure will be required to serve a**

broad set of needs. Many of these questions are presently relevant in 2010 but are not simple issues that will result in solutions with a few more years of intensive effort. Instead, they reflect challenging scientific problems that will likely take decades to solve, especially if only limited resources are available. These include the need for a global observational framework with sustained ability to monitor change in the ocean and enhance prediction of the coupled ocean-atmosphere system, a capability to focus on process studies that improve understanding, a focus on environmentally sensitive regions or areas of national security, and the flexibility to deploy infrastructure during events or emergencies.

Ocean Infrastructure Categories

In this report, U.S. ocean research infrastructure is defined as "the full portfolio of platforms, sensors, data sets and systems, models, supporting personnel, facilities, and enabling organizations that the nation can bring to bear to answer questions about the ocean, and that is (or could be) shared by or accessible to the ocean research community as a whole." The committee focused on ocean research infrastructure that could be considered community-wide or shared assets, in that they are available to the ocean science community as a whole. The wide array of infrastructure assets currently in use and needed for 2030 include mobile and fixed platforms, in situ sensors and sampling, remote sensing and modeling, and data management and communications. In addition, enabling organizations will be necessary to foster technology innovation and to help train the future ocean science workforce.

An examination of trends revealed that, in the past two decades, the use of floats, gliders, remotely operated vehicles, autonomous underwater vehicles, and scientific seafloor cables has increased; the use of ships, drifters, moorings, and towed platforms has remained stable; and the use of human occupied vehicles has declined. Based on these trends and on the major science questions for 2030, it is anticipated that utilization and capabilities for floats, gliders, remotely operated vehicles, autonomous underwater vehicles, submarine scientific cables, and moorings will continue to increase significantly for the next 20 years. Ships will continue to be an essential component of ocean research infrastructure; however, the increasing use of autonomous and unmanned assets will broaden the demands for a wide range of ship capabilities. Many sensor capabilities have increased: longevity, stability, data communications, adaptability, and access to harsh environments. These improvements are mostly dependent on innovations occurring outside the ocean science field, and the oceanographic community will continue to benefit from innovations in sensor and other technologies across many fields.

Recommendation: To ensure that the United States has the capacity in 2030 to undertake and benefit from knowledge and innovations possible with oceanographic research, the nation should

- **Implement a comprehensive, long-term research fleet plan to retain access to the sea.**
- **Recover U.S. capability to access fully and partially ice-covered seas.**
- **Expand abilities for autonomous monitoring at a wide range of spatial and temporal scales with greater sensor and platform capabilities.**
- **Enable sustained, continuous time-series measurements.**
- **Maintain continuity of satellite remote sensing and communication capabilities for oceanographic data and sustain plans for new satellite platforms, sensors, and communication systems.**

- **Support continued innovation in ocean infrastructure development. Of particular note is the need to develop in situ sensors, especially biogeochemical sensors.**
- **Engage allied disciplines and diverse fields to leverage technological developments outside oceanography.**
- **Increase the number and capabilities of broadly accessible computing and modeling facilities with exascale or petascale capability that are dedicated to future oceanographic needs.**
- **Establish broadly accessible virtual (distributed) data centers that have seamless integration of federal, state, and locally held databases, accompanying metadata compliant with proven standards, and intuitive archiving and synthesizing tools.**
- **Examine and adopt proven data management practices from allied disciplines.**
- **Facilitate broad community access to infrastructure assets, including mobile and fixed platforms and costly analytical equipment.**
- **Expand interdisciplinary education and promote a technically skilled workforce.**

1
Introduction

"The ocean dominates Earth's surface and greatly affects our daily lives. It regulates Earth's climate, plays a critical role in the hydrological cycle, sustains a large portion of Earth's biodiversity, supplies food and mineral resources, constitutes an important medium of national defense, provides an inexpensive means of transportation, is the final destination of many waste products, is a major location of human recreation, and inspires our aesthetic nature." – Oceanography in the Next Decade, 1992

In its 2004 report *An Ocean Blueprint for the 21st Century*, the U.S. Commission on Ocean Policy (USCOP) recommended the development of "a national ocean and coastal infrastructure and technology strategy to support science, resource management, assessments, enforcement, and education" (USCOP, 2004). One of the USCOP's tasks was to develop an inventory of U.S. infrastructure for ocean science, education, and various management and industry activities; this revealed that significant components of the U.S. infrastructure were aged or obsolete, and in some areas capacity was insufficient to meet the needs of the ocean community. The USCOP expressed concern that there was a growing technology gap in U.S. facilities, as well as a decline of national leadership in marine technology development. Both of these issues could result in increasing reliance on foreign facilities, potentially reducing the access of U.S. researchers to new technologies, data, and opportunities.

In response to *An Ocean Blueprint for the 21st Century*, the administration formed the National Science and Technology Council's Subcommittee on Ocean Science and Technology (SOST)[1] to coordinate the nation's ocean research enterprise among the federal agencies. In 2007, SOST released *Charting the Course of Ocean Science in the United States for the Next Decade: An Ocean Research Priorities Plan and Implementation Strategy*, with key strategies that focused on compelling ocean-related societal and scientific issues (stewardship of natural and cultural ocean resources, increasing resilience to natural hazards, enabling marine operations, the ocean's role in climate, improving ecosystem health, and enhancing human health; JSOST, 2007). Through continued planning for ocean science needs beyond the next decade, SOST has been evaluating the current status and future needs of the nation's research infrastructure. Federal agencies with ocean responsibilities will need to anticipate the directions that ocean research could take over the next decades because of the lengthy lead times for planning, designing, funding, and building major infrastructure assets, and because of the long service life of many of these assets (often 25-30 years or more). Balancing the competing needs of construction and ongoing support is a major challenge to sustaining the U.S. ocean research enterprise. Given current struggles to maintain, operate, and upgrade major infrastructure elements while maintaining a robust research portfolio, a strategic plan is needed for future

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[1] Formerly the Joint Subcommittee on Ocean Science and Technology (JSOST). Member agencies are the Arctic Research Commission, the Department of Agriculture, the Department of Commerce (National Oceanic and Atmospheric Administration), the Department of Defense (U.S. Army Corps of Engineers, Office of Naval Research), the Department of Energy (Office of Science), the Department of Health and Human Services (Centers for Disease Control and Prevention, Food and Drug Administration, National Institutes of Health), the Department of Homeland Security (U.S. Coast Guard), the Department of the Interior (Bureau of Ocean Energy Management, Regulation and Enforcement, U.S. Geological Survey), the Department of Justice, the Department of State, the Department of Transportation (Maritime Administration), the Environmental Protection Agency, the Executive Office of the President (Council on Environmental Quality, Domestic Policy Council, Office of Management and Budget, Office of Science and Technology Policy), the Joint Chiefs of Staff, the Marine Mammal Commission, the National Aeronautics and Space Administration, the National Science Foundation, and the Smithsonian Institution.

investments to ensure that new facilities provide the greatest value, least redundancy, and highest efficiency in terms of operation and flexibility to incorporate new technological advances. SOST sought advice from the National Research Council on a strategy for addressing the nation's ocean research infrastructure needs in 2030, focusing on facilities and hardware needed to address significant oceanographic research questions. The Statement of Task is found in Box 1.1. Committee biographies can be found in Appendix A.

Box 1.1
Statement of Task

The National Research Council will assemble an expert committee to provide advice and a perspective from the worldwide ocean community on the types of U.S. ocean infrastructure that will facilitate research in 2030, including advice as to what criteria may be most appropriate for setting priorities.

The committee will identify major research questions anticipated to be at the forefront of ocean science in 2030 based on national and international assessments, input from the worldwide scientific community, and ongoing research planning activities. Next, the committee will define categories of infrastructure that should be included in planning for the nation's ocean research infrastructure of 2030 and that will be required to answer the major research questions of the future, taking into consideration

- New scientific and technological developments, including adoption of capabilities and discoveries outside of the ocean sciences;
- Interdependence of various infrastructure assets and multipurpose or multiuser assets;
- How anticipated changes in the oceans, its interactions with the atmosphere, land, sea ice, marine and terrestrial ecosystems, and humans, and commercial enterprises might affect demand for various assets and operational characteristics;
- Potential use of infrastructure assets supported by federal, state, and local governments and by industry to collect data for multiple goals;
- Potential for emerging technology to increase the substitutability of various infrastructure components, thus providing greater flexibility or surge capacity;
- Potential opportunities to phase out programs or facilities in order to develop capabilities in new research areas; and
- Institutional or policy barriers, if any, that may hinder the optimal use of facilities and infrastructure. This would include restrictions on the use of facilities and infrastructure by nontraditional users, including private industry, and possible ways to optimize the use of research facilities.

The report will provide advice on the criteria and processes that could be used to set priorities for the development of new ocean infrastructure or replacement of existing facilities. It will not recommend specific new infrastructure or facility fabrication or construction investments. In undertaking this task, the committee will consider a variety of issues, such as partnerships with other nations and industry, constraints on acquisition and operation of research platforms, and suitability of facilities for addressing a diversity of scientific endeavors. In the same context as *Charting the Course of Ocean Science in the United States for the Next Decade: An Ocean*

Research Priorities Plan and Implementation Strategy, this study will address societal issues. In addition, the committee will recommend ways in which the federal agencies can maximize the value of investments in ocean infrastructure. This may include practices that would facilitate the transition of facilities and infrastructure for research into operational use.

During the course of this study, the National Ocean Council was established to implement the *Final Recommendations of the Interagency Ocean Policy Task Force* (Executive Order 13547, July 19, 2010). The implementation strategy for the National Ocean Policy (CEQ, 2010) includes the following priorities: ecosystem-based management; coastal and marine spatial planning; informing decisions and improving decision making, coordination and support; resiliency and adaptation to climate change and ocean acidification; regional ecosystem protection and restoration; water quality and sustainable practices on land; changing conditions in the Arctic; and ocean, coastal, and Great Lakes observations, mapping, and infrastructure. SOST has also been in the process of updating *Charting the Course of Ocean Science in the United States for the Next Decade: An Ocean Research Priorities Plan and Implementation Strategy*. [2]

WHAT IS INFRASTRUCTURE?

The Merriam-Webster Dictionary[3] defines “infrastructure” as “the underlying foundation or basic framework (as of a system or organization)” or “the resources (as personnel, buildings, or equipment) required for an activity.” Consistent with this definition, U.S. infrastructure for ocean research could be broadly defined as the full portfolio of platforms, sensors, data sets and systems, models, computational and network services, personnel, facilities, and enabling organizations that the nation can bring to bear to answer questions requiring understanding of the ocean.

For the purpose of this report, the committee adopts a slightly narrower definition that focuses on the shared or community resources accessible to the U.S. ocean research enterprise. This excludes personnel and resources associated exclusively with a particular investigator’s research activities, which are often very specialized, prototypes in development, or fully dedicated to a particular task. Under the committee’s definition, U.S. ocean research infrastructure is

> *the full portfolio of platforms, sensors, data sets and systems, models, supporting personnel, facilities, and enabling organizations that the nation can bring to bear to answer questions about the ocean, and that is (or could be) shared by or accessible to the ocean research community as a whole.*

As defined here, ocean research infrastructure is a national portfolio of resources and assets that include technology, facilities, data, people, and institutions. This portfolio changes over time in response to federal, state, local, and private-sector investments in ocean research infrastructure and to developments in oceanography and other fields (information technology, power systems, robotics, and genomics, among others). The state of the nation’s ocean research infrastructure at any point in time determines how well, how quickly, and at what cost the nation can obtain answers to basic and applied questions about the ocean. However, significant components of

[2] http://www.whitehouse.gov/administration/eop/ostp/nstc/oceans
[3] http://www.merriam-webster.com/dictionary/infrastructure

U.S. ocean infrastructure are currently insufficient to meet needs for the ocean research community (see Box 1.2).

The committee defines the ocean research community in the broadest possible terms, with inclusion of the entire ocean science enterprise. While academia is a significant part of this group, the ocean research community encompasses scientists and policy makers at all levels of government and within industry and nonprofit foundations.

Box 1.2
Ocean Science Infrastructure on the Decline

Many pieces of infrastructure that enable U.S. scientists to conduct crucial studies in the ocean are clearly degrading. In this box, two examples of at-risk infrastructure are discussed.

Infrastructure capabilities that allow study of the high-latitude ocean are waning, although these regions are among the most sensitive to a warming climate due to the amplification of temperature changes nearest the poles. Arctic sea ice is already in decline (Stroeve et al., 2007), with implications for ecosystem changes, U.S. jurisdiction interests, national security, and commercial shipping routes. However, the United States is having difficulty ensuring the continued operation of ice-breaking research vessels able to function in multiyear ice. The largest icebreakers, the U.S. Coast Guard's *Polar Star* and *Polar Sea*, are over 30 years old and have exceeded their service lives. At the time of writing, the *Polar Star* has recently been reactivated from caretaker status (where the crew is removed and engines and systems are shut down), and the *Polar Sea* returned to operations after engine casualties. Newer ice-breaking research vessels such as the U.S. Coast Guard Cutter *Healy* were designed to operate in multiyear ice only in conjunction with a heavier ship, which would break a path for them to follow. The lack of heavy icebreaker capabilities will cause the nation to be dependent on leasing or operating in collaboration with foreign icebreakers to conduct science missions in high latitudes. Additionally, resupply missions to Antarctic research bases are also dependent upon icebreakers from other countries. The current decrease in U.S. icebreaking capability makes high-latitude research more complex and adds an element of risk because the enabling infrastructure is not within the nation's direct control. In addition, the U.S. Coast Guard is in danger of losing valuable skill sets, as crew from the heavy icebreakers are reassigned to different positions.

Ocean color satellites have been a key contributor to understanding the impact of climate on ocean biology (Behrenfeld et al., 2006). Ocean color data are used in identifying and monitoring conditions that could lead to harmful algal blooms, and were used to identify patches of oil during the Gulf of Mexico *Deepwater Horizon* well explosion and oil spill. The Sea-viewing Wide Field-of-view Sensor (SeaWiFS)/Moderate Resolution Imaging Spectroradiometer (MODIS) sensors were launched in a sequence designed to provide a continuous, intercomparable time-series of chlorophyll concentrations throughout the ocean since 1997 (McClain, 2009). However, SeaWiFS ceased operations in December 2010 and both MODIS sensors are beyond their lifespan; there is no U.S. mission of equal quality planned to be in space until 2019 or later. The capability to produce climate-quality observations of ocean color is presently threatened, as some questions regarding access to foreign ocean color data remain unresolved. The ability to detect shifts in ocean biology on a global scale is endangered at a time when a shifting climate might be expected to cause significant change in oceanic primary production.

REPORT SCOPE

This report addresses the factors for federal agencies to consider as they plan investments that will affect ocean research infrastructure over the next 20 years. As noted above, the report focuses on components of infrastructure that are or could be shared as a community-wide resource. It excludes certain categories of ocean research personnel (such as principal investigators, administrators, and graduate students) and facilities and equipment that are private, proprietary, or in the inventory of an individual scientist and cannot be shared by the ocean research community as a whole.

The report describes categories of ocean research infrastructure, reviews how infrastructure components have evolved over the past 20 years, and considers the science questions that are likely to determine the infrastructure that will be needed in 2030. These science questions include basic, exploratory work that seeks to broaden our knowledge about the ocean in general ways, as well as applied work that seeks to generate information to address specific societal needs. The committee examines past trends in ocean research infrastructure development and categorizes essential infrastructure assets for the next 20 years, suggests how federal agencies could prioritize investments in ocean research infrastructure, and discusses ways that the value of these investments could be maximized.

The report does not make recommendations about specific changes to U.S. ocean research infrastructure, nor does it assign priorities to future infrastructure investments or to the science questions that the shared infrastructure is intended to support. However, critical needs for specific infrastructure categories are mentioned in the text, in that the science research of the future cannot be done without these types of assets. Decisions regarding prioritization are to be made by federal agencies and other sponsors, with appropriate input from the broad ocean science community. It is the committee's belief that the processes and considerations suggested in this report will inform the approach that federal agencies take over the next two decades to ensure the availability of an effective and efficient shared ocean research infrastructure for supporting world-class basic and applied ocean research in the United States.

SOCIETAL DRIVERS

Ocean research is driven by science questions. These questions, in turn, can arise from the work of individual investigators seeking to broaden basic knowledge and understanding of the ocean through exploration and scientific investigation of ocean phenomena, from the need to generate applied information to address specific societal concerns, or from some combination of basic and applied interests. A representative list of major science research questions for 2030, and their implications for infrastructure, is discussed in detail in Chapter 2. The list of major research questions could have been organized in a variety of ways, including by discipline, by region, or thematically. For this report, the committee chose an organization based on each question's relationship to compelling societal objectives. **These four overarching societal drivers are: enabling stewardship of the environment, protecting life and property, promoting sustainable economic vitality, and increasing fundamental scientific understanding**. These objectives were determined by the committee, based on a synthesis of national ocean policy objectives (e.g., USCOP, 2004; JSOST, 2007; CEQ, 2010). It should be kept in mind that there is overlap between the societal drivers and the knowledge bases they require, and that some science questions could easily fall into more than one category. In this report, each question is placed in a single category.

Basic science questions evolve naturally, as research shifts the frontiers of knowledge and as technological advances make possible new kinds of inquiries. Applied science questions evolve as the information base increases or as national priorities change in response to major economic, political, and environmental developments. Some of the important societal needs related to the ocean have been with us for many years and are likely to remain important in 2030 and beyond (e.g., managing human activities such as fishing or energy extraction, mitigating impacts of natural hazards such as tsunamis, and using the ocean effectively for national security). These questions often remain unanswered because of limitations in the technology needed to address them. For example, genomics developments have recently enabled new fishery management options based on identification of distinct genetic subpopulations. Investments that motivate and nurture new technological developments and infrastructure are likely to allow previously unanswerable questions to gain traction. Other questions have gained in importance in recent years and are likely to be more prominent in 2030 than they are today or were in 1990 (e.g., the role of the ocean in global climate or on human health). The time is right for a new look at the ocean infrastructure that will be necessary to support these needs in the future: the traditional societal drivers of ocean research for much of the 20th century (national defense, offshore oil and gas, fisheries, and transportation) have been expanded into a broader context that now includes global climate change, environmental quality, energy, and ecological sustainability (CNA, 2007).

THE LINK BETWEEN OCEAN RESEARCH INFRASTRUCTURE AND SOCIETAL DRIVERS

Ocean research infrastructure provides the foundation on which basic and applied marine research activities are carried out. These research activities involve the deployment of platforms, sensors and sampling devices to collect samples and data, the analysis of samples and data (often in shore-based facilities), and the construction of models to explain natural phenomena and develop predictive capabilities. The models drive future data needs which, in turn, improve the models. Information produced by research and models represents the best answers to date to the questions that motivated the research. These answers advance fundamental understanding of ocean science and connected global issues, develop the future priorities related to ocean research and technology, and help inform policy decisions such as marine resource management. They also inform the next set of scientific questions that are asked as new phenomena, threats, and opportunities connected to the ocean are discovered. There are fundamental links between ocean research infrastructure, ocean science activities, and societal questions and the benefits associated with answering them (Figure 1.1).

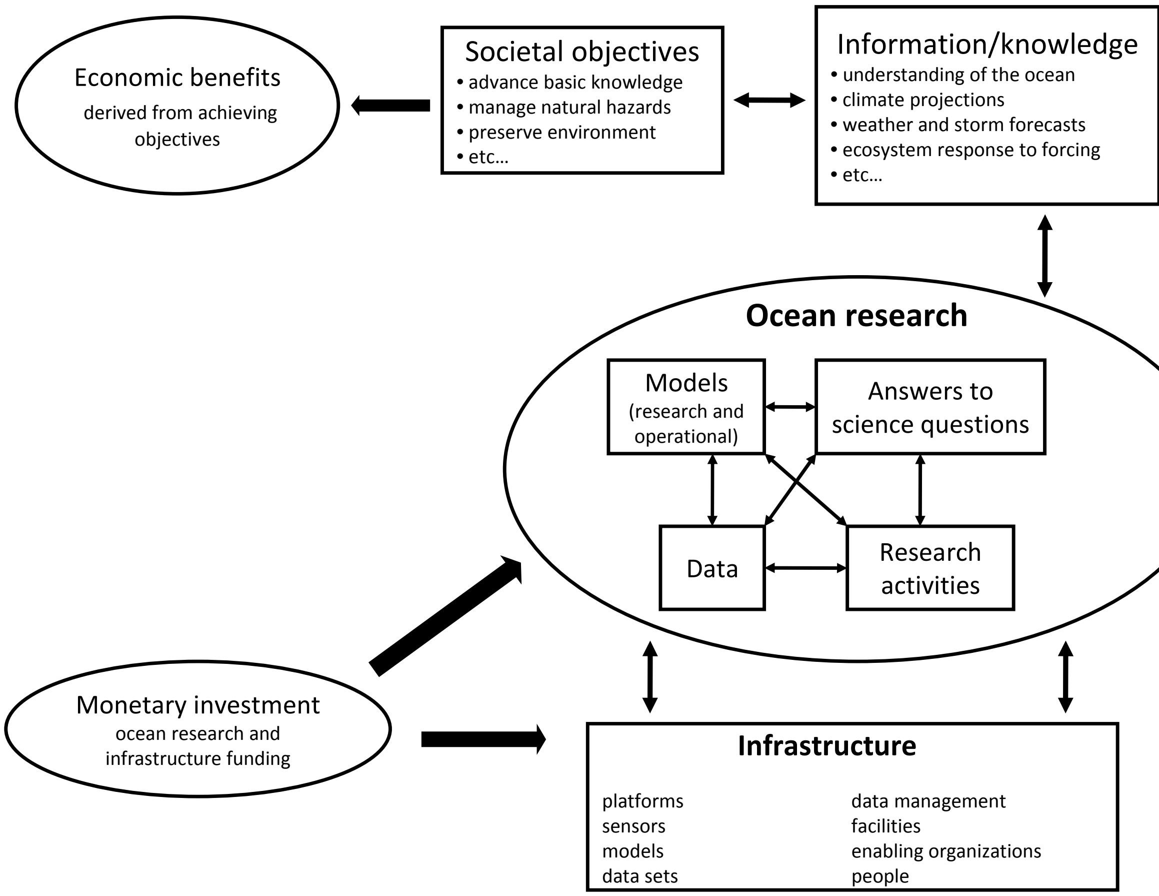

Figure 1.1. Conceptual diagram illustrating links between ocean infrastructure, scientific research, relevant societal objectives, and benefits associated with achieving these objectives.

The linkages shown in Figure 1.1 represent "flows" that often go in both directions, and it is possible to think of the connection between infrastructure and societal objectives as either top down or bottom up. Starting at the top, every societal objective implies a demand for certain information, the acquisition of which has a certain value for society. Acquiring the information often requires answering science questions and/or developing and validating models (for example, models of fish stock recruitment or climate change). Science questions lead to research activities (funded research projects of investigators in both public and private ocean organizations), which result in data collection, analysis, and model development. Data and models also feed back to science questions and research activities by suggesting the next set of questions to be answered. All of this work relies on ocean research infrastructure for the tools and resources to collect, manage, and analyze data. Some models and data sets are considered part of the infrastructure (e.g., global ocean models, widely used climate models). Others, specific to the work of one or two investigators, would fall into ocean research. Ocean science and research activities make use of infrastructure (e.g., ships, buoys, community models) and, in some cases, add to the infrastructure (e.g., by developing new data sets that become part of infrastructure), leading to some overlap between infrastructure and research activities.

Following the linkages bottom up from infrastructure to societal benefits also suggests a useful approach to thinking about infrastructure priorities. Each piece of ocean research infrastructure has an associated cost. Each piece of infrastructure also enables or supports research and modeling activities and, therefore, supports the production of information, which contributes to certain societal objectives—and thus to the aggregate societal benefits produced. The task of prioritizing ocean research infrastructure investments can therefore be interpreted as maximizing the net benefits from infrastructure investments over time by choosing the best combination of infrastructure investments subject to a budget constraint for a given period of time.

A formal optimization of this kind requires extensive information about the value or benefit generated by achieving each societal objective to some degree, and about the linkages between each piece of infrastructure and these objectives in addition to the price of infrastructure. A rational approach to prioritizing investments in infrastructure has to assign (whether explicitly or implicitly) a value to both societal goals and to basic research and technology development. This report takes a first step in assembling that information by associating science questions with infrastructure components (Chapter 4) and suggesting the factors that federal agencies should consider in quantifying the linkages between infrastructure investments and outcomes (Chapters 5 and 6). The uncertainty associated with future benefits from infrastructure investments, in part due to unanticipated applications, is also recognized in the report.

STUDY APPROACH

The Committee on an Ocean Infrastructure Strategy for U.S. Ocean Research in 2030 was assembled by the National Research Council to provide recommendations to SOST, which is composed of the federal agencies with interests and/or responsibility for the ocean environment. In addition to SOST agencies, the committee envisions that this report will be of use for policy makers and the greater oceanographic community.

The committee determined that the charge (Box 1.1) was written broadly and the most significant aspects of the charge were embedded in paragraph text. These main points are

1. ***Identify major research questions anticipated to be at the forefront of ocean science in 2030.***
2. ***Define categories of infrastructure that should be included in planning for the nation's ocean research infrastructure of 2030.***
3. ***Provide advice on the criteria and processes that could be used to set priorities for the development of new ocean infrastructure or replacement of existing facilities.***
4. ***Recommend ways the federal agencies can maximize the value of investments in ocean infrastructure.***
5. ***Address societal issues in the same context as*** **Charting the Course of Ocean Science in the United States for the Next Decade: An Ocean Research Priorities Plan and Implementation Strategy.**

It is these five points that were used to structure the report. The Statement of Task also includes a bulleted set of considerations that are addressed within the report chapters and were used to focus and refine specific issues.

In order to address its charge and formulate conclusions and recommendations, the committee reviewed relevant ocean policy documents, community and agency strategic plans, peer-reviewed publications, and input from the ocean science community in response to a public solicitation. The information gathering process for this report also included presentations by and discussions with representatives of federal agencies, community groups, and experts in a variety of scientific and engineering disciplines. This was accomplished through meeting open sessions with invited presentations, a workshop with 20 invited speakers (Appendix B), community input solicited through advertisements in scientific journals, and a session at the 2010 Ocean Sciences Meeting (Appendix C).

REPORT ORGANIZATION

This report identifies a number of issues related to strategic thinking about ocean infrastructure needs and capabilities for 2030. Chapter 2 discusses major science research questions that are expected to be of importance in the next 20 years. In Chapter 3, the committee considers ocean infrastructure trends in the last 20 years (1990-2010) and categorizes the types of infrastructure for consideration when planning for future U.S. ocean research infrastructure. Linkages between the major research questions and needed infrastructure assets and capabilities for 2030 are explored in Chapter 4. Criteria and processes that could be used to set priorities for infrastructure investments is addressed in Chapter 5, while Chapter 6 evaluates ways that federal investments in ocean research infrastructure could be maximized.

Major Research Questions in 2030

One of the committee's primary tasks was to "identify major research questions anticipated to be at the forefront of ocean science in 2030 based on national and international assessments, input from the worldwide scientific community, and ongoing research planning activities" (see Box 1.1). In response to this charge, a range of recent government plans, task force documents, research planning assessments, disciplinary reports, and primary literature (e.g., NSF, 2001; USCOP, 2004; JSOST, 2007; CEQ, 2010) were reviewed by the committee. From these documents, and from information gathering sessions with experts in ocean science and policy, the committee identified 32 compelling science questions that are anticipated to be at the forefront of ocean science in 2030, ranging from broad global challenges that require both interdisciplinary and multidisciplinary research to regional, local, or discipline-specific topics. These questions are clearly relevant for 2010 but are not simple issues that will result in solutions with a few more years of intensive effort. Instead, they reflect challenging scientific problems that will likely take decades to solve, especially if only limited resources are available.

The act of defining research questions that will still be relevant in 2030 has many challenges. Almost certainly, new discoveries and technological advances will alter the research landscape, redefining or even providing answers for some questions. It is nearly impossible to anticipate the nature of such transformational discoveries and even more difficult to pose questions that anticipate their impacts. Instead, the committee (guided by the planning assessments cited above) focused on questions that are not only likely to still be relevant, but potentially even more pressing in 2030. For example, nearly 20 years ago *Policy Implications of Greenhouse Warming* (NRC, 1992) posed a series of research issues associated with geoengineering schemes as potential avenues to mitigate climate change. The past few years have seen numerous workshops and reports devoted to developing geoengineering research agendas as a response to climate change (e.g., IPCC, 2005; The Royal Society, 2009). The science has certainly advanced over the two decades between these reports, but compelling science questions on the viability and impacts of these options remain.

While such a list of questions can never be exhaustive, the committee feels these are comprehensive enough to capture the major infrastructure needs for 2030. As discussed in Chapter 1, **these questions are organized within the context of four overarching societal drivers: enabling stewardship of the environment, protecting life and property, promoting sustainable economic vitality, and increasing fundamental scientific understanding.** These drivers are similar to critical themes identified in *Charting the Course of Ocean Science in the United States for the Next Decade: An Ocean Research Priorities Plan and Implementation Strategy* (listed in Chapter 1). This chapter also aligns with several priority objectives of the National Ocean Policy (CEQ, 2010; NOP, 2010), discussed in greater detail within specific science questions.

ENABLING STEWARDSHIP OF THE ENVIRONMENT

In the next 20 years, significant anthropogenic environmental impacts are very likely, given the magnitude of the growing world population[1] (De Souza et al., 2003; Rockstrom et al., 2009). However, increased understanding of the ocean's physical, chemical, and biological responses, particularly in the context of anthropogenic forcing factors (e.g., climate change,

[1] http://www.census.gov/ipc/www/idb/worldpop.php

resource extraction and utilization, waste production and nutrient pollution), has potential to limit many adverse impacts.

Human activities, from fishing to energy extraction, are having impacts on all regions of the ocean, from estuaries to the deep ocean. However, perhaps the most significant and striking impacts are found in coastal and polar regions. The coastal zone, an area vulnerable to multiple stressors, is of particular societal and environmental significance. Although it comprises only about 8 percent of the Earth's surface, this area supports over 25 percent of total global primary production and yields nearly 90 percent of present world fisheries production (Ryther, 1969; Sherman, 1994). Ocean-related activities and industries provided over 2.3 million jobs in 2004.[2] About 35 percent of the world's population currently lives within 100 km of a shoreline (Nicholls and Small, 2002); this number is projected to grow to 75 percent in a few decades (Vitousek et al., 1997). Over two-thirds of the world's largest cities, with populations greater than 1.6 million, are located in coastal areas. These are often in the vicinity of estuaries or coastal wetlands, accounting for over 50 percent of wetland loss (Walker, 1990; Anderson and Magleby, 1997). Coastal governance issues (e.g., coordination and support of ocean and coastal management; coastal and marine spatial planning[3]) are currently at the forefront of both public attention and national priorities (CEQ, 2010) and this is not expected to decrease by 2030.

The polar regions will almost certainly also be of profound importance in the next 20 years, as noted by inclusion in the National Ocean Policy (NOP) objectives (CEQ, 2010; NOP, 2010). While they do not have significant populations in numbers, they are presently subjected to rapid environmental changes (e.g., warming, sea ice reduction, changes in freshwater fluxes) that may have great impacts for commercial activity, including resource extraction and transportation. These also require special considerations when discussing ocean infrastructure needs. The following 13 questions were chosen to encompass a broad range of issues regarding environmental stewardship from the poles to the equator.

How Will Sea Level Change on a Range of Spatial and Temporal Scales and What Are the Potential Impacts?

The trapping of heat by anthropogenic greenhouse gases is likely to lead to sea level rise on a wide range of spatial and temporal scales (NRC, 2010b). As so many people live and work near sea level, sea level study and prediction will continue to be a topic of active research in the coming decades. In 2007, the Intergovernmental Panel on Climate Change (IPCC) estimated sea level rises between 0.18 and 0.6 m by 2100 (IPCC, 2007). More recent estimates that take into account ice melt on Greenland and western Antarctica increase these estimates to between 0.8 and 2.0 m (Pfeffer et al., 2008). Increased heat in the ocean-atmosphere system causes sea level rise in two ways: (1) a warmer ocean is less dense, and thus has more volume even if its mass remained constant; (2) melting of ice on land adds mass to the ocean, raising sea level (Nicholls and Cazenave, 2010). Even if these fundamental effects were perfectly understood and predicted, there would still be issues related to regional sea level rise that depend strongly on local conditions (Milne et al., 2009), including subsidence, tides, and storm activity. Tides and storms

[2] http://www.oceaneconomics.org

[3] According to the *Final Recommendations of the Interagency Ocean Policy Task Force* (CEQ, 2010), U.S. coastal and marine spatial planning "is a comprehensive, adaptive, integrated, ecosystem-based, and transparent spatial planning process, based on sound science, for analyzing current and anticipated uses of ocean, coastal, and Great Lakes areas."

contribute to local inundation, so the most damaging effects of a higher sea level will likely be felt more frequently. Seasonal effects could be significant, as runoff contributes to flooding in areas of high precipitation. For low-lying coastal communities, sea level rise will be a threat to societal infrastructure (e.g., streets, buildings, sewage, drinking water supplies, gas, electricity [Nicholls and Cazenave, 2010]). Ports and naval facilities, in particular, will need to address the impact of sea level rise and changing dynamics of coastal erosion and sedimentation in order to maintain effective operations. Also of concern are more than 200 existing marine laboratories that currently provide support for a wide range of ocean research and education activities (Sebens, 2009), which will have to adapt to coastline changes as a result of rising sea level. On regional and global scales, ocean temperature and therefore sea level will continue to change in response to natural, interannual modes of climate variability such as the El Niño-Southern Oscillation (ENSO), and many of these changes will be irreversible over both short and long time scales (Solomon et al., 2009).

How Will Climate Change Influence Cycles of Primary Production?

Major changes have and will continue to take place in the world's ocean (e.g., changes in temperature, stratification, circulation, oxygen distributions, trace metals inputs, and pH) (e.g., Sarmiento et al., 2004; Doney et al., 2009; Reid et al., 2009; Keeling et al., 2010; Steinacher et al., 2010). These changes all have direct and indirect impacts on ecosystem processes, including limitation of primary production by nutrients, shifts in the major phytoplankton groups that dominate open ocean waters, and changes in zooplankton behavior and distributions (Reid et al., 2009). Global trends in primary productivity have been linked to changes in surface temperature and mixed layer dynamics (Behrenfeld et al., 2006; Martinez et al., 2009; Chavez et al., 2011). While some of the basin scale trends are correlated with natural oscillatory cycles (e.g., the North Atlantic Oscillation, Pacific Decadal Oscillation), the exact mechanisms that force changes in ecosystem productivity are still uncertain (Martinez et al., 2009). Indeed, a recent study concludes that long (~40 years) records of persistent, high-quality, global ocean scale data are needed to separate decadal oscillations from climate effects on ocean productivity (Henson et al., 2009; Chavez et al., 2011).

Modulation of the surface ocean ecosystem's composition, stock, and productivity influences the biological pump that functions to transport atmospheric carbon dioxide (CO_2) incorporated into organic carbon into the deep ocean (Sarmiento and Gruber, 2006). However, the link between surface productivity, fluxes to depth, and the rate at which this material degrades in the ocean interior is currently not well understood and quantified (Burd et al., 2010). The challenge of understanding the ocean's role in the global carbon cycle and its response to a changing environment requires an expanded scale of observation in both space and time (K.S. Johnson et al., 2009; Chavez et al., 2011). Global-scale observations of phytoplankton stock, functional group distributions, and productivity are currently constrained by, and limited to, remotely sensed ocean color which senses only the near-surface conditions of the ocean. New observational strategies are needed to study and understand the link between phytoplankton productivity, carbon export, and climate forcing.

How Will Marine Ecosystem Structure, Biodiversity, and Population Dynamics Be Shaped by a Changing Ocean Environment?

Interactions between climatic forcing and anthropogenic changes in greenhouse gas concentrations affect global ocean circulation, which in turn influences global climate (e.g., Broecker, 1997; Clark et al., 2002; Sutton and Hodsen, 2005). These interactions will have an impact on ecosystem dynamics. Changes in species composition, species distribution, or trophic interactions, which can be caused by shifts in the geographic range of ecosystem components, may result in alterations of ecosystem resilience and productivity (Pereira et al., 2010). The degree of genetic connectivity and species-specific life history characteristics mediate the resiliency of populations and communities and the ability to recover from both human and natural sources of disturbance. Studies of the mechanisms of genetic connectivity (both passive transport of gametes or early life stages and active movements of older individuals) are needed to identify the space and time scales of biological and physical processes that link populations and communities, and to identify factors that enhance or limit gene flow and dispersal.

Community response to disturbance is also determined by patterns of species interactions. For example, disturbance of corals or other habitat-forming organisms may have a larger impact on the community than a similar magnitude of disturbance to other taxa (Sebens, 1994). Similarly, the removal of important predators in some ecosystems has been shown to significantly alter abundances in different trophic levels (e.g., their prey, their prey's prey, other predators of their prey [Wootten, 1994; Estes and Duggins, 1995]). Ecosystem-based management approaches, such as that advocated by the NOP (CEQ, 2010), are presently being developed in part to address these issues.

Disturbances to species composition and distribution include invasive species, which can displace native species, change community structure and food webs, alter fundamental processes such as nutrient cycling and sedimentation, and are a major threat to marine biodiversity (Carlton and Geller, 1993; Molnar et al., 2008). Invasive species have transformed marine habitats around the world, caused human disease, and led to significant ecological and economic damage (Takahashi et al., 2008). Many marine species have been transported to nonnative areas by ship ballast water or hulls. By 2030, it is predicted that commercial shipping will be able to exploit seasonal ice-free Arctic shipping routes (e.g., Wilson et al., 2004; Stroeve et al., 2008); this may exacerbate the movement of invasive species and have other impacts (e.g., vessel whale strikes). The foundations for a quantitative global assessment of the impacts of invaders and their routes of introduction will likely be in place by 2030, but additional information will be needed to develop large-scale strategies necessary to prevent future introductions while adapting to existing invaders.

The combination of large-scale biogeographical shifts, changes in local community structure caused by ocean warming and acidification, and impacts from invasive species will have far-reaching consequences for marine biodiversity, ecosystem structure, and population dynamics. Yet many of the current changes and their impacts remain unreported, for lack of comprehensive global marine ecosystem monitoring efforts. In order to provide effective stewardship of the marine environment, infrastructure that can quantify ecosystem changes and manage human activities in response is a need for 2030.

How Will Marine Organisms and Ecosystems Be Affected by Ocean Acidification?

Marine biogeochemistry and ecosystems are likely to be affected by the chemical changes related to increasing dissolved CO_2 in the ocean, as well as the attendant ocean acidification (Feely et al., 2004; Fabry et al., 2008; NRC, 2010d). Lower carbonate saturation states are apt to lead to less calcification, diminishing alkalinity removal from the surface ocean into the deep ocean. Over thousands of years, lower carbonate saturation will lessen the sedimentation of calcium carbonate ($CaCO_3$), altering the carbonate compensation depth (where dissolution equals supply) and lysocline depth (where seafloor carbonate dissolution begins and accelerates as a function of increasing depth). The response of biological productivity to the diverse factors affected by ocean acidification is likely to alter the global ocean nutrient distribution.

Phytoplankton may respond directly to increased dissolved CO_2 through faster carbon uptake when other factors are not limiting (Riebesell, 2004). Many phytoplankton and zooplankton species are sensitive to other chemical changes associated with decreasing pH (e.g., trace metal speciation changes, which affects the bioavailability of essential metals such as iron or zinc, and the toxicity of other elements such as copper and arsenic) (Shi et al., 2010). However, understanding how these complex ecosystems respond to ocean acidification is extremely limited. Laboratory experiments and field observations suggest that calcifying organisms and communities (e.g., planktonic foraminifera, coral reefs, and oyster reefs) can be affected by present ocean acidification levels and will be strongly disturbed by doubled atmospheric CO_2 (e.g., Anthony et al., 2008; De'ath et al., 2009). The impact of these disturbances on community food webs, however, is unknown. Of particular concern is the ability of corals to respond to increased ocean acidity, because they form habitat for many ecologically and commercially important species (Hoegh-Guldberg et al., 2007). There are also direct chemical responses to ocean acidification. Decreased pH would affect both organic and inorganic chemical speciation of trace metals that form strong oxyhydroxide complexes such as iron, aluminum, and thorium, and alter the kinetics of reactions. Extreme shifts in pH (comparable to that expected in the 22nd century [Caldeira and Wickett, 2003]) could affect the stable redox state by altering the uptake ratios of elements and their subsequent recycling from biological debris. However, it has also been suggested that, with the exception of calcification, other major biogeochemical cycles will not be affected by ocean acidification (Joint et al., 2011).

How Will Climate Change Influence the Distribution of Chemical Elements?

Climate change is likely to influence the distribution of chemical elements through ocean circulation and temperature, biogeochemical responses to the physical climate, and alterations in weathering and transport of key nutrients. A warmer climate will tend to stabilize upper ocean stratification, diminish vertical mixing, and reduce the upward flux of nutrients and productivity (e.g., Reid et al., 2009; Sarmento et al., 2010). However, an altered climate is also likely to affect wind patterns and hence the positions and strengths of currents, upwelling zones, and the timing of seasonal transitions; these changes are more difficult to predict without very high resolution coupled ocean-atmosphere models and data to force and constrain them. All other things staying constant, warmer surface water will contain less oxygen, leading to lower oxygen at depth. Reduced oxygen will lead to the expansion of denitrification zones and a long-term (thousands of years) reduction in the oceanic nitrate inventory, although this could be offset by high anthropogenic fixed nitrogen emissions (Keeling et al., 2010). Changes in winds and continental climate could alter the flux of dust and atmospheric aerosols into the ocean, influencing the distribution of high-nutrient, low-chlorophyll regions (Jickells et al., 2005). Additionally, climate-induced changes in temperature, salinity, and pH will affect mineral solubility (e.g., $CaCO_3$) and trace element speciation (Reid et al., 2009). The effect of climate change and anthropogenic emissions in continental settings will alter weathering and transport by rivers, with potentially large consequences for the coastal ocean, and in the longer term (many thousands of years), for the entire ocean.

How Do the Distributions and Fluxes of Organic Carbon Components Evolve in an Altered Ocean?

Carbon has a vital role for supporting all life on Earth. Dissolved organic carbon (DOC) in the ocean is one of the largest pools of fixed carbon on the planet, approximately equal to the amount of CO_2 in the atmosphere (Hedges, 2002). Fluxes of organic carbon may be expected to change markedly in a warmer climate (Riebesell et al., 2009). This is of significance because fixed carbon can be converted into sugars during photosynthesis and is then usable by heterotrophs. The amount of carbon residing in this pool is thought to have changed by two to three orders of magnitude over geologic times scales (Rothman et al., 2003). In the modern ocean, DOC exported to the ocean interior contributes about 20 percent of the global ocean biological pump (Hansell and Carlson, 2002). This export occurs largely by overturning circulation, which is likely to be altered due to future changes in ocean stratification; the DOC fields and export in a more stratified ocean will be considerably different than what is observed today. Much of the DOC in the ocean has resisted qualitative and quantitative analysis, as the microbial processes that control its composition and abundance are enigmatic (Hedges et al., 2000). Turnover in some components is extremely fast, while much of the material has an apparent ^{14}C age of thousands of years (Druffel et al., 1992). Thus, models of global carbon cycling are limited by knowledge of the time scales for DOC cycling in the ocean. The processes that regulate interactions of this material with the microbial ecosystem are just beginning to be understood. Emerging new analytical tools provide scientists with the capability to directly probe composition and rates of change of a broad spectrum of components in the DOC pool (Mopper et al., 2007). These capabilities can be linked with environmental genomics and studies of protein structure and expression to greatly expand the understanding and predictive capabilities regarding the vast pool of DOC in a changing climate (Kujawinski, 2011).

How Will Ocean Circulation and the Distribution of Heat in the Ocean and Atmosphere Respond to Natural and Anthropogenic Drivers?

The ocean's capacity to transport, store, and exchange huge amounts of heat with the atmosphere has a profound effect on the climate system—both natural and anthropogenic. Natural climate variability orchestrates large changes in weather and climate over much of the globe on interannual and longer time scales (Joyce, 2001; Visbeck et al., 2001; Trenberth et al., 2002; Kerr, 2005). One such example is ENSO, a recurring change in the distribution of heat on the equator that involves weakened upwelling in the eastern Pacific and attendant warming (Philander, 1990). Impacts of ENSO are felt in fisheries off Peru, western U.S. coastal waters, precipitation across North America, hurricanes striking the southeastern United States, and sometimes in global-scale atmospheric conditions (McPhaden, 1999). Basin-scale changes in sea surface temperature (SST) of the subtropical North Pacific have a dominant mode (the Pacific Decadal Oscillation), with known effects on precipitation (Davis, 1976; Mantua et al., 1997). Ocean warming due to anthropogenic climate change involves both trapping of heat by greenhouse gases and its redistribution. A complete knowledge of the ocean's energy balance, as well as the redistribution of heat by ocean currents, is fundamental to understanding the climate system's response to natural and anthropogenic drivers. The ocean's boundary currents, especially those on the western sides of basins, are key to poleward heat transport (Bryden and Imawaki, 2001). In turn, it is expected that the increased heat and freshwater added to the ocean will affect the stratification, currents, and ocean conveyor belt. Future research surrounding this question is likely to focus on sustained observations, analysis of changes as they occur, and improved modeling for prediction.

How Will Alterations in the Global Water Cycle Influence the Ocean?

Alteration in the global water cycle is a crucial issue for civilization. The ocean is the main reservoir of free water on the planet, containing 97 percent of the Earth's water (Baumgartner and Reichel, 1975). It accounts for 86 percent of global evaporation and 78 percent of global precipitation (Schmitt, 1995, 2008) and is central to regulating the water cycle. Because the vapor pressure of water is an exponentially increasing function of temperature, alterations in the water cycle can be expected and have already been documented with climate change (e.g., Curry et al., 2003; Boyer et al., 2006; Yu, 2007). Water evaporates more readily from a warmer ocean, so an intensification of the water cycle and changes in the distribution of salinity are expected with anthropogenic warming. Cloud-climate feedbacks, which will remain a major research challenge, are an important element of understanding changes to the global water cycle. Freshening of the high-latitude ocean through increasing input of freshwater from melting will increase ocean stratification (e.g., Schmitt, 2008), suppressing mixing and greatly affecting nutrient supplies and ocean ecosystems. Increased stratification could also slow down the ocean conveyor belt, which will affect the large scale flux of freshwater, heat, and carbon dioxide in the ocean (e.g., Yashayaev and Clarke, 2008). Ocean salinity feeds back on the circulation and mixing (Schmitt, 2008) and thus has influence on ecosystems and future climate states. In addition, distributions of SST are good predictors of rainfall on land (Schmitt, 2008). Large changes in drought and flood patterns will affect both ecosystems and societal infrastructure.

How Will Changes at Coastal Boundaries Alter Physical and Geochemical Processes?

Changes in coastal boundaries include both gradual and abrupt alterations of the shoreline, wetlands, and seafloor. These can be natural changes such as erosion or deposition, subsidence, faulting, and storm or tidal surges, or they can be consequences of human activities. Anthropogenic changes to coastal boundaries include creation of artificial boundaries (e.g., breakwaters, jetties), modifications to wetlands and rivers (e.g., infilling, channelization, subsidence due to oil and gas activity, damming and reduced sediment supply), and potential impacts from climate change (e.g., sea level rise and loss of coastline) (e.g., Nicholls and Cazenave, 2010). Physical and geochemical fluxes across the coastal boundaries include, but are not limited to, significant air-sea interactions, riverine and groundwater inputs to the ocean, and saltwater intrusion to the coastal zone. These processes occur at a wide range of scales, from the submeter scale to many kilometers. Included in this range is the submesoscale, where variability is spatially intermittent with highly energetic regions depending on proximity of varying water masses and currents. Understanding physical processes at the submesoscale promises improved prediction of chemical and biological distribution at coastal boundaries. Meanwhile, time scales for dynamically important coastal processes also span orders of several magnitudes, from seconds to months or even years, and effects can accumulate over time.

How Will Coastal Ecosystems and Communities Respond to Multiple Stressors?

Coastal regions throughout the nation and world are simultaneously affected by a number of significant stressors. Human activity (e.g., agriculture, sewage treatment, runoff) alters both the concentration and composition of nutrients entering marine systems (Peierls et al., 1991; Howarth et al., 1996). Excessive amounts of nitrogen and phosphorus are entering streams and rivers, eventually reaching estuarine and coastal waters and causing eutrophication, which can result in harmful algal blooms and episodes of hypoxia (Anderson et al., 2002). Chemical pollutants can severely affect the biology of marine organisms. A variety of commercially important species bioaccumulate toxic pollutants, while other species' reproductive traits are impacted by estrogenic chemicals from human activity (Morel et al., 1998; Vos et al., 2000). Coastal development and recreational activities have led to habitat loss and degradation for many species including fish, marine mammals, and seabirds, particularly in coral reef and sea grass communities. Commercial and recreational fishing affect coastal ecosystems, both through the removal of target species and the unintentional bycatch of other organisms (Stevens et al., 2000; Pauly et al., 2002). Marine shipping is introducing many nonnative species to coastal areas (Ruiz et al., 2000). On top of these near-term ecosystem stressors, communities will also have to respond to potential changes in temperature, acidity, and ultraviolet exposure due to climate change (Halpern et al., 2008). The cumulative effects of these various stressors will likely affect ecosystems in complex ways that cannot be predicted by simply adding the effects of each individual component (Crain et al., 2008). This highlights the importance of efforts that develop ecosystem-based monitoring and management tools for marine resources but also shows the inherent challenges involved in effectively implementing these tools.

What Are the Critical Interactions Among Ocean, Ice, Land, and Atmosphere in Polar Regions and How Will They Influence Physical and Biological Changes?

One of the most dramatic signs of rapid change in polar regions is the observed decrease in sea ice cover in the Arctic Ocean; between 1979 and 2009 the annual minimum extent of Arctic sea ice cover decreased at a rate of ~11 percent per decade (Stroeve et al., 2008). These changes in the extent and concentration of sea ice can alter the seasonal distributions, geographic ranges, patterns of migration, nutritional status, reproductive success, and ultimately the abundance and stock structure of several fish, marine mammals and seabird species (e.g., Tynan and DeMaster, 1997). Furthermore, because the albedo (surface reflectivity) of snow and ice is several times that of ocean water, loss of sea ice increases the amount of solar radiation that is absorbed by the Arctic Ocean, warming the surface waters and creating a positive feedback cycle that causes even more sea ice to melt and thus amplifying warming trends. Along the West Antarctic Peninsula, midwinter surface atmospheric temperatures have increased by 6°C (5.4 times the global average) during the past half century, 87 percent of the glaciers are in retreat, and the concentration of winter sea ice has decreased (Ducklow et al., 2007, and references therein). Heat from the ocean is implicated as a major driver for the deglaciation, as increased supply of heat associated with Upper Circumpolar Deep Water flux is believed to be associated with strengthening winds over the Southern Ocean. The increased heat is itself partly a consequence of anthropogenic activity (greenhouse gas emissions and/or ozone depletion). Atmosphere-ocean-ice interplay at the West Antarctic Peninsula results in a positive feedback that amplifies and sustains atmospheric warming.

Rapid climate changes in polar regions are triggering pronounced shifts and reorganizations in regional ecosystems and biogeochemical cycles (Moline et al., 2008). While large ecosystem changes have been detected (e.g., shifts from marine mammal to pelagic fish [Grebmeier et al., 2006]), linking shifts in the physical system to biological changes remains difficult; however, overcoming this gap is a critical step in establishing any level of predictive skill (Schofield et al., 2010a). The complexity of marine ecosystems, combined with chronic undersampling, limits the understanding of how a shifting ocean will affect regional and local marine food webs.

What Advances Will Be Made in Prediction and Mitigation of Oil Spills and Industrial Accidents in the Ocean?

With the future expansion of commercial activities in coastal waters and the ocean, ocean sciences must be prepared to address accidents and spills. The U.S. Coast Guard's National Response Center reports that there were over 34,000 spill incidents of all types in 2010.[4] Perhaps of greatest concern are oil spills. In the 25-year period of 1974-1997, there were 742 oil tanker spills worldwide that released over 1,000 barrels (136 metric tons) of oil each (NRC, 2007b). In U.S. waters over 70,000 barrels (~9,800 metric tons) of oil or refined petroleum products are spilled every year on average (NRC, 2003b). In April 2010, the explosion and sinking of BP's Gulf of Mexico *Deepwater Horizon* oil platform resulted in an unprecedented disaster, with 60,000 barrels (~8,200 metric tons) of oil per day issuing from the deepwater well for 87 days (National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling, 2011).

Spill responses include deployment of mechanical containment and recovery systems (e.g., booms, skimmers) or nonmechanical methods (e.g., surface burning, oil dispersants). Dispersants act to reduce break up and dilute the oil by mixing it into the ocean. The biological and physical processes that determine the ultimate fate of dispersed oil, and its potential toxicity to the marine environment, are poorly understood (National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling, 2011). Of particular concern is the fate of dispersed oil in areas with high suspended solids, as it is unknown how chemically dispersed oil interacts with suspended sediments, over both short and long terms, compared to naturally dispersed oil (NRC, 2005).

The danger of possible oil spills in the Arctic will be an issue of future interest. Decreasing Arctic sea ice (Stroeve et al., 2008) as a result of climate change will attract greater amounts of commercial shipping and oil and gas exploration. An Arctic oil spill is likely to be much more difficult to contain than in other regions: spills in or under ice-covered areas would be harder to track, they would require different techniques than those in open water, and harsh, remote conditions would increase the difficulty of getting spill recovery assets in place.

A related issue is the existence of over 8,500 sunken vessels worldwide (Michel et al., 2005), three-quarters of which date back to World War II (Hamer, 2010). These shipwrecks could harbor between 2.5 and 20 million tons of oil (Michel et al., 2005), as well as hazardous chemicals and munitions. The lower estimate of oil contained within these shipwrecks is at least twice as much as the *Deepwater Horizon* spill (Hamer, 2010).

What Are the Potential Impacts on the Ocean from Geoengineering?

Geoengineering can be classified as deliberate actions that modify environmental processes in order to mitigate other environmental impacts that result from human activities (The Royal Society, 2009) and are generally considered global in scope (NRC, 1992). Many projects presently being discussed focus on storing CO_2 in the ocean, either by (1) pumping liquid CO_2

[4] http://www.nrc.uscg.mil/incident_type_2000up.html (accessed October 2010).

into the deep ocean or into the subseafloor, (2) enhancing weathering reactions of CO_2 with carbonate or silicate minerals and storing the products in the ocean, or (3) accelerating natural mechanisms of ocean carbon uptake by seeding the ocean with nutrients, thus removing CO_2 from the atmosphere. Direct injection of CO_2 into the deep ocean will decrease acidification of surface waters but will exacerbate the problem at depth as a result of CO_2 leaks or natural seepage back to the ocean floor (Caldeira and Wicket, 2003; Blackford et al., 2009). Early experiments on deep sea communities suggest that they may be more sensitive to changes in pH due to increased CO_2 than shallow water communities (Barry et al., 2004). In addition, elevated dissolved CO_2 concentrations may impose a physiological strain on marine animals, especially in hypoxic regions, which are likely to expand as the ocean absorbs anthropogenic CO_2 or it is injected into the ocean as part of geoengineering projects (Peltzer and Brewer, 2008; Brewer and Peltzer, 2009). Enhanced weathering reactions avoid the major pH changes (and ensuing acidification) associated with storing CO_2 directly in the ocean, but are potentially expensive and require extensive mining of source materials (The Royal Society, 2009). Perhaps the most discussed nutrient addition project is iron fertilization (Cullen and Boyd, 2008), which follows the principle that growth rates and biomass accumulation by phytoplankton are limited by the availability of iron in as much as 40 percent of the world ocean (Moore et al., 2002). If iron could be added to these deficient areas (via ship or other platform), it would increase plankton growth rates and perhaps increase removal of carbon dioxide from the atmosphere (Coale et al., 1996). These types of experiments would result in a deliberate modification of marine ecosystems, which could shift many open ocean areas from a low-biomass, low-primary productivity condition to moderate productivity (similar to the coastal ocean). It is difficult to predict the impacts of this activity with certainty, but concerns have been raised about the formation of low-oxygen areas and harmful plankton blooms (Cullen and Boyd, 2008) and the potential limited impact of fixing carbon in the deep ocean (e.g., de Baar et al., 2005). Other geoengineering projects at more modest scales have also been discussed, such as reoxygenation of the Baltic Sea to reduce phosphorus and decrease seasonal eutrophication (Stigebrandt and Gustafsson, 2007).

PROTECTING LIFE AND PROPERTY

The protection of life and property is a compelling societal objective. The research that supports this objective continues to focus on predicting and mitigating natural hazards associated with the solid earth (e.g., earthquakes and volcanoes) and weather (e.g., severe storms and drought). In addition, several new areas have become more prominent either because of recent catastrophic events (e.g., tsunamis) or growing concerns related to climate change and variability (e.g., sea level rise and ocean acidification). The prediction and mitigation of adverse human health outcomes has emerged as a major area of research related to climate change science. Societal concerns, combined with the potential for significant advancement in prediction and mitigation, are likely to drive interest in these six research areas well beyond 2030.

How Does Strain Accumulate in Underwater Volcanoes and Offshore Fault Zones and What Is Needed for Better Forecasting of Major Events?

The effects of offshore earthquakes can be monumental, whether direct (e.g., ground shaking and rupture) or indirect (e.g., triggering a tsunami). Many of the largest earthquakes in the world occur offshore.[5] In the United States, major offshore seismic hazards span the west

[5] http://earthquake.usgs.gov/earthquakes/eqarchives/year/byyear.php

coast from California to Alaska, including the offshore component of the San Andreas Fault as well as the Cascadia and Alaska subduction zones. Although paleoearthquake data can constrain occurrence intervals, earthquakes still cannot be predicted. In the next two decades, there is likely to be progress on this front, as earthquake early warning methods that detect the beginning of a large fault rupture based on initial portions of the primary (compressional) waves have recently been developed (Allen et al., 2009, and references therein). This allows for a warning to be issued before the arrival of larger, more damaging secondary (shear) waves. As observations that are collected close to earthquake epicenters provide extra information that can strengthen early event warning systems (McGuire, 2008; Yamada and Mori, 2009), instrumenting offshore seismic hazards could improve prediction and detection of potentially damaging offshore earthquakes.

The majority of seafloor volcanism occurs along the global mid-ocean ridge spreading network, within ocean island arc environments, and at hot spots. Shallow, large volcanoes common in arc, back-arc, and hotspot environments can present significant environmental hazards. One historic example of this was the 1883 Krakatou eruption in Indonesia, which changed global climate through its eruption of ash and gases (The Krakatoa Committee of the Royal Society, 1888; Self and Rampino, 1981) and led to a tsunami that killed 36,000 people living around the Sunda Strait (Kious and Tilling, 1996). Understanding of how strain accumulates in the seafloor, the spatial and temporal evolution of crustal movement, and the migration and release of magma and volatile elements is critical to developing predictive models of volcanic eruptions, and possibly lessening their impacts.

How Can Understanding and Prediction of Tsunamis Be Improved?

Tsunamis can result from earthquakes, submarine and aerial landslides, volcanic eruptions, and in rare instances meteorite impacts that rapidly displace large volumes of water in the ocean. Generally, damaging tsunamis are caused by earthquakes greater than magnitude 7 (NRC, 2011b). However, catastrophic submarine landslides caused both by volcanic eruptions, large-scale collapse of volcanic islands, earthquakes, or other slope instabilities can also lead to tsunami generation; historic mega-tsunamis reaching 365 m above sea level have been related to flank collapse (Moore et al., 1989, 1994; Clague et al., 2002; McMurtry et al., 2004; Pérez-Torrado et al., 2006). Tsunami waves can be centimeters to tens of meters tall, last over a period of several hours, and cause flooding of low-lying areas, greatly affecting coastal communities. The December 2004 Sumatran earthquake and resulting tsunami fundamentally changed the global perception of tsunami threat, with the loss of over 200,000 lives and billions of dollars in property damage (Schiermeier and Witze, 2009). The ability to predict the initiation of tsunami waves remains as elusive as the ability to predict earthquakes and landslides; however, once a tsunami-generating event has occurred, the arrival time of the first waves can be predicted for a given site within a few minutes. This is the same timeframe in which a "near-field" tsunami (one that originates near an at-risk community) can occur. Tsunami models have also performed reasonably well in forecasting tsunami wave heights since the installation of an open ocean sea level observing network; however, near real time wave height forecasts are only available with considerable delay on the order of a fraction of an hour or more (NRC, 2011b). While efforts to create a global warning system and educate at-risk communities have expanded significantly since the 2004 tsunami, the next two decades are likely to see increased population growth and property development along the coast. Maintaining the tsunami warning systems, and educating this population about high-risk, low-probability events like tsunamis will remain a challenge (NRC, 2011b).

How Can Understanding and Prediction of the Path and Intensity of Severe Storms Be Improved?

Hurricanes and other severe weather events have the largest economic impact of any natural hazards (Kunkel et al., 1999). Prediction of hurricane and tropical storm paths has improved; however, progress is still needed in the prediction of the intensity of such severe weather (NRC, 2010f). While climate variability and change may influence severe weather, this remains an area of active research (Bader et al., 2008; NRC, 2010b). According to the IPCC's Fourth Assessment Report (Pauchiri and Reisinger, 2007), it is more likely than not that there is a human contribution to the observed trend of hurricane intensification since the 1970s. While there is increasing certainty of the link between climate change and more intense hurricanes and tropical storms, the effects of climate change on their frequency remains unclear (Bender et al., 2010; Knutson et al., 2010). El Niño events in the Pacific, which occur every 4-7 years, tend to suppress hurricane activity in the Atlantic, particularly inhibiting the formation of major hurricanes (Category 3 or higher). Climate change also has potential to impact the distribution, frequency, and intensity of other forms of severe weather (e.g., coastal flooding), with great impacts on coastal populations. Increased storm frequency and severity will also increase risks to all maritime operations. Ports, ships, and offshore structure (e.g., oil platforms and wind farms) will need to be designed and engineered to withstand extreme conditions and to ensure crew safety and environmental protection. As demonstrated by the 2005 devastation of the Gulf Coast by Hurricane Katrina, especially in the context of a changing climate, hurricane prediction and mitigation of impacts will remain a top priority for ocean and atmospheric science.

How Will the Extent and Characteristics of Sea Ice and Icebergs Change in the Future and How Can the Impacts of Sea Ice Change Be Mitigated?

Sea ice collisions create pressure ridges that rise several meters above sea level and descend tens of meters below the air-sea interface (Williams et al., 1975; Wadhams and Horne, 1980; Wadhams, 1988), posing a collision hazard to ships transporting personnel and materials within the Arctic and Southern oceans, as well as the North Atlantic, Bering Sea, and Great Lakes. Climate change has led to significant thinning of ice shelves at both poles (Pritchard et al., 2009), causing ice shelf collapse in both the Antarctic (Scambos et al., 2009) and Arctic (Copland et al., 2007) that release hazardous chunks of ice into the Southern and Arctic oceans. Declining sea ice cover, as noted in the Arctic (NOAA Arctic Report Card, 2010) also has implications for sea level rise (Shepherd et al., 2010). Since 1979, satellites have monitored the changing extent of ice in and around the polar seas (Zwally et al., 2002; Stroeve et al., 2007, and references therein), but cloud cover limits the ability of satellites to precisely map the distribution of sea ice and icebergs, and existing models cannot accurately predict where ice will be found. In addition to posing collision hazards, large icebergs have grounded in the shoals off McMurdo Station (Robinson et al., 2010), hampering efforts to resupply that important Antarctic scientific station. Along the Arctic and sub-Arctic coastlines, the reduced span of shore-fast ice leads to greater exposure to storm surges; as a result, many shorelines are eroding rapidly with attendant loss of societal infrastructure to the native communities that live there (ACIA, 2004).

What Is the Role of Coastal Pollutants and Pathogens on Human and Ecosystem Health?

Humans are significantly altering the coastal environment, with many actions that have potential to negatively affect human health. There is a growing need to identify the source, transport, fate, and impact of chemicals in common use by industry, agriculture, and households that are eventually discharged into coastal waters. Anthropogenic activity has changed the concentration and composition of nutrients entering marine systems (Peierls et al., 1991; Howarth et al., 1996), leading to degraded coastal water quality. Increased nutrients lead to greater growth of phytoplankton and/or macroalgal biomass, which heightens turbidity, depletes oxygen, decreases marine biodiversity, and alters ecosystem structure and function (NRC, 2000a; USCOP, 2004). This has been linked to increased frequency and intensity of harmful algal blooms around the world (Hallagraeff, 1993; Pearl, 1997; Anderson et al., 2002; Babin et al., 2008). Harmful algal blooms can lead to devastating fish and mammal kills, and can sicken and even kill humans (Anderson, 1994; Glibert et al., 2005). Another form of pollution, sewage discharge in coastal waters, can lead to increased levels of pathogens and viruses, which can be unsafe both for human exposure and for a variety of marine life (e.g., Goyal et al., 1984; Lipp et al., 2001). The production and use of traditional (e.g., PCBs [polychlorinated biphenyls], heavy metals) and emerging contaminants is also likely to continue into the future. Many emerging contaminants, including compounds such as flame retardants, insect repellents, pharmaceuticals (e.g., steroids, hormones, antibiotics, analgesics), and domestic waste (e.g., detergents, fragrances, caffeine) persist in the environment, accumulate in tissues, and can be toxic to humans and aquatic life. Others interfere with hormone systems governing reproduction and growth (Morel et al., 1998; Vos et al., 2000).

How Do Changes in the Coupled Ocean-Climate System Affect Human Health and Welfare?

Broad-scale shifts in the ocean-climate system are likely to affect human health patterns. ENSO is associated with changes in precipitation patterns across the globe with major implications for human health and welfare (Glantz et al., 1991). For example, ENSO increases the flood frequency for coastal California significantly (Andrews et al., 2004), while other regions are affected by more severe droughts (Philander, 1990). Changes in these precipitation patterns have been linked to epidemics of malaria on the Indian subcontinent and South America (Bouma and van der Kaay, 1996; Bouma and Dye, 1997). In East Africa, Rift Valley Fever[6] (a viral zoonosis) epidemics have coincided with unusually high rainfall associated with ENSO-related Pacific and Indian Ocean SST anomalies (Linthicum et al., 1999).

In and around the Arctic Ocean, climate-related changes are having diverse effects on human populations and their physical and physiological well-being. Arctic environmental change has already adversely affected critical ecosystems that many native communities are dependent on for their livelihoods. The decreasing time available to use shore-fast ice as a platform (Druckenmiller et al., 2009) in combination with a general decrease in sea ice extent (Stroeve et al., 2007) has resulted in shorter seasons for subsistence hunters to find bears, walruses, and seals, which are staples of many indigenous diets (ACIA, 2004). The net result of these factors, in combination with other societal forcing functions, is a migration of some indigenous populations out of Arctic communities. Beyond these examples of direct effects, indirect impacts such as changes in ecosystem health or sea level are discussed throughout this chapter.

[6] http://www.who.int/mediacentre/factsheets/fs207/en/

PROMOTING SUSTAINABLE ECONOMIC VITALITY

The United States, with over 12,000 miles of coastline,[7] has strong economic ties to the ocean. Traditional uses, such as oil and gas extraction, fisheries, and recreation, are still large components of the ocean economy. Other activities, including aquaculture, wind power, and marine hydrokinetic resources, are likely to become much more important in the next two decades. Scientific research that identifies oceanic resources in the broader context of impacts that might be incurred through utilization will promote this societal objective. Sustainability of these resources for future generations is of great importance, as is minimizing adverse impacts on the marine environment. The next three questions examine these important future issues.

How Can Humanity Ensure Sustainable Food Production in the Ocean?

The ocean and inland waters provide about 20 percent of the protein supply for a growing human population (UNFAO, 2009). Overexploitation of fisheries stocks and unsustainable fishing practices have created significant threats to marine biodiversity (Pauly et al., 2003; Myers and Worm, 2003; Worm et al., 2006, 2009) and to food security in some parts of the world. Global wild fishery catches leveled off in the 1980s (Pauly, 2002) and some experts fear large-scale extinctions of commercially important species (Dulvy, 2003). Since the 1980s, per-person seafood production has kept pace with population growth only because of the growth of aquaculture production. Even with better management of wild fish stocks, aquaculture is expected to play an increasingly important role in future global seafood supply (UNFAO, 2009). Both wild capture fisheries and aquaculture production have the potential to create significant impacts on ocean systems. Trawling and other benthic fisheries can severely impact communities through the destruction of seafloor habitat (Thrush and Dayton, 2002). Overfishing of predatory species can fundamentally alter food webs, which has the potential both to impede recovery efforts for the stocks and to lead to jellyfish blooms that further affect fisheries (Scheffer et al., 2005; Purcell et al., 2007). Characteristics of deep sea fish (e.g., slow growth rates and maturation, long life, and low birth rates [Devine et al., 2006]) also make them susceptible to overfishing, although the full impacts of removing these deep-sea species from the food web are not yet well known (Koslow et al., 2000). Aquaculture is responsible for the introduction of a variety of nonnative species, and the animal waste products from some operations are a significant source of water pollution (Wu, 1995; Ruiz et al., 2000). In addition, many aquaculture programs involve the farming of carnivorous species that rely on fishmeal and fish oil (NRC, 2011a), increasing total fishing pressure in other fisheries (Naylor et al., 2000). Research into potential methods for sustainably managing fisheries, such as monitoring the status of fish stocks and their role in ecosystems, creating accurate catch limits and establishing marine protected areas, will be critical to ensure future food production from the ocean. Equally important is the goal of maintaining ocean biodiversity, which may be difficult to achieve while also maximizing fisheries (Brander, 2010). Management strategies that enable both sustainable fisheries and biodiversity conservation are needed and will require improved environmental and fisheries data resources and substantially better modeling capabilities. The use of ocean space for farming finfish, shellfish, and algae (Goldburg et al., 2001; NRC, 2010c) will also need to be balanced against competing energy, national security, and recreational needs.

[7] http://shoreline.noaa.gov/_pdf/Coastline_of_the_US_1975.pdf

How Can Humanity Maximize Energy and Mineral Resource Extraction, While Minimizing Adverse Environmental Impacts?

For the foreseeable future, traditional oil and natural gas extraction will continue to fill a significant proportion of U.S. energy needs (e.g., Musial and Butterfield, 2004; Greene et al., 2007). The U.S. outer continental shelf is a major focal point for energy industries, accounting for an estimated 30 percent of national oil production and 11 percent of natural gas production in 2009.[8] In recent years, there has been increasing oil production in deep waters (over 1000 ft), especially in the Gulf of Mexico (USCOP, 2004). The scope of energy extraction is likely to continue to incorporate deeper waters, as well as smaller reservoirs and additional, alternative sources.

One such source is methane hydrate, an ice-like substance formed from a combination of gas and water at high pressures and low temperatures. Burning methane produces less carbon dioxide than other fossil fuel combustion and its abundance in U.S. continental margins and permafrost could provide greater energy security for the United States (NRC, 2004a, 2010e). While most methane hydrate is found at low concentrations and is not currently economically viable, more concentrated methane hydrate accumulations (found in deepwater marine and Arctic sands [Boswell and Collett, 2006]) could be likely targets for a future economic resource. However, potential degassing of methane hydrate at atmospheric conditions is a technical challenge for recovery and could affect the global carbon cycle.

There is also international interest in mining seafloor massive sulfide deposits that contain economically valuable minerals (Hoagland et al., 2010). In some cases, such as oil and gas production, resource utilization in the ocean is driven by the difficulty of satisfying demand with economically accessible terrestrial resources.

What Is the Ocean's Potential as a Source of Renewable Energy?

Commercial activity in the ocean is growing and may possibly become an important part of the U.S. energy portfolio, especially the unique opportunities to harness renewable energy. These include installations of wind farms in coastal environments, development of marine hydrokinetic power (from waves, tides, ocean currents, and ocean thermal gradients), and siting of solar collectors on a large scale. Renewable energy activities, like offshore wind farms and marine hydrokinetic systems, exploit unique properties of the ocean; in this case, higher wind speeds that occur over the ocean as compared to land or strong wave energy or tidal currents at certain locations (e.g., Bay of Fundy, Hudson River). In each case, the economic viability of these sources will be enhanced by matching optimal environmental conditions with appropriate energy infrastructure design. Each of these uses will have some associated environmental and societal impacts in addition to their significant economic value: habitat disturbance or destruction, injury or fatalities for birds and marine organisms, aesthetic concerns, and changes to indigenous cultures. Comprehensive coastal and marine spatial planning (such as that outlined in the NOP [CEQ, 2010]) will be needed to manage these and other competing activities in the ocean. The optimization of renewable energy production while minimizing impact represents an important, emerging area of research.

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[8] http://www.boemre.gov/stats/PDFs/OCSProductionTemplate2009.pdf

INCREASING FUNDAMENTAL SCIENTIFIC UNDERSTANDING

Beyond their societal objectives, investigating the science research questions posed in the previous sections will, in turn, contribute to increases in fundamental understanding of the ocean and its relationship to the Earth system. Fundamental research, even if not directly applicable to a problem of societal relevance, has considerable merit in its own right. It has a long history of producing discoveries that advance scientific understanding, many of which eventually lead to an increased ability for stewardship of the environment, protection of life and property, and promotion of sustainable economic vitality. An essential component is understanding-driven research, which provides a foundation to increase current knowledge of the ocean in order to improve predictive capability. There is also a compelling need for human exploration, both to understand how Earth functions and to unravel the many remaining mysteries on the nature of physical, biological, chemical, and geological processes that occur and interact. These 10 fundamental questions range widely in scope and scale, from entire earth system processes to individual organisms.

How Does Earth's Interior Work, and How Does It Affect Plate Boundaries, Hotspots, and Other Surface Manifestations?

Understanding of the Earth's interior is critical to a range of societal issues, including earthquake detection and hazard assessment; the development of volcano and tsunami warning systems; the role and effect of fluids in the Earth's crust; energy and mineral resource exploration; and even nuclear test monitoring and treaty verification (Forsyth et al., 2009). The past four decades of geophysical research have established that heat from the Earth's deep interior powers convection in its liquid outer core, generating a planetary magnetic field, and that heat in the solid mantle drives plate tectonics. Mantle convection also regulates the chemical composition of the surface layers, drives the exchange of materials between the planetary surface and its deep interior, and produces chemical fluxes into the ocean and atmosphere. Although it is known that the mantle and core are in constant convective motion, their motion can neither be precisely described nor confidently calculated with respect to past differences (NRC, 2001, 2008b). Patterns of convection are poorly understood, although there may be internal boundaries resulting from chemical differentiation within the mantle, with mineralogical phase changes controlled by pressure and temperature (Forsyth et al., 2009). Finally, although plate tectonic theory explains many surface features of the planet, it is not currently understood why Earth has plates or what the relationships might be between plate tectonics and Earth's abundant water, continents, and life. Further study of Earth's interior can help determine what the surface environment was like in the past and predict what it might become in the future.

What Are the Plausible Rates and Magnitudes of Climate Change?

Earth history contains a rich and diverse record of climate change, operating across a broad spectrum of time scales (Ruddiman, 2010). Given the evidence for significant anthropogenic influence on the climate system, better understanding of the rates at which climate changes and the climate system's sensitivity to various factors have become extraordinarily important to society. For example, sea level was over 120 m lower than present at the peak of the last glacial period about 20,000 years ago (Church et al., 2008), then rose between 19,000 and 7,000 years ago (Lambeck and Chappell, 2001). From approximately 2,000 years ago to about 1900, sea level changed very little (Lambeck et al., 2004), but anthropogenic increases of greenhouse gas concentrations are causing sea level rise. The rate and magnitude of future climate change is closely tied to the expected impacts both on human and natural systems, and many of the changes may be largely irreversible within millennial time scales (Solomon et al., 2009). Therefore, an increasing ability to predict future climate change and to better understand uncertainties in climate prediction is also an urgent societal need. Clarifying possible rates of climate change is critical to understanding potential resiliency of global marine ecosystems. High-resolution oceanic and terrestrial paleoclimate records help assess rates and magnitude of past climate change in the context of Earth's surface, atmospheric composition, and variations in solar input, and may provide analogues for predicted future change. At the same time, describing changes in the modern climate system, while focusing on areas of greatest uncertainty in current climate processes, is likely to improve predictive skill and increase understanding of complex interplay of processes within the climate system.

How Can the Effects of Ocean and Atmosphere Interactions be Better Parameterized?

Interactions between the ocean and atmosphere are complex and multilayered: the atmosphere imparts momentum to the ocean; precipitation and evaporation affect ocean salinity; heat and gas exchange between the atmosphere and ocean; dust containing nutrients and toxins is deposited from the atmosphere to the ocean; cloud condensation nuclei are injected into the atmosphere from the ocean; sunlight is attenuated by the atmosphere and infrared radiation emitted from the ocean is trapped by the atmosphere. These interactions directly and indirectly affect physical, chemical, and biological processes in the ocean. The atmosphere is driven by SST, so knowledge of the upper ocean is needed for prediction of climate and weather, including improved hurricane prediction. Ocean circulation is largely driven by winds, so accurate knowledge of wind stress is essential to the specification and prediction of currents at all scales. In addition, wind-driven ocean waves modulate fluxes of many properties (e.g., gas exchange). All of these fluxes are essentially turbulent, requiring parameterization to relate them on larger-scale, easier-to-measure quantities, and to be represented in models. Ocean-atmosphere interactions also drive the coupled biogeochemical system. In polar regions, sea ice acts as a porous layer between the ocean and atmosphere, as well as a source of gas fluxes, even in winter. The surface ocean microlayer regulates particle and gas exchange into the overlying atmosphere. Both the microlayer and seawater below it produce and concentrate organic compounds that are potentially ejected into the air; however, limited measurements of the resulting aerosols' organic compositions constrain current understanding and modeling.

What Processes Dominate Mixing in the Ocean and on What Space and Time Scales?

Observation, theoretical understanding, and parameterization of mixing are essential to climate prediction. The ocean is a global turbulent fluid, with length scales ranging from ocean basins to molecules and time scales from seconds to centuries or longer. All of these scales interact, so that mixing processes occurring at small scales end up affecting global circulation. However, mixing processes must be parameterized in ocean climate models, as they occur at scales too small to be directly simulated, given the resolution of present-day models. The ocean is also a highly anisotropic fluid, with vertical gradients much stronger than horizontal gradients. Maintenance of the vertical stratification requires mixing to balance the upwelling that occurs through the deep ocean (Munk, 1966). Ocean observations of turbulent mixing have established that there is relatively small diffusivity in the interior ocean (Gregg, 1989), while substantial mixing is found in surface and bottom boundary layers and in regions of flow over rough topography (Davis et al., 1981; Polzin et al., 1997; Sanford and Lien, 1999). Sources of energy for mixing are dominated by the wind and the tide. Tidal mixing has received a great deal of attention as the time scale is predictable and amenable to observation (Rudnick et al., 2003). Wind is an important energy source (Wunsch and Ferrari, 2004), whether it occurs directly through the surface mixed layer or indirectly through mesoscale eddies spun off of major ocean currents. The study and parameterization of horizontal stirring of the ocean, the submesoscale (scales of kilometers), and subgridscale processes for ocean models (Fox-Kemper and Ferrari, 2008) are central to climate predication and likely to remain important. One of the properties of turbulence is intermittence, so that variability is concentrated in space and time, as at ocean fronts or under storms. The study and prediction of such events is an ongoing research question.

How Does Fluid Circulation Within the Ocean Crust Impact Chemistry and Biology of the Subseafloor and the Hydrosphere?

The oceanic crust is the largest fractured aquifer system on the planet. Fluid circulation through the crust and overlying sediments generates enormous chemical fluxes in the ocean, profoundly alters the composition of basement rock, and supports a potentially vast subseafloor biosphere (Fisher, 2005; Fisher and Wheat, 2010). Hydrothermal flow significantly influences the thermal, mechanical, and chemical state of subducting tectonic plates, impacting seismicity and volcanism (e.g., Gill, 1981; Peacock and Wang, 1999). High-temperature hydrothermal fluids are produced at mid-ocean ridge vent systems, but low-temperature fluid circulation occurs in approximately half of the seafloor crust (Parsons and Sclater, 1977; Fisher and Von Herzen, 2005), accounting for two to three orders of magnitude more seawater circulation than the mido-cean ridge (Davis and Elderfield, 2004). Off-axis fluids within the seafloor can be transported laterally tens of kilometers (Fisher et al., 2003), which has implications for microbial connectivity and movement in the subseafloor. Despite its importance for global-scale processes in the ocean, the subsurface fluid flow system is undersampled and its biogeochemical impacts are not yet well resolved.

How Does the Deep Ocean Biosphere Inform the Origin and Evolution of Life?

Ocean sciences will continue to play a leading role in understanding the fundamental, unresolved questions of how Earth's life began and has evolved over time. The late-1970s discovery of submarine hydrothermal vents fueled by undersea volcanoes (Spiess et al., 1980) led to the hypothesis that life may have originated in these hot spring systems (Corliss et al., 1981). Since that time, over 200 active vent systems have been discovered and studies of these environments have profoundly changed thinking on where and under what conditions life exists on Earth (e.g., Wilcock et al., 2004; Kelley et al., 2005; Martin et al., 2008). The field of astrobiology uses limits from vent environments (e.g., temperature, pressure, salinity) to guide the search for life on other planets (Woodruff and Baross, 2007). It also uses advancements in molecular sciences and in experimental analyses focused on abiotic synthesis of organic compounds, which have driven new hypotheses about the conditions necessary for life and its evolution (e.g., Shock et al., 1990; Cody et al., 2004). Beyond the vents, the most extensive populations of microscopic life may exist in vast, largely unexplored areas of oceanic crust and sediment away from active mid-ocean ridge systems. Using ocean drilling core samples, microbial activity has been documented at depths of over 500 m beneath the seafloor (Parkes et al., 1994) and the total amount of carbon associated with subseafloor bacteria and archaea exceeds that of any other ecosystem on Earth (Gold, 1992; Whitman et al., 1998). Genetic and functional diversity of the deep ocean biosphere, conditions under which organisms can live and thrive, and their contributions to oceanic carbon and other biogeochemical cycles are just beginning to be explored.

What Regulates the Diversity and Rates of Molecular and Biochemical Evolution in the Ocean?

The last two decades have revealed staggering molecular, biochemical, and species diversity in the ocean, a complexity that is reshaping views of the structure of oceanic food webs (e.g., Delong and Karl, 2005). Studies in the 1970s underestimated the number of microorganisms by three orders of magnitude; marine viruses (arguably the most abundant and diverse form of life on Earth) were only appreciated in the 1980s (e.g., Fuhrman, 1999). The Census of Marine Life,[9] which operated from 2000 to 2010, detected numerous new megafauna species, and mass sequencing of microbes in the oligotrophic Sargasso Sea revealed over a million protein-encoding genes and discovered a large number of new genes (Venter et al., 2004). Despite this progress, existing biodiversity has still not been quantified nor have robust abundance estimates been achieved, and it is not well understood how physical, chemical, and biological factors maintain diversity. Interpreting microorganism complexity is further complicated by potentially high rates of lateral gene transfer and mutation, which suggest high rates of molecular evolution in the ocean (Frigaard et al., 2006; Oliver et al., 2008). How this molecular evolution translates into the innovation of new species and biochemical pathways is an open question. Oceanographers are drawing upon rapid advances in technology from the medical sciences to perform techniques such as genome sequencing, quantification of protein structure and expression, and metabolite analysis in order to address marine problems. It is anticipated that the resulting data sets will help scientists more accurately study the evolution, biochemistry, physiology and diversity of marine organisms.

What Is the Biodiversity of the Deep-Sea Pelagic Ecosystem?

Understanding ocean ecosystem dynamics and predicting changes over time requires knowledge of species diversity, distribution, and abundance throughout the ocean (Pereira et al., 2010). While species living in the ocean's upper reaches are relatively well known, far less can be said about species in the bathypelagic (1000 to 4000 m) and abyssopelagic (4000 to 7000 m) zones (Robison, 2004, 2009; Heino et al., 2010; Wiebe et al., 2010). This lack of knowledge is even more notable since the bathypelagic zone accounts for 60 percent of the ocean's volume, making it the largest marine habitat on Earth. Comprehensive understanding of deep-sea biodiversity has eluded oceanographers because of the fragility, rarity, small size, and/or systematic complexity of many taxa, as well as the difficulty in sampling the more mobile larger invertebrates and fish (Sutton et al., 2008, 2010). For many groups, there are long-standing and unresolved questions of species identification, systematic relationships, genetic diversity and structure, and biogeography (e.g., G. Johnson et al., 2009).

The global geographic scale of the investigations required to address these issues, as well as the three-dimensional complexity of the world ocean, make complete knowledge of marine deep-sea biodiversity and ecosystem dynamics challenging. New technologies and advanced sensors will play a significant role in developing fundamental knowledge about deep-sea ecosystems. However, physical access to remote regions of the ocean and the deep-sea interior

[9] http://www.coml.org/

will still be required to discover and observe the organisms living in these areas, and to understand their interactions and dynamics.

What Are the Modes and Roles of Sensory Systems and Intra- and Interspecies Communication in Structuring Marine Ecosystems?

Marine organisms have extraordinary abilities to sense and respond to their surroundings and, in many cases, to actively communicate within or between species. These sensory processes underlie many observed spatial and temporal patterns that cannot be explained by ocean physics or chemistry. Basic sensory systems used to perceive environmental conditions and communicate within and between species include vision (e.g., light vs. dark, complex colors, patterns, shapes, movements), hearing (acoustic signals of varying wavelength and sound patterns), chemosensory (waterborne “smell,” surface-bound “taste” compounds), and somatosensory (e.g., physical contact, temperature, body position, pain). These mediate all fundamental biological and ecological processes, spanning from reproduction to habitat selection and predator-prey interactions. For example, sea anemones perceive chemical signals from other anemones that have been wounded by predators and respond with a characteristic defensive contraction (Howe and Sheikh, 1975); packs of dolphins utilize sonar to coordinate swimming behavior, aggregating prey in small spatial zones to minimize grazing effort (Benoit-Bird et al., 2004); and bioluminescence in the deep ocean has been hypothesized to help increase reproductive success and/or provide protection against predators (e.g., Haddock et al., 2010). Communication is also found commonly in microbial systems, where quorum-sensing bacteria produce and release chemical-signal molecules that increase in concentration as a function of cell density to stimulate gene expression of neighboring bacteria. Communication can regulate a diverse array of physiological activities (e.g., symbiosis, virulence, competence, conjugation, antibiotic production, motility, sporulation, biofilm formation) (Miller and Bassler, 2001). Because these sensory mediated processes are central to evolutionary life histories, population dynamics, and community ecology, a more complete understanding will be central to predicting marine organisms’ responses to various ocean environmental changes in the future and for developing sustainable ecosystem-based management strategies.

How Does the Ocean Contribute to the Earth’s Carrying Capacity?

The Earth’s carrying capacity, or maximum number of organisms that can be supported without undergoing environmental degradation,[10] is dynamic and ultimately finite. With a human population that is projected to exceed 9 billion by 2050 (UN, 2009), people have become the dominant consumer of most of the world’s major ecosystems (Rees, 2003). However, the human population needs more than ecosystem products; there are many ecological goods and services provided by nature that are essential for human sustainability (Costanza et al., 1997). These fall into three categories: renewable natural capital (e.g., species, ecosystems), replenishable natural capital (e.g., oxygenated air, freshwater), and nonrenewable natural capital (e.g., fossil fuels, minerals) (Rees, 1996). The current human population is living beyond sustainable means provided by renewable and replenishable natural capital and is sustainable only by use of nonrenewable resources (Daily and Ehrlich, 1992). For example, industrialized fisheries, which are calculated to dramatically reduce community biomass in less than two decades (Myers and

[10] An alternate definition is “the amount of use an area, resource, facility, or system can sustain without deterioration in quality (NRC, 2002).

Worm, 2003), represent a domain in which carrying capacity issues are already clear and may turn some renewable resources into nonrenewable capital. Nutrient pollution related to terrestrial agriculture and ocean aquaculture also affects carrying capacity, as they are implicated in the development of oxygen minimum zones and hypoxia (e.g., Turner and Rabalais, 1994; Diaz and Rosenberg, 2008) and raise concerns about coastal pollution (e.g., Costa-Pierce, 1996), respectively. Oil and gas production and mineral extraction, other nonrenewable resources on time scales of human development, can have significant impacts on the ocean environment. More research is needed into the ocean's contributions to human carrying capacity, especially with regards to oxygen production, climate moderation, carbon removal from the atmosphere, and production of food and mineral resources.

3
Ocean Infrastructure for 2030: Categories and Trends

Changes in infrastructure over the last two or more decades provide an important perspective when planning for the next two decades. The committee identified trends in the development and use of supporting infrastructure for ocean research, focusing mainly on the last 20 years (1990-2010), as a means to extrapolate toward 2030. When taken in association with the major research questions found in Chapter 2, these trends guided the committee's discussion of infrastructure categories that should be included for planning the next 20 years and are achievable with attention and support. Many of the questions deal with changes in spatial and temporal range and resolution, needs for more precise, accurate sensors, or development of advanced sensors for important physical and biogeochemical properties. Where possible, these are discussed in terms of changes over the last 20 years and likely trajectories for the next two decades. Infrastructure assets and trends are divided into the following categories: mobile and fixed platforms, in situ sensors and sampling apparatus, remote sensing, modeling, computational and network services, and supporting infrastructure.

The chapter focuses on common or shared infrastructure rather than supporting infrastructure generally found in the inventory of an individual scientist, as this is often prototype or highly specialized. Many current ocean infrastructure assets began in this manner and were nurtured to maturity over a period of years by astute sponsors. This leads to another emerging challenge, related to agency support for the development of new instruments. Many of the sensors and platforms currently in widespread oceanographic use arose from investments by the Office of Naval Research (ONR) under the aegis of national security. The ONR technology investment is no longer strongly aligned with many of the ocean research questions expected to be of interest in 2030, leading to its diminished role in sustained funding for "high-risk, high-reward" ocean infrastructure. **To foster innovation and technological advancements in the ocean sciences, federal agencies will need to encourage a risk-taking environment.** However, this is difficult under the current peer-review system.

A brief review of usage and trends associated with each specific type of infrastructure is provided, with supporting information drawn from examinations of referenced reports, presentations by invited speakers, community input, and committee members' expert judgment. Technology and infrastructure trends for the future are then discussed, including ways in which ocean infrastructure will need to evolve to meet future research goals, and the types of capability that will need to be developed.

MOBILE PLATFORMS

Research Vessels

The UNOLS and Federal Fleets

Oceanography has historically required access to the sea, and it is anticipated that ships will continue to be an essential component of ocean research infrastructure (USCOP, 2004; NRC, 2009b; NRC, 2009b). The past few decades have seen a trend toward lower total ship days per year for the University-National Oceanographic Laboratory System (UNOLS) academic research fleet (a 13 percent decline from 2000-2008; NRC, 2009b). At the same time, operational days for the largest research vessels (Global Class) have generally increased over the past 20 years; they are the most highly subscribed vessels in the fleet. This trend may be related to increasing interdisciplinary and multidisciplinary science, as well as the Global Class's ability to support multiple science operations with a larger science party, greater laboratory areas, and more deck space (NRC, 2009b).

The UNOLS Fleet Improvement Plan (2009) projects reductions of nearly 40 percent in available ships by 2025, due to ship retirements and fewer new vessels entering the fleet, yet **a lower demand for access to the ocean is not anticipated.** The cost of ship operations increased 75 percent from 2000 to 2008, largely influenced by rising crew and fuel costs (Fleet, 2009b; Figure 3.1). Over the past 10 years there have been several instances of academic research vessels being laid up to offset rising costs, resulting in fewer ship days being funded. There has been continued use of ships of opportunity (e.g., foreign icebreakers, small ships with global capability to deploy autonomous platforms) and specialized ships (e.g., submersible support ships; fisheries vessels), some of which are part of the UNOLS or federal ship fleets. This move toward specialized ships reflects an effort to optimize the limited resources available for seagoing operations. It also supports the idea that the recent decline in funded ship days for the academic research fleet does not reflect a corresponding lack of science demand, but is rather affected by agency budgets and investigator's proposal success rates (NRC, 2009b).

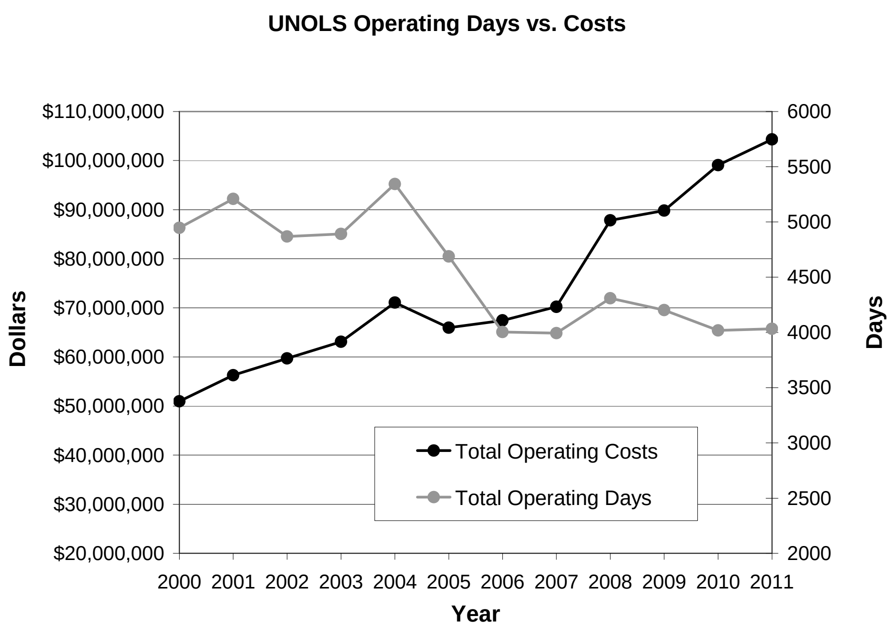

Figure 3.1. UNOLS fleet total operating costs (black) versus number of ship days (gray). SOURCE: Data from UNOLS Office.

Mission-oriented marine research and survey ships are currently operated by the National Oceanic and Atmospheric Administration (NOAA) and the Environmental Protection Agency, among others, to support their congressional mandates for efforts such as fisheries surveys, ecosystem assessments, water quality assessments, hydrographic surveys, and seafloor mapping (Interagency Working Group on Facilities, 2007). NOAA has recently acquired four advanced, acoustically quiet fishery survey vessels and has several more being built or planned. In support of priority objectives laid out in the National Ocean Policy (CEQ, 2010), these ships will remain essential components of ocean research infrastructure.

The nature of shipboard work may change as a consequence of increasing numbers and capabilities of over-the-side systems (NRC, 2009b), which will increase operational efficiency. Increasingly multidisciplinary and interdisciplinary research requires vessels with support for a wide diversity of platforms and instruments, and increasing ship costs motivate greater use of autonomous assets. To meet these needs, the past two decades have seen significant increases in dynamic positioning and station holding capabilities, multibeam and sidescan sonar systems, and more complex sensors and instrumentation. This has also led to an increasing dependence on shipboard science technical support. One metric for planning future fleet capacity and capability could be the number of scientists using the academic fleet in larger interdisciplinary groups versus those in smaller, focused campaigns, taking into account potential locations for future research. Another metric could be the number and capabilities of extended duration instruments, including autonomous vehicles, which could lessen the number of scientists at sea. **Future trends include a fleet composed of both adaptable, general purpose platforms and specialized ships to meet a broad range of research activities; sustaining the number of larger, general purpose platforms; and growing the capabilities and numbers of smaller ships.** The committee endorses the following recommendation from the 2009 NRC report *Science at Sea: Meeting Future Oceanographic Goals with a Robust Academic Research Fleet*: **"The future academic research fleet requires investment in larger, more capable, general purpose Global and Regional class ships to support multidisciplinary, multi-investigator research and advances in ocean technology."**

Icebreakers and Other Polar Assets

With the loss of polar assets over the past two decades, there is diminished capability for the United States to address polar science questions. The United States currently conducts high-latitude oceanographic research using a combination of U.S. Coast Guard icebreakers, charters, and international partners (NRC, 2009b), as well as limited use of U.S. Navy submarines. Icebreakers are uniquely capable of carrying out ship-based science in ice-covered oceans; as such, they require specialized construction, operations, and maintenance. While the reduction of ice cover in the Arctic during summer and fall has been dramatic (e.g., Stroeve et al., 2008), ensuring access to both the Arctic and Antarctic in the foreseeable future will still require the ability to operate in fully or partially ice-covered areas. Nuclear submarines provide a unique under-ice capability; from 1993 to 2005, the U.S. Navy made these available to civilian ocean science researchers through the Scientific Ice Expeditions program (SCICEX Science Advisory Committee, 2010). Nuclear submarines complement icebreakers and have potential for increased ocean research use but are not a replacement for future needs. They provide an efficient mapping platform (e.g., for multibeam operations) but do not support the types of over-the-side operations that are and will be carried out from a ship. They are also very expensive for routine science missions, and unlikely to become less so.

While scientific research at high latitudes is characterized by a high level of international collaboration, **the loss of U.S. icebreaker capability may become an issue of national security and competitiveness in future years.** The committee endorses the following recommendation from the 2007 NRC report *Polar Icebreakers in a Changing World: An Assessment of U.S. Needs*: **"The United States should continue to project an active and influential presence in the Arctic to support its interests."**

Scientific Ocean Drilling Platforms

From 1985 to 2003, the oceanographic community had access to the *JOIDES Resolution* riserless drillship as part of the Ocean Drilling Program (ODP) and, later, the Integrated Ocean Drilling Program (IODP). After a refit from 2006 to 2009, the *JOIDES Resolution* returned to service and is expected to remain available for science operations through the end of IODP in 2013. In 2000, the Japanese riser drillship *Chikyu* was built and has since been used for science operations in support of IODP. The number of operational days for the *JOIDES Resolution* has decreased 30 percent between 2003 and 2009 (Brad Clement, personal communication, 2010). International agreements, such as those used by IODP to ensure access to very expensive infrastructure assets like drillships, are perhaps one method to increase the use and efficiency of ocean research infrastructure worldwide. Leasing arrangements with the industrial sector may also be an option to pursue (Fleet Review Committee, 1999).

Summary

A national long-range plan for the overall capacity and mix of capabilities of the U.S. academic research vessels is clearly warranted (e.g., Fleet Review Committee, 1999; Federal Oceanographic Facilities Committee, 2001; USCOP, 2004; NRC, 2009b; UNOLS, 2009). Such a plan could lay out the resources needed for technology upgrades and new construction, and phase out of older platforms; explore usage trends and alternative options for use, such as leasing; direct interagency agreements and international opportunities; and provide a roadmap for tracking progress. The committee endorses the following recommendation from the 2009 NRC report *Science at Sea: Meeting Future Oceanographic Goals with a Robust Academic Research Fleet*: **"Federal agencies supporting oceanographic research should implement one comprehensive, long-term research fleet renewal plan to retain access to the sea and maintain the nation's leadership in addressing scientific and societal needs."**

Submersible Platforms

Human Occupied and Remotely Operated Vehicles

Since the early 1990s, the dominant working platforms for the deep ocean science community have been human occupied vehicles (HOVs) and remotely operated vehicles (ROVs). In a much more limited capacity, U.S. Navy nuclear submarines have also been used (see previous section). Prominent among the current platforms are the HOV *Alvin* and the ROVs *Jason* and *Jason II*, in part due to their participation in the National Science Foundation-funded National Deep Submergence Facility[1] (NDSF). While *Alvin* use has decreased by approximately 20 percent over the past two decades (1,339 dives from 1990 to 1999; 1,070 dives from 2000 to 2009), there has been a dramatic increase in both the number of ROVs available and their use for science. For example, *Jason* and/or *Jason II* dives increased from 162 during 1990-1999 to 527 dives during 2000-2009 (Annette DeSilva, personal communication, 2010). Other non-NDSF funded ROVs, operated by several U.S. institutions, have also seen increases in usage over this timeframe. For example, Monterey Bay Aquarium Research Institute (MBARI) ROVs logged approximately 3,500 dives during the same time period (Steve Etchemendy, personal communication, 2010).

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[1] http://www.whoi.edu/page.do?pid=8419

The increase in ROV use reflects a variety of factors including advancements in robotic technologies, such as better manipulator dexterity; increased payload ability, equivalent to HOVs; and longer sustained dive times. There is also more use of telepresence, which allows shore-based audiences to virtually participate in ROV operations. Current industry use of ROVs offers some possibilities for next generation science, including higher power systems and multiple vehicles operating in the same area. Based on the committee's assessment of science questions in 2030, **the demand for highly capable ROVs is very likely to increase, while the demand for HOVs is likely to remain stable.** Although HOV use has declined modestly in the past two decades, ongoing and planned *Alvin* upgrades[2] will increase its depth rating from 4,500 to 6,500 m, enabling it to operate in 98 percent of the ocean.[3]

One future direction may be in the use of hybrid vehicles that combine components of traditional ROVs and autonomous underwater vehicles (AUVs) for greater capability and operations at full ocean depth, such as the hybrid ROV *Nereus*. Another may be in increased use of nonnuclear submarines, such as smaller air-independent propulsion platforms, which are common in navies other than the United States.

Submersible vehicles have also seen increasing sophistication in sensors and sensor payloads as well as quality of and ease of obtaining navigation. To eliminate the time required to deploy and calibrate long-baseline transponder arrays, there have been trends toward using a combination of GPS navigation and ultra-short baseline acoustic tracking on the ship to determine the position of the underwater vehicles, and DVL (Doppler Velocity Log)-aided inertial navigation systems (e.g., Whitcomb et al., 1999; Kinsey et al., 2006, and references therein) on the underwater platforms to achieve high-accuracy positioning (within meters). This is a critical need for addressing many of the science questions anticipated in 2030.

Towed Systems

Towed platforms became critical components of ocean exploration during the past two decades, capturing acoustic and optical imagery as well as oceanographic data and samples for many environments, ranging from just below the sea surface to the deep seafloor (e.g., Wiebe et al., 2002; Davis et al., 2005). Unlike analogous sensors mounted on ship hulls, sensors mounted on towed platforms can be deployed more flexibly from a range of vessels, including ships of opportunity. Moreover, their depth can be controlled from the surface, providing better control. Often the cable connecting a towed system to the surface vessel serves as its own platform for small sensors like thermistors and plume recorders (Baker and Milburn, 1997), which serve to provide nearly synoptic views of the water column during the towed system's primary mission. **In the past decade, seafloor survey operations have begun to shift from use of towed vehicles to use of AUVs, particularly in deep water.** While towed vehicles can be supplied power from the ship, and therefore operate higher-power sensors, AUVs can operate at higher speeds than is typical of deep tow, offer a very stable platform for sonar sensors, and are capable of closely following seafloor terrain. However, towed systems are likely to continue to be a method for collecting samples, including seawater from depth for shipboard analysis, in the near future. As AUV capabilities increase, there is likely to be some impact on the use of towed systems. This is especially true in areas where it is difficult to deploy towed systems, such as ice-covered seas. AUVs are currently the preferred sonar mapping platform in commercial industries

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[2] http://www.whoi.edu/page.do?pid=51855
[3] http://www.bbc.co.uk/news/science-environment-11938904

such as oil and gas. **As AUVs mature and their cost of operation drops, towed platform applications will likely continue to migrate to AUVs.**

Autonomous and Lagrangian Systems

Autonomous and Lagrangian platforms operate without tethers to ships or to the seafloor (Rudnick and Perry, 2003). Included in this class of devices are drifters that move with the surface current, floats with adjustable buoyancy that profile the water column from surface to depth, underwater gliders that fly horizontally with up-down profiling, and self-propelled AUVs. This category of platforms has seen a remarkable increase in capabilities, numbers, and use over the past two decades (Dickey et al., 2008).

The increasing effectiveness of autonomous and Lagrangian platforms has been influenced by "consumer" technologies driven by commercial markets outside ocean science. Circa 1990, there were only a few 8-bit microprocessor systems with sufficiently low power consumption for autonomous deployments, and they had volatile solid-state memory and limited computational power and data storage. In 2010, processors with orders-of-magnitude-higher computational power can navigate systems, command sensors and actuators, adapt missions, and retain gigabytes of data in robust solid-state memory. There have been parallel improvements in power availability, including the transition from alkaline to lithium batteries. **Consumer-driven advances in microelectronics are likely to continue to benefit the ocean research community through increased platform capabilities.** This will be enabled by modular platforms that can easily accommodate rapidly evolving sensors.

In coming years, autonomous and Lagrangian platforms are likely to be deployed in larger numbers to provide improved spatial coverage and resolution during process studies, routine monitoring, and event response. This will lead to a need to form scalable arrays of devices, optimized for the specific task and available at locations of interest. In sufficient numbers and with a sustained presence, such arrays can provide data that are currently needed for routine model assimilation and skilled forecast models.

Drifters

The first observations of ocean flow were probably by surface drifters, including work by Benjamin Franklin (1785) and Irving Langmuir (1938). With the advent of satellite communication in the 1970s and 1980s, the use of drifters increased rapidly. Global deployment takes place through the Global Drifter Program,[4] an array that grew from fewer than 100 satellite-tracked drifters in 1988 to at least 1,250 in 2010. Drifters can carry a wide variety of sensors, measuring such variables as temperature, salinity, wind, light, passive radiation, and atmospheric pressure; these types of observations have led to global maps of surface circulation (Niiler et al., 2003). The use of drifters is seeing growing application in the coastal ocean, especially in dispersion studies (e.g., pollutant tracking, larval transport). **Due to their wide commercial availability, relatively low cost, and ease of use, drifters will continue to be used. A broader suite of sensors, especially for ocean-atmosphere flux studies and monitoring, are needed for future science research.** Newer developments in drifter-like assets include surface floats that can develop propulsion from wave action near the surface, which allows them to travel separately from the local surface drift.

[4] http://www.aoml.noaa.gov/phod/dac/index.php

Floats

The first neutrally buoyant floats were designed to observe subsurface currents (Swallow, 1955). During the 1970s and 1980s, float tracking began to make use of the ocean sound channel, and eventually autonomous profiling floats were developed to periodically surface for navigation updates and data telemetry by satellite (Davis et al., 1992). In addition to velocity measurement, floats have measured a wide and growing variety of oceanic variables (e.g., temperature, salinity, chlorophyll fluorescence, dissolved oxygen, nitrate); this is almost certain to increase by 2030. Because floats are stable, they are also able to observe challenging quantities like turbulent microstructure and vertical velocity (D'Asaro, 2008). Today, the international Argo program sustains at least 3,000 floats in the global ocean, each providing a 1,000- or 2,000 m profile of temperature and salinity once every 10 days (Roemmich et al., 2004). The present 3,000-float array was populated in less than 10 years. **Future trends include an increase in numbers of floats; variety of observations; enhanced two-way satellite communication for active piloting and adaptable missions; full profiling of the entire water depth; and under-ice capabilities to extend float coverage to high latitudes.** The need for longer endurance across a wide range of sensor types and environments will undoubtedly bring challenges in power requirements; these might be met by innovative methods of energy storage or harvesting. The Argo-type float array has been very successful and shows great promise for a robust, low-cost global capability that can provide subsurface observations able to inform both at sea campaigns and skillful ocean models.

Gliders

Underwater gliders are the fulfillment of Stommel's (1989) vision of buoyancy-driven devices that profile vertically while flying horizontally on wings. In the last decade, gliders have transitioned from prototypes (Eriksen et al., 2001; Sherman et al., 2001; Webb et al., 2001) to widely used tools for a variety of research purposes (e.g., Davis et al., 2003; Rudnick et al., 2004; Glenn et al., 2008; Hodges and Fratantoni, 2009), with several hundred now in operation. For example, the Navy has commissioned 150 gliders for use in both oceanographic research and national security (Rusling, 2009). Gliders can carry many types of sensors (e.g., temperature, salinity, velocity, nutrients, optics, fluorometry, acoustics), a suite which is likely to grow in the next two decades. Because gliders are typically recovered and reused (unlike many floats and drifters), there will be pools of gliders that can be made available for event response; the scientific community mobilized several gliders in response to the *Deepwater Horizon* oil spill. **With more robust capabilities, including the ability to work under ice and in other extreme environments, and longer endurance, gliders are very likely to become ubiquitous elements of regional ocean observing systems by 2030.** A likely trend is toward easier deployment, perhaps from ships of opportunity, offshore platforms, or aircraft. In the next 20 years, gliders may become inexpensive enough to lessen the need for recovery.

Autonomous Underwater Vehicles

AUVs are self-propelled, uncrewed underwater vehicles. Basic characteristics include a power source, payload capabilities, and onboard controls capable of executing missions without regular human supervision. AUVs have been configured to carry a wide variety of in situ sensors, including water samplers. In comparison to gliders or floats, AUVs are more flexible platforms because they can travel at a chosen depth as well as steer, climb, and dive in response to commands, preprogrammed instructions, or adaptable observation strategies. While most current AUVs are optimized around higher power payloads (e.g., multibeam or side-scan sonar) and therefore have generally shorter endurance than gliders (days versus months), in principle they will be capable of greatly increased range and endurance by 2030. A prototype long-range AUV was recently demonstrated (Bellingham et al., 2010). As with gliders, most AUVs can operate in a range of environments (e.g., the continental shelf [Brown et al., 2004; Johnson and Needoba, 2008]; coral reefs [Shcherbina et al., 2008]; under ice [Nicholls et al., 2008]) and can be deployed from multiple platforms. The oil and gas industry routinely uses AUVs for deepwater mapping, the U.S. Navy has spent at least two decades making large investments in AUV technology for a range of military applications, and NOAA uses multi-instrumented AUVs that can be deployed from its fisheries survey vessels to augment a variety of marine ecosystem investigations.

In 1990, there were no AUVs in routine operation for science and today there are a range of commercially available vehicles. **While still in their infancy as platforms, a substantial improvement of AUV capabilities, reliability, and usability can be expected over the coming decades.**

Developmental Concepts

Energy storage is a fundamental limitation for all autonomous systems at sea. While battery technology has advanced in past decades, progress has been incremental rather than revolutionary. Development of new battery systems has been primarily driven by the portable electronic industry to power devices such as cell phones and laptops. However, the advent of electric cars promises to generate further technical advances relevant to marine instrumentation. Not only may this industry create new high-energy-density systems, it is likely to encourage an increased focus on safety, a particular concern in marine applications. There are also some classes of electrochemical energy storage systems peculiar to the marine environment, including seawater batteries that depend on the surrounding environment for an oxidizer. Advanced lithium-based seawater batteries with very high specific energy have been developed in prototype and may be in common use by 2030.

Environmental energy (sun, wind, wave, thermal, chemical) offers a promising route to power the growing inventory of autonomous platforms used for oceanographic research. Solar power on ocean moorings was rare in the 1990s and is routine today, as are wind power generators. Solar-powered AUVs that recharge their batteries at the ocean surface have been tested (Crimmins, 2006). One type of profiling drifter uses thermal temperature differences to generate electrical power.[5] There has also been development of autonomous surface vessels that scavenge energy for propulsion. One device uses wave energy for propulsion and has demonstrated ranges of thousands of kilometers even in low sea states (Willcox et al., 2009). Autonomous sailing vessels have also been developed (Neal, 2006) and have potential to serve as research platforms.

In addition to the broad categories of systems described in earlier sections, a number of platforms have been developed either as prototype systems or as specialized solutions to specific sensing problems. For example, seafloor experiments and observations can be carried out by benthic landers or crawlers (e.g., Sayles, 1993; Smith et al., 1997). These range from comparatively simple sensor platforms to systems capable of carrying out perturbation experiments on the seafloor (Sherman and Smith, 2009). With the installation of scientific cabled

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[5] http://solo-trec.jpl.nasa.gov/SOLO-TREC/

observatories, some of these systems are being designed to be operated attached to a cabled system, while others are intended to operate autonomously. The power and bandwidth available through cabled systems can be used to extend AUV operations, potentially making them independent of a ship for extended periods. AUV docking has been demonstrated by many groups (Cowen, 1997; Singh, 2001; Stokey, 2001; Evans, 2003; Fukasawa, 2003; Allen, 2006) with more recent work exploiting the capabilities of cabled observatories (McEwen et al., 2008). Another developmental concept with ocean research applications are unmanned aerial vehicles (UAVs) equipped with GPS, energy-harvesting solar cells, and diverse sensor packages. These UAVs could monitor the ocean surface in the same manner as a drifting buoy and reposition themselves via flight (Meadows et al., 2009).

FIXED PLATFORMS AND SYSTEMS

Ocean Moorings

Since the development of moored surface buoys in the 1960s, mooring developments have enabled a wide range of studies addressing fundamental climate, weather, physical, and biogeochemical questions. Arrays of moorings provide the backbone to many ocean networks today, from ocean-atmosphere interactions to global tsunami warning, with increased utility through real-time two-way communications and profiling capability. **Although their uses may evolve, moorings will remain a key element of ocean observing infrastructure by providing high-frequency fixed location data to supplement spatial data collected by mobile sampling networks and satellite remote sensing.** Importantly, they also mark the surface location of subsurface infrastructure and sensor networks; therefore, even without sensors, moorings provide an invaluable service. Within the United States, only a limited number of federal and academic institutions maintain the expertise to build reliable deep-ocean moorings and to overcome the difficult operating conditions encountered in the ocean. Coastal moorings, which often have lesser observational requirements but more challenging surface environments and hazards, have attracted a larger number of commercial, federal, and academic institutions capable of development and deployment. Mooring systems will continue to be critical for both fundamental research and routine monitoring needs through 2030.

Seafloor Cables

The need for sustained, long-term scientific observations and data collection in the coastal and deep ocean (NRC, 2003a) has resulted in deployment of seafloor cables, which provide high power and bandwidth and continuous real-time two-way communications. In the 1990s, early systems included deployment of dedicated seafloor cables or took advantage of existing telecommunication cables no longer used by industry. For example, the Japanese DONET cable was driven by a national need to better understand undersea earthquakes. During the past 10 years, the distribution and capabilities of science cables have expanded globally with many countries now deploying seafloor networks. The United States currently has several existing or planned cables (e.g., Long-term Ecosystem Observatory,[6] Martha's Vineyard Coastal Observatory,[7] Kilo Nalu Nearshore Reef Observatory,[8] Monterey Accelerated Research System,[9] OOI Regional Scale Node[10]). **Use of seafloor cables will increase in the coming**

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[6] http://rucool.marine.rutgers.edu/
[7] http://mvcodata.whoi.edu/cgi-bin/mvco/mvco.cgi
[8] http://www.soest.hawaii.edu/OE/KiloNalu/
[9] http://www.mbari.org/mars/

decades because of their ability to host a wide variety of platforms and sensors and their high power and bandwidth capability. The large-scale construction and installation of cabled observatories has begun only recently, along with early stage instrument development. Scientific use is still in the future, so the impact of cabled observatories cannot yet be predicted. A future trend could include some means to remotely recover physical samples in lieu of research cruises, perhaps via released data capsules collected by unmanned vehicles.

Borehole Observatories

Since 1991, over a dozen borehole observatories (Circulation Obviation Retrofit Kits [CORKs]) have been installed in ODP and IODP borehole sites to characterize subseafloor hydrological regimes. These platforms were first envisioned in the late 1980s as a method to investigate hydrologic perturbations in the subseafloor associated with faulting and diking, tidal forcing, and other physical events (Davis et al., 1992; Becker and Davis, 2005). Since that time, CORKs have been augmented with fluid and microbial sampling capabilities, thermistor arrays, pressure sensors, and in situ seismometers and strain gauges. In the past few years, active tracer experiments between boreholes have measured formation permeability and flow rates in subseafloor aquifer systems. **Because study of the subseafloor currently suffers from very sparse in situ observations, the numbers of borehole observatories and the types of sensors available for deployment are likely to grow in the coming decades.** In association with cabled observatories, some CORKs can and will be able to utilize high power and bandwidth for real-time monitoring of basement conditions. With increased power capabilities, borehole sensors could expand to include mass spectrometers and in situ microbial analyzers for co-registered measurements of chemical properties and subseafloor microbial communities.

Summary Conclusion

In the past two decades, use of floats, gliders, ROVS, AUVS, and scientific seafloor cables has increased; use of ships, drifters, moorings, and towed arrays have remained stable; and use of HOVs has declined. Based on these trends, utilization and capabilities for floats, gliders, ROVs, AUVs, ships, and moorings will continue to increase for the next 20 years and HOV use is likely to remain stable. Ships will continue to be an essential component of ocean research infrastructure; however, the increasing use of autonomous and unmanned assets may change how ships are used. Cabled observatories are only now being installed on a large scale, and while their use will undoubtedly increase due to increased availability, the nature of their scientific impact cannot be predicted.

DATA TELEMETRY AND COMMUNICATIONS

Communications to and from platforms at sea has changed dramatically in the past two decades. In 1990, scientific communications from ship to shore occurred primarily through voice calls patched through a satellite, to a shore operator, and then linked to a collect phone call. By 2000, scientists at sea had access to email that was sent between ship and shore a few times per day, allowing for limited communications and data exchange. Today, real-time connection to the Internet is routine, including the ability for real-time video transmission. These fleet improvements have led to a greatly increased capacity to conduct complex, interdisciplinary projects, to encompass the broader community of scientific knowledge, and to engage the public.

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[10] http://www.ooi.washington.edu/rsn/

An array of low-power, low-Earth-orbit satellite communication systems has enabled rapidly evolving capabilities for communications to autonomous platforms. In 1990, the Argos satellite system[11] was the primary link for scientific data from remote platforms. Communications were only one way, from platform to shore, and data transmission was limited to about 16,000 bits/day. Today, the Iridium satellite system[12] provides global coverage with two-way communications at a rate of 2,400 bits/second, a 10,000-fold speed improvement. Seafloor cabled networks offer much higher, bidirectional bandwidths but are likely to be limited to a few, fixed locations for the foreseeable future. Both types of systems allow scientists on shore to operate sensor systems in an adaptive mode, based on the data taken or on other sources of information, such as remote sensing imagery.

Some of these communication technologies have been essential to the development of ocean science capabilities and have no equivalent replacement. For example, virtually all low-Earth satellite communication systems have gone bankrupt at some point. Without support from sources such as the Department of Defense, key communication systems such as Iridium might not currently be available. Unfortunately, the means of communication for autonomous systems generally remains fixed for the duration of a long deployment or the platform's lifetime, often years. The risk of a single-point failure due to a sole means of communication is clear and argues for some redundancy in data pathways, as well as a set of standards common to any provider. An innovative redundancy solution is "store and forward" capability, which could be located on commercial ships and aircraft, offshore platforms, or even miniature satellites. These systems could provide backup capabilities, as well as services in areas that currently have poor coverage, such as polar regions. Another solution by 2030 could be networked devices that pass information along to other members until the data arrives at a node with connectivity to shore. Advances in the application of key enabling infrastructure like GPS will continue to be driven by commercial activity, but could lead to breakthroughs in geolocation. **Two-way communications, especially for platforms, has been truly transformative in the last two decades and will remain essential to ocean research infrastructure assets in the future. However, key infrastructure components are reliant on technologies outside of the ocean science community, particularly satellite communication and GPS.**

IN SITU SENSORS

Mobile and fixed platforms provide access to the ocean, but the sensors that operate aboard them are the essential elements that enable observations over broad spatial and temporal scales. Many new platforms have enabled the transition from infrequent ship-based measurements to a sustained ocean presence, but there is a continuing need for innovative, robust, low-cost sensors to explore the ocean. The types of data collected 20 years ago to simply constrain initial conditions for ocean models are now routinely used in real-time, data-assimilating forecast models. Modeling needs for a variety of societal objectives will continue to grow in the coming decades, and the in situ data collected from the ocean will need to reflect a broad range of processes and constrain parameters for best model fidelity. Trends for the future include more multidisciplinary sensor packages with long endurance, stability, and range in multiple operating environments. Along with improved performance and reliability, it will be essential to get precise sample and data locations in the undersea environment, especially with the almost ubiquitous use of geographic information systems and the increasing move toward

[11] http://www.argos-system.org
[12] http://www.iridium.com/

coastal and marine spatial planning, as outlined in the National Ocean Policy (CEQ, 2010). The problem of biofouling in the upper ocean, however, remains a challenge for the sustained performance of oceanographic sensors.

Physical Sensing

The primary in situ sensors for physical oceanography are integrated conductivity, temperature, and depth (CTD) units and sensors for current velocities. The CTD was introduced in the 1970s and by the 1990s was commonly used in shipboard operations. In 2010, CTDs were common on almost all situ platforms (e.g., moorings, floats, AUVs). The U.S. National Oceanographic Data Center receives about 5,000 ship-generated vertical CTD data profiles each year, while profiling floats currently deliver about 10,000 profiles per month, albeit only to depths of 2,000 m (Freeland et al., 2009). In 1990, the state of the art for observing ocean currents was moored, mechanical current meters, and acoustic Doppler current profilers (ADCPs) had just been introduced as a commercial product. Today, nearly all current measurements are from ADCPs, which can sample over broad depth ranges at variable resolutions, can provide vertical velocity, are immune to most fouling, and have high reliability. Acoustic Doppler velocimeters, which sample three-dimensional velocity in one location at high frequencies, are now enabling measurements of turbulent energy and can provide an estimate of turbulent fluxes when coupled with other rapid sampling sensors (e.g., for O_2; Lorrai et al., 2010).

Although basic sensor technologies for physical oceanography are well established, the challenge will be to extend observations across all spatial and temporal scales, including to the microscales at which turbulent dissipation takes place. This is likely to lead to high volumes of data at smaller scales and higher frequencies. Another area of importance will be sensors that measure fluxes (heat, mass, and momentum) at the ocean surface, coupled with gas exchange rates for chemically active and inert components. Together, these data will be critical to understanding ocean-atmosphere interactions, particularly during high wind and storm events. At larger scales, acoustic methods that enable remote sensing of the ocean interior and tomography are expected to continue. Their application may be more likely through adaptive arrays from a mix of mobile platforms. Optical and radar remote sensing techniques for ocean surface processes are currently largely satellite based, but developments in focal plane arrays and miniature radars offer opportunities for small, relatively inexpensive sensors that could be deployed on mobile platforms (e.g., small aircraft [Dugan and Piotrowski, 2003], tethered balloons, commercial aircraft [following the current practice of automated atmospheric sensors for weather forecasting; Moninger et al., 2003]) or at fixed locations (e.g., coastal video monitoring[13]). In addition, tide gauge networks and sensors capturing river outflow and precipitation will continue to be needed for understanding physical processes in coastal and near-shore regions.

Chemical Sensing

The past two decades have seen a dramatic increase in chemical sensors for oceanographic research, including sensors capable of operating in some of the most extreme environments on Earth. In 1990, there were almost no chemical sensors in routine use for

[13] http://www.coastalwiki.org/coastalwiki/Argus_video_monitoring_system

autonomous, in situ applications. Instead, virtually all chemical measurements required scientists aboard a research vessel collecting samples for later laboratory analysis. **Today, new sensors are rapidly developing as a result of technical advances in a number of fields outside oceanography. As size, power requirements, and costs drop, advanced chemical sensors are likely to expand greatly.** Oxygen sensors have been deployed on hundreds of profiling floats (Gruber et al., 2009); sensors that measure carbon dioxide partial pressure operate on moorings around the world (Borges et al., 2009); and nitrate sensors have been deployed for multiple years (Johnson, 2010; Johnson et al., 2010). These sensors sample on the same scale as CTDs, providing unprecedented spatial and temporal resolution for chemical parameters. Figure 3.2 shows 8 years of dissolved oxygen measurements made from a profiling float near the Hawaii Ocean Time-series study site. These data were used to resolve a long-standing debate on whether the open ocean consumes or produces oxygen, demonstrating that the large oxygen maxima appearing within the euphotic zone each summer were a result of an oxygen-producing ecosystem (Riser and Johnson, 2008). Such long-term chemical measurements have only been accomplished in the past decade.

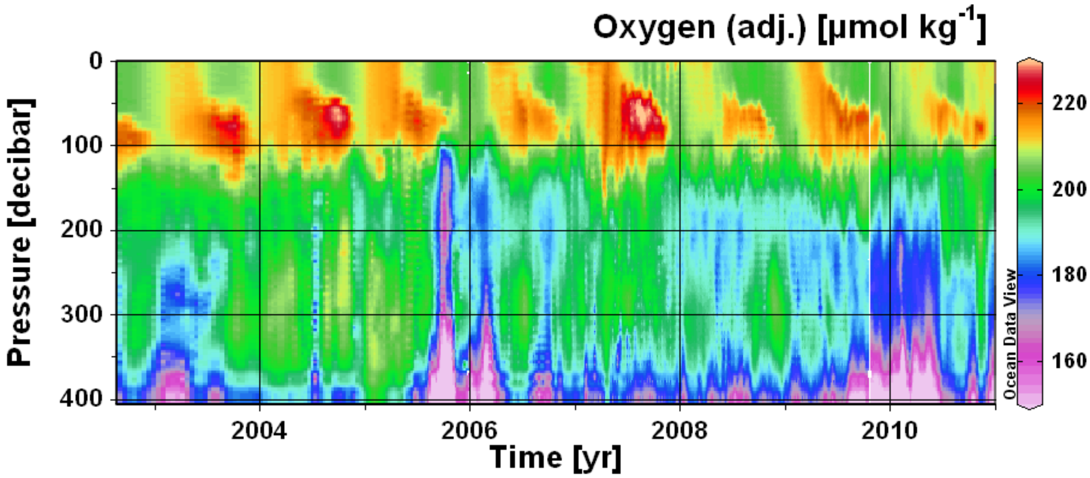

Figure 3.2. Dissolved oxygen measurements collected near the Hawaii Ocean Time-series study site.

Prototype research sensors for trace elements, inorganic carbon species, and a variety of nutrient elements are currently being developed, while other chemical sensors are currently being used in extreme environments (e.g., hydrothermal vents, anoxic sediments). Most recently, in situ mass spectrometers mapped the subsurface oil plume resulting from the *Deepwater Horizon* oil spill (Camilli et al., 2010). Often, these prototypes can suffer from problems due to excessive mechanical complexity, biofouling, or insufficient temporal stability. However, the success of oxygen, carbon dioxide, and nitrate sensors demonstrate that chemical sensors are at a level similar to physical oceanographic sensors in the early 1990s; undoubtedly, there will be a significant increase in their use aboard autonomous platforms by 2030. **Sensors that enable observations of the CO_2 system (including pH) and speciation of key micronutrients, such as iron, will be central to a number of studies, especially as micronutrient analytical systems are miniaturized or made more portable.**

Biological Sensing

Since the early 1990s, a rapid increase in in situ optical and acoustic sensors have allowed for estimation of bulk properties of phytoplankton and detritus, while in situ multifrequency acoustic and optical imaging systems now allow for the determination of phytoplankton and zooplankton stocks. The development of kinetic fluorometers in the mid-1990s provided a means to estimate rate processes. The oceanographic community is currently leveraging technology development from other fields, particularly the medical sciences, to take advantage of the growth in nanotechnology, high-throughput sequencing devices, high-resolution imaging, increased computing power, and networked arrays to substantially increase in situ sampling capabilities. Examples of such systems include in situ sensors that analyze genetic information in order to characterize water column organisms and use co-registered fluorescence measurements to quantify population abundance and physiology. In situ flow cytometers with imaging capabilities are being utilized for sorting, characterizing, and quantifying millions of organisms per day (Olson and Sosik, 2007; Sosik and Olson, 2007). Increasingly, acoustic monitoring systems that were traditionally used for geophysical and national security issues are now being used for biological sensing (e.g., tracking whales [Spaulding et al., 2009], estimating fish populations [Makris et al., 2006, 2009]). The latter example, which employs ocean acoustic waveguide remote sensing, enables areal surveys of pelagic fish populations several orders of magnitude greater than current survey methods.

Future trends in biological sensing will involve improved rate and flux measurements, which are crucial inputs for carbon mass balance, as well as onboard gene sequencing. Key to meeting needs in 2030 and beyond, particularly in coastal and near-shore environments, will be relatively small and inexpensive versions of biological sensors that can replicate today's complicated laboratory techniques for collecting genomic, protienomic, and metabolamic data.

Geophysical Sensing

Geophysical measurements are essential to understanding the mechanics of the oceanic crust. The past decade witnessed the first long-term, in situ deployments of seismic sensors in the crust, including broadband seismometers, short-period seismometers, and networked seismic arrays on cabled observatories. Currently, these types of sensors can detect diking and eruptive events along mid-ocean ridges, visualize hydrothermal upflow zones, and are even used for earthquake early warning systems. **Future trends include further developments in underwater geodetics, where bottom pressure recorders and acoustic extensometers measure small-scale vertical and horizontal movements of the seafloor** (e.g., inflation or deflation of submarine volcanoes, faulting or magma intrusion [Fox et al., 2001; Chadwick and Stapp, 2002], changes due to tsunami wave trains). Because the ability to assimilate real-time data from cabled seafloor seismic and pressure sensors will increase, it is very likely that use of these arrays will grow and become routine components of earthquake early warning and tsunami warning systems.

Downhole logging tools remain important technologies to measure crustal permeability, geochemistry, and fracture geometry and will follow trends set within scientific ocean drilling programs. The use of chirp sub-bottom profilers for deducing acoustic and physical properties of ocean sediment and subseafloor is likely to increase, as is the development and use of omnidirectional sonar systems able to sense in all directions with one acoustic ping. Multibeam sonars will continue to grow in capability, as will the performance of synthetic aperture sonars, providing increased ability to resolve seafloor features.

Many sensor capabilities have increased—longevity, stability, communications, and access to harsh environments. These improvements are mostly dependent on innovation from

outside the ocean science field. The ocean science community will continue to benefit from other fields' innovations in sensors and technology.

SAMPLING

Despite encouraging improvements in sensor technology, a majority of studies in chemical and biological oceanography and marine geology will continue to require the collection of water, rock, and sediment samples, filtered particulates from seawater, and organisms for study. Aboard ship, sampling systems presently available (rosettes with continuous CTD, O_2, fluorescence, and transmittance) are a substantial improvement over wire-clamped Nansen bottles with reversing thermometers, but there are significant needs for more capable oceanographic sampling systems. In addition, ship-based sampling will continue to be important for ground-truthing satellites, validating sensors before and after deployment, process studies, and long-term archiving.

Chemical Samplers

Currently available shipboard hardware is grossly contaminating for many chemical elements, including radioisotope systems that are not normally contamination prone and trace metals that can create artifacts in biological experiments. One of the highest priorities for chemical sampling is truly uncontaminated stationary and underway surface sampling systems for a broad range of research studies. Systems designed for uncontaminated sampling of trace gases and metals (such as CTD systems designed for CLIVAR and GEOTRACES) need to be transitioned to wider availability. Currently, there are only a few automated water samplers for use on moorings. While they are not yet routine or compact enough for use on autonomous vehicles, **the next 20 years could see great advances in automated water sampling**. Development of improved fluidic systems for chemical analyzers (e.g., pumps, valves, connectors) or alternative particulate sampling systems would be particularly valuable.

Biological Samplers

Many tools for biological sampling of the water column and seafloor systems (e.g., nets, Niskin bottles, sediment traps) have not evolved significantly in the past two decades, and despite technical advances it is very likely these samplers will continue to be used in the near future. For microbial communities, several sampling strategies have been emerging over the last decade, including profiling or towed systems equipped with pumps that pipe organisms through bio-optical instruments (Herman et al., 2004), video imaging (Davis et al., 2005), and flow cytometers (Sieracki et al., 1998; Olson and Sosik, 2007); in situ, extended-duration, time-series samplers that filter fluids for DNA and subsequent onshore analysis (Scholin et al., 2009); and efforts to develop sample collection and preservation approaches for autonomous vehicles. For zooplankton and higher trophic levels, sampling is still dependent on net tows (see review by Wiebe and Benfield, 2003) and often on acoustically quiet research vessels. Although multifrequency, multibeam, broadband, and ocean acoustic waveguide remote sensing acoustic sensors are rapidly evolving, these approaches still require physical samples for calibration (Lavery et al., 2007; Trenkel et al., 2008; Makris et al., 2009; Stanton et al., 2010). In addition, collecting delicate and soft-bodied organisms is not possible with nets, although this is routinely done with ROVs, an approach that may evolve to capture an even broader range of organisms. In the case of larger organisms (e.g., seals, sea lions) marine ecologists have successfully used smaller, less costly instrument packages to turn the animals themselves into sampling platforms for oceanographic properties (e.g., Biuw et al., 2007; Costa et al., 2008), a trend that is likely to continue to increase by 2030.

Geological Samplers

Over the past 20 years, scientific ocean drilling through ODP and IODP has played a vital role in sampling oceanic sediments and crust, and measuring physical properties within the crust and overlying sediments. As oceanic sediments are one of the best sources for high-resolution, long-duration, spatially distributed paleoclimate records, these data will continue to be needed to understand past and future climate change (IODP Science Plan, 2013-2023). In addition to ODP and IODP, shallower sampling of the ocean crust and sediment is currently done through coring systems available on a variety of research ships (e.g., the Woods Hole Oceanographic Institution long corer mounted on the *R/V Knorr* [Curry et al., 2008]). ROV drilling systems have also been used for extracting small hard rock cores (e.g., Stakes et al., 1997). **The need for both shallow and deep coring and drilling will continue in the next 20 years in order to investigate paleoclimate, structure of the oceanic crust, and the subseafloor biosphere**. In general, there has been a decrease in dredging operations to collect rock samples, but a concomitant increasing use of wax corers (which collect glassy rock fragments) on towed or autonomous systems and high-precision sampling through ROVs and HOVs. Geological sampling on the seafloor has also been facilitated by significant increases in bathymetric resolution that allow for more accurate sampling methodologies. Sediment traps, which collect samples for studies of concentration, particle size distribution, vertical flux, and horizontal transport will also continue to be needed.

REMOTE SENSING

Remote sensing includes sensors and platforms that provide ocean data from above the ocean surface, including satellites, piloted and autonomous aircraft, and land-based, ice-based, and offshore installations to sense the ocean. Use and availability of remotely sensed data has increased significantly in the past 20 years, and these types of data are now utilized for a range of fundamental and applied problems (NRC, 2008a). Current remote sensing capabilities provide critical environmental parameters (e.g., sea surface temperature [SST], ocean color, altimetry, wind speed and direction, ocean surface currents, ocean waves, sea ice and ice shelves, glaciers, atmospheric properties) that can also be used for applied data products of societal relevance (e.g., vessel traffic, ice flows, spill trajectories). For 2030, these capabilities will need to be sustained and greatly expanded, and they will continue to require groundtruthing from manned and autonomous platforms.

Satellite

Physical parameters available from space-based sensors provide information on ocean temperature, wind speed and direction, sea surface height and topography, sea ice distribution and thickness. Biogeochemical parameters are derived from ocean color radiometers (e.g., pigment concentration, phytoplankton functional groups, size distribution, particle concentration, colored dissolved organic material). These observations require active scatterometry, microwave array spectrometers, microwave imagers, multibeam altimetric lidars, and altimeters, among others (NRC, 2007b). Future trends involve LIDAR to provide depth-resolved particle concentration, mixed-layer depth estimates, and ice sheet measurements; polarimeters to provide particle composition; and hyperspectral resolution from the ultraviolet to the near infrared, which allows for better separation of phytoplankton functional types and separation of dissolved absorption from that of particles. In addition to sustaining critical global measurements, there is considerable potential for innovation with a planned salinity sensor and proposed measurement of ocean carbon and surface fluxes using multiple sensors synergistically. **There are several specific needs for improved scientific understanding: improved coastal remote sensing algorithms for ocean color, interferometer scatterometers that provide higher resolution wind fields closer to the coast, sensors that combine infrared and microwave channels to provide all-weather SST fields with higher spatial and temperature resolution, and more precise surface salinity sensing.**

Most present environmental satellites are polar orbiting, covering the whole globe over a period of days. Adding geostationary satellites, of which few are currently available, will provide the possibility to sense the same area of the ocean several times a day, thus providing better temporal ability to resolve tidal effects as well as real-time data during episodic events like hurricanes or oil spills. High-latitude fluxes need continuous monitoring by polar orbiting and geostationary satellites for adequate sampling. Special satellite systems with multifrequency visible and infrared channels at several look angles are also needed. A future trend in short timescale temporal sampling, although rarely achieved today, may be satellite tasking for a "spotlight" sequence of images (e.g., Schofield et al., 2010). Spatial resolution has increased steadily for many satellites (e.g., from 4 km down to 250 m for ocean color) and is expected to continue in the future. Atmospheric correction, a present-day challenge, is likely to be better addressed in the next two decades. Similarly, signal to noise characteristics have been improving steadily and could be further mitigated by temporal image processing.

An analysis of the trends in space-based Earth science over the past decade (NRC, 2007b) indicates that global observations from space are at considerable risk, with both operating missions and the number of operating sensors in decline. In other cases, the replacement sensors on operational platforms are less capable than the original research platforms. Remote sensing capabilities and data continuity are declining; vector wind, all-weather SST, altimetry, and ocean color measurements are at risk. **Plans for new satellite capabilities and for continuity of certain sensor capabilities have not been realized in recent years, with the likelihood of gaps in coverage for key data in the future.** This is particularly serious for ocean color data, as all existing U.S. ocean color satellites have exceeded their projected life span and could fail at any time, leaving a high probability of research-quality data gaps (Siegel and Yoder, 2007; Turpie, 2010).

Airborne

Availability of UAVs has grown in the past decade, ranging in size and capability. Airborne piloted and autonomous platforms (e.g., planes, balloons, UAVs) have been used for several years to map shallow topography, identify fish abundance, image the coastal ecosystem, and track pollutants. Sensors are similar to those on satellites but, given their lower operating altitude, have significantly higher spatial resolution and may be capable of flying below and around cloud cover. Today, these assets are available at government labs and private companies with little use by academia but it is expected that **UAVs will follow the growth trajectory of AUVs and become far more utilized for oceanographic research by 2030.** Smaller UAVs are already being launched and recovered by oceanographic ships. Their sensor payloads can be refreshed and adapted more readily than spaceborne sensors and can fill in satellite coverage gaps, and can also be used as communications relays. Aircraft of all types, but particularly UAVs, allow unprecedented response to episodic events, whether natural or manmade, and are already an important part of the portfolio of platforms needed to understand oceanographic processes. Additionally, certain radar remote sensing payloads (e.g., synthetic aperture radar) are currently being miniaturized for use aboard UAVs. Success in adapting these types of sensors to UAVs will almost certainly also lead to other airborne platform uses by 2030. However, there are significant regulatory restrictions surrounding their use.

Fixed

The number of high-frequency (HF) radar sites used to measure surface currents has grown rapidly in recent years. In the past 10 years, they have been deployed over most of the U.S. coast. HF radar arrays are also extending offshore via buoys and fixed offshore platforms. There is strong momentum to build a national backbone, as surface current data are highly valuable for both fundamental research (e.g., coastal circulation models) and applied needs (e.g., search and rescue, safe offshore platform operations). More routine use of HF radars on ships and multifrequency HF radars to estimate near-surface vertical current shear is likely to enable new types of shallow water observations by 2030. Furthermore, increased industrial ocean activities could provide new platforms for placing sensors and for greater, more persistent coverage of the ocean surface.

Likewise, the network of cameras for observations of near-shore wave dynamics and beach topography has also grown in coverage and utility. Ground-based radars have also been used to detect ice extent.[14] **Owing to relatively low costs of implementation and operation, as well as their sustained coverage, the next two decades are likely to see significant growth in both numbers and capabilities of visible and infrared imaging systems from fixed sites as well as ships, satellites, and both piloted and autonomous aircraft.** This will enable air-sea interaction studies at smaller scales and more locations than previously accomplished.

MODELING AND COMPUTATIONAL INFRASTRUCTURE

The past two decades have seen great growth in numerical models of ocean circulation as part of the larger set of Earth system models. Examples include ocean general circulation models, nested regional models, coupled physical-biological models, and coupled ocean-atmosphere climate models. These models have been used in sea level rise prediction, carbon and heat storage calculations, and defense and homeland security applications. There has been rapid growth in the development and use of models that assimilate ocean observations to construct dynamically consistent predictions and hindcasts of ocean state. Modern ocean models take into consideration many types of processes, including ocean sea ice dynamics, mixed-layer dynamics and open ocean turbulence, marine biogeochemistry, and ecosystem processes. **The field of ocean modeling has advanced rapidly in the past two decades, but more work is needed to increase fidelity for improved forecasting.** Development of these models has been aided by the exponential growth of computer processing speed and memory capacity, reduced electrical power requirements, and steadily decreasing costs.

In most instances, the ability to model physical processes far exceeds the ability of the models to resolve important chemical and biological processes. **Multidisciplinary models will be needed to address many of the major science research questions for 2030 and are almost certain to enable answers to societally relevant questions of Earth system dynamics.** Models have become increasingly more interdisciplinary (e.g., combining ecosystem, cryosphere, and surface wave processes), although much remains to be done to quantify different processes.

[14] seaice.alaska.edu/gi/observatories/barrow_radar

Models are also being run at higher resolution to simulate dynamical features of importance (e.g., mesoscale eddies, flow constrictions, coastal upwelling) and temporal and spatial scales important to biological processes. Skillful parameterizations will continue to be needed for unresolved dynamics of a range of processes. One such example is upper-ocean mixing, which is driven by surface fluxes and so is coupled to the atmosphere and such phenomena as aerosols. Parameterizations will also be increasingly needed to incorporate rate laws for biogeochemical and other processes. **Given the demand across many disciplines, computational capacity will continue to be stressed in 2030. For the oceanographic community, this suggests a future need for broadly accessible centers with exascale or petascale capability**, where teams of experts can be colocated with cutting-edge computational and modeling resources, healthy competition of ideas and methods can be fostered, and data products with basic and applied uses can be produced.

These modeling centers will need to assimilate disparate, growing data streams to sustain skillful simulations and forecasts. In the next 20 years, a subset of these modeling capabilities will include integrating the deep ocean with shelf seas for ecosystem-based management; using coupled ice, ocean, and atmospheric models to predict ice movement and thickness; using coupled ocean, surface wave, and atmospheric models for simulations of severe storms and coastal inundation; modeling tsunami arrival times and inundation zones; estimating marine resources for projected growth of industrial activities in the ocean; and modeling potential outcomes of geoengineering experiments.

The total volume of data produced by numerical models cannot be completely stored. Practical considerations influence what final model products can be saved, and what intermediate steps are discarded. While approaches are currently being developed to manage model complexity and data produced, the need to make decisions on what to archive will persist. This is driving the push for dedicated petaflop and higher computing power and data storage systems for ocean modeling, which is only likely to be met in a limited number of real or virtual locations and might leverage on evolving computing capacity being developed by commercial entities. **The issue of creating broadly accessible modeling centers that dedicate significant resources to oceanographic needs requires further study in the near future, so that they can be in place by 2030.**

DATA MANAGEMENT

This important crosscutting infrastructure category is subject to rapid changes, driven almost entirely outside the field of ocean sciences. Trends in this area include growing collaborations between computer and ocean scientists, leading to the emergence of a new class of scientific activity structured around networked access to observational information (Hey et al., 2009). Driven in large part by commercial activity, network and computational infrastructure that currently supports ocean scientists is undergoing significant evolution. Further change seems likely as the computational and network paradigm dominating industry shifts to cloud computing. Cloud computing refers to a new paradigm in which pervasive connectivity allows access to location-independent computational and storage resources and long-distance collaboration via the Internet and cellular networks. The current investment in cloud computing resources, led by commercial entities like Google, Microsoft, and Amazon, is creating a large infrastructure that may in turn transform the sciences, including the data-rich ocean sciences of 2030.

The evolution of data management in the ocean sciences needs to include a framework for a common lexicon across disciplines and applications, creation of distributed virtual centers for data deposit, broad accessibility for users from scientists to policy makers, and user-friendly archiving and synthesizing tools. Virtual data centers could be formed for a variety of disciplinary data: river outflow and tide gauges, terrestrial dust transport, seafloor mapping and seismicity, ocean hydrography, biogeochemistry, and ecosystem structure and status, genomics, and many others. A major need for success in the realm of data management is to **establish seamless integration of federal, state, and locally held databases, so that relevant data can be easily retrieved by a range of users.** Programs such as the Global Earth Observation System of Systems[15] will assist in bringing relevant observations together from different networks in order to provide maximized societal use. A continuing concern will be who owns, funds, and maintains these databases; however, excellent precedents are being set by programs such as the Marine Geoscience Data System,[16] the Biological and Chemical Oceanography Data Management Office,[17] the Palmer Station Long-Term Ecological Research Data Management Office,[18] and Rolling Deck to Repository.[19]

ENABLING ORGANIZATIONS

Sponsors

A long-standing strength of the U.S. ocean sciences is the diversity of funding sources and the variety of sectors represented in the ocean research community, which ensures flexibility in how scientific research is performed and evaluated. Most basic research in ocean science is done in academia and government. The academic research community relies on funding from the National Science Foundation (NSF), NOAA, and ONR. With the exception of NSF, these agencies have applied ocean research missions, with significant intramural research and operational activities. Other mission agencies, such as NASA, the Department of Energy, and the Defense Advanced Research Projects Agency also provide focused ocean science and ocean engineering related support.

Increasingly, there are opportunities to focus and leverage resources among the federal agencies, which could maximize returns on ocean research investments both internally and externally, minimize costs for individual agencies, and draw in new federal and private-sector partners. Programs like the National Oceanographic Partnership Program have been critical to these efforts by providing a mechanism for multiple agencies to collaborate on a specific focus, with leveraged partnership between academic, federal, nonprofit, and commercial partners. Organizational frameworks that promote collaboration between agencies can help to ensure effective leveraging of resources in the coming decades.

State and local government support is also central to the ocean science and engineering communities. Major contributors include state universities and community colleges that employ a large segment of academic oceanographers, often with strong connections to societal and economic issues of regional or local importance. However, the trend for state investment is mixed at best, and recent budget deficits have forced some consolidation within the university system. Local county and township governments tend to have smaller amounts of research funds, despite an increasing appreciation of the major economic impact provided by the ocean to local

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[15] http://www.earthobservations.org/geoss.shtml
[16] http://www.marine-geo.org
[17] http://www.bco-dmo.org
[18] http://pal.lternet.edu
[19] http://www.rvdata.us

communities. Nonetheless, there are many opportunities to share and to leverage local and state infrastructure (e.g., research vessels, shore-based laboratories, regional ocean observing systems) for common goals at the national and even international level. The National Ocean Council, via its Governance Coordinating Committee, appears to have a mechanism to foster this collaboration on a local to regional scale (CEQ, 2010); this could be exploited more fully.

Finally, the past decade has seen an increase in basic and applied research investments funded by nonprofit foundations, as well as increased partnerships between different ocean science sectors (e.g., academic, industry). In recent years, foundations have had high impact by providing resources and momentum to key research areas within their scope of interest. There are also growing partnerships with diverse industry interests (e.g., oil and gas, aquaculture, ocean energy). In view of the increasing demand by society for services and products related to the ocean, encouraging cooperation and joint infrastructure investment between the industrial sector, academia, and government is likely to foster greater success for all.

Community-Wide Facilities

Currently, there are a limited number of community-wide facilities and organizations in the ocean sciences; their development is usually driven by cost and expertise issues. However, the logistical challenges inherent in conducting ocean research have led to increasing use of such facilities. These efforts are usually a means to address the technical needs and costs required for (1) platforms, sensors, and analytical equipment; (2) compiling, managing, and maintaining large complex data sets; and (3) computing and modeling. Facilities that are supported and accessed by a broad base of ocean science users can focus on specialized areas of ocean infrastructure, while providing cost effectiveness and standardized, reliable services.

One of the most successful examples is the growth of data and modeling centers (e.g., NOAA's National Oceanographic Data Center and National Geophysical Data Center, National Center for Atmospheric Research) . Numerous data centers have been created over the past 20 years and, given the diversity of new observation systems, the range of data available to the broader community (including education and the interested public) through distributed data centers are very likely to grow. Barriers to be overcome include data accessibility and impediments to collaboration, which are critical to continued success. For community-wide facilities that provide laboratory analyses, independent verification and calibration is needed to provide sustained confidence in the data being produced.

Successful community-wide organizations need broad support at several levels of government. UNOLS has been an exemplar of this type, having strong engagement between academic, state, and federal partners. UNOLS provides academic and government oceanographers with access to the research fleet through coordination of ship schedules and operations, as well as managing standards and safety and ensuring standard instrumentation aboard each vessel. It also schedules deep submergence assets (HOVs, ROVs, AUVs) and use of research aircraft. **By 2030, it is expected that consortia similar to UNOLS could facilitate broad community access to other infrastructure assets, including other mobile or fixed platforms (e.g., AUVs, gliders, drifters, moorings, seafloor cables and nodes, UAVs) or expensive analytical equipment.** The creation of new community-wide facilities for ocean research infrastructure will be dictated in large part by technology innovations that either simplify operations and maintenance requirements or lower purchase and operation costs, as well as broad involvement and acceptance. However, they could also be driven by federal agencies as a means to maximize infrastructure effectiveness while minimizing costs.

Technology Development, Validation, and Transfer Groups

To address the various societal needs of 2030, new innovations need to be created, matured, and transitioned into operations. A number of federal agencies and private foundations support design and construction of new in situ and remote sensors and platforms. Some novel work in sensor development has been supported through the federal government's Small Business Innovation Research Program.[20] In addition, several laboratories, research groups, and private companies are actively developing the next generation of ocean infrastructure (e.g., MBARI, SRI International Marine Technology Program). However, to ensure that basic science understanding, forecasting, and management decisions are based on accurate, precise, and comparable data, there is a fundamental need to verify and validate the performance of new and existing instrumentation. Enabling organizations that facilitate the development and adoption of effective and reliable sensors and platforms for ocean science will continue to be needed in the future. These types of organizations (e.g., the Alliance for Coastal Technologies[21]) can provide technology users with an understanding of sensor performance and data quality and provide technology developers and manufactures with opportunities for beta testing, system validation, and insights into various user needs, applications, and requirements through independent laboratory and field testing of prototype and off-the-shelf instrumentation. Such efforts help to accelerate critical instrument development and operationalization, while minimizing the risks of error and failure often associated with young technologies.

Shipboard Technical Support Groups

The responsibilities of shipboard technical support groups span a number of key areas, including safety, over-the-side handling of equipment, communications and shipboard computer networks, operation of hull mounted and underway sensors, quality control of collected data, and troubleshooting and repair of failed equipment. These responsibilities have evolved significantly from 1990 to 2010, in response to the increasing availability and complexity of sampling gear and, as well as the increasing breadth of federal regulations. Today, a marine technician's duties may involve aspects of a bosun, chemical safety officer, satellite communications specialist, network administrator, and electronics technician. **These groups are an integral component of the U.S. oceanographic fleet. As shipboard assets grow more complex, there will be an increased need for highly technically skilled workers aboard academic research vessels.**

EDUCATION AND WORKFORCE TRAINING

As mentioned earlier in the chapter, ocean research infrastructure trends point toward greater complexity of ocean infrastructure and enormous volumes of data flow. Interdisciplinary work both influences and is driven by infrastructure and data; **by 2030, it is likely that interdisciplinary education will be even more developed than today. However, the trends also suggest greater need for a technically skilled workforce, both for academic research and support, and for implementing monitoring and observations.** Undergraduate programs in environmental and Earth systems science need to evolve to fill this need, especially if their graduates are encouraged to move into technical fields. Oceanography also needs to attract more computer science and engineering graduates to sustain innovation. While one role of academic institutions is to train future oceanographers, other organizations could be established to focus on the specific technical skills needed for future ocean research workforces, including early career

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[20] http://www.sba.gov/aboutsba/sbaprograms/sbir/index.html
[21] http://www.act-us.info/

experiences like internships. Presently, there is some effort toward education and training at the community college level for field support staff (e.g., the Marine Advanced Technology Education Center[22]). Similar enabling organizations could be created to address other critical education and training needs, including analytical methods, data management and archiving, and equipment maintenance and repair. None of these are currently covered in traditional university degree programs; certificate programs could bridge this gap and provide useful standards for both the technical and research workforce in academic and private sectors.

[22] http://www.marinetech.org

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Infrastructure Needs and Recommendations

The science research questions posed in Chapter 2 and the infrastructure categories described in Chapter 3 lead to a number of major ocean infrastructure needs anticipated for 2030. First, this chapter details overarching infrastructure needs related to a majority of the scientific questions and societal objectives discussed elsewhere in the report. Each societal objective is then examined for needs of special note, followed by a summary of recommendations regarding ocean research infrastructure for national needs. Finally, Table 4.1 summarizes the categories of infrastructure. The table details the essential capabilities each type of asset will need in 2030, as well as capabilities to be advanced or developed. It is worth noting that the complexities of dealing with the harsh ocean environment create special challenges for building and maintaining robust research infrastructure.

OVERARCHING INFRASTRUCTURE NEEDS

Ships, satellite remote sensing, arrays of in situ observations, and shore-based laboratories are the foundation for ocean research infrastructure. The most essential infrastructure component will continue to be the ability for scientists to go to sea aboard research vessels, a capability that complements and enables the increasing suite of autonomous technologies and remote sensing data expected to be available in the next two decades. Ships form the backbone for all ocean observations; for example, they serve as platforms for sample collection, for deployment of remotely operated and autonomous vehicles, and as tenders for instrument maintenance. Shore-based laboratory facilities will continue to be required as a natural extension to ship-based sampling, for analytical work, and for coastal observations.

Several space-based observations are key for the ocean sciences, such as vector sea surface winds, all-weather sea surface temperatures, sea ice distribution and thickness, ocean color and ecosystem dynamics, dust transport, sea surface height and topography, mass balance of ice sheets. Planned missions with sensors that provide global coverage of ocean salinity[1] and atmospheric carbon dioxide[2] will add to this measurement base.

The global, internationally supported array of 3,000 Argo profiling floats (measuring temperature, salinity, and depth) is another critical component. Expansion of this network, both in terms of numbers and capabilities, will further enable study of the ocean's physical, biological, and chemical processes while providing essential data for assimilation into global models. Sensor capabilities for profiling floats are expanding (e.g., oxygen, bio-optics, nitrates, rainfall rates, vertical current speeds), with additional sensors for pH, pCO_2, and acoustics in development.

Extensive fleets of underwater gliders and autonomous underwater vehicles (AUVs) capable of operating in both expeditionary and long-duration modes, outfitted with a much broader suite of multidisciplinary, biofouling-resistant sensors will also be needed (e.g., physical [conductivity, temperature, and depth; stable salinity], chemical [O_2, pH, nitrate], biological [acoustic, genomic], biogeochemical, and imagery [visual, acoustic]). AUVs will be capable of providing increased power and space for advanced sensors and more complex payloads.

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[1] http://aquarius.nasa.gov/
[2] http://oco.jpl.nasa.gov/

Moorings and ships with more capable sensors will provide local refinement needed for further quantification of processes measured and offer replenishment to AUVs operating in the vicinity.

The nested observation network together with embedded campaigns described above place a premium on widely shared data; this will achieve greater success if incentives are included for commercial operations in the coastal region to participate in data collection and use. Data management and data repositories are and will become increasingly important given the large data sets being collected for both global and regional studies, including climatological, oceanographic, geological, chemical, and biological data. Many of the science questions and societal objectives will require adaptive sampling as well as event response capabilities (see Box 4.1).

Box 4.1 Ocean Infrastructure Needs: A Case Study From the *Deepwater Horizon* Oil Spill

The 2010 Deepwater Horizon oil spill in the Gulf of Mexico provides a timely example of how infrastructure from a diverse range of academic, federal, and commercial entities was required to respond to the disaster in a timely fashion. A notable feature is that no single sector (government, industry, or academia) had sufficient infrastructure to adequately handle the incident. Instead, assets from many sources and sectors were pooled for the effort. Response was limited to those sectors that had available resources that could be provided in a timely fashion, arguing for some infrastructure redundancy to be built into future inventories. The response to the oil spill was coordinated through the federal government, which reached out to external partners to develop an ocean observing capacity to improve field planning and forecast skill for the trajectory of the oil. The Navy provided ocean current forecasts informed by a variety of data sources. Satellite and high-frequency (HF) CODAR data provided by the federal government and universities was complemented by a wide range of in situ measurements. Ship-based measurements were complemented by in situ spatial drifters, underwater gliders, and remotely operated vehicles (figure, below). Data and findings were communicated through specialized web portals that were designed to facilitate collaboration between far-flung team members. For example, the glider network deployed to study the circulation represented assets from the U.S. government, industry, nonprofit groups, and universities throughout the country. The availability of web-based social networks allowed this distributed team to work together to define circulation patterns and better understand the potential dispersion of oil throughout the Gulf.

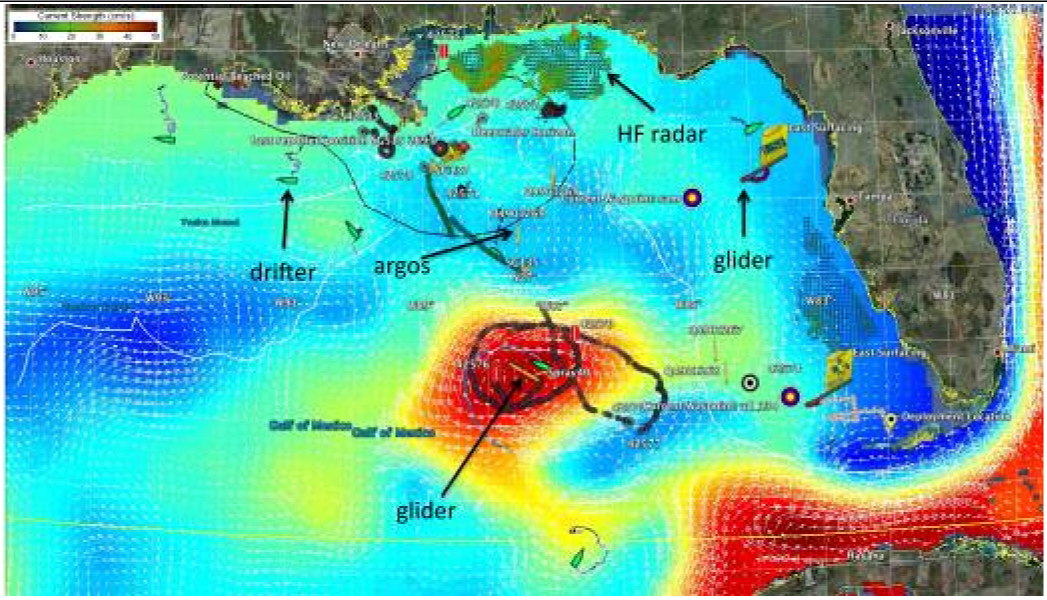

Figure. Some of the infrastructure deployed during the *Deepwater Horizon* oil spill in the Gulf of Mexico. The color map and vectors represents a Naval Oceanographic Office ocean model simulation, and graphics and tracks represent in situ assets that were deployed in response to the spill.

Enabling Stewardship of the Environment

The ability to observe, understand, and predict changes to the environment, such as the climate system, ocean chemistry, ecosystems, and the water cycle, requires a comprehensive array of ocean infrastructure. Importantly, these problems demand capacity at both global scales and regional scales, to examine areas of high stress (e.g., coastal zone) or rapid change (e.g., polar regions). Environmental stewardship demands the full array of present capabilities in the ocean sciences and is a major impetus for needed improvements in both sensor and sampling capabilities to meet needs in 2030.

Another component essential for environmental stewardship are accurate measures of sea level, presently accomplished through a network of tide gauges as well as observations of precipitation over the open ocean, river runoff, sea-surface height, and surface currents. This societal need is also driving the development of comprehensive global ocean models at higher spatial and temporal resolution, with coupled biological and chemical systems, as well as the need for specific process models and the availability of additional capabilities (e.g., tide models to reliably predict storm surge associated with sea level rise). Data will be assimilated into modeling capabilities that include fully coupled air-sea-land regional forecast models.

In addition, infrastructure assets targeted specifically to observe impacts of geoengineering (e.g., deep ocean observations for liquid CO_2 sequestration; upper ocean observing systems for iron fertilization experiments) will be required as the likelihood of such activities increases. Stewardship of the environment will also require the capability and flexibility to make disparate, distributed infrastructure assets available in the event of oil spills and industrial accidents (see Box 4.1).

Protecting Life and Property

The infrastructure required to address questions associated with the protection of life and property can be subdivided into areas related to the solid earth, weather and climate, and human health. The hazards associated with each of these areas can call for very different types of observations in addition to observations of many common processes. However, all efforts to protect life and property have three shared attributes. In each case:

- The primary objective is to increase the likelihood of warning populations in advance of destructive events, thereby limiting the magnitude of the impact.
- A key observational strategy is to focus on regions prone to certain events (e.g., monitoring the Cascadian margin for earthquakes, or urban beaches for pathogens).
- Meeting the primary objective—timely warnings—requires an increase in predictive capability that ingests significant volumes of real-time multidisciplinary data and information rapidly across vast distances.

For example, tsunami prediction is dependent on a very large network of pressure-sensing buoys that monitor the ocean for tsunami-generating waves. High-power and bandwidth cabled seafloor observatories, networks of seismometers, passive acoustic systems, and a broad suite of sensors deployed on autonomous or moored platforms beneath, at and above the ocean or ice surface are also necessary infrastructure for earthquake and volcano hazard assessments. Accurate maps of the seafloor are a necessary prerequisite for solid earth hazard assessments, whether to improve predictions of tsunami travel times or submarine volcanic eruptions. Finally, communications systems that are independent of local power fluctuations should be installed in threatened communities to provide warnings and educational programs undertaken so that populations understand what to do when an event occurs.

Quantifying the role of humans in altering coastal ecosystems will require sustained observations (especially in urbanized or populated coastal regions), as well as utilization of new suites of biological and genomic sensors and instruments to detect and quantify a variety of pollutants and emerging contaminants or pathogens. Regional spatial mapping will need to be coupled to data-assimilative physical and biological models. This will require augmenting marine stations and coastal networks with mobile platforms capable of providing the spatial data in a sustained manner as well as during events. These coupled networks can be combined with marine geospatial planning tools and high-resolution regional models nested with forecast models to provide forecasts with sufficient accuracy to assist in marine planning to mitigate physical changes (rising sea level, coastal inundation). The development of cheap and fast analysis systems that can be broadly distributed to coastal areas as well as developing nations will be important to address ecosystem and human-health issues on local, regional, and global scales.

Promote Sustainable Economic Vitality

The ocean infrastructure needs associated with economic vitality involve two disparate approaches. The first approach involves the identification of resources, whether food-based, energy, minerals and materials, or aesthetic and social (e.g., tourism, recreation). The second approach involves an assessment of the impacts of resource extraction or utilization, either to minimize environmental degradation or to ensure sustainable use. Observing systems will thus need to support improved understanding of the factors that enable efficient and effective resource extraction while increasing the understanding ocean ecosystem health, and providing the observational capability that will allow monitoring of commercial activity and its consequences. Examples include assessment of fisheries stocks, identification of the location and characteristics of potential energy sources from gas hydrates, or identification of the preferred sites of wind farms based on wind intensity, variability, and persistence. Each has specific observational requirements. For example, a better understanding of the distribution and characteristics of methane hydrates requires subsurface remote sensing and safe drilling capabilities. In contrast, surface-based radars, vector winds from space, and high-resolution models are required for site assessments for wind farms. Placing HF radars on offshore installations for such commercial activities as wind farms, aquaculture, or seafloor resource extraction is a desirable expansion of capability. Coastal and marine spatial planning will be needed to organize all of the competing uses in the ocean (CEQ, 2010).

In contrast, the determination of the environmental effects of industrial activity will involve repeated surveys or continuous monitoring to detect changes in ecosystem structure as well as process studies designed to understand ecosystem response to perturbations characteristic of industrial activity or commercial fisheries. Thus, infrastructure needs include efficient methods for a full suite of platforms and sensors for mapping the benthic environment, fluid sampling, measuring ocean properties, assessing ecosystem structure, and detecting changes that result from geoengineering or industrial activity. This argues for a complex and diverse set of infrastructure deployed at sites of major resource extraction.

Increase Fundamental Scientific Understanding

Infrastructure that can be used to address fundamental research questions need targeted observation, analysis, and modeling capabilities at specific spatial and temporal scales, which can be embedded in a larger dynamical context. Increases in fundamental understanding are built upon the global and regional infrastructure described in previous sections, but very often also enable the ability to address societal concerns. Needs highlighted in this section will not only support the fundamental science questions but will also help to achieve societal objectives discussed elsewhere in the report.

Sampling needs include novel biogeochemical sensors that are resistant to biofouling and adaptable for multiple platforms (e.g., ships, drifters, floats, AUVs, moorings) to study changes in ocean properties (e.g., acidification); advanced biological and genomic sensors to identify and quantify organisms from microbes to marine mammals (e.g., optical and acoustical techniques for zooplankton biomass and community structure); sensors that can sample the deep ocean biosphere to inform origin of life studies and to understand how life responds to various kinds of stresses; high-resolution analytical tools that enable detailed analysis of carbon components in the ocean; the capability to investigate sensory systems and organism communication in the ocean with advanced chemical, acoustic, and optical sensors on scales from microbes to whales; and satellite or airborne capabilities to study ocean-atmosphere fluxes (e.g., heat, radiative, mass, chemical, biological).

Other infrastructure required for fundamental understanding includes marine geospatial planning tools that are coupled to assimilative models in order to manage a variety of ocean observations; sustained observations of coastal seafloor boundary changes and fluxes via mapping, seismic, geomagnetic, drilling, borehole, and sediment-water interface observation; advanced downhole remote sensing tools to understand fluxes, processes, and reservoirs related to the formation of Earth's lithosphere; creation of subsurface acoustic positional networks;

development of advanced forecasting models with petascale or exascale[3] computing capabilities to address specific processes that require high-spatial-resolution computations; and seafloor cabled observatories, which provide a continuous high bandwidth and power for sampling a full range of geophysical variables, benthic communities, and the overlying water column.

SUMMARY OF OCEAN INFRASTRUCTURE RECOMMENDATIONS

Recommendation: To ensure that the United States has the capacity in 2030 to undertake and benefit from knowledge and innovations possible with oceanographic research, the nation should

- **Implement a comprehensive, long-term research fleet plan to retain access to the sea.**
- **Recover U.S. capability to access fully and partially ice-covered seas.**
- **Expand abilities for autonomous monitoring at a wide range of spatial and temporal scales with greater sensor and platform capabilities.**
- **Enable sustained, continuous time-series measurements.**
- **Maintain continuity of satellite remote sensing and communication capabilities for oceanographic data and sustain plans for new satellite platforms, sensors, and communication systems.**
- **Support continued innovation in ocean infrastructure development. Of particular note is the need to develop in situ sensors, especially biogeochemical sensors.**
- **Engage allied disciplines and diverse fields to leverage technological developments outside oceanography.**
- **Increase the number and capabilities of broadly accessible computing and modeling facilities with exascale or petascale capability that can be used for future oceanographic research needs.**
- **Establish broadly accessible virtual (distributed) data centers that have seamless integration of federal, state, and locally held databases, accompanying metadata compliant with proven standards, and intuitive archiving and synthesizing tools.**
- **Examine and adopt proven data management practices from allied disciplines.**
- **Facilitate broad community access to infrastructure assets, including mobile and fixed platforms and costly analytical equipment.**
- **Expand interdisciplinary education and promote a technically skilled workforce.**

[3] Most current computing is done at the terascale. Petascale, which is currently being developed, is 1,000 times faster than terascale. Exascale is another 1,000 times faster than petascale (NRC, 2008c).

Table 4.1. Summary of Shared Infrastructure Assets and Required Capabilities for 2030

Infrastructure Category and Essential Role in 2030	Capability to be Advanced	Capability to be Developed
MOBILE PLATFORMS		
Research Vessels		
Provide access to the sea for process study campaigns, event-driven responses, surveys and mapping, and routine monitoring. Ship-based work will be widely augmented with over-the-side platforms, as well as remote data and modeling results.	● Fleet planning as part of a national 5-10 year infrastructure review process, including platform construction, renewal, and onboard equipment upgrades	
	● Continued availability of special purpose ships that can also be used for general purpose research	
	● Flexibility in fleet scheduling, for efficient use, event response, and surge capacity	● International sharing agreements and possible leasing arrangements to meet special needs (demand for a surge, unforeseen events and special purpose capabilities like icebreaking or scientific ocean drilling)
	● Ability to meet increased demand for rapid launch and recovery for diverse arrays of autonomous platforms	● Simultaneous over-the-side operations (e.g., multiple autonomous platforms, towed systems, and/or submersibles, perhaps involving multiple wires)
	● Increased use of volunteer observing ships to collect and transmit underway scientific data to national repositories for verification and analysis	
SUBMERSIBLE PLATFORMS		
HOVs and ROVs		
Provide water column and seafloor access for process study campaigns, event-driven responses, surveys and mapping as well as routine monitoring, and sampling.	● Improved ability to recover water column, seafloor, and subseafloor samples	● Continued development of advanced ROV capabilities (e.g., higher power, greater depth ratings, sampling tools, sensors)
	● Broader ranges of biological, chemical, and optical sensors	
	● More sophisticated sonar systems for bathymetry and water column uses	
	● Advancements in underwater navigation for more precise and geodetic referenced vehicle locations	● Permanent, large-scale subsurface acoustic positional networks (analogous to GPS) for improved undersea navigation

	● Continued development of hybrid ROVs	
		● Broader use of nuclear submarines and air-independent propulsion submarines for polar research
Towed Systems		
Provide observations and sampling from near surface to just above the seafloor, with use on research vessels or ships of opportunity.	● Broader ranges of biological, chemical, and imaging sensors	● Reconnaissance sampling using high-speed data uplinks that allow for simultaneous video and sample recovery
Autonomous and Langrangian Systems (e.g., Drifters, Floats, Gliders, AUVs)		
Provide scalable, adaptable arrays with near real time observations for process study campaigns, event-driven responses, surveys and mapping, routine monitoring, and assimilation into forecast models.	● Scalable, multiplatform arrays capable of local, regional, and global-scale observations at broader ranges of spatial and temporal resolution	● Equip platforms with broader suites of multidisciplinary in situ sensors (detailed in section below on in situ sensors)
	● Improved battery power for increased mission duration, expanded range, and ability to support more sensors	● Autonomous refueling, at-sea energy harvesting, or other methods for replenishing or self-generating power
	● Expanded ocean depth capability for a variety of platforms ● AUVs with larger payloads, higher endurance, and ability to work in rough conditions (e.g., high currents, sea states, ice coverage) and at all expected working temperatures ● Improved under ice capability for all autonomous platforms	● Full ocean depth capability for a variety of platforms
		● Increased deployment options for autonomous platforms such as volunteer ships or aerial vehicles
	● Advancements in underwater navigation for more precise and geodetic referenced vehicle locations	● Permanent, large-scale subsurface acoustic positional networks (analogous to GPS) for improved undersea navigation
SHIPBOARD TECHNICAL SUPPORT		
Provide professional technical support to embarked research teams.	● Broader skill sets to keep pace with emerging new systems, techniques and communications	

DEVELOPMENTAL CONCEPTS		
Nuture long-term high-risk, high-reward infrastructure assets.	● Continued support for unique prototypes (e.g., benthic landers, AUV seaplanes)	● Autonomous refueling, at-sea energy harvesting, or other methods for self-generating power
FIXED PLATFORMS AND SYSTEMS		
Moorings		
Provide surface and water column observations with high spatial and temporal resolution, including persistence at key locations and groundtruth for remote sensing. Provide full integration with mobile autonomous systems.	● Continued, sustained support of centers for deep ocean mooring design, construction and deployment	
	● Ability for docking mobile autonomous systems (e.g., AUVs, benthic crawlers)	
Cabled Seafloor Observatories		
● Provide continuous real-time power and communication to coastal, deep ocean, and seafloor instruments and networks. Routine interactions with mobile autonomous systems.	● Ability for docking mobile autonomous systems (e.g., AUVs, benthic crawlers)	
		● Multiple data extraction modes (e.g., long range acoustic communication) ● Autonomous or manual release of automatically collected data capsules and samples
Borehole Sensor Systems		
● Provide routine and continuous in situ measurements of subseafloor properties (e.g., pressure, hydrology, geology, chemistry, biology).	● Continued developed of long-endurance sensors (e.g., chemical, physical) and clean systems for microbial studies	● Local energy harvesting and data telemetry (e.g., acoustic modems, LED offload to nearby transiting platforms)
	● Networking borehole sensors with cabled seafloor observatories for coupled studies of the subseafloor, the seafloor, and adjacent water column	
IN SITU SENSORS		
Provide essential measurements over very broad spatial and	● Advances in sensor technologies that increase	● Robust, long-endurance autonomy (e.g., communications, power) in all

temporal scales. Sensor suites mounted on multiple platforms provide continuous observations and sustained ocean presence.	survivability while decreasing power consumption and cost	environments including extremes of temperature, chemistry, and pressure
	● Sensor network capabilities to measure optical, physical, and biogeochemical properties (e.g., salinity, oxygen, pH, carbon export) ● Biofouling resistant sensors (especially for salinity), in order to increase longevity and mission duration ● Reliable, foul-proof sensors for the upper 5 m of the ocean and in coastal regions ● Long endurance sensors for deep ocean surveys ● Embedded underwater navigation for more precise and geodetic referenced sensor locations	
Physical		
Provide measurements essential to physical process studies and baseline dynamical contexts for biogeochemical sensors.	● Measurements of the exchange of mass (e.g., gases, aerosols, sea spray, water vapor), momentum, and energy (including heat) across the air-sea interface in a broad variety of conditions (e.g., high wind conditions, severe storms) ● Techniques to infer gas exchange under high wind conditions with chemically active (e.g., DMS) and inert (e.g., CO_2, Ar) atmospheric gases	
	● Fully networked and widely accessible data on river outflows, precipitation, and from tide gauges	● Optical imagery for spatial and temporal observations of ocean surface, estuarine, and riverine processes
Chemical		
Provide routine time-series measurements for major and trace elements, carbon species, nutrients, and pollutants in a broad range of environments.	● Observations of the carbon dioxide system (including pH), major and micronutrients, and elemental speciation of key micronutrients (such as iron) ● High-resolution analytical tools that enable detailed analysis of oceanic carbon	

	components	
	● More portable micronutrient analytical systems and speciation analysis for assessing micronutrient speciation and determining its influence on biological activity	
		● Sensor methods for surface micro-layer chemistry
	● Sensors for identification of chemical pollutants	● Cheap, easily available sampling systems for testing for chemical pollutants
Biological		
Provide routine measurements with small, inexpensive sensors that replicate current complicated laboratory techniques and yield data for developing coupled models.	● Development of methods to obtain organism-specific growth rates and advective, turbulent, and sinking fluxes	
	● Sensors for identification of plankton biomass and community structure—genetic, imaging, and acoustic	● Cheap, species survey sampling systems for broad distribution throughout coastal regions
	● Sensors for identification of higher trophic levels (e.g., fish, marine mammals)—genetic, imaging, and acoustic	● High throughput genomic, protionomic, metabolamic techniques
	● Sensors for toxin identification (including harmful algal blooms and pathogens)	● Cheap, small toxin sampling systems for broad distribution throughout coastal regions
		● Wide-area benthic sensors for seafloor mapping to provide estimates of benthic community state and function
Geological/Geophysical		
Provide measurements for understanding solid earth processes of the ocean crust and mitigating geohazards.	● Seafloor strain measurements (e.g., extensometer), seismic reflection and refraction to detect seismic events in remote areas of the ocean	● Global-scale, reliable, continuous sensor networks for real-time measurement and warning of seismic, volcanic or mass wasting events
	● Ability to measure bathymetry and processes occurring beneath and at the margins of glaciers, ice shelves, and sea ice including observations at the base of the ice canopy	
	● Deepwater mapping systems with better sensors (e.g., lower power) and automatic seafloor	● Wide-area benthic sensors for seafloor mapping at high resolution, including the ability to penetrate the

	classification algorithms ● EM sensors that provide proxies for crustal fluids	seafloor
SAMPLING SYSTEMS		
Provide systematic collection of physical samples for study, routine monitoring, and groundtruth of in situ sensors and remote sensing.		
Chemical		
	● Broader availability of uncontaminated systems and methods (e.g., GEOTRACES rosettes)	● Clean and compact systems that could be deployed on autonomous platforms and/or moorings
Biological		
	● Automatic classification for biological species including automated image recognition, tagging, and acoustic spectroscopy	
Geological		
	● Broader availability of shallow crust coring systems aboard multi-purpose or leased vessels ● Broader use of seafloor rock drills on purposed ROVs	
REMOTE SENSING		
Provide remote observations over broad temporal and spatial scales for sea surface height, temperature, and salinity; ocean color; winds; precipitation; ice; and radiation.	● Swath altimeters that provide higher resolution sea surface height fields and submesoscale (<10 km) resolution closer to the coast ● Improved coastal remote sensing algorithms for ocean color ● Nested imagery in order to scale spatial and temporal variabilities for comparison to point measurements ● Interferometer scatterometers that provide higher resolution wind fields closer to the coast ● LIDAR for near-surface ocean and ice sheet measurements	

	● Sensors that combine infrared and microwave channels to provide all-weather sea surface temperature fields with higher spatial and temporal resolution	● Higher spectral resolution ● Remote estimates of river outflows and tidal, surge, and inundation elevations ● More robust wetland remote sensing to include key biological, geological, and chemical parameters ● Capability to study ocean-atmosphere fluxes
Satellite		
Provide global to regional scale remote observations.	● Sustained gravity missions that inform crustal, ocean circulation, and geoid observations	● Geostationary ocean color and LIDAR remote sensing capability
Airborne		
Provide low-cost, regional to local-scale remote observations with adaptive and event-driven capabilities.	● Increased use of unmanned aerial vehicles for campaigns and monitoring ● Ability to remotely measure ocean surface and ice properties beneath cloud cover	● Use of commercial aircraft to collect and transmit ocean surface observations
Fixed Systems		
Extend observational systems to increasing numbers offshore, land, and ice locations for both fundamental research (e.g., coastal circulation models) and applied needs (e.g., search and rescue, safe offshore platform operations).	● Increased use of electro-optical and infrared instruments for monitoring and long time-series data ● Completion of the land-based HF radar network	● Extension of broad area surface current arrays (e.g., HF radar, optical imagery) to offshore activities (e.g., offshore platforms, wind farms, volunteer observing ships) ● Increased use of tethered aerial platforms ● Increased data gathering capabilities through expanded use of commercial ocean activities

MODELING AND COMPUTATIONAL INFRASTRUCTURE		
Community-based centers with capabilities for increased resolution models supporting basic research and operational assimilative predictions.	● Broadly accessible centers with exascale or petascale capability to support and run coupled models; store and manage vast amounts of diverse information; visualize, query and interpret data in four dimensions; and also mine, distill, and summarize key information ● Skillful parameterizations of upper ocean mixing, including production of marine aerosols and indirect climatic influences with reliable methods to separate marine aerosol from other type of aerosols (i.e., land, pollution) ● Regional predictions of anthropogenic CO_2 uptake and release ● Increased coupling of biogeochemical and physical models	● Direct assimilation of many additional channels of remotely sensed and in situ global array data (versus algorithmic or other preprocessing of the data).
	● Quantitative rate laws that can be incorporated into biogeochemical models ● Integration of the deep ocean with the shelf seas for ecosystem-based management, including safety and environmental impacts for various industrial activities	● Food web models that can accurately predict the competitive success of specific taxa ● Marine resource estimates for projected growth of industrial activities in the oceans
	● Coupled ice, ocean, and atmospheric models to predict ice movement and thickness and to link with observed changes in ecosystems and biogeochemical cycles in polar regions	
	● Coupled ocean, surface wave, and atmospheric models to improve simulations of severe storms pathways and coastal inundation	● High-resolution hurricane forecast models that are much more sensitive to effects of the ocean, adjacent coastal lands, and estuaries on storm intensity
	● Tsunami arrival times and inundation areas	● Advanced tsunami warning systems with low false-alarm rates for coastal residents, especially in developing and under-developed countries ● Estimating outcomes of geoengineering experiments
DATA MANAGEMENT		
Manage vast amounts of	● Improved approaches to	● International agreements to make

multidisciplinary data with high informational value for fundamental or applied research and societal use as well as ensure access for a broad base of users.	analyze data using common frameworks and interchangeable lexicon (e.g., informatics)	databases broadly accessible
	● Archiving and synthesizing tools for metadata and data	● Integrated, open access to local, state, and federal metadata and data resources
	● Protein data banks, sequencing facilities and databases, with metadata on instrumentation, calibrations, analytical sources of error ● Virtual (distributed) center for river outflow, precipitation, and tide gauge data ● Virtual (distributed) center for land dust transport, waves, surf conditions and surface currents from land, coastal and offshore sites ● Sustained, expanded, broadly accessible (distributed) virtual centers for bathymetry, sidescan, multibeam and seismic data storage	
DATA TELEMETRY AND COMMUNICATIONS		
Maintain and expand robust two-way communications for a broad range of ocean research infrastructure.	● Expand redundant, parallel, and standard communication pathways to avoid dependence on a single infrastructure provider	● Establish “store and forward” communication capabilities using industrial partners (e.g., passenger planes in high latitudes, offshore commercial operations, etc.)
ENABLING ORGANIZATIONS		
Sponsors		
Maintain U.S. ocean science strength through diversity of funding sources and the variety of sectors represented, ensuring flexibility in how research is performed and evaluated.	● Greater use of interagency and cross-sector programs (e.g., National Oceanographic Partnership Program)	● Increased private-sector participation via foundations and service sectors of the ocean industry (e.g., oil and gas, shipping)
Community Facilities and Centers		
Provide and sustain physical or virtual (distributed) advanced community-wide facilities for ocean research infrastructure where users can interact with cutting-edge technology in a manner that simplifies operations and maintenance	● Broader access to calibration standards and complex (chemical, genetic, optical, acoustic) analytical instruments	● Increased private-sector participation via foundations and service sectors of the ocean industry.

requirements and/or lowers purchase and operation costs.		
	● Shore-based laboratory that provide capabilities for high-throughput measurements and maintain complicated, expensive equipment	
	● Sustained expertise to continued operations and increased access to polar field stations	● Community facilities that support scientific operations in all types of extreme or remote environments
	● Biological laboratory facilities for constraining organism life history parameters for ecosystem models (e.g., sensitivity to temperature, nutrient concentration, presence of other organisms)	

5
Setting Priorities for Ocean Infrastructure Investments

The infrastructure and research investments required to address most of the compelling scientific questions are substantial. The development and maintenance of Earth observing systems have been a significant challenge for decades and major elements of the observing system are actually in decline (NRC, 2007b). Consequently, the competition for resources to develop and maintain the infrastructure needed to support scientific investigations is growing. A list of infrastructure requirements, matched to scientific questions and societal needs, is by itself insufficient guidance to ensure appropriate investment for infrastructure that will facilitate ocean research in 2030. Instead, it needs to be accompanied by mechanisms or criteria for prioritization.

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

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

This committee expands upon these proposed questions on the basis that ocean research infrastructure will increasingly be judged on its importance to society. Public investment in the research enterprise exists as part of a social contract, first articulated by Vannevar Bush in his seminal document, "Science the Endless Frontier" (Bush, 1945). It describes a framework in which investment in the basic sciences is motivated by benefits that are realized by the public (e.g., improvement in the standard of living, higher productivity, increased jobs, national security). Government research investments today are often connected to the societal benefits that might accrue, providing greater linkage between basic research and application than was implied in Bush's brief report. In this chapter, the committee describes a framework in which ocean infrastructure investments are prioritized by their potential societal contributions within an economic valuation. It is important to note that societal contributions for the public good can come in many forms, including the value of job creation or avoidance or mitigation of natural disasters. As the 20th century saw enormous investments in research motivated by the Cold War, the 21st century may see investments motivated by a wish to avoid or lessen the impact of environmental catastrophes.

Research infrastructure in place in 2030 will shape both the nature and quality of ocean science that is undertaken, as well as the value that this science will generate for informing policy and management decisions. As noted throughout the report, the degree to which ocean research infrastructure is of compelling importance to society can be judged based on potential contributions toward enabling stewardship of the environment, protecting life and property, promoting sustainable economic vitality, and increasing fundamental scientific understanding.

A PROCESS TO SET PRIORITIES

Each piece of infrastructure enables or supports a set of data collection and/or modeling activities, and therefore supports the production of information, which has value. The same piece of infrastructure also has a cost associated with it (e.g., building and maintaining a ship or computer model, training and supporting a technician, archiving and making accessible a data set). The task of prioritizing ocean research infrastructure investments can be interpreted as maximizing net benefits over time by choosing the best combination of infrastructure investments needed to address the science within budget constraints. The committee concedes that there may be other legitimate considerations beyond those spelled out in this report, but most likely these could all be incorporated into an economic optimization framework.

The bottom-up linkage from infrastructure to societal benefits shown in Figure 1.1 provides a useful approach to thinking about infrastructure priorities. An important feature of this prioritization is economy of scale and scope, as a given piece of infrastructure may support multiple research activities, models, and science questions. For example, a particular mooring may support multiple sensors, each sensor can supply data that feed into several models, and each model can contribute information to one or more societal objectives. In addition, a system of coordinated sensors can provide information that is more valuable than their individual contributions. An approach of this kind requires knowledge about the value (benefit) generated by specific information about the ocean and its contribution to achieving societal objectives; linkages between each piece of infrastructure and this specific information; and the cost of each piece of infrastructure.

The value of information (Howard, 1966; McCall, 1982; Nordhaus, 1986) relevant to societal objectives is determined by the degree to which the information allows decision makers to achieve an economically better outcome. The role of information is to reduce the uncertainty under which these decisions are made. For example, the societal objective of managing the nation's commercial marine fish stocks for maximum sustainable yield can be advanced by improving the quality of information represented by stock assessments and forecasts of fish stock abundance under different levels of fishing effort, environmental conditions, and ecological interactions. When information (e.g., stock assessments, forecasts, interactions between species within and across tropic levels) is less than perfect, fisheries managers must make decisions with greater uncertainty. Uncertainty can be addressed by either reducing the fish catch below the theoretical sustainable yield or by accepting an increased risk that the stock will be overexploited. If these assessments and forecasts were perfect, fisheries managers could allow fishing closer to maximum sustainable yield without risking overexploitation or other adverse ecological consequences. By increasing yield without reducing sustainability, the economic value of the fish stock to the nation could be maximized. The difference in economic outcomes with and without the information is its value.

While infrastructure costs can usually be determined with considerable accuracy, the value of information in most cases can only be estimated (e.g., Adams et al., 1995; Nordhaus and Popp, 1997; Teisberg and Weiher, 2000; Williamson et al., 2002). Certainty about the value of information from research investments decreases the further it is removed from helping to answer specific applied questions; this uncertainty is greatest for basic science investments, where the nature of the answers and their applications are by definition not well identified in advance. Uncertainty about the expected value of information from infrastructure investments arises from several sources, including uncertainty about the performance of new technologies, the nature of information generated by new technologies or research activities, and the value that the information will in fact generate. Uncertainty can lead to missed opportunities in commercial market assessments, when comparing a well-known market with an arguably better but less well defined market (e.g., the "Innovator's Dilemma" [Christensen, 1997]). Deep-mapping autonomous underwater vehicles (AUVs) provide an ocean technology market example. They are an example of a disruptive new technology introduced to the established seafloor survey market, which had relied upon deep towed systems prior to AUV use. Due to the established companies' hesitancy in adopting a new technology or because of their already significant investment in the existing technology, smaller survey companies using AUVs were able to quickly gain a strong market.

It is not necessary to have perfectly accurate estimates of the value of information in order to make reasonable prioritization decisions. It is necessary, however, to employ a rigorous and harmonized approach that will need to be undertaken at a national level—one that is consistent across and between all relevant agencies, and one that treats uncertainty about returns from investments in a systematic way. Uncertainty in making ocean research infrastructure choices can be addressed in part through mechanisms for the treatment of uncertainty in investment decisions (Dixit and Pindyck, 2010), and the emerging theory and practice of strategic decision making about real options in research and development (Trigeorgis, 1996). Much of this work is focused on investment in research and development by firms seeking to maximize profits from future technology improvements (Bowman and Moskowitz, 2001; Huchzermeier and Loch, 2001; Weeds, 2002; Gunther-McGrath and Nerkar, 2004; Wang and Hwang, 2007), but these problems are structurally analogous to the challenge facing government agencies as they seek to maximize return from research infrastructure investments.

Economic value estimations begin with mapping research questions to infrastructure requirements. In Chapter 4, the committee takes a first step in assembling the information needed to map infrastructure components to relevant ocean research questions for 2030. More detailed mapping of linkages between future infrastructure and information produced may require formal or informal simulation exercises (e.g., Observing System Simulation Experiments). As with the estimation of future economic benefits, there are limits to the precision with which this kind of mapping can be carried out; but development of a framework, however approximate, can indicate trends useful for prioritization. **The challenge of prioritizing ocean research infrastructure investments is best approached by estimating the economic costs and benefits of each potential infrastructure investment, and funding those investments (subject to budget constraints) that collectively produce the largest expected net benefit over time.** Indeed, the net societal benefit from investment in ocean science infrastructure is likely to be high. The process of prioritization needs to incorporate uncertainty in the value of information from future ocean science, including uncertainty about the economics of the societal interests, and uncertainty about the ability of future science to produce information relevant to those interests.

CONSIDERATIONS TO SET PRIORITIES

As mentioned throughout this report, the science research questions were selected based on their potential to contribute to four major societal objectives: **enabling stewardship of the environment, protecting life and property, promoting sustainable economic vitality, and increasing fundamental scientific understanding**.

The infrastructure needs required to address the broad range of ocean research questions can be prioritized using an economic framework that includes consideration of important criteria, such as:

1. **Ability to address the science**
2. **Affordability, efficiency, and longevity**
3. **Ability to serve other missions or applications**

Each of these major considerations, which are listed in the order in which they should be applied, encompasses a variety of other factors and questions that contribute to the determination of the value of ocean science and, by implication, the value of the infrastructure necessary to support that science.

Usefulness for addressing major science research questions

- How important is the infrastructure in addressing and resolving one or more science questions?
- How dependent is an area of research on the specific infrastructure?
- Does the infrastructure provide the appropriate level and quality of data? Are the measurements and analyses provided sufficient to support science and reduce uncertainty for decision making?
- What is the potential for quantum leaps in understanding or capability?

Affordability, efficiency, and longevity

- Is there an appropriate infrastructure portfolio to manage uncertainty?
- Does the infrastructure have design flexibility to take advantage of future trends in technology (e.g., through upgrades, component swap-out)?
- Does the infrastructure portfolio avoid redundancy with investments by nonocean industries or agencies?
- What is the unit cost of observation (cost per unique observation) provided by this infrastructure, and how does the cost compare to that of other forms of measurement for the same information?
- Is there an appropriate infrastructure portfolio to manage a combination of sustained, episodic, and event-driven requirements?
- Is the infrastructure broadly accessible to the ocean research community? Does it promote or leverage community talents or capabilities?
- Does the infrastructure leverage other sources of support (e.g., from states, international partnerships, public-private partnerships, or the private sector)?
- What is the balance between risk and potential benefits? Is risk managed appropriately (e.g., by spreading investment in technology development over several competing groups)?
- Is the infrastructure technologically mature, or are there limiting technological (or other) challenges?

Capacity to contribute to other missions or applications

- Does the infrastructure serve multiple science questions or applications that yield multiple benefits, especially across more than one domain or discipline?
- Does the infrastructure improve or enhance collaborations?
- Does the infrastructure serve other issues of national strategic importance (e.g., leadership in ocean science and technology, resource development, national security, education)?
- What is the potential for serving applications or missions in multiple agencies?

These considerations can assist in the process of determining costs and benefits to prioritize ocean research infrastructure investment decisions; such a process would optimistically result in a well-supported economic argument for a particular set of infrastructure investment priorities encompassing all federal agencies with a role in ocean research. In the process to optimize investments in ocean research infrastructure outlined above, decision makers (e.g., federal, state, and local governments) will naturally take into account subsidiary considerations that help define the net benefits associated with development, maintenance, and eventual replacement of specific infrastructure. Developing the detailed structure of that process and its application is beyond the scope of this report.

Recommendation: Development, maintenance, or replacement of ocean research infrastructure assets should be prioritized based on (1) usefulness for addressing important science questions; (2) affordability, efficiency, and longevity; and (3) ability to contribute to other missions or applications. Such prioritization will maximize societal benefit for the nation.

6
Maximizing Research Investments in Ocean Science

Chapter 5 defines the criteria that could be used to prioritize the development, maintenance, and eventual replacement of research infrastructure that will be needed to answer fundamental and applied scientific research related to the ocean. This chapter builds upon that discussion by including best practices that could be used to maximize the value of federal investments in ocean infrastructure for research: effectively managing existing resources; providing access to data, information, and facilities; fostering collaboration at several organizational levels; facilitating the transition of infrastructure from research to operational use; and ensuring the next generation of ocean science infrastructure.

These best practices are placed within a conceptual framework that follows the general development pathway of ocean infrastructure assets: prototype infrastructure is developed to respond to science needs; mature technologies are deployed in direct support of science; and finally, infrastructure is used for long-term, routine observation in support of numerous societal and scientific needs. Of course, there is not always a direct correspondence between infrastructure needed to conduct ocean science research and that needed to support long-term, routine monitoring of the ocean. However, an effective development process fully exploits the ability to successfully use both cutting-edge technology and infrastructure standardized for operational use. National investments can be further optimized if the observations related to routine monitoring are of a nature and quality sufficient to support primary research objectives.

This framework also recognizes the inherent collaborative, interdisciplinary, and multidisciplinary nature of ocean research, which is critical to its continued success. A number of recent reports (NRC, 1999, 2004b; ORRAP, 2007) address collaboration or interdisciplinary research, with conclusions that are applicable to this discussion. Overall, interdisciplinary research and collaboration have been increasing for decades. This is evidenced by an increased scope of new funding initiatives, newly generated academic fields and departments, and changes in both student interests and societal needs.

Ultimately, the success of ocean infrastructure will be measured by how well it enables advancement of the ocean sciences. Yet, there are recent indications that the process by which science is accomplished can be transformed in a data-rich environment (known as "The Fourth Paradigm"; Hey et al., 2009). In 1990, the user community of the ocean science infrastructure largely consisted of seagoing scientists who required access to ships and submersibles. In 2030, the user community will likely be quite different, with a greater percentage of scientists who interact with the ocean only remotely, through ocean data supplied via the internet. While the trajectory of science cannot be predicted, it seems likely that significant transformations are in store, and indeed will likely be enabled by a more effective ocean infrastructure. This argues above all for an ocean infrastructure which will be highly responsive to the needs of a changing ocean science enterprise.

EFFECTIVE MANAGEMENT OF RESOURCES

Coordinated Strategic Planning

As demonstrated in Chapters 2 and 3, oceanographic research in the next two decades will encompass a broad scope of scientific questions and require a wide assortment of ocean infrastructure assets. While long-range planning has often been advocated to promote the most efficient use of expensive assets such as ships, **the committee strongly believes that**

coordinated strategic planning for critical infrastructure assets needs to be established. In 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 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. It is expected that this could be done both within the agencies and collectively, through interagency coordination such as the Subcommittee on Ocean Science and Technology's (SOST's) Interagency Working Group on Ocean Partnerships. Engaging both the broad ocean research community and stakeholders advocating for societal needs could provide valuable insight into the planning process.

Life-Cycle Planning

Effective resource management for infrastructure requires long-term planning that takes into consideration the cost of support over its full life cycle. Beyond the initial cost of developing and deploying infrastructure assets, maintenance, operations, and upgrades can be significant cost factors. Yet, to sustain the required level of data quality from infrastructure, sufficient maintenance (including routine calibration) needs to be done on a regular basis. In addition, full life-cycle costs need to include support for training technical personnel to sustain infrastructure assets, for the user community to access them, and for student education to provide future scientists and technicians able to continue to utilize the assets. Full life-cycle planning would also need to take into consideration any interdependencies between ocean infrastructure assets, and how to best support and exploit those connections.

Periodic Reviews

It is important to periodically evaluate federally funded ocean research infrastructure in order to best decide where future investments should be made and where obsolete or underutilized assets could be discontinued. As a current example, the University-National Oceanographic Laboratory System (UNOLS) consortium regularly assesses its users, engages in internal plans for fleet improvement, and responds to external reviews. Another example is NASA's use of decadal surveys[1] (NRC, 2007b) to prioritize future space science needs. In a similar fashion, **community-based reviews of major infrastructure assets are periodically needed to account for changing societal needs, new or different facilities, technology developments, and development, maintenance, and replacement costs.** Timing of these reviews should be based on capabilities specific to different types of assets, including projected lifespan.

Efficient Use of Infrastructure

As part of the research proposal process, principal investigators could be required to justify that they are making efficient use of national infrastructure (if relevant to their project). This justification could be added as a criterion to be reviewed (for example, including "Efficient Use of Infrastructure" to "Intellectual Merit" and "Broader Impacts" during the National Science Foundation [NSF] proposal process) and could include a brief consideration of existing infrastructure; emerging technologies that could be effectively used; and/or justification for developing alternative assets that could potentially yield greater benefit than more traditional infrastructure capabilities.

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[1] http://science.nasa.gov/earth-science/decadal-surveys/

Asset Flexibility

Finally, current planning for ocean infrastructure does not reflect sufficient consideration of surge capacity in order to respond to unanticipated ocean incidents. As the ocean is increasingly used for large-scale human activity, major incidents and disasters will happen. This was evidenced by the *Deepwater Horizon* oil spill in the Gulf of Mexico, which resulted in repurposing academic and federal research vessels, individual investigator assets like gliders, and private commodities such as charter boats for incident response and cleanup. The federal investment could be maximized by ensuring that there are comprehensive plans in place to anticipate such events, with both adequate facilities and strategies to quickly deploy personnel and assets when needed. There are also opportunities to involve industries in planning, possibly during their permitting processes.

Recommendation: Federal ocean agencies should establish and maintain a coordinated national strategic plan for critical shared ocean infrastructure investment, maintenance, and retirement. Such a plan should focus on trends in scientific needs and advances in technology, while taking into consideration life-cycle costs, efficient use, surge capacity for unforeseen events, and new opportunities or national needs. The plan should be based upon a set of known priorities and updated through periodic reviews.

Recommendation: National shared ocean research infrastructure should be reviewed on a regular basis (every 5-10 years) for responsiveness to evolving scientific needs, cost effectiveness, data accessibility and quality, timely delivery of services, and ease of use in order to ensure optimal federal investment across a full range of ocean science research and societal needs.

PROVIDING ACCESS TO DATA, INFORMATION, AND FACILITIES

Efficient access to raw data, to information (data that has been processed and interpreted), and to capable facilities is critically important to the scientific enterprise and maximizes the return on investment in oceanographic data collection (Wright, 2005; Baker and Chandler, 2008; Mascarelli, 2009). Such access supports published literature, enables global syntheses of scientific knowledge, allows important confirmation and ground-truthing of results, enables rediscovery and reuse of data for novel purposes, facilitates informed policy making, and reduces decision uncertainties. Modern data management systems that are designed to reduce procedural, institutional, or cultural barriers to data access and to facilitate data-intensive scientific research are needed. An informatics approach, where computational, cognitive, and social aspects of information technologies are taken into account (Hey et al., 2009; Nativi and Fox, 2010), could assist federal agencies in realizing the full potential of their investments in ocean sciences (Helly et al., 2003; Baker and Chandler, 2008). Sound data management practices, substantial improvement of national data repositories, increased access and use of facilities, and engaging the public are best practices to implement this approach.

Sound Data Management Practices

Sound data management practices organize and optimize data so that they can be effectively retrieved, preserved, analyzed, integrated into new data sets, and shared across communities. Such practices include proper data documentation and curation, data accessibility, re-analysis of historical data, encouraging database growth through data set submission, implementing crossdisciplinary searching, and collaborative editing capabilities.

Data Documentation, Curation, and Quality Assurance and Quality Control

In general, proper data storage includes supporting metadata, quality and fitness-for-use statements, and measurement error or uncertainty estimates. This is critically important for ocean research, as data are often collected in remote, hard-to-access areas. Data management facilities need to support efficient archival services and provide the capability to migrate data to different formats as computer technologies evolve (e.g., Miller et al., 2009). The Marine Metadata Interoperability Project[2] and Quality Assurance of Real Time Oceanographic Data[3] are current examples of such efforts. Involving early career scientists in these and other activities will lead to better understanding of the fundamentals and implications of data reduction and quality management.

Making Data Searchable and Freely Accessible

Accessibility to data is an important management practice that requires well-tested, user-friendly services and protocols that continue to improve their utility, efficiency, and interoperability (e.g., Open Geospatial Consortium web mapping services; Lassoued et al., 2010). There is also a need to ensure that scientific results funded by federal agencies (including those data taken by agency scientists) are made available to the general public, not just those with access to scientific journals.

Curation and Reanalysis Capabilities for Historical Data

It is impossible to return to the time and location at which historic observations were made or measurements recorded. Resampling may not even be possible in all cases. Hence, long-term stewardship of data and metadata, including data rescue, are vitally important (NRC, 2009a; Porter, 2010; "Data for eternity," 2010, p. 219).

Encouraging Data Set Submission and Peer Review

An appropriate protocol that better enabled scientists to receive citation credit for posting their data in the public domain could encourage more investigators to release their data, and would also allow for better peer review of data sets (e.g., using digital object identifiers as is routine for journal articles; Parsons et al., 2010; Helly, 2010). Federal funding could be linked to mandatory data set submission, with additional funding withheld for noncompliant scientists.

Implementing Cross-disciplinary and Umbrella Searching

Umbrella searches would enable scientists from a variety of disciplines (e.g., atmospheric science, genetics, electrical engineering, computer science) to access oceanographic data. This approach requires the use of controlled vocabularies when providing metadata descriptions, which can be used to create thesauri in these cross-disciplinary catalogs as well as ordered groupings of spatial, thematic, and temporal reference objects; these, in turn, can be used to tag and link metadata and data (e.g., Isenor and Neiswender, 2009).

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[2] http://marinemetadata.org/

[3] http://nautilus.baruch.sc.edu/twiki/bin/view

Participatory, Collaborative Editing Capabilities
Collaborative online analysis of oceanographic data would allow scientific users to augment an existing data set with additional data or descriptions in order to improve the data set, add value, and provide context. This approach would be similar to the use of scientific wikis or crowd-sourcing, which are driven by the open-source software movement (e.g., Waldrop, 2008).

Improving National Data Repositories

Presently, data are still not always systematically archived at national data centers like the National Ocean Data Center, and archived data are rarely available in a timely manner—remarkable in an "information age." Additionally, while centralized facilities are an intuitive solution to data management, often the best arbiter of data quality is its original source, combined with collected comments of users and reviewers. National data repositories are likely to find more success by implementing a distributed system where local partnerships are used to gain access to data, allowing teams of data scientists, information managers, domain experts, and data originators to better enable data discovery and integration across systems. The partnerships could make use of a standards-based informatics approach designed to ensure effective access to and permanent archiving of data.

Program or project offices often serve as data repositories, facilitating the dissemination, preservation, and storage of research-related data. These types of offices generally ensure routine and consistent data delivery to national data centers, as well as routine and consistent data access for data assembly centers. Best practices for these offices include planning for data dissemination and data set archival when the program ends, which could logically be expected for all federally funded science programs (whether extramural or intramural).

Access and Best Use of Community-Wide Facilities

There are presently several examples of broadly accessible community-wide facilities in oceanography and allied disciplines, including those that provide sample analyses (e.g., National Ocean Sciences Accelerator Mass Spectrometry Facility for C^{14} dating; see Box 6.1), instruments (e.g., U.S. National Ocean Bottom Seismography Instrument Pool), modeling capability (e.g., the National Center for Atmospheric Research [NCAR] Community Earth System Model), and coordination of distributed assets (e.g., UNOLS, Incorporated Research Institutions for Seismology). These types of facilities are crucial for connecting people to needed resources that may be too expensive for one investigator, necessitate an array of many instruments for a limited time, or require specific calibrations or unique facilities. However, these facilities also promote interaction and opportunities for collaboration. Given the increased volume and complexity of data, it is likely that utilization of existing facilities will be increased and new facilities established as infrastructure needs are redefined. One example of such a facility is the Ocean Observatories Initiative,[4] which seeks to provide novel platforms and near real time data for research and education on a broad scale.

Federal agencies will need to prioritize investments and maximize value by recognizing which efforts are best serving their communities and continuing those investments, especially in those that employ contemporary approaches to information management (e.g., Baker and Chandler, 2008; Hey et al., 2009; NRC, 2009a; Nativi and Fox, 2010; Wright et al., 2010). These efforts use infomatics concepts to develop flexible information systems that support ongoing

[4] http://www.interactiveoceans.washington.edu/story/Ocean+Observatories+Initiative

maintenance, implementation, and dynamic redesign for both localized and broad-scale needs (Baker and Chandler, 2008).

Box 6.1
The National Ocean Sciences Accelerator Mass Spectrometry (NOSAMS) Facility

The creation of the NSF-supported NOSAMS facility (figure, below) at the Woods Hole Oceanographic Institution, in the late 1980s, was driven by a request from the World Ocean Circulation Experiment and Joint Global Ocean Flux Study planning committees. These were motivated by the recognition that radiocarbon was an important tracer of ocean circulation, ventilation, and carbon cycle processes. The development of accelerator mass spectrometry (AMS) radiocarbon measurements on seawater was an enabling technology. It reduced the water sample size requirements from approximately 200 liters to less than a liter, so that routine shipboard sampling could be achieved using traditional methods on hydrographic expeditions.

The development of a global ocean radiocarbon data set presents climate modelers with an important tool for testing model performance on a variety of spatial and temporal scales. The facility currently measures radiocarbon for a wide range of samples (including seawater, marine sediments, carbonates, and many kinds of organic materials), with applications ranging across paleoceanography, organic biogeochemistry, environmental forensics, and ocean circulation studies. Due to growing community demand for radiocarbon measurements, the analytical throughput of NOSAMS has grown from ~1,000 to over 6,000 samples per year over the last two decades.

The primary service that NOSAMS provides to the oceanographic community is “beginning to end” sample processing and measurement expertise. This allows individual investigators access to expertise and instrumentation that is too expensive and complex to be maintained locally. In a typical year, NOSAMS receives more than 500 batches of samples submitted by over 250 separate investigators. Advancement in methodologies has lowered the amount of carbon required for a precision measurement by an order of magnitude since the facility’s inception. NOSAMS has developed the first true continuous-flow AMS system, opening the door to coupled gas chromatography–continuous-flow accelerator mass spectrometry and other related methods. There is also economy of scale—the per-sample cost of measurement, as measured in constant dollars, has declined over the years while measurement quality has improved.

NOSAMS is funded on a renewable 5-year cooperative agreement, receiving about half of its support directly from NSF and garnering the remaining operational expenses from client fees. The fee structure is two-tiered, with U.S. federally funded researchers paying a subsidized price (about 50 percent of full cost). The advantage of this approach is that it provides some fiscal stability for the facility while encouraging a healthy level of market-driven dynamics. The facility is governed by an external advisory board that meets and reports on an annual basis to NSF, and there is also a midterm (2.5-year) review that is carried out by an NSF-appointed panel. The cooperative agreement is awarded via a peer-reviewed proposal; the last award, in Spring 2008, was the fifth. NSF will re-compete the facility for the next cycle and will likely issue the request for proposals in late 2011.

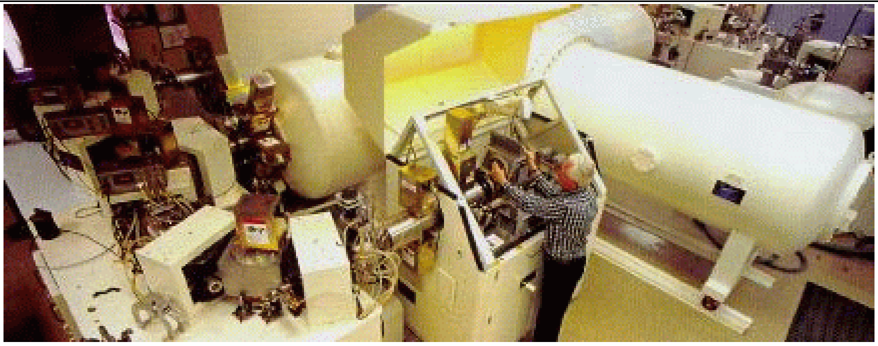

Figure. Photograph of Bob Schneider loading samples into the tandetron accelerator ca 1997. SOURCE: Tom Kleindinst, Woods Hole Oceanographic Institution.

Public Engagement

Data with supporting documentation will continue to become more publicly available as principles of data management are integrated into research programs (NRC, 2009a; Ryan et al., 2009; Stocks et al., 2009). As the proliferation of data portals and web mapping sites continues, the public is more likely to use oceanographic information if it is packaged in intuitive user interfaces that are targeted for specific stakeholder groups (e.g., currents for boating enthusiasts, fisheries data for resource managers and the commercial fishing community) but also address broader issues (e.g., ecosystem-based management, marine spatial planning, incident response). Improving data accessibility for general use also helps to foster a more science-literate society, a goal of the National Ocean Policy (CEQ, 2010).

The growing volume and complexity of ocean research data requires the use of sound data management practices, improvements to national, distributed data repositories, better accessibility and use of community-wide facilities, and increased engagement with stakeholders and the general public.

Looking Beyond the Ocean Sciences

It would be beneficial for federal agencies to periodically examine and adopt data management practices that come from beyond the ocean sciences, as well as approaches to grow access to and use of community-wide facilities. Proven efforts from beyond the ocean sciences can be very informative and helpful. Examples include NCAR, which provides to its community access to supercomputers, model development, source code, and over 8,000 Earth science data set collections.[5] Community-specific organizations that focus on data use and data quality will also be valuable to the ocean sciences (for example, the National Center for Ecological Analysis and Synthesis and the American Geophysical Union's Earth and Space Sciences Informatics Focus Group).

PROMOTING COLLABORATION

Substantial and meaningful collaboration between nations; across agencies; among federal, state, and local governments; among academic, government, nongovernmental, and industry sectors; and between disciplines will not only maximize the value of infrastructure investments but will in fact be required to meet the growing science and societal needs of 2030 and beyond. These partnerships will work at a maximum level when the goals, responsibilities,

[5] http://cdp.ucar.edu/home/home.htm

resources, and data sharing and limits are agreed upon at the onset. For the ocean research enterprise, these types of collaborations are inherently interdisciplinary and multidisciplinary. However, the overall success rates and effectiveness of all collaborations need to be substantially improved.

Between Nations

Working between nations presents the greatest challenges, but it also has the greatest potential gains. The global ocean is simply too large and has too many complex challenges for individual nations to manage. In order to make progress in the realm of international ocean infrastructure, explicit agreements on data sharing, permissions and security, resource allocation, and networking of system collections will be needed. Individual nations cannot sustain all innovative, continuous, frequent, or large-scale (e.g., global) sampling programs of interest. Instead, international collaborations, even among a few key contributors at a time, are essential to produce data that can be used in the study of large-scale or globally ranging processes, such as climate change or geohazards. Such collaborations are required to maintain networks of global satellite infrastructure for physical properties such as temperature, wind, or ocean color, for example. Intergovernmental bodies (such as the United Nations Educational, Scientific and Cultural Organization Intergovernmental Oceanographic Commission, which cosponsors the Voluntary Observing Ship program with the World Meteorological Organization) and political entities (e.g., the European Union) could be leveraged as vehicles to more efficiently utilize ocean infrastructure.

International collaboration also presents opportunities for capacity building and strengthening international relationships with developing nations. While agreements do exist between the United States and other nations, fundamental structural impediments prevent unified requests for proposals, joint proposal preparation, joint review, and joint funding of collaborative international projects. Too often the final review and funding become parallel processes, yielding multiple points of failure. These barriers need to be identified and lowered in order to have true international collaboration in ocean science research.

Across Federal Agencies

Because each federal agency has a different mandated mission, creating successful working relationships between agencies can be difficult. Institutional barriers between federal agencies, generally associated with varying missions and cultures, can prevent essential collaborations needed for planning operation and maintenance of critical, broad-scale, high-cost, ocean research infrastructure assets (including ships, observing systems, and satellites [see NRC, 2007b, for further discussion]). There are also barriers put in place by the legislative branch of government and the nature of the appropriations process. However, as evidenced by the National Oceanographic Partnership Program, interagency collaboration is indeed both feasible and fruitful. Science objectives, whether research-related or society-relevant, provide the focal point for collaboration, and both program managers and working level scientists need to be involved from the outset. An advocate for the "sum of the parts" is a useful mechanism to foster improved success (ORRAP, 2007). The ocean-related federal agencies also choose to fund their extramural research in different modes, involving varying criteria and peer-review roles. While these differences can lead to challenges for agency collaborations, research funding, and strategic choices for infrastructure assets, sponsor diversity has also generally been a means to foster competition and creativity.

Between Federal, State, and Local Governments

At the federal, state, and local levels, impediments to collaboration often stem from differences in missions, cultures, and available resources, as well as perceptions of overlapping jurisdiction. These differences will be greater than for federal agencies and therefore require more adaptation by participants to overcome the disparities. Successful collaboration can be built upon identification of mutual benefit between levels of government. For example, NOAA's Cooperative Institutes[6] promote collaboration and involvement between federal agencies and universities. The committee endorses the general approach found in the NRC report *Adapting to the Impacts of Climate Change* (NRC, 2010a), which combines federal coordination with state-based initiatives. As individual states move forward with plans to manage their ocean resources, strong collaboration between state governments, regional associations, and the federal government are likely to lead to better outcomes at all levels.

Among Academic, Government, Nongovernmental, and Industry Sectors

In expectation of increasing commercial ocean ventures by 2030 and growing debates about proper regulation of those activities, partnerships between sectors are likely to be needed to build and maintain infrastructure, particularly in the coastal ocean. However, differences in resources, skills, organizational cultures, and ranges of desired outcomes will also be much greater between these different sectors, and in fact there may often be little overlap. When working across these sectors, the focus will need to be on specific outcomes and timelines, with clear and explicit agreements on resources and any limits on information sharing. Organizations like the Consortium for Ocean Leadership,[7] whose members comprise oceanographic institutions, aquaria, and commercial companies, can facilitate linkages between these sectors.

Between Disciplines

The research community has inherent motivation to rapidly adopt knowledge and tools that enhance individual scientific endeavors. Impediments to collaboration across disciplines (whether ocean sciences or allied fields) stem primarily from the magnitude of current science and technology developments, as well as variations in culture and terminology, all of which pose significant challenges. Multidisciplinary and interdisciplinary science programs have been moderately successful in overcoming these challenges by defining their research programs in terms of the problems to be addressed as well as the inherent scientific issues. This approach is likely to continue to have advocates among the federal agencies, within industry, and increasingly, in academia.

Substantial collaboration on many levels is needed to maximize the nation's investment in ocean research infrastructure: between nations; among federal agencies; at local, state, and federal governments; between academic, industry, government, and nongovernmental sectors; and within and among ocean science and allied disciplines.

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[6] http://www.nrc.noaa.gov/ci/index.html
[7] http://www.oceanleadership.org/

Enabling Transition of Ocean Infrastructure from Research to Broader Societal Application

Many infrastructure capabilities developed by the scientific community for fundamental scientific research have broader applications. However, it is often challenging to create infrastructure that simultaneously meets both research and operational requirements. To address critical societal needs, it is expected that many ocean infrastructure assets will continue to evolve from a research context operated by principal investigators or research agencies to routine, sustained observing and monitoring resources operated by mission agencies, the private sector, or dedicated organizations (ORRAP, 2007). The sustained value of the investment, as well as measure of its successful transition, is dependent on continuing the data's scientific utility for a variety of purposes, from research to applications. Research and end user involvement, not just during the transition from research but also throughout the lifespan of the monitoring infrastructure, is a best practice that is also likely to optimize data quality at a level sufficient for scientific research (ORRAP, 2007). However, sustainable, reliable operations and data continuity are also dependent on adequate resources.

The meteorology community has developed approaches to address many of these issues, which could have direct applicability for ocean infrastructure (e.g., NRC, 2000b, 2003c). For example, the NOAA Climate Program Office's Transition of Research Applications to Climate Services[8] program was established to enable transition of mature climate information techniques, applications, and tools from research and development to sustained operations and services, where these products can be used by decision makers at a variety of levels. An analysis of lessons learned in meteorology with a view toward their applicability to ocean research infrastructure would be of considerable value to federal agencies and state and local governments.

Successful transitions between research and operations will also require engaging the commercial sector. While it is challenging to stimulate commercial investment, particularly with the constraint of limited market, broadening to industry helps to ensure viability and competitiveness. Federal agencies can play a role in this regard, particularly in effecting efficiencies and economies of scale. One way is to have industry-government collaborations in standardization and acquisition of potentially transitionable assets. Successful transition of technologies in various stages of maturation needs careful management of a number of dynamic balances as well as skilled, broadly experienced people.

Ocean infrastructure that can successfully transition from research to routine operational use is needed, especially in areas that have broad societal applications. Organizational mechanisms that enable scientific research user oversight of the capability through and after transition to routine operations are needed, as well as resources to ensure that data quality is known and remains of sufficient quality for research use.

Ensuring the Next Generation of Ocean Science Infrastructure

The technological foundations underpinning ocean infrastructure continue to evolve rapidly, enabling both incremental changes and revolutionary new capabilities. Development of future ocean research infrastructure will encourage exploration of new pathways to make successful technologies broadly available to the research and operational communities. New capabilities are also often accompanied by the creation of business opportunities that support

[8] http://www.climate.noaa.gov/cpo_pa/nctp/

economic growth. Best practices for encouraging the next generation of ocean infrastructure include allocating adequate resources for developing new innovations, which ensures continual improvement of research infrastructure; sustaining efforts into the long term (a decade or more), which allows research teams to pursue promising technologies for the full development-to-application cycle; and supporting refinement and validation of prototype technologies, building user awareness, and promoting early opportunities for commercial exploitation (e.g., through efforts like the Small Business Innovation Research Program, the Alliance for Coastal Technologies, or the Environmental Protection Agency's Environmental Technology Verification program [also see Chapter 3]).

While it is impossible to predict which technologies and capabilities will attract capital in the global marketplace of 2030, it is likely that many ocean science infrastructure components will appeal to only small markets. In these cases, incentives could be provided to develop assets that have potential to address societal needs (e.g., by reducing the cost of capital through government guarantees). In order to ensure that optimal investments transition from research to operation and commercialization, such considerations could be part of the 5-10 year formal infrastructure review.

In addition, encouraging "high-risk/high-reward" activities makes certain that novel approaches remain part of the technology portfolio, as does funding alternative, competitive development approaches as a means to mitigate risk while maximizing opportunity. Another method is to incentivize collaboration, which encourages communication and lowers barriers between oceanography and allied disciplines (e.g., medicine, engineering, computer science). A final but essential step is educating and training the next generation of engineers, technologists, and scientific users to create new capabilities in research infrastructure and continue the use of data generated.

Ensuring the next generation of ocean science research requires a competitive and innovative ocean research enterprise. This includes sustaining long-term efforts, encouraging high-risk activities, supporting technology maturation and validation, ensuring adequate resources, incentivizing collaboration, and promoting education and training for future scientists and engineers.

CONCLUDING REMARKS

The major science questions expected to be at the forefront of ocean science in 2030 will encompass a broad range of issues from fundamental inquiry to issues with great societal relevance. While it is likely that, due to unanticipated advances in technology, some of the questions in this report will be answered in the next two decades, others will continue to be of importance for decades beyond 2030. The categories of infrastructure, framework for investment prioritization, and ways to maximize research investments outlined in this report provide guidance that will enable the federal agencies and their partners (local and state governments, academia, ocean industries) to make wise choices when planning for the future ocean infrastructure investments. **Addressing the most significant oceanographic research and societal issues in 2030 will require a comprehensive range of infrastructure. As ocean science continues to evolve toward more interdisciplinary and multidisciplinary research, a growing suite of infrastructure is needed.**

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Appendix A

Committee and Staff Biographies

Committee

Eric J. Barron (Chair) is the president of Florida State University. Prior to this appointment he was the director of the National Center for Atmospheric Research, and before that he was dean of the Jackson School of Geosciences at the University of Texas at Austin. Before joining the University of Texas he served as dean of the College of Earth and Mineral Sciences at Pennsylvania State University. Dr. Barron's research interests are climatology, numerical modeling, and Earth history. During his career, he has worked diligently to promote the intersection of the geological sciences with the atmospheric sciences and the field of Earth system science. He has authored or coauthored more than 120 peer-reviewed papers in geology, oceanography, and climate. Dr. Barron chaired the Science Executive Committee for NASA's Earth Observing System and NASA's Earth Science and Applications Advisory Committee. He has also served as chair of the USGCRP Forum on Climate Modeling, the Allocation Panel for the Interagency Climate Simulation Laboratory, the U.S. National Committee for PAGES and the NSF Earth System History Panel. Dr. Barron has served on numerous National Research Council (NRC) committees, and was a repeat member of the Board on Atmospheric Sciences, and has also served as chair and co-chair of the board. Dr. Barron is a fellow of GSA, AGU, AMS, and AAAS. In 2002, he was named a fellow of the National Institute for Environmental Science at Cambridge University. In 2003, he received the NASA Distinguished Public Service Medal. He received a B.S. in geology from Florida State University and an M.S. and Ph.D. in oceanography from the University of Miami.

Rana Fine (Vice Chair) is a professor of marine and atmospheric chemistry at the University of Miami's Rosenstiel School of Marine and Atmospheric Science (RSMAS). Her current research objective is to better understand the role of the oceans in climate change, occurring on time scales of up to decades. She is interested in the physical processes that determine the oceans' capacity to take up atmospheric constituents such as carbon dioxide, especially through air-sea interactions and ocean mixing. She was the Elected President of the Ocean Sciences Section of the American Geophyscial Union from 1996 to 1998 and served on the WOCE Scientific Steering Committee. Dr. Fine is a former member of the Ocean Studies Board (OSB) and has served on several NRC committees related to oceanography; she recently served on the OSB Evolution of the National Oceanographic Research Fleet Committee. She is presently chair of the UCAR Board of Trustees. She received her Ph.D. from the University of Miami in 1975.

James Bellingham is Chief Technologist at the Monterey Bay Aquarium Research Institute. His personal research interests revolve around the development and use of autonomous underwater vehicles (AUVs). He has spent considerable time at sea, leading more than 20 AUV expeditions in locations such as the Antarctic, North Atlantic, Mediterranean, South Pacific, and the Arctic. At present he is developing a new class of long-endurance AUVs and associated control methodologies for biological process experiments. Dr. Bellingham founded the Autonomous Underwater Vehicle Laboratory at the Massachusetts Institute of Technology (MIT) and co-founded Bluefin Robotics Corporation, a leading manufacturer of AUVs for the military, commercial, and scientific markets. Jim presently serves on a number of advisory groups, including the Naval Research Advisory Committee and the Ocean X PRIZE. He has previously served on the Deep Submergence Science Committee, numerous National Science Foundation (NSF) and Office of Naval Research (ONR) advisory groups, as well as several NRC committees related to oceanography and naval research. His honors and awards include the Lockheed Martin Award for Ocean Science and Engineering, WHOI Steinbach Visiting Scholar, and the Fourteenth MIT Robert Bruce Wallace Lecture. Dr. Bellingham earned his Ph.D. in physics from MIT in 1988.

Emmanuel Boss is a professor at the School of Marine Sciences, University of Maine. He is an aquatic physicist who uses and develops novel sensing techniques to study aquatic biogeochemistry. He has coauthored more than 60 peer-reviewed scientific papers and book chapters. Dr. Boss serves as co-chief-editor of Biogeosciences as well as a member and external advisor to several national and international scientific committees and programs. Boss received a B.S. in mathematics and physics with minor in atmospheric sciences and an M.S. in oceanography from Hebrew University in Jerusalem, Israel. In 1997, he received a Ph.D. in oceanography from the University of Washington.

Ed Boyle (NAS) is a professor of ocean geochemistry at the Massachusetts Institute of Technology. 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. Dr. Boyle obtained some of the first valid data for several trace metals in the ocean (a field that had been plagued for decades by sample contamination and analytical problems). For the past 25 years, he has been tracking the evolution of the anthropogenic Pb transient in the ocean, from its first perceptible rise in the middle of the 19th century (based on sediment and annually banded coral records) through the decrease due to the phasing out of leaded gasoline. He has also worked on Pb and other anthropogenic trace metals in Greenland ice cores and estuaries. Dr. Boyle discovered that Fe in the deep southwest Pacific derives from distant hydrothermal vents. Additionally, he has shown that Cd in some species of benthic foraminifera tracks the Cd content of the bottom water they grow in, and has applied this finding to sediment cores to trace past changes in ocean deepwater 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 was the first to observe a predicted response of deep Atlantic Ocean chemistry to abrupt climate change during the Younger Dryas event 12,900 years ago. Dr. Boyle received a B.A. in chemistry from the University of California, San Diego, and a Ph.D. from the MIT/WHOI Joint Program in Oceanography. In 2008, Dr. Boyle was elected as a member of the National Academy of Sciences.

Margo Edwards is a senior research scientist and former director of the Hawaii Mapping Research Group with the Hawaii Institute of Geophysics and Planetology at the University of Hawaii at Manoa. Her current scientific research focuses on using mapping skills to search for disposed military munitions (DMMs) south of Pearl Harbor, Hawaii, in water depths from 300 to 550 m. Dr. Edwards is part of the Scientific Ice Expedition Science Advisory Committee, a collaborative project between the U.S. Navy and civilian scientists for geological and environmental research in the Arctic Ocean. She has served as the Chair of the University-National Oceanographic Laboratory System (UNOLS) Arctic Icebreaker Coordinating Committee from 2004 to 2007 and on the NRC Committee on Designing an Arctic Observing Network. Dr. Edwards earned her Ph.D. in marine geology and geophysics from Columbia University in 1992. Dr. Edwards most recently served on the NRC Committee on Evolution of the National Oceanographic Research Fleet.

Kenneth S. Johnson is a senior scientist at the Monterey Bay Aquarium Research Institute. Dr. Johnson was previously affiliated with the Moss Landing Marine Laboratories at San Jose State University. His research interests are focused on the development of new analytical methods for chemicals in seawater and application of these tools to studies of chemical cycling throughout the ocean. These methods have been used in a variety of studies of metal cycling in the ocean, including copper and iron metal speciation and oxidation. He has also developed a variety of sensors and analyzers that operate in situ to depths of 4,000 m, which have been used to study chemical species from deep-sea hydrothermal vent systems to nitrate in coastal ponds surrounded by intensive agricultural activities. He is a former chair of UNOLS, and has numerous publications which are accompanied by many honors in his field. Dr. Johnson has served on the NRC Committee on Reference Materials for Ocean Science, the Marine Chemistry Study Panel, and the Committee on Marine Environmental Monitoring. He received B.S. degrees in chemistry and oceanography from the University of Washington, in addition to a Ph.D. in oceanography from Oregon State University.

Deborah Kelley is a professor at the University of Washington's School of Oceanography. She is a marine geologist interested in understanding how submarine volcanoes and hydrothermal processes support life in the absence of sunlight. She also has an interest in how the concentrations and compositions of volcanic gases change as magmas deep within the seafloor cool, and how these gases are transported to the seafloor. Field areas that her work is currently focusing on include the Endeavour Segment of the Juan de Fuca Ridge, the accretionary margin off of Vancouver Island, and the Lost City hydrothermal field at 30°N on the Mid-Atlantic Ridge. Dr. Kelley also develops sensors for interdisciplinary studies of hydrothermal vents. She is the chair of the UNOLS Deep Submergence Science Steering Committee, Co-Chair of the Replacement Oversight Committee for the new Alvin submersible, and has previously served on the RIDGE Executive committee. She is the Project Scientist for the Regional Scale Nodes component of the NSF Ocean Observatories Initiative. Dr. Kelley received both a B.S. and an M.S. in geology from the University of Washington, and a Ph.D. in geology from Dalhousie University.

Hauke Kite-Powell is a research specialist at the Marine Policy Center of the Woods Hole Oceanographic Institution. His research focuses on public- and private-sector management issues for marine resources and the economic activities that depend on them. His current research projects include the policy issues surrounding costs and benefits from improved ocean observing activities; use of ocean space for nontraditional activities, such as wind power; and the economics and management of marine aquaculture operations. Dr. Kite-Powell served on the NRC Committee on Assessment of Technical Issues in the Automated Nautical Chart System, and is currently serving on the Committee on Best Practices for Shellfish Mariculture and the

Effects of Commercial Activities in Drake's Estero, Pt. Reyes National Seashore, California. Dr. Kite-Powell earned his Ph.D. in ocean systems management from MIT.

Steven Ramberg is a Distinguished Research Fellow at the Center for Technology and National Security Policy at the National Defense University (NDU) on assignment from the Applied Research Laboratory of Penn State University. At NDU he occupies the Chief of Naval Research Chair. During his career, he served as a fellow and as vice president for Arete Associates; as the Director of the NATO Undersea Research Centre (NURC) in LaSpezia, Italy; and as Director and Chief Scientist for ONR after joining ONR in 1988. His career at ONR also involved oversight of ocean, atmosphere and space programs in basic research through applied programs including the Navy-owned research vessels in the academic fleet as well as inaugurating the National Ocean Partnership Program (NOPP). Earlier, he worked at the Naval Research Laboratory, where he published over 60 unclassified papers in the archival literature on fluid dynamics of bluff bodies, nonlinear ocean waves, stratified wakes, turbulence near a free surface and related remote sensing topics.

Daniel L. Rudnick is currently a professor at Scripps Institution of Oceanography. Dr. Rudnick is an observational oceanographer whose research focuses on processes in the upper ocean. Of particular interest are fronts and eddies, air-sea interaction, the stirring and mixing of physical and biological tracers, and the effect of oceanic structure on acoustic propagation. He is keenly interested in observational instrumentation, having been involved in the use and/or development of moorings, towed and underway profilers, and autonomous underwater gliders, and has sailed on over 25 oceanographic cruises, over half as chief scientist. His work has led to over 50 peer-reviewed publications. Dr. Rudnick has served on various panels and committees for NSF, NOAA, and ONR. He was formerly the Deputy Director of Education at Scripps Institution of Oceanography, and he currently serves on the Ocean Studies Board and has recently chaired an NRC committee (Oceanography in 2025: A Workshop). He earned his Ph.D. in oceanography in 1987 from Scripps Institution of Oceanography, and his B.A. in physics at the University of California, San Diego.

Oscar Schofield is a professor at the Institute of Marine and Coastal Science at Rutgers University. His research interests include environmental regulation of primary productivity in aquatic ecosystems, physiological ecology of phytoplankton, hydrological optics, and integrated ocean observatories. He has been an active participant in the LEO-15 monitoring site at the Rutgers Coastal Ocean Observation Lab. He is involved with the cyberinfrastructure component of the Ocean Observatories Initiative, the Integrated Ocean Observing System, and works with the state of New Jersey on monitoring coastal water quality. Dr. Schofield serves as a member of the American Society of Limnologists and Oceanographers, Phycological Society of America, Oceanography Society, and the American Geophysical Union. He is an author on over 100 peer-reviewed publications. He has been chief scientist for almost a dozen research expeditions in addition to numerous seasonal field expeditions and over 150 one- to two-day expeditions. Dr. Schofield has served on the NRC Committee on Implementation of a Seafloor Observatory Network for Oceanographic Research.

Mario Tamburri is a research associate professor at the Chesapeake Biological Laboratory, University of Maryland Center for Environmental Science and the Executive Director of the

Alliance for Coastal Technologies (ACT). His research interests include chemical ecology of aquatic organisms, nonnative species, larval settlement and recruitment, and coastal sensor technologies. His current research projects include working with stakeholders in the ocean technology community to transition emerging technologies to operational use rapidly and effectively; maintain a dialogue among technology users, developers, and providers; identify technology needs and novel technologies; document technology performance and potential; and provide the Integrated Ocean Observing System with information required for the deployment of reliable and cost-effective networks. Dr. Tamburri received a B.S. from the University of California, Santa Barbara, an M.S. from University of Alabama, and a Ph.D. from the University of South Carolina in biology and marine science.

Peter Wiebe is a scientist emeritus at Woods Hole Oceanographic Institution. His research interests include the quantitative population ecology of zooplankton with emphasis on zooplankton small-scale distribution and abundance, organic matter transport into the deep sea, the biology of Gulf Stream Rings, zooplankton associated with deep-sea hydrothermal vents, dynamics of populations on Georges Bank and on the continental shelf region of the Western Antarctic Peninsula, acoustical determination of zooplankton biomass, abundance, and size, and the census of holozooplankton biodiversity in the world's oceans. He works with the Census of Marine Life and U.S. GLOBEC, is involved in instrumentation development to further studies of plankton, and has been a leader in the development and operation of a data management system for biological, physical, and chemical ocean data. He received a B.S. from North Arizona University in zoology and mathematics and a Ph.D. from the University of California, San Diego, in biological oceanography. Dr. Wiebe is a member of the American Association for the Advancement of Science (elected Fellow, May 1984), the American Society for Limnology and Oceanography, Phi Kappa Phi, and the American Geophysical Union. He has served the NRC as a member of the Committee on Undersea Vehicles and National Needs.

Dawn J. Wright is a professor of geography in the Department of Geosciences at Oregon State University and holds an adjunct professorship in the College of Oceanic and Atmospheric Sciences. She has authored or coauthored more than 85 articles and 5 books on marine geographic information systems, hydrothermal activity and tectonics of midocean ridges, and marine data modeling and cyberinfrastructure. Dr. Wright has participated in over 20 oceanographic research expeditions worldwide, including 10 legs of the Ocean Drilling Program and 3 dives in the Alvin submersible. Her research currently focuses on coastal/ocean cyberinfrastructure, geographic information science, benthic terrain and habitat characterization, and the processing and interpretation of high-resolution bathymetry and underwater videography and photography. Dr. Wright was a member of the NRC OSB/Board on Earth Sciences and Resources (BESR) Committee on National Needs in Coastal Mapping and Charting, and currently serves on the BESR Committee on Strategic Directions for the Geographical Sciences in the Next Decade, as well as the BESR Standing Committee on Geophysical and Environmental Data. She currently serves on the NRC Ocean Studies Board. Dr. Wright's awards include an NSF CAREER award, a Fulbright to Ireland, the Raymond C. Smith Distinguished Alumni Award from the University of California at Santa Barbara, and the Oregon State University Honors College Professor of the Year award. In 2007 she was named U.S. Professor of the Year for the state of Oregon by the Carnegie Foundation for the Advancement of Teaching and the Council for the Advancement and Support of Education. She earned an individual interdisciplinary Ph.D. in physical geography and marine geology from the University of California at Santa Barbara.

Staff

Deborah Glickson is a senior program officer with the Ocean Studies Board. 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 staff of the National Academies in 2008, she has worked on studies including *Realizing the Energy Potential of Methane Hydrate for the United States* (2010), *Science at Sea: Meeting Future Oceanographic Goals with a Robust Academic Research Fleet* (2009) and *Oceanography in 2025: Proceedings of a Workshop* (2009).

Heather Chiarello was a senior program assistant with the Ocean Studies Board until September 2010. She graduated Magna Cum Laude from Central Michigan University in 2007 with a B.S. in political science and a concentration in public administration. Heather joined the National Academies in July 2008. She is currently a senior program assistant with the Committee on International Security and Arms Control in the Policy and Global Affairs Division of the Academies.

Emily Oliver is a program assistant with the Ocean Studies Board. She graduated from Colgate University with Honors in Geography in 2010. Ms. Oliver joined the Academies in October 2010.

Appendix B

Speakers

Ocean Infrastructure Strategy Workshop, February 2-3, 2010 Held in Conjunction with Meeting 2 of the NRC Committee on an Ocean Infrastructure Strategy for U.S. Ocean Research in 2030

SESSION 1: FACILITIES

AL PLUEDDEMANN, Woods Hole Oceanographic Institution
"Sustained Time Series Observations – 2030"

PETE BARLETTO and JOHN DELANEY, University of Washington
"High bandwidth and Abundant Power: A Foundation for Next Generation Science in the Ocean Basins"

DOUG TOOMEY, University of Oregon
"Seismological Contributions to Understanding Earth's Dynamic Systems in 2030"

GWYN GRIFFITHS, National Oceanography Centre, Southampton
"The Evolving Nature of Ocean Infrastructure in the Hands of PIs, Facilities and Contractors"

JIM BELLINGHAM, Monterey Bay Aquarium Research Institute
"One Vision of Ocean Robots in 2030: Pervasive, Persistent, and Busy"

TIM LEACH , The Glosten Associates
"Designers View of Future Impacts on R/Vs"

SESSION 2: A DIFFERENT PERSPECTIVE

E. PAUL OBERLANDER, Woods Hole Oceanographic Institution
"Conceptual Illustration to Create a Vision of Ocean Infrastructure"

GUY NORDENSON, Princeton University/Guy Nordenson and Associates
"On the Water | Palisade Bay and MoMA/Rising Currents: Design Research and Analysis of a New New York Upper Harbor"

SESSION 3: INSTRUMENTATION

GINGER ARMBRUST, University of Washington
"Oceanography in the Genomics Era"

DEIRDRE MELDRUM, Arizona State University
"Swarming Sensorbots to Understand the Oceans"

LIZ KUJAWINSKI, Woods Hole Oceanographic Institution
"Organic Biogeochemistry: From Molecules to Microbes to Global Change"

BOB CARLSON, Honeywell
"Ocean Sensing and Instrumentation in 2030"

DAVE WHELAN, The Boeing Company
"Future Aerospace Systems"

TIM STANTON, Woods Hole Oceanographic Institution
"Sonar Remote Sensing of Marine Organisms in the Year 2030"

TOM WEBER, University of New Hampshire
"Some Thoughts on Acoustic Remote Sensing of the Ocean in 2030: Integrating and Expanding Approaches"

SESSION 4: DATA AND MODELING

BOB HALLBERG, NOAA Geophysical Fluid Dynamics Laboratory
"Global Ocean Simulation and Climate Projection Infrastructure Needs for 2030"

SHUYI CHEN, University of Miami
"Fully Coupled Modeling for Ocean Prediction in Coming Decades"

ENRIQUE CURCHITSER, Rutgers University
"Ocean Research (in 2030) as Part of the Earth System: A Modeler's Perspective"

PETER FOX, Rensselaer Polytechnic Institute
"Ocean and Marine Informatics in 2030"

DAN FAY, Microsoft
"Surfing the Oceans of Data to 2030: An eScience Perspective"

Appendix C

2010 Ocean Sciences Meeting, February 22-26

Session on "Ocean Technology and Infrastructure Needs for the Next 20 Years"
MT23A and MT35A

ORAL PRESENTATIONS (MT23A) – Tuesday, February 24, 2010

Presenter: JOHN DELANEY
Coauthors: Deborah Kelley, Kendra Daly, Douglas Luther
"A Rationale and Approach for Next-Generation Ocean Science"

Presenter: CHRIS SCHOLIN
"Development of 'Ecogenomic Sensors' for Use with Coastal and Global Ocean Observatories"

Presenter: PETER FOX
Coauthors: Suzanne Lawrence, Andrew R Maffei
"Bringing Informatics to the Forefront of an Ocean Infrastructure Strategy for U.S. Research by 2030"

Presenter: VIVKI LYNN FERRINI
Coauthors: Suzanne Carbotte, Andrew Maffei, Stephen Miller, Shawn Smith, Robert Arko, Cynthia Chandler, Karen Stocks, Mark Bourassa
"Transforming the Academic Fleet into and Integrated Global Observing System: The Rolling Deck to Repository (R2R) Program"

Presenter: NORMAN FARR
Coauthors: Maurice Tivey, Jonathan Ware, Clifford Pontbriand, Daniel Frye
"Integrated Optical/Acoustic Communications System for Deep Sea Data Transfer and Vehicle Control"

Presenter: KANNA RAJAN
Coauthors: Frederic Py, John Phillip Ryan
"The Role of Artificial Intelligence Techniques for Adaptive Robotic Observations"

Presenter: BRANDON SACKMANN
Coauthors: Mary Jane Perry, Eric D'Asaro, Craig Lee
"The Role of Artifical Intelligence Techniques for Adaptive Robotic Observations"

Presenter: KENNETH SEBENS
"Marine Laboratories: Ocean Infrastructure and Technology for Research and Education"

POSTER PRESENTATIONS (MT35A) – Wednesday, February 25, 2010

Presenter: LESTER LEMBKE-JENE
Coauthors: Bonnie Wolff-Boenisch, Roberto Azzolini, Paul Egerton, Joern Thiede
"Exploring the Polar Oceans in the 21st century – The European Research Icebreaker AURORA BOREALIS Project"

Presenter: DAVID FORUCCI
Coauthors: Dale N. Chayes, Steve Roberts
"Conducting Science at Sea in the Arctic; An Update on the Facilities and Support Aboard the US Coast Guard Icebreaker Healy"

Presenter: CLARE REIMERS
Coauthors: Annette M DeSilva, Dave Hebert
"A Report on the UNOLS 2009 Fleet Improvement Plan: Findings, Recommendations, and Implementation"

Presenter: DEBORAH GLICKSON
Coauthors: Ronald Kiss, Richard Pittenger, Francisco Chavez, Margo Edwards, Rana Fine, Nancy Rabalais, Eric Saltzman, James Swift, William Wilcock, Dana Yoerger
"Science at Sea: Meeting Future Oceanographic Goals with a Robust Academic Research Fleet"

Presenter: JAY PEARLMAN
Coauthors: Daniel Rudnick, Mary Jane Perry, Robert Holman, Deborah Glickson
"What Does the Future Hold? – Thoughts from the 2009 'Oceanography in 2025' Workshop"

Presenter: DANIEL SCHWARTZ
Coauthor: Philip A McGillivary
"Autonomous Air and Sea Systems as Components of Future Ocean Science Infrastructure: Status, Needs and Barriers"

Presenter: W. WILSON
"Meeting U.S. Needs for Sustained, Systematic Observations of the Oceans from Satellites"

Presenter: JOAQUIN HERNANDEZ-BRITO
Coauthors: Eric Delory, Octavio Llinas
"PLOCAN: a Permanent Observing System for the Central-Eastern Atlantic Ocean"

Presenter: EDWARD ROGGENSTEIN

Coauthors: David Finnegan, Robert Heitsenrether, Mark Bushnell
"Development of Iridium Short Burst Data Messaging for Reliable Data Transmission and Potential for Event-Driven Two-Way Communications"

Presenter: EDWARD DEVER
Coauthors: John Kemp, Don Peters, Walt Waldorf, Chris Wingard, Toby Martin, Craig Risien
"Recent Shallow Water Mooring Test Results off Newport, OR"

Presenter: DAVID FISSEL
Coauthors: Thomas Helzel, Vincent Mariette, Marc Pavec, David Lemon
"Coastal Radar 'WERA', a Tool for Hazards Management"

Presenter: JNANESHWAR DAS
"Towards Model Based Autonomy for Marine Bloom Prediction and Tracking with Multiple AUVs"

Presenter: JONATHAN BERGER
Coauthors: Kanna Rajan, Frederic Py, David A. Caron, Gaurav Sukhatme
"The Extended Draft Platform: A High Power, High Bandwidth, Deep Ocean Science Observatory"

Presenter: GARETH LAWSON
Coauthors: Andone C. Lavery, Peter Wiebe
"Current Technological Developments and Future Needs for Quantifying the Distribution and Abundance of Marine Zooplankton"

Presenter: ANDREY ZATSEPIN
Coauthors: Alexander Ostrovskii, Dmitriy Shvoev, Vladimir Solovyev
"Ocean Moored Profiler Aqualog"

Presenter: JOHN ORCUTT
Coauthors: Frank L. Vernon, Cheryl L Peach, Matthew Arrott, Alan D Chave, Oscar Schofield, Michael J Meisinger, Claudiu Farcas, Emilia Farcas, Ingolf Krueger, Jack Kleinert
"The Cyberinfrastructure Model for the NSF Ocean Observatories Initiative: A 20-year Prospective"

Presenter: STEVEN FOLEY
Coauthors: Jonathan Berger, John A. Orcutt, Frank L. Vernon
"Advanced Communications for Remote Ocean Platforms in the Coming 15 Years"

Presenter: PETER WORCESTER
Coauthor: Brian D. Dushaw
"A Global Ocean Acoustic Observing Network"

Presenter: JOHN MORROW
Coauthors: Randall Lind, Standord Hooker, Germar Bernhard, Charles Booth

“Recent Advances in Shallow Coastal Radiometry”

Appendix D

Acronym List

ADCP	Acoustic Doppler Current Profiler
AGU	American Geophysical Union
AMS	Accelerator Mass Spectrometry
ASV	Autonomous Surface Vessels
AUV	Autonomous Underwater Vehicle
CHIRP	Compressed High Intensity Radar Pulse
CODAR	Coastal Ocean Dynamics Applications Radar
CORK	Circulation Obviation Retrofit Kit
CTD	Conductivity, Temperature and Depth
DARPA	Defense Advanced Research Projects Agency
DOC	Dissolved Organic Carbon
DONET	Dense Oceanfloor Network System for Earthquakes and Tsunamis
DVL	Doppler Velocity Log
EM	Electromagnetic
ENSO	El Niño/Southern Oscillation
EPA	Environmental Protection Agency
GC-GFAMS	Gas Chromatography–Continuous-Flow Accelerator Mass Spectrometry
GEOSS	Global Earth Observation System of Systems
GPS	Global Positioning System
HF	High Frequency
HOT	Hawaii Ocean Time-series
HOV	Human Operated Vehicle
IODP	Interagency Ocean Drilling Program
IPCC	Intergovernmental Panel on Climate Change
IRIS	Incorporated Research Institutions for Seismology
JGOFS	Joint Global Ocean Flux Study
JOIDES	Joint Oceanographic Institutions for Deep Earth Sampling
LIDAR	Light Detection and Ranging
MBARI	Monterey Bay Aquarium Research Institute
MODIS	Moderate Resolution Imaging Spectroradiometer

NAO	North Atlantic Oscillation
NASA	National Aeronautics and Space Administration
NAVO	The Naval Oceanographic Office
NCAR	National Center for Atmospheric Research
NDSF	National Deep Submergence Facility
NOAA	National Oceanic and Atmospheric Administration
NOP	National Ocean Policy
NOPP	National Oceanographic Partnership Program
NOSAMS	National Ocean Sciences Accelerator Mass Spectrometry
NRC	National Research Council
NSF	National Science Foundation
ODP	Ocean Drilling Program
ONR	Office of Naval Research
OSSE	Observing System Simulation Experiments
PDO	Pacific Decadal Oscillation
PCB	Polychlorinated Biphenyl
ROV	Remotely Operated Vehicle
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SOST	Subcommittee on Ocean Science and Technology
SST	Sea Surface Temperatures
UAV	Unmanned Aerial Vehicle
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNOLS	University-National Oceanographic Laboratory System
USCOP	U.S. Commission on Ocean Policy
WHOI	Woods Hole Oceanographic Institution
WOCE	World Ocean Circulation Experiment