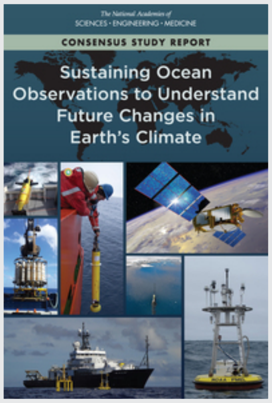

Sustaining Ocean Observations to Understand Future Changes in Earth's Climate

DETAILS

150 pages | 6 x 9 | PAPERBACK
ISBN 978-0-309-46680-6 | DOI 10.17226/24919

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Sustaining Ocean Observations to Understand Future Changes in Earth's Climate

Committee on Sustaining Ocean Observations to Understand Future Changes in Earth's Climate

Ocean Studies Board

Board on Atmospheric Sciences and Climate

Division on Earth and Life Studies

A Consensus Study Report of

The National Academies of
SCIENCES · ENGINEERING · MEDICINE

THE NATIONAL ACADEMIES PRESS
Washington, DC
www.nap.edu

THE NATIONAL ACADEMIES PRESS 500 Fifth Street, NW Washington, DC 20001

This activity was supported by the National Oceanic and Atmospheric Administration under Award Number WC133R-11-CQ-0048 and the National Academy of Sciences' Arthur L. Day Fund. Any opinions, findings, conclusions, or recommendations expressed in this publication do not necessarily reflect the views of any organization or agency that provided support for the project.

International Standard Book Number-13: 978-0-309-46680-6
International Standard Book Number-10: 0-309-46680-6
Digital Object Identifier: https://doi.org/10.17226/24919

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

Printed in the United States of America

Cover image credits: Upper left, NOAA AOML; Upper middle, Climate Central/SOCCOM (https://soccom.princeton.edu/); Upper right, NASA; Middle, Argo Program (http://www.argo.ucsd.edu/, http://doi.org/10.17882/42182); Lower right, NOAA PMEL; Lower left, Hans Graber, University of Miami; Middle left, NOAA AOML.

Suggested citation: The National Academies of Sciences, Engineering, and Medicine. 2017. *Sustaining Ocean Observations to Understand Future Changes in Earth's Climate*. Washington, DC: The National Academies Press. doi: https://doi.org/10.17226/24919.

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Acknowledgments

This report was greatly enhanced by discussions with participants at the Committee's meetings and workshops as part of this study. The Committee would like to acknowledge, especially, the efforts of those who gave presentations at the Committee meetings: Krisa Arzayus (NOAA), Cynthia Atherton (Heising-Simons Foundation), Jim Baker (Clinton Foundation), Molly Baringer (NOAA), Annalisa Bracco (Georgia Institute of Technology), Ryan Carlon (Liquid Robotics), Andy Clark (Marine Technology Society), Emmett Duffy (Smithsonian Institution), Michael Freilich (NASA), Katy Hill (World Meteorological Organization), John Holdren (White House Office of Science and Technology Policy), Greg Johnson (NOAA), David Legler (NOAA), Adena Leibman (Office of Senator Whitehouse), Eric Lindstrom (NASA, Global Ocean Observing System), Craig McLean (NOAA), Marcia McNutt (National Academy of Sciences), Gary Mitchum (University of South Florida), Rick Murray (National Science Foundation), Mike Patterson (U.S. CLIVAR Project Office), Allison Reed (U.S. Department of State), Spencer Reeder (Paul Allen Foundation), Kathleen Ritzman (Scripps Institution of Oceanography), Chris Sabine (NOAA), Ray Schmitt (Woods Hole Oceanographic Institution), Sophie Seeyave (Partnership for Observation of the Global Oceans), Rick Spinrad (NOAA), Jed Sundwall (Amazon Web Services, Inc.), John Trowbridge (Woods Hole Oceanographic Institution), Roger Wakimoto (National Science Foundation), Stan Wilson (NOAA), Zdenka Willis (Integrated Ocean Observing System), Bob Winokur (Michigan Technological University), Nathalie Zilberman (Scripps Institution of Oceanography). The committee would also like to thank staff at JCOMMOPS for providing data on observing programs used in the tables and figures of the report.

This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, 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 thank the following individuals for their review of this report:

Melbourne Briscoe, Ocean Geeks, LLC
David Halpern, Jet Propulsion Laboratory
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Carl Wunsch, Massachusetts Institute of Technology

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the report's conclusions or recommendations, nor did they see the final draft of the report before the release. The review of this report was overseen by **Robert Duce,** Texas A&M University, College Station, and **William Young,** Scripps Institution of Oceanography. They were responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

Preface

The global ocean covers some 70 percent of the Earth's surface. In responding to the growing awareness that the ocean plays a key role in the climate of the Earth, its variability, and change in the climate, many nations and a number of intergovernmental agencies have moved forward to support and coordinate sustained observing of the ocean. Yet, there are many challenges that arise in building toward an observing system that reaches to include the remote regions and full depths of the ocean.

At meetings of the ocean science community in recent years, Carl Wunsch, D. James Baker, and Ray Schmitt have given talks and led Town Hall meetings to stimulate the community to think of how best to proceed to develop a plan and support for sustained ocean observing. They brought the National Academies of Sciences, Engineering, and Medicine into the dialog, and this study, funded by the National Academies' Arthur L. Day Fund with additional support from the National Oceanic and Atmospheric Administration, is one result.

The Ocean Studies Board of the National Academies developed the statement of task for this committee, inspired by discussions with Carl Wunsch, D. James Baker, and Ray Schmitt. Notionally, a two-phase approach to this topic of sustaining ocean observations to understand future changes in Earth's climate was developed. In the first stage, which is the work of this committee, the goals include considerations of what observations are most critical, of the specifications for those observations, of the present approaches to sustained ocean observing, and of the challenges to long-term ocean observing. A second stage was also discussed, where new models or approaches to sustained ocean observing would be pursued.

This report builds on the inputs from many in the ocean science community, reflecting what was learned at a workshop convened by the committee and a number of invited presentations. The contributors are listed in the Acknowledgments section. The committee is also greatly indebted to Study Directors Susan Roberts and Emily Twigg, April Melvin, and staff from the Ocean Studies Board and the Board on Atmospheric Sciences and Climate. This report came to fruition through their efforts.

Mary Glackin and Robert A. Weller, *Committee Co-Chairs*

Contents

Summary

The ocean is an integral component of the Earth's climate system. It covers about 70 percent of the Earth's surface and acts as its primary reservoir of heat and carbon, absorbing over 90 percent of the surplus heat and about 30 percent of the carbon dioxide (CO_2) associated with human activities, and receiving close to 100 percent of fresh water lost from land ice. Heat and CO_2 are absorbed at the ocean's surface and transported throughout the ocean depths through the overturning circulation. Although exchange across the ocean's turbulent surface boundary layer can happen rapidly, in hours or days, and significant exchange of water between the boundary layer and the stratified main thermocline occurs over timescales of years to decades, deep water takes many decades to millennia to return to the surface, acting as long-term storage for heat and CO_2 and thereby lessening the near-term impacts of climate change. Because of the long timescales governing the exchange of heat, carbon, and fresh water in the ocean, long-term observational datasets spanning many decades are required to fully document, understand, and predict the climate system, and to detect and attribute changes driven by human activities.

VALUE OF SUSTAINED OBSERVATIONS

With the accumulation of greenhouse gases in the atmosphere, notably CO_2 from fossil fuel combustion, the Earth's climate is now changing more rapidly than at any time since the advent of human societies. Society will increasingly face complex decisions about how to mitigate the adverse impacts of climate change such as droughts, sea-level rise, ocean acidification, species loss, changes to growing seasons, and stronger and possibly more frequent storms. To

BOX S.1
What Are Ocean Observations for Climate?

- Ocean observations are made using both **satellite** and **in situ** (located within the water) instrumentation.
- In situ observations are carried out using **fixed and mobile platforms** such as tide gauges, data buoys, moorings, ship-based observations, profiling floats, ocean gliders, and surface drifters.
- Priority **ocean variables observed for climate** are sea state, ocean surface stress, sea ice, sea surface height, sea surface temperature, subsurface temperature, surface currents, subsurface currents, sea surface salinity, subsurface salinity, ocean surface heat flux, and dissolved inorganic carbon.
- The ocean observing enterprise is an **end-to-end system** built on engineering, operations, data management, information products, and the associated human capabilities, which are supported by the planning and governance by international coordination entities and by regional and national agencies.

make informed decisions, policy makers will need information that depends on understanding the dynamics of the planet's climate system. Because these dynamics will evolve as the climate warms, the ability to anticipate and predict future climate change will depend on ongoing observations of key climate parameters to tune and enhance models. Observations play a foundational role in documenting the state and variability of components of the climate system and facilitating climate prediction and scenario development. Regular and consistent collection of ocean observations over decades to centuries would monitor the Earth's main reservoirs of heat, CO_2, and water and provides a critical record of long-term change and variability over multiple timescales. Sustained high-quality observations (described in Box S.1) are also needed to test and improve climate models, which provide insights into the future climate system. With knowledge gained through these observations and models, more informed decisions can be made about how to respond and adapt to the impacts of climate change on national security, the economy, and society.

STUDY TASK AND APPROACH

This study committee was charged with considering processes for identifying priority ocean observations that will improve understanding of the Earth's climate processes, and the challenges associated with sustaining these observations over long time frames (see Box S.2 for the Statement of Task). International bodies, the Global Climate Observing System (GCOS) and the Global Ocean Observing

System (GOOS), established to coordinate observing activities among nations have developed processes for identifying and developing specifications for the highest priority ocean climate observations. The committee reviewed these processes and determined that they represent a robust approach to identifying Essential Climate Variables (ECVs) and Essential Ocean Variables (EOVs) and the requirements for observing these variables. Recognizing the value of this international consensus process, the committee focused its attention on the "challenges to maintaining long-term observations and suggest[ing] avenues for potential improvement." These challenges are described in this report and conclusions addressing approaches for overcoming these challenges are provided.

BOX S.2
Statement of Task

Maintaining long-term, continuous, ocean-data records for understanding, monitoring changes in, and modeling climate changes are essential, yet, challenging. An ad hoc committee will consider processes for identifying and characterizing the most critical, long-term ocean observations and identify limitations of the current approaches.

When considering the various processes for selecting and characterizing high-priority, long-term ocean observations, the committee will discuss potential factors such as:

- Accuracy, precision, frequency, and spatial resolution of observations;
- Duration of observations (e.g., what criteria would be used to determine when observations should be sustained at high priority, are no longer needed for a given parameter or when an observation would be superseded by a different type of observation, for example through a new/different technology);
- Inherent value and/or tradeoffs of increasing multidisciplinary observations across a limited number of networks/platforms vs initiating additional observing systems;
- Complementarity of an observation to another set of observations (or network); and
- Current or near-future technology that could be used to develop a more cost-effective observational system.

The committee's report will identify challenges to maintaining long-term observations and suggest avenues for potential improvement. During the study, the committee will convene a workshop to gather expert opinions on the process for prioritizing long-term, ocean climate observations and discuss international approaches to selecting and sustaining ocean observations, as well as other topics that are important for the design of sustainable, long-term ocean observing systems.

The Statement of Task directed the committee to focus on ocean observations for climate; hence the work of the committee considered the priority variables that are most needed to address the ocean's role in climate. However, the committee recognizes that there are important ocean variables to observe outside of the scope of this study, such as observations of shorter term phenomena and of the impacts of a changing climate on ecosystems.

HEAT, CARBON, AND FRESH WATER BUDGETS

This report identifies three distinct global budgets that help define critical observations for understanding climate: heat, carbon, and fresh water. These were selected because of the central role the ocean plays in each and for their ability to inform climate model projections and detect changes within the climate system. Ocean observations have contributed to vital insights into changes in these budgets and informed understanding of other related ocean changes, such as sea-level rise. Uninterrupted time series of observations are required to distinguish natural variability of ocean processes from changing long-term climate trends. Although ocean general circulation models employ data assimilation methods to estimate the state of the ocean and provide quantitative estimates of how well the observations constrain these budgets, closing these budgets will require extension of ocean climate observations to the full depth of the ocean and into poorly sampled regions such as the polar seas. Additional research will be needed to develop the advanced observing capabilities needed to quantify the full suite of processes contributing to each budget.

Heat Budget

Ocean warming accounts for about 90 percent of the net global surface heat gain. Hence, accurate estimates of ocean heat content provide a fundamental index of the present climate system that also will be a determinant of future global surface warming as ocean circulation returns heat stored in the depths to the sea surface. Because heat absorbed by surface ocean waters is transported laterally and vertically through the depth layers and basins of the ocean via mixing and currents, there is no single variable that can be measured to determine ocean warming. On a regional basis, closure of the heat budget requires observations of ocean heat content, air-sea heat exchange, heat transport by ocean currents, and mixing, whereas the global balance is between the global integrals of heat gain and air-sea flux. The challenges for measuring temperature in the ocean (as a measure of heat content) have been to sufficiently sample spatially (across the global extent and full depth of the ocean) and frequently enough to account for the temperature variability induced by global ocean circulation, air-sea fluxes, and mixing.

Carbon Budget

About 30 percent of the CO_2 released by human activities has been absorbed by the ocean, reducing the amount in the atmosphere and the associated greenhouse effect. However, dissolved CO_2 becomes a weak acid that lowers the pH of sea water, a phenomenon termed ocean acidification, which will limit the capacity of the ocean to absorb more CO_2 in the future and can have negative effects on marine life. Other carbon sinks exist in the ocean, but the dissolution of CO_2 from the atmosphere is by far the main ocean carbon sink on a decadal-to-century time frame. Closure of the carbon budget requires measurement of either surface water partial pressure of CO_2 (pCO_2) or pH, total dissolved CO_2 and alkalinity.

Fresh Water Budget

The fresh water budget is important for understanding changes in the salinity of the ocean, a parameter that influences ocean circulation due to stratification, and therefore heat and carbon exchange between the ocean surface and the atmosphere. Ocean salinity is a measure of the salt content of sea water; it is decreased by dilution (through fresh water input from precipitation, river outflows and surface runoff, or ice melt) and increased by evaporation. Evaluation of the fresh water budget requires observations of salinity, temperature, sea ice, velocity, and mixing within the ocean, and the fluxes of fresh water into and out of the ocean in the form of precipitation, continental and ice sheet runoff, and evaporation.

Sea Level Reflects Heat and Budgets

Sea-level rise, one of the leading indicators of a warming climate, will have major impacts on coastal communities and economies, affecting shipping, national and homeland security, tourism, and other valuable societal activities. The ocean heat content provides estimates of rates of thermosteric sea-level rise, the rise in sea level caused by the expansion of the ocean as it absorbs increasing amounts of heat. The net fresh water input to the ocean, which increases when higher temperatures cause land ice to melt and run off into the ocean, is the other major contribution. To assess these components of the heat and fresh water budgets, in situ measurements of temperature and salinity are needed throughout the water column. Moreover, ocean current observations are required to evaluate the transport of heat and salt and their effects on regional sea level. Refining the calculations of these budgets based on a comprehensive set of in situ measurements will advance our understanding of global and regional sea-level change, which is essential for assessing risks to coastal communities and infrastructure in the United States, and to low-lying regions worldwide.

Progress Achieved by Ocean Observations

For each of these budgets and for projections of sea-level change, significant progress has been made through the development of sustained global ocean observing, with synoptic coverage of some ocean properties from satellite remote sensing, and in situ sampling by the global array of profiling floats, repeat sampling from ships along lines that cross the ocean basins, collection of long time series at fixed sites using moorings, and other methods. We do not yet directly measure all the processes involved in the heat, carbon, and fresh water budgets, and full closure of these budgets remains a scientific and technical challenge. The ability to close these budgets will be aided by expansion of observations into poorly sampled regions, by the development of methods to quantify as yet unmeasured processes, and by the deployment of new sensors to sample biogeochemical properties and aid investigation of the carbon budget. Further, it is likely that with time, new scientific targets will mature as drivers for sustained ocean observing and require assessment of new priorities.

Finding: The current ocean observing system has made significant contributions to better understanding the ocean's role in the Earth system, including its heat, carbon, and fresh water budgets, and to better understanding global and regional sea-level change. Sustaining, optimizing, and increasing ocean observing capability will further improve understanding of the ocean's role in climate.

BENEFITS OF OCEAN OBSERVATIONS BEYOND CLIMATE

A sustained suite of ocean climate observations will yield a better understanding of future changes in Earth's climate and also benefit many other shorter term interests of science, commerce, and human safety. Modern weather forecasting relies on the same satellites and in situ measurements used for observing the ocean for climate. Increasingly, observations of ocean temperatures, patterns of sea surface temperature, and even sea-ice extent are used with models to reliably forecast hurricane intensities and tracks as well as seasonal precipitation and storminess. Tide gauges that provide information on sea-level rise are also used to track changes in water level resulting from storms and assess the potential for coastal inundation. Sustained ocean observations are critical for monitoring changes to the environmental conditions that may impact marine life such as coral reefs and commercially important fisheries and aquaculture.

Finding: The ocean observing system contributes not only to our understanding of climate variability and change, but also to a wide variety of other services including weather and seasonal-to-interannual forecasting, living marine resource management, and marine navigation. This understanding of climate variability and change and other services underpins national defense, economic, and social policy decisions.

PRIORITY OCEAN OBSERVATIONS

The Global Climate Observing System

Due to the global nature of climate observations, international frameworks have been developed through GCOS that establish observing requirements for adequate sampling resolution, long-term coordination, data sharing, and capacity building. This vital early step in global climate observing was established with the goal of providing comprehensive information on the total climate system, involving a multidisciplinary range of physical, chemical, and biological properties, and atmospheric, oceanic, hydrological, cryospheric, and terrestrial processes. GCOS has a process for developing implementation plans to articulate and address what have been identified as the ECVs to measure across the entire Earth system.

The Global Ocean Observing System

The GOOS program arose to meet research and operational requirements for internationally coordinated networks of both in situ and remote ocean observing platforms. Similar to GCOS's ECVs, expert panels have developed the EOVs, which are judged by the international community to be the priority variables to be observed in the ocean, with overlap between the ECVs and EOVs in the area of ocean climate. There is a rigorous structure in place for these expert panels to develop technical standards for the sampling requirements of the EOVs. The process of identifying EOVs is ongoing; as scientific and societal needs evolve and as the readiness and feasibility of observing specific variables advances, the expert panels will update their assessments and EOV lists will change. GOOS developed the Framework for Ocean Observing, which articulates the requirements and technical readiness of a multidisciplinary ocean observing system to meet both scientific and societal needs. GOOS utilizes this framework to guide implementation of an integrated and sustained ocean observing system by identifying the science requirements for addressing societal issues, the types of observations they require, and deployment and maintenance needed for the production of impactful and relevant information to address those issues.

Finding: The GOOS efforts are effective at promoting international cooperation to sustain the ocean climate observing system. Its guiding document, the Framework for Ocean Observing, and the associated procedures for establishing priority observation—the Essential Ocean Variables—are constructive for defining ongoing requirements (precision, frequency, spatial resolution) for sustained ocean observations and provide a solid foundation for selecting and prioritizing ocean variables for sustained observing.

The GOOS is coordinated internationally, with significant contributions from the United States. There have been agreements with other nations for specific contributions, such as for the Tropical Pacific Observing System. The Joint Technical Commission on Oceanography and Marine Meteorology provides coordination to both oversee and guide global ocean observing and to provide a forum for increasing observing capacity through enrollment of new nations and capacity building.

Finding: Opportunities exist to increase the spatial coverage and multidisciplinary nature of sustained ocean observations through U.S./international (either bilateral or multilateral) coordination and sharing of resources.

Finding: Capacity building enhances international support for the sustained ocean observing system and is valuable for increasing international use of the information and sharing of observing responsibilities.

During the course of its work, the committee identified many challenges to building and sustaining the essential elements of an ocean observing system for climate. These challenges encompass coordination among both intergovernmental organizations and U.S. federal agencies, national priority setting and planning, provision of stable funding, workforce support and training, and observing infrastructure and technology development. A description of the current status and the remaining challenges is summarized below.

INTERNATIONAL COORDINATION CHALLENGE

GOOS provides the framework under which nations can plan and prioritize their ocean observing activities. Although GOOS does not provide a mechanism for sustaining national commitments, this international coordination and cooperation for ocean observing is generally considered to be effective. However, **the issue of access within Exclusive Economic Zones (EEZs) for deploying observing system elements, or for the drift of mobile platforms such as Argo floats, remains a challenge and can act as a disincentive to deploy in some regions of the global ocean**. About 30 percent of the area of the global ocean lies inside the EEZs of coastal nations or within other maritime zones such as the region governed by the Antarctic Treaty System, and it is critical for a global ocean observing system to maintain instruments deployed inside EEZ boundaries and those drifting across them.

Conclusion on International Cooperation: The Global Ocean Observing System organization has effectively engaged countries and built capacity for this global enterprise for ocean climate observing. A challenge remains in obtaining

global access to national EEZs for drifting platforms which could be addressed by the National Ocean Research Leadership Council.

NATIONAL PRIORITY SETTING

Within the United States, federal agencies engage in the intergovernmental negotiations at the international level, and are the primary supporters of ocean observing activities through funding for research, technology, and operations. This includes building and maintaining the research fleet needed for equipment deployment, maintenance, and operations; conducting research through federal laboratories and operational programs; and serving as coordinators on the international stage. These U.S. investments contribute to the international program, but with the knowledge gained through ocean observing, national issues related to the economy, society, and national security can also be addressed. Oceanographic institutions also operate a significant portion of the observing system with support from federal grants, and conduct research that contributes to the state of knowledge of the ocean and its role in climate change. Some philanthropic and nonprofit organizations provide funding for ocean conservation research and technological development.

> *Finding: Raising awareness of the importance and value of sustained ocean climate observations could increase support for the observing system from multiple sectors, including philanthropic organizations.*

The primary U.S. federal agencies that contribute to ocean observing are the National Oceanic and Atmospheric Administration (NOAA), the National Science Foundation (NSF), and the National Aeronautics and Space Administration, with additional support for technology development from the Office of Naval Research (ONR). Federal activities among these agencies and others are coordinated through an array of interagency working groups under the National Science and Technology Council. The National Ocean Research Leadership Council (NORLC), established by the National Oceanographic Partnership Act in 1996 (P.L. 104-201), is organized within this structure and is charged with promoting partnerships to strengthen ocean observing, research, and education. The Subcommittee on Ocean Science and Technology, co-chaired by representatives from NOAA, NSF, and the White House Office of Science and Technology Policy, oversees the Interagency Ocean Observation Committee (IOOC), which was established under the Integrated Coastal and Ocean Observation System (ICOOS) Act of 2009 (P.L. 111-11) to “advise, assist and make recommendations on matters related to ocean observations.”

NATIONAL COORDINATION, PLANNING, AND FUNDING CHALLENGE

Although the interagency bodies described above have responsibilities to coordinate activities associated with ocean climate observing, the committee has not been able to identify a clear national leadership position for this intersection of ocean, climate, and observing. Neither has the committee been able to identify a national plan to sustain and expand this critical ocean observing system for climate change. Although Congress recognized the need for sustained ocean observations in the ICOOS Act, the annual budgets have not matched the costs of sustaining the current system in terms of workforce, infrastructure, and data management. **The absence of an overarching long-term (e.g., 10-year) national plan with associated resource commitments and lack of strong leadership presents a challenge for sustaining U.S. contributions to ocean observing, by inhibiting effective coordination and multiyear investments in the many components of the observing system.**

> *Finding: The continuity of ocean observations is essential for gaining an accurate understanding of the climate. Funding mechanisms that rely on annual budget approval or short-term grants may result in discontinuity of ocean climate measurements, reducing the value of the observations made to date and in the future.*

Conclusion on Planning: Because of the extended time frame required for climate observations, a decadal plan for the U.S. ocean observing system would be the most effective approach for ensuring that critical ocean information is available to understand future climate. Consistency of the decadal plan with the Framework for Ocean Observing would optimize U.S. investments relative to contributions of the international community, with plan updates likely required to align with international activities during the 10-year period. Elements of a decadal plan include identification of requirements, assessment of the adequacy of the current system, components to be deployed over the 10-year period, potential for technological advancements, and an estimate of resources necessary to implement the plan. The National Ocean Research Leadership Council (NORLC) has the mandate under the ICOOS Act to oversee development and adoption of a long-term plan and NORLC could be responsible for its periodic assessment and update, possibly utilizing the IOOC and the Ocean Research Advisory Panel. Progress in implementing the plan would depend on the engagement of the broader stakeholder community and coordination with international partners in the global ocean observing system.

Conclusion on Partnership: An Ocean–Climate Partnership (OCP) organization described further in Chapter 5 would be an effective mechanism to increase engagement and coordination of the ocean observation science community with

nonprofits, philanthropic organizations, academia, U.S. federal agencies, and the commercial sector. Through their shared interests in the observational data and associated products, the OCP members could work together toward the goal of sustaining the ocean climate observing system.

WORKFORCE CHALLENGE

Much of the in situ ocean observing system is operated by academic and government research institutions and the experts they employ. Research institutions and their funding sources place a high priority on peer-reviewed, original research, with consequent attention to the value and quality of the observations. The observing system elements that have deep roots in research laboratories and that are led by scientists who are also supported to utilize the data from the observing system have demonstrably high success.

> *Finding: Direct scientific involvement in sustained observing programs, from design to implementation to analysis, synthesis, and publication, ensures that the ocean observing system will be robust in terms of data quality, incorporation of new methods and technologies, and scientific analyses; all are essential elements for realizing the value of long-term, sustained observations.*

For individual scientists, starting up and implementing an ocean observation activity is time-consuming and may be difficult without substantial institutional support and guarantees of long-term funding. By its very nature, observational science typically requires years of data collection before results are publishable. This acts as a disincentive for early-career scientists contemplating participation in ocean observing activities beyond utilization of existing datasets. **The long-term investment required to develop and sustain the necessary expert workforce of the future is a challenge due to limited professional rewards or career incentives at research institutions and laboratories to ensure intergenerational succession of scientists, engineers, and technical staff.** Success to date in the development, deployment, and operation of ocean observing infrastructure has been enabled by a relatively small but dedicated group of scientists and other professionals who have devoted their careers to this activity, even though the long-term nature of the research is typically not rewarded in the academic community.

Conclusion on Workforce: Direct scientific involvement in sustained observing programs, from design to implementation to analysis, synthesis, and publication, ensures that the ocean observing system will be robust in terms of data quality, incorporation of new methods and technologies, and scientific analyses. Thus, intergenerational succession of scientists is critical for sustaining the

observations on climate timescales. The OCP could focus on improving career incentives for the scientific workforce as a priority.

THE END-TO-END SYSTEM

The ocean observing enterprise is an end-to-end system that not only relies on ocean climate observing scientists, but also on the development of technologies by engineers, deployment and maintenance of observing platforms from ships, and the management and application of the processed data.

Finding: To avoid data gaps and ensure the required data quality and the accessibility of the data for monitoring climate over decades, ocean observing initiatives will need to plan for the end-to-end scope of expenses associated with observing programs, including appropriate logistical planning and all processing including data analysis, data management, and scientific involvement.

New Technology Challenge

The ocean is a challenging environment for making sustained observations, driving the need for ongoing technological advances in the platforms and sensors. New technological developments can increase the effectiveness and efficiency of ocean observing instruments to collect data in harsh environments for several years, thus avoiding the high costs of maintenance which often requires a substantial amount of ship time. The maturation of sustained ocean observing has benefited from the investments of U.S. agencies, such as ONR and NSF, in the development of ocean observing platforms and sensors. Declining and flat budgets have reduced funding available for investments in new technology and improvements to existing technology. **The limited investment in advancing technological capabilities is a challenge that, if addressed, will yield significant returns over the lifetime of sustained observing platforms through development of more robust and efficient sensors and platforms and through the maturation of observing methods to address existing and new scientific challenges.**

Conclusion on Technology: Declining investments have slowed the development of new technology, which is proven to expand the capability, the efficiency, and therefore the capacity of the observing system. Some philanthropic efforts have in part filled this gap and the OCP could encourage more support there.

Research Fleet Challenge

While new technologies such as autonomous ocean-going vehicles hold promise, ships, and in particular global- and ocean-class vessels, still will be required to deploy and maintain ocean observing platforms. Establishment of ocean observing sites, such as moored observatories or repeat ship-occupied sampling lines, which require regular visits by ships every year or every decade (and may require long transits) introduce significant demands on the days at sea available each year from the U.S. research fleet. **The decreasing number of global- and ocean-class research vessels is creating a shortfall in the infrastructure required for sampling the global ocean and expanding collection into poorly sampled regions such as the polar seas.** Ships require long-term planning and investment, and maintenance of a capable fleet of research vessels is an essential component of the U.S. effort to sustain ocean observing.

Conclusion on the Research Fleet: While new technology holds promise for access to the ocean, a capable fleet of research vessels, including those with global reach, is essential to sustaining the U.S. contribution to ocean observing.

POTENTIAL NEW MODELS OF SUPPORT FOR SUSTAINED OCEAN OBSERVING

This report identifies the many benefits of sustaining and growing the capabilities of the global ocean observing system to advance climate science and improve capabilities to anticipate changes critical for decisions on mitigating and adapting to climate change. Because ocean climate data are needed to inform national security, economic, and societal decisions on climate change and other ocean-related issues and given the intergovernmental negotiations required for participating in a global system, responsibility for supporting the ocean observing system falls predominantly on the federal government in the United States. However, limited funding means there is a need to prioritize efforts and increase the efficiency of existing operations. In addition to prioritizing limited government spending, there is also an opportunity to create new models for partnerships of the government with the private and nonprofit sectors in order to accomplish shared goals for ocean observing and research.

1

Introduction

Humans inhabit only one planet, and the climate of that planet is changing. There is a strong scientific consensus that human-induced increases in greenhouse gases, especially carbon dioxide (CO_2), are driving more rapid and profound changes to climate than at any time since the advent of human societies. These human-driven, or anthropogenic, changes are known to be well beyond the range of natural fluctuations that occur on a variety of timescales. They are observed in the Earth's atmosphere, on land, in the ocean, and in the cryosphere, and are detectable in global and regional averages of many important climate variables, such as increasing temperatures in the ocean and atmosphere.

What will future generations need to know to understand the Earth's climate system? This is the fundamental question underlying the interest in sustaining critical observing systems. Regular and consistent collection of environmental observations over decades to centuries provides a record of how the climate is changing and of its range of fluctuations and variability. Sustained observations are also necessary to collect the critical data used to validate, calibrate, and refine climate models that provide insights about future events. Improved climate models will help to ensure the best possible answers to questions about future weather patterns (e.g., drought, heat waves, tropical storm strength and frequency, and agricultural growing seasons), about regional shifts in average climate conditions, and about other aspects of a changing climate that will impact society (e.g., rate and extent of sea-level rise, ocean acidification, species loss, and occurrence of floods and droughts). Sustained observations of environmental variables are thus essential to advance understanding of the state of the climate system now and in the future.

This report focuses on the observational needs for the ocean component of the Earth's climate system. The ocean covers about 70 percent of the Earth's surface and acts as its primary reservoir of heat and carbon, absorbing over 90 percent of the surplus heat (Rhein et al., 2013), about 30 percent of the CO_2 emissions associated with human activities (Ciais et al., 2013), and it receives close to 100 percent of fresh water from melting land ice, which contributes directly to global sea-level rise. Heat and CO_2 are absorbed at the ocean's surface and, from there, transported throughout the ocean depths along complex pathways. Although exchange across the ocean's turbulent surface boundary layer can happen rapidly, in hours or days, and significant exchange of water between the boundary layer and the stratified main thermocline occurs over timescales of years to decades, deep water takes many decades to millennia to return to the surface, acting as long-term storage for heat and CO_2 and thereby lessening the near-term impacts of climate change (Ciais et al., 2013). As a result, even if CO_2 emissions stopped tomorrow, surface heat and CO_2 concentration would continue to change for centuries due to ocean processes, contributing to prolonged deviations from preindustrial climate conditions (Zickfeld et al., 2017). Because changes in heat, carbon, fresh water, and other properties of the ocean that interact with climate typically occur over such long timescales, long-term, sustained observing (over decades and longer) is required to fully document and understand the climate system, to detect and attribute changes driven by human activities, and to predict how the climate system will likely behave in the future.

THE NEED FOR OBSERVATIONS AND MODELS

The argument has been made that we have passed from the Holocene into the Anthropocene, the first epoch wherein the human enterprise is a demonstrable force majeure shaping the planet (Crutzen and Stoermer, 2000). In the Anthropocene, understanding the dynamics of our planet's climate system acquires new and profound value to enable societies and commerce to adapt to and predict the changes that lie ahead. Observations play a foundational role in documenting change, improving understanding of the climate system, and facilitating future climate predictions and scenario developments. With the knowledge gained through these observations and their analysis, informed decisions can be made about mitigating greenhouse gas emissions or responding and adapting to impacts of climate change relevant to national security, the economy, and society.

Climate models are the best available tools for providing insight into possible scenarios of the future climate system. These models are tested, calibrated, and improved through information gained from observational records. Models incorporate our mechanistic understanding of how the climate system operates to extrapolate into future climate regimes, beyond what has been observed in the past or present. As our understanding of the many interacting phenomena on our planet improves, and as computing power grows, climate models increasingly go well beyond just simulating purely physical interactions to comprehensively including the wide range of biogeochemical and ecological interactions that govern the evolution of the Earth system as a whole. There are many aspects of climate models that can be informed by existing and future observations: the mean state of the ocean (e.g., temperature and salinity, circulation patterns, sea level, and pH), the magnitude of the seasonal and diurnal cycles, the climate response to aerosols in the atmosphere from volcanic events, and the observed changes since the advent of systematic observational systems. Some models already do a reasonable job of capturing many well-observed climate patterns and natural modes of variability, including seasonal and diurnal cycles. Through data assimilation, models can formally maximize the information that can be gained from available observations about present anomalies as a starting point for skillful projections out to decadal timescales. There are important emergent properties of the climate system that will require sustained and additional long-term observations to improve climate models, including the overall climate sensitivity (i.e., how much the global mean temperature changes for a given change in net absorption of solar radiation, known as radiative forcing); the efficiency of heat and CO_2 uptake by the ocean; the rate of ocean acidification; changes in evaporation and precipitation; and the sensitivity of mass loss from polar ice sheets, mountain glaciers, and ice caps to temperature changes in the ocean and atmosphere. It is only in comparison of climate models with sustained high-quality observations of the evolving state of the climate system, including the oceans, that models can be evaluated, calibrated, and improved.

THREE IMPORTANT BUDGETS FOR CLIMATE

As understanding of and skill in predicting climate variability improves, careful consideration of the needs for sustained observations and sufficiency of existing programs is warranted. An important test of our understanding and of the sufficiency of current observations is to ask whether we can reconcile the inputs to, exchanges among, and storage of energy or specific elements within the components of the Earth system: the ocean, land, atmosphere, and cryosphere. In other words, can we create a balance sheet that accounts for all contributions to this budget? For example, does the sum of the measured heat increases of the atmosphere, land, and ocean correspond to the net energy input from solar radiation? The net global imbalance of energy is a very small residual between incoming solar and outgoing longwave radiation. Temperature measurements in the ocean allow for a more accurate estimate of accumulated heat than is possible for net atmospheric radiation. With sufficient observations, it should be possible to close the heat budget, within the accuracy and sampling of the observations, and account for the observed change in radiative forcing. Comparison of the inputs, exchanges, and storage parameters between a model and observations allows for characterization of the accuracy of the representation of the key processes used to close the budget within the model, which is critical to then projecting future changes.

This report focuses on three distinct global budgets as a way to illustrate the importance of sustained ocean observations for climate: heat, carbon, and fresh water. These budgets were selected for their ability to inform climate model projections, to detect and attribute changes within the climate system, and for the fundamental role the ocean plays in each. They are also well recognized as priority areas within the international ocean observing community, as discussed later in this report. Quantifying and closing these three budgets requires global ocean observing systems that provide ongoing, calibrated measurements to monitor short- and long-term changes indicative of the evolving state of the Earth's climate. Observations and subsequent improvements to the processes built into climate models based on these observations also allow for more informed societal and policy responses to a changing climate. For example, the heat budget is central to understanding the delayed warming of the Earth's surface temperatures due to the ocean's heat uptake and storage (Winton et al., 2010; Fyfe et al., 2016). Similarly, a thorough understanding of the carbon budget can be used to help predict future atmospheric CO_2 concentrations under various greenhouse gas emission scenarios. Balancing the carbon budget requires observations of the amount and rate of absorption of atmospheric CO_2 by processes in the ocean and on land. This information can then be used to predict how much CO_2 will be absorbed by the ocean versus remain in the atmosphere and can help guide future emissions policy to reduce the extent of future warming. It also informs the rate at which ocean acidification increases.

The fresh water budget is important for understanding changes in ocean salinity. Salinity and temperature determine sea water density, which sets the vertical stratification of the ocean. Generally, temperature is the dominant driver of this stratification with warmest water at the surface and coldest in the deep ocean, but salinity can be an important determinant when fresh water inputs are large, such as in regions of high rainfall and river outflow, in polar regions where sea ice melts, and in cold waters where salinity dominates sea water density. Low surface salinity makes the surface waters more buoyant, increasing the stability of stratification and decreasing vertical mixing, which reduces the exchange of heat and carbon with the deep ocean. A low-salinity surface "lens" allows for higher sea surface temperature (at low latitudes) and lower sea surface temperature (at high latitudes), and influences the local air-sea exchange of heat.

These budgets also provide critical information about sea-level rise. The heat budget provides estimates of rates of thermosteric sea-level rise, the rise in sea level caused by the expansion of ocean water as it absorbs increasing amounts of heat (Church et al., 2013). Increases in the net fresh water input to the ocean occur when rising temperatures cause significant melting or dynamic instabilities of land ice, which also contributes to sea-level rise and may be the dominant contribution to sea-level rise in the future (Church et al., 2013). Closure of the sea-level budget requires additional estimates of the water mass transfer from land to ocean, which are provided by satellite gravity and cryosphere observations. Coordinated satellite and in situ observations are needed to understand risks to coastal communities and infrastructure in the United States and the low-lying regions worldwide. Our current understanding of the sea-level budget has also benefited from some redundancy in the observing system components (sea surface height by satellite altimetry, thermosteric expansion from Argo floats, and ocean mass by satellite gravity), which is fundamental for characterizing the drivers of sea-level change as well as their uncertainties.

Though only three global ocean budgets and their associated observations are detailed in this report, there are other key long-term ocean observations that are important for monitoring and understanding the effects of both short- and long-term changes in the oceans. These include distributions of dissolved oxygen and nutrients (which can directly impact marine ecosystems) and documentation of changes in marine ecosystems. Like observations for climate, the value of the observational record for detecting significant changes and distinguishing between natural variability and human-induced change is dependent upon the continuity of the observations over the long term.

THE OCEAN CLIMATE OBSERVING SYSTEM

Observations of the ocean developed as a result of growth in technical capability combined with increased understanding of the need to observe the ocean following World War II. Initially, sampling of the ocean was exploratory, with limited observation of the global patterns and variability of subsurface ocean properties. An incomplete and hence biased view of temperature, salinity, and density distributions was pieced together from regional surveys and a few more extensive efforts, such as the German survey of the Atlantic Ocean in the 1920s, the International Geophysical Year survey of the Atlantic Ocean in 1957-1958, and surveys of the Pacific and Indian Oceans in the 1960s. Except for measurements at isolated mid-ocean weather stations in the Northern Hemisphere to support early transoceanic aircraft flights, basin-scale surveys did not include regularly repeated measurements. Instead, regular observing was mostly confined to coastal regions where there were concerns about fisheries (e.g., U.S. West Coast) or navigational hazards such as sea ice. In 1982, an unusually strong El Niño climate anomaly, an event that occurs as part of the natural El Niño–Southern Oscillation (ENSO) climate phenomenon, went undetected until it was fully developed because of insufficient in situ observing capacity in the tropical Pacific (McPhaden et al., 1998). This strong El Niño had enormous ecological and economic impacts around the Pacific Rim, including erosion and flooding in agricultural and residential areas and declines in fish and seabird populations, due to rainfall and temperature extremes (see, e.g., Valle et al., 1987; Arntz and Tarazona, 1990; Storlazzi et al., 2000).

To ensure that events like this "El Niño surprise" would not be repeated, more systematic ocean observing began to be implemented. The World Climate Research Programme (WCRP) mounted a major project, Tropical Ocean Global Atmosphere (TOGA, 1985-1994), including installation of a permanent ENSO Observing System (ENSO OS) in the tropical Pacific Ocean. TOGA drove major advances in understanding tropical climate variability and the ENSO OS enabled seasonal forecasting of ENSO and its regional impacts. In the same era, the growing realization of the global ocean's central role in climate, including the massive oceanic storage of heat and its transport by ocean circulation, provided the impetus for the WCRP's World Ocean Circulation Experiment (WOCE). WOCE included an intensive global ocean survey made by research vessels between 1991 and 1997, as well as satellite and in situ observations of the time-varying circulation. At this time, in addition to the physical observations carried out under TOGA and WOCE (which also had a geochemical component, including a global survey of ocean carbon, nutrients, and oxygen), interest in the oceanic role in the carbon cycle gave rise to the Joint Global Ocean Flux Study (JGOFS), whose objective was to quantify and understand the time-varying exchange of carbon between the atmosphere, ocean, seafloor, and continents. In addition to their observational achievements, TOGA and WOCE catalyzed the development of a new generation of autonomous instrumentation that continues to revolutionize ocean observation today.

The ocean climate observing system as it stands today is described in the remainder of this report. The system has continued to evolve and grow as platform and sensor technology has improved and as the needs for understanding the climate and budgets have been better identified and prioritized. The dominant components of the ocean observing system are the in situ elements, including profiling floats, ocean gliders, global drifters, moorings, tide gauges, data buoys, and ship-based observations. These elements collect the data needed to better quantify components of the three budgets. Satellites remotely collect complementary data on limited parameters such as sea surface height, sea surface temperature, surface wind stress, ocean mass, and, recently, sea surface salinity. Although satellites are only usable for some types of data collection, the integration of in situ and satellite observations through formal synthesis or data assimilation allows for detailed knowledge of specific aspects of the climate system, greater spatial coverage than is available for many in situ measurements alone, and intercalibration between observing platforms. The need to periodically replace platforms as well as the introduction of new, more capable and effective observing methods are anticipated, but overlapping of methods and intercalibration will be required to document the comparability and quality of new methods and thus ensure the continuity and quality of observational records. In addition, ongoing research on and development of new sensors and observing methods will go from a pilot stage to maturity and routine deployment in order to measure variables and quantify processes not yet routinely observed and to address new scientific challenges. Altogether, this ocean climate observing system provides information critical for understanding the current and future state of the climate, improving predictability of natural climate cycles, and making decisions with respect to mitigating and adapting to adverse changes arising from long-term, anthropogenic climate change.

THE END-TO-END SYSTEM

The successful collection of sustained observations in the ocean is built on a foundation spanning a wide range of activities and actors. As illustrated in Figure 1.1, the deployment of a given component of the observing network is built on engineering, operations, data management, and information products that are supported through planning and governance from international and regional coordination entities and by national agencies. Planning and governance activities include the proposals and the administration of the proposals that generate the funding support within the government agencies; administration of observing system operations in federal, state, or academic research organizations; development and documentation of performance metrics; coordination between partners within the United States and internationally; and representation of the U.S. component of the observing system as part of globally coordinated and multiplatform arrays of ocean observing elements. Engineering activities address platform design and improvement, including life extension and reliability, sensor selection and testing, power needs, and data telemetry and platform tracking. Operations include construction and procurement, predeployment testing, finding ships for deployment, deploying floats, and monitoring performance in the field. Observational scientists and technical staff deploy moored instrumentation at fixed sites, sample

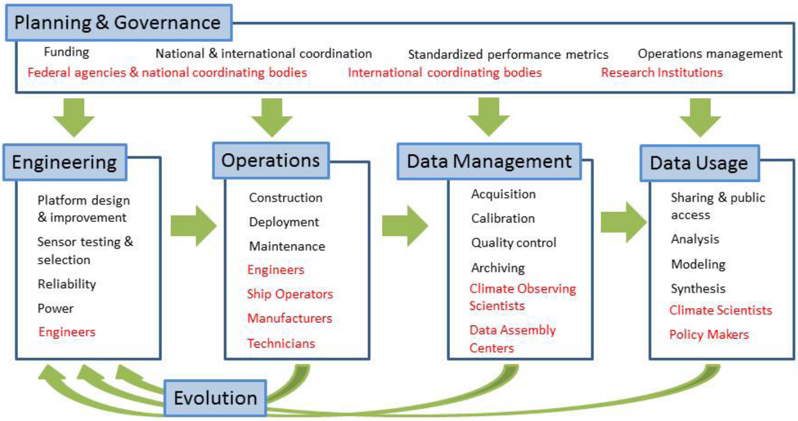

FIGURE 1.1 The end-to-end system of ocean observing includes a wide array of roles and responsibilities performed by a diverse range of communities. Blue boxes indicate overarching activities, black text illustrates the primary responsibilities within each activity, and red text shows the expert workforce needed. SOURCE: Committee.

from research ships, or use research or volunteer observing ships to deploy instrument platforms that either drift on the sea surface, make underway measurements, or take profiles within the water column. Data management involves acquisition, processing, and calibration of the raw data by the observing system operators, quality control, and storage of raw and processed data in national and international data centers. The data are then used by the wider community of researchers, extending beyond those involved in the operations of the observing system itself. Data assimilation plays an important role in the synthesis of the diverse but disparate observational data streams and heterogeneous sampling patterns. Insights gained from both observing operations and data use result in ongoing improvements to data collection, distribution, and instrumentation which contribute to continuous evolution of the observing system over time.

An example of this end-to-end system is the global network of Argo profiling floats, which includes participants from a wide range of communities. More than 23 countries now contribute to the global Argo program infrastructure, and participate in international coordinating efforts to standardize priorities and performance metrics. In the United States, five laboratories (federal and academic institutions) operate the Argo program with funding from the federal government; each of these five groups is led by a principal investigator who makes the day-to-day and multiyear decisions directly relevant to that laboratory's operations including equipment, deployment, and data processing. Data processing for Argo floats, which measure temperature, sea water conductivity (an indicator of salinity), and pressure, includes real-time preparation of temperature and salinity profiles as a function of pressure from the temperature and conductivity data with initial automated data quality screening, and also the delayed-mode preparation of fully quality-controlled temperature and salinity profiles drawing on additional sources, such as shipboard profiles, for float calibration. Data are provided through an Argo-specific data archive and forwarded to national ocean data archives. Analysis activities are undertaken by students, postdocs, and principal investigators, many of whom are not within a group that deploys the floats; their experience with the data often feeds back into improvement in operations or data quality. This example illustrates the need for a wide range of engineering, field operations, technical, and scientific talent that is well coordinated to ensure success of the end-to-end system and the importance of adequate financial resources to support sustained ocean observing.

The ocean observing system is largely supported by the federal government in the United States. Agencies coordinate their investments in ocean observing and in ocean science broadly through interagency bodies. The federal government identifies priorities for the ocean observing investments and participates in international structures where global priorities are developed. However, as described above, implementation of the end-to-end system relies on wide expertise from a broad range of actors from research institutions, private industry, and nonprofits.

STUDY TASK AND APPROACH

This study committee ("the committee") has been charged with considering processes for identifying priority ocean observations that will improve understanding of the Earth's climate processes and the challenges associated with sustaining these observations over long time frames (see Statement of Task in Box 1.1). The committee determined that the existing international bodies that coordinate observing activities among nations have developed detailed, robust, and ongoing processes for identifying and developing sampling specifications for the highest priority ocean climate observations. Rather than duplicating these

BOX 1.1
Statement of Task

Maintaining long-term, continuous, ocean data records for understanding, monitoring changes in, and modeling climate changes are essential, yet challenging. An ad hoc committee will consider processes for identifying and characterizing the most critical, long-term ocean observations and identify limitations of the current approaches.

When considering the various processes for selecting and characterizing high-priority, long-term ocean observations, the committee will discuss potential factors such as:

- Accuracy, precision, frequency, and spatial resolution of observations;
- Duration of observations (e.g., what criteria would be used to determine when observations should be sustained at high priority, are no longer needed for a given parameter or when an observation would be superseded by a different type of observation, for example through a new/different technology);
- Inherent value and/or tradeoffs of increasing multidisciplinary observations across a limited number of networks/platforms vs initiating additional observing systems;
- Complementarity of an observation to another set of observations (or network); and
- Current or near-future technology that could be used to develop a more cost-effective observational system.

The committee's report will identify challenges to maintaining long-term observations and suggest avenues for potential improvement. During the study, the committee will convene a workshop to gather expert opinions on the process for prioritizing long-term, ocean climate observations and discuss international approaches to selecting and sustaining ocean observations, as well as other topics that are important for the design of sustainable, long-term ocean observing systems.

efforts, the committee has focused its attention on "challenges to maintaining long-term observations and suggest[ing] avenues for potential improvement." The importance of long-term ocean observations has been widely recognized in the scientific community, but sustaining these measurements has been difficult, in part due to unpredictable funding streams under the annual cycle of government appropriations, tight budgets, and competing priorities for funding within government agencies (Baker et al., 2007; Wunsch et al., 2013). This report focuses primarily on the in situ elements of the observing system. Remote sensing using satellites is coordinated across nations and subject to planning and coordination in the United States under the decadal surveys conducted by the National Aeronautics and Space Administration (https://decadal.gsfc.nasa.gov). To date, in situ ocean observing has not been the subject of such coordination within the United States, and the committee effort reflects their determination that the greatest need for improved coordination to sustained ocean observing is associated with the in situ effort. Additionally, the in situ ocean observing system is a technically challenging enterprise, with observing platforms deployed in remote locations far from land and for long time spans in order to collect the data that improve our understanding of the global climate. As well, the in situ system is one that will evolve further, as capabilities increase to transition new observing methods to maturity and as new scientific challenges in understanding climate need to be addressed by additional observations.

A major activity of the committee was the convening of a 2-day information-gathering workshop, during which members of the U.S. and International Ocean observing community described the global ocean observing system and its evolution and the processes in place for prioritizing ocean observing investments. Participants in the discussions included researchers and decision makers from the U.S. government, academic institutions, and international coordination groups. The agenda and panelists from the workshop can be found in Appendix B.

The committee evaluated the strengths and needs of the existing elements of the global observing system and its ability to measure climate variability, with thematic emphasis on the three budgets described earlier in this chapter: heat, carbon, and fresh water. The committee determined that sustained and improved measurements of heat, carbon, and fresh water system components will continue to provide and strengthen crucial information in understanding climate and significantly improve modeling capabilities, while also serving as the basis for findings that could be applied more broadly in the context of other important observations. The committee used global sea-level rise as an example of a climate-dependent property that requires global ocean observations and has great societal impact. Although the focus is on variables related to these budgets, the committee does not intend to suggest that these three budgets are the only important variables to measure for long-term climate trends. The committee also recognizes that changes in climate can have serious consequences for biological processes and that variables related to changing ecosystems and observations of these impacts are critical, but not the focus of this report. Instead, improvements in the ability to model the heat, carbon, and fresh water budgets may allow for predictions of future changes to the Earth's ecosystems.

A system designed for carrying out long-term climate observations will provide benefits for other near-term areas of science, commerce, and human safety. This is acknowledged as an important aspect of the system by the committee (discussed further in Chapter 2). However, for the purposes of their task to describe priority observations for understanding the Earth's future climate, the committee did not find it appropriate to weight the benefits of any observing system or variable by its near-term benefits.

This report focuses primarily on open ocean observing system elements that contribute to the fundamental understanding of long term trends in the Earth's climate system. Most coastal ocean observing platforms have been developed to address applications with important short-term societal benefits. For assessing shorter term climate variability and climate impacts, coastal regions play an important role, but with the exception of sea level these observations are less critical for understanding long-term climate trends. The budgets of heat, fresh water, and carbon that are foci of this report are dominated by the vast volume of the global open ocean. Although it might be ideal to include coastal observations at some point, because these systems were developed at a more local level to address shorter term societal needs (such as early detection of algal blooms), they are distinct from the system of global observations, and less critical to the concerns detailed in this report.

In the remaining chapters of this report, the committee highlights the importance of an ocean climate observing system (Chapter 2), and describes the strengths and challenges of existing international frameworks (Chapter 3) and the associated U.S. contributions to the ocean observing system (Chapter 4). The findings and conclusions from the committee for improvements to overcome challenges and explore potential new models for sustaining ocean observations are detailed in Chapter 5. Information presented in Chapter 5 may also inform a possible second phase of this project, which would consist of a workshop to explore innovative new methods and partnerships for supporting sustained ocean observations.

2

Collection and Use of Sustained Ocean Climate Observations

The in situ ocean observing system that exists today provides a diverse suite of critical climate information documenting the present state of the ocean. When sustained, this information can capture the change and evolution of the ocean and inform our understanding of the linkages between the ocean and climate. Ocean circulation patterns that affect climate act on very long timescales, providing a strong impetus for designing and sustaining a long-term observing system. The existing observing system has evolved, and will continue to evolve, with experience, technological advancements, and coordination within the international ocean observing community. The integration of in situ ocean measurements with data from other types of observational systems, satellites in particular, has resulted in significant advances in our understanding of the fundamental role of the oceans in climate change processes. This improved knowledge spans the three budgets that are the focus of this report—heat, carbon, and fresh water—as well as many other metrics that have direct societal relevance, including sea-level rise. This chapter describes the ocean observations necessary to close the heat, carbon, and fresh water budgets, drawing on work conducted at the international level to develop specifications for a global network of observing platforms collecting priority ocean data (described further in Chapter 3). The in situ ocean observing system also addresses many other societal needs, ranging from weather prediction and hurricane tracking on short timescales, to evolution of the ocean ecosystem and fisheries on longer timescales. Expanded observational capacity into poorly observed areas of the ocean, technological improvements, and well-developed data assimilation methodologies are needed to advance the contributions of the ocean observing system toward understanding climate.

PROGRAMS AND INFRASTRUCTURE OF THE PRESENT OCEAN OBSERVING SYSTEM

The present ocean observing system is comprised of numerous programs foundational to the collection of in situ, climate-related data (Table 2.1). The groundwork for coordination of these programs was established at the OceanObs'99 conference, when the ocean science and observing community met to evaluate the technical readiness, capabilities, and contributions of different elements of the global ocean observing efforts then under way (Smith and Koblinksy, 1999). Among the foundational in situ elements were the profiling floats (Argo), ship-based profile and water sampling (GO-SHIP), moorings that collect time series (OceanSITES), global sea-level observing (tide gauges, GLOSS), observations made from merchant ships (SOT and SOOP), drifting surface buoys and moored buoys for weather and other observations (DBCP), and coastal and regional observing efforts (in the United States, this consists of the 11 regional systems that make up the Integrated Ocean Observing System, IOOS). As new research and data needs are identified and new instrumentation and platforms are developed and proven, they are added to existing programs. The observing programs outlined in Table 2.1 are implemented under the umbrella of the international Global Ocean Observing System (GOOS) framework, of which the United States is an important actor in most programs, with substantial contributions from government agencies and academic institutions that are detailed in Chapter 4. As understanding of the ocean's role in climate continues to develop, additional observing requirements are expected to be identified and growth in the multidisciplinary aspect and diversity of the observing system is anticipated.

The primary infrastructure needed to maintain the in situ global ocean observing system includes the measurement platform itself, as well as the research ships from which deployment, maintenance, and recovery of equipment occurs. The human resources needed to develop and maintain these programs and infrastructure are also an essential component, as described in Chapter 1.

IMPROVEMENTS TO THE BUDGETS CONSTRAINED BY OCEAN CLIMATE DATA

Ocean observations have contributed to the vital insights into changes in the heat, carbon, and fresh water budgets of the planet and informed understanding of other related ocean changes, including sea-level rise. This section briefly describes the ocean observations that have led to improved understanding of these budgets, illustrates changes based on collected data, and identifies key knowledge gaps where increased observational efforts are required to close the budgets globally. Closing these budgets has been identified as a priority in national and international global ocean observing planning and climate research programs (US CLIVAR, 2013; Benway et al., 2016; GCOS, 2016). These programs provide the highest level of guidance for building and sustaining ocean observing and out-

TABLE 2.1 Programs of the Global Ocean Observing System[a]

Ocean Observing Program	Program Elements	Program Size	U.S. Share	Scale	Budgets Informed
Argo	Argo profiling floats	3900+ floats worldwide	2,078 floats; Scripps Institution of Oceanography (SIO), U. Washington, WHOI, NOAA/PMEL, NOAA/AOML 100 extras floats by U.S. Navy	Regional Global	Heat Fresh water
	Deep Argo (pilot)	30 deep floats currently in regional pilot arrays	21	Regional Global	Heat Fresh water
	Biogeochemical Argo (BGC-Argo) (pilot)	300 floats currently having 1 or more BGC sensors	142	Regional Global	Carbon
Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP)	Full ocean depth, decadal repeating hydrographic transects	61 lines (54 core, and 7 associated lines with greater sampling frequency and fewer requirements)	19 lines NOAA/OOMD funds NOAA/PMEL and AOML. NSF funds SIO plus about 8 academic institutions	Regional Global	Heat Carbon Fresh water
OceanSITES	Moored buoys, time-series sites	290 sites	128 active sites; Many U.S. institutions (NOAA, NSF, SIO, LDEO, WHOI, UW, U. Miami, U. Hawaii, MBARI).	Regional	Heat Carbon Fresh water

continued

TABLE 2.1 Continued

Ocean Observing Program	Program Elements	Program Size	U.S. Share	Scale	Budgets Informed
The Global Sea Level Observing System (GLOSS)	Long-term climate change and oceanographic sea level monitoring	290 stations in the Global Core Network (GCN)	NOAA operates 25 stations, University of Hawaii operates 52 stations	Regional Global	Heat Fresh water
Ship Observations Team (SOT)	Voluntary Observing Ships (VOS) surface atmosphere measurements	Weather observations from about 1,700 operational ships around the world.	The U.S. VOS Program services about one quarter of the world's VOS fleet.	Regional Global	Heat Fresh water
	Automated Shipboard Aerological Programme	Atmospheric profiles with balloons launched by about 20 ships, mainly North Atlantic	No U.S. participation	Regional	Heat
	Ship of Opportunity Program (SOOP) eXpendable BathyThermograph (XBT) temperature profiles	Approximately 15,000 XBTs are deployed per year in 36 repeating boundary current and ocean-spanning transects, 2,000 XBTs elsewhere	NOAA/AOML and SIO are together responsible for about 25 repeating transects in the Atlantic, Pacific, and Indian Oceans	Regional	Heat
	Ship of Opportunity Program (SOOP) Surface water CO_2 (transitioning from pilot to mature)	Approximately 50 ships are outfitted with automated pCO_2 systems worldwide	NOAA/OOMD funds: AOML,PMEL, ESRL/GMD and 3 academic partners who provide 30% of the global observations in SOCAT	Global	Carbon

Data Buoy Cooperation Panel (DBCP)	Surface Drifter	1461	830: NOAA/AOML, SIO Many U.S. institutions	Global	Heat Fresh water
	Fixed Platform	103	9	Regional	Heat Fresh water
	Ice Buoy	23	4	Regional	Heat Fresh water
	Metocean Moored Buoy	379	209	Regional	Heat Fresh water
	Tsunameter	35	28	Regional	Heat Fresh water
Coastal and regional GOOS systems	Buoys, tide gauges, radar stations, gliders (international Glider Network coordination is at pilot stage)	14 GOOS Regional alliances	Integrated Ocean Observing System (IOOS)	Regional	Heat Carbon Fresh water

[a] Table is accurate as of February, 2017 though the number of deployed platforms may frequently change. Information obtained from JCOMMOPS (http://www.jcommops.org), NOAA (http://www.vos.noaa.gov/), U.S. GO-SHIP (https://usgoship.ucsd.edu/hydrotable/), GLOSS (http://www.gloss-sealevel.org/), SOCAT (http://www.socat.info) and individual contributors. To avoid duplication, programs that utilize the elements of the programs listed here have been left out. The Tropical Moored Buoy Array is part of both OceanSITES and DBCP.

line specifications for spatial and temporal sampling of priority ocean observation variables (described further in Chapter 3), and the committee has drawn on these activities to describe the observing requirements for closing the three budgets.

Whenever possible, the ocean observing system design includes direct measurement of all elements of the budgets, to avoid residual calculation of unmeasured terms. A modest degree of redundancy across observing platforms is valuable to understand and characterize measurement and sampling errors. Existing observation gaps inhibit the ability to capture the full temporal and spatial variability of the ocean and its linkages to climate. To fully close the budgets that inform understanding of climate, observations of ocean climate variables need to be extended to the full depth of the ocean, regions of vigorous circulation such as western boundary currents and the Antarctic Circumpolar Current, and to more far-reaching areas such as the polar regions—including under sea ice, areas that are becoming newly ice-free, and near where the ocean is in contact with the polar ice sheets. Additionally, to distinguish seasonal-to-decadal variability from multidecadal trends, uninterrupted time series of observations need to be collected at a frequency sufficient to capture the shorter timescale patterns. As capabilities to measure new variables mature and new scientific and societal needs emerge, additional variables will be added to the ocean observing network to aid in closing the budgets and advancing understanding of the ocean's role in climate.

Heat Budget

An accurate estimate of ocean heat content, formed by depth-integration of temperature anomalies, is a fundamental index of the evolving climate system and a determinant of how much future global surface warming is expected for a given future increase in CO_2 emissions (and other greenhouse gases). Water has a much higher heat capacity than the atmosphere, resulting in about 90 percent of the net global surface heat gain (i.e., the Earth's radiative imbalance) going into warming of the oceans (Levitus et al., 2012). The ocean is the dominant reservoir for heat in the climate system. Heat absorbed by ocean waters is distributed laterally and vertically through the depth layers and basins by mixing and currents. Satellites measuring the Earth's net radiation imbalance can help quantify the interannual variability in ocean heat content (Johnson et al., 2016b), but are not sufficiently accurate to capture multiyear trends and need to be calibrated by ocean observations for absolute accuracy. In situ measurement of temperature change in the ocean, integrated over depth and area, is the most accurate way of monitoring the multiyear heat budget of the Earth's climate system. On a regional basis, closure of the heat budget requires observations of ocean heat content, air-sea heat exchange, heat transport by ocean currents, and mixing, while the global balance is between the global integrals of heat gain and air-sea flux.

The challenge for ocean observing has not been simply that of making accurate temperature measurements (present shipboard instruments can measure to an accuracy of 0.001°C). Instead, the challenges lie in collecting samples across the vast spatial extent and full depth of the ocean to form robust spatial averages (or integrals), and with high enough frequency to capture temperature changes accompanying the seasons, storms, and passage of features such as eddies (e.g., Wunsch, 2016). Undersampling translates into large uncertainty in heat content estimates. Although surface drifters and commercial and research ships provide in situ temperature observations near the ocean surface and satellite remote sensing provides spatial coverage by mapping sea surface temperature, the need for temperature observations at depth has been identified as a crucial measurement to account for heat movement and storage in deeper layers of the ocean.

Prior to 2004, temperature profiles were collected by ships, either lowering instruments that recorded temperature as a function of depth (CTDs, which measure conductivity, temperature, and depth) or dropping expendable bathythermograph (XBT) probes. However, there were relatively few high-quality ship-based profiles, and these were not well distributed across the globe or across seasons. Since about 2004, the Argo program has been the dominant source of near global coverage of ocean temperature profiles to a depth of 2,000 m. The Argo program has been transformational through its contribution to the heat budget, by covering a much greater fraction of the global ocean, and at much higher frequency, than is possible with ship-based technologies. Calibrated temperature sensors are used and Argo data are checked against profiles from ship-based measurements to ensure data accuracy. Today, over 3,900 Argo floats, each profiling every 10 days, provide about 140,000 temperature (and salinity) profiles per year from the sea surface to 2,000 m depth, with measurements spread across the globe. Estimates of ocean heat content use Argo data together with other datasets, including shipboard hydrography (thermometers and CTDs) and XBTs, in order to extend the datasets to pre-Argo decades (Johnson et al., 2016a).

As a result of the global Argo program that revolutionized sampling of the upper ocean, estimates of ocean heat content using very different analytical methods converged (Figure 2.1a). This improvement has been attributed to reliable, consistent data collection across the globe, even while managed by many different research organizations. This is in contrast with prior variability in estimates caused by differences in researcher compilation and analysis of sparse historical temperature data records.

Figure 2.1b, showing the changes in heat content in both the Argo-sampled upper 2,000 m and in the deeper ocean based solely on shipboard profiles, shows that increasing heat content penetrates below 2,000 m and so measuring only to this depth misses information needed to close the changing heat budget. Current estimates indicate that the deep ocean may have contributed about 10-15 percent of the total heat storage since the 1950s (Rhein et al., 2013; Llovel et al., 2014). Although Argo sampling has been a great advancement, the availability of temperature data from deeper than 2,000 m remains limited. To address this, new Deep Argo floats have been developed and are currently being deployed

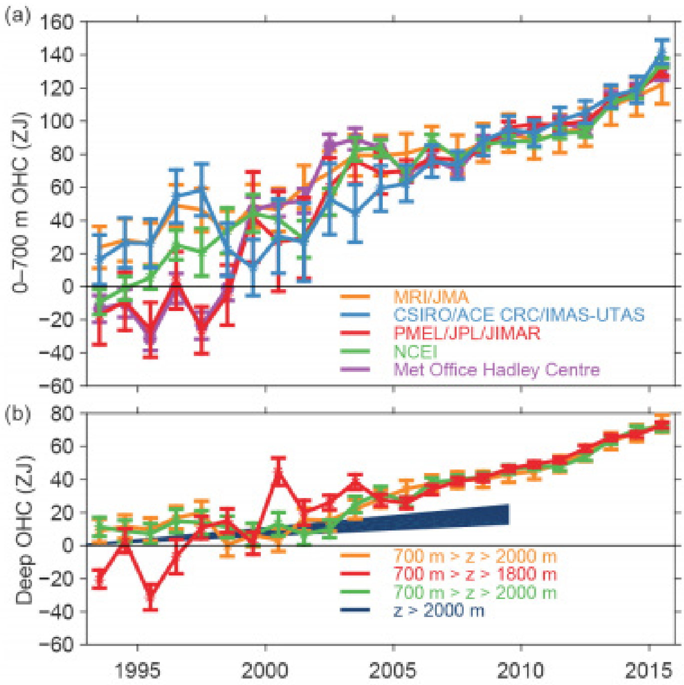

FIGURE 2.1 In situ ocean heat content (OHC) in zetajoules (ZJ, or 10^{21} Joules) estimated by five organizations in (a) the upper 700 m of the ocean and (b) collected between 700 and 2,000 m in depth from four of the same organizations for the 1993 to 2015 time period. SOURCE: Johnson et al., 2016a, with data sources cited therein.

in regional pilot arrays. This new Deep Argo program will extend sampling to 6,000-m depth and enable estimation of ocean heat gain over the full water column. The addition of the Deep Argo program illustrates how the ocean observing system is evolving in response to the goal of closing the global heat budget. Tracking the absorption of heat by the ocean into the future will be improved by sustaining this new program as well as continuing the sampling of the upper 2,000 m.

Other advancements in deep ocean observations include the addition of temperature sensors to existing moorings at depths greater than 2,000 m, which adds high temporal resolution of deep temperature variability to complement the Deep Argo program. To further enhance the value of the Argo program, sampling is planned to be extended into previously unsampled waters, including ice-covered and newly ice-free polar regions. The needs for and uses of deep ocean temperature data extend well beyond closing the global heat budget. Deep ocean temperature data are needed to initialize and constrain ocean models and improve their representation of mixing of heat downward into the deep ocean. Changes in deep ocean temperature are a measure of change in the large-scale ocean circulation (Purkey and Johnson, 2013). Warming of the deep ocean contributes to the thermal expansion of the ocean that is a contributor to sea-level rise.

However, although progress has been made to quantifying how much and where heat is stored in the ocean, further work remains to improve understanding of all terms in the heat budget. Some of the key observations needed to quantify contributions to the heat budget (e.g., surface heat flux and transports of heat) are reflected in present efforts to identify and prioritize variables ready to be observed (see further discussion in Chapter 3). Other processes, vertical mixing in particular, continue to be the subject of ocean research projects that stimulate ongoing development of methods to estimate and directly observe their contributions. This research and development feeds into the overall context for sustained ocean observing and may in time demonstrate observing methods suited to sustained use. For now, it is important to work not only toward this but also to build understanding of all contributions to the heat budget.

Carbon Budget

Quantifying the capacity of the ocean to absorb CO_2 from the atmosphere is essential to predicting climate warming and changes in ocean chemistry. When CO_2 is removed from the atmosphere, radiative forcing decreases and climate warming is lessened. Each year, the ocean absorbs, and also emits, an amount of CO_2 equivalent to approximately 10 percent of the total mass in the atmosphere (Ciais et al., 2013); however, as slightly more CO_2 enters the ocean than leaves it, the partial pressure of CO_2 (pCO_2) in the ocean rises. This dissolved CO_2 becomes a weak acid that lowers the pH of sea water (negative logarithm of the hydrogen ion concentration), a phenomenon termed ocean acidification. Ocean acidification has complex implications for marine life; growth rates of some marine plants may increase while many other organisms are expected to suffer negative impacts, for example, by reducing the availability of carbonate ions used to build calcium carbonate shells and coral skeletons, resulting in weaker structures. (NRC,[1] 2010). The dominant sink of anthropogenic carbon in the ocean on the decadal-to-centuries timescale is the dissolution of CO_2 into surface sea water, which mixes into the rest of the ocean. Although there are other carbon sinks that operate on this timescale (e.g., sedimentation and salt marshes), none of them approaches the capacity of that resulting from CO_2 dissolution. On longer timescales (millennia and beyond), the neutralization of anthropogenic CO_2

[1] Effective July 1, 2015, the institution is called the National Academies of Sciences, Engineering, and Medicine. References in this report to the National Research Council are used in an historic context identifying reports published prior to this date.

by the dissolution of calcium carbonate sediments becomes important and could restore atmospheric CO_2 to lower levels, but this would occur over many tens of thousands of years (Ciais et al., 2013).

In the carbon system, measurement of two parameters defines the others through chemical equilibrium. Surface water pCO_2 is important because it directly influences air-sea exchange, and extensive data have been obtained by underway research and merchant vessels. There is a close relationship between pH and pCO_2, and measurement of either one provides comparable information; until recently, pH has not been extensively measured but it may become preferable with the recent availability of new sensors. A second parameter is also necessary, the most useful being alkalinity or total dissolved inorganic carbon. These parameters generally have only been available from shipboard measurements on research vessels. A useful estimate of alkalinity can also be provided by regional regression estimates from measurement of temperature, salinity, and nutrients or oxygen. In situ measurements of the rise in atmospheric CO_2 concentration concurrent with the ocean's increase in pCO_2 and decrease in pH clearly illustrate a correlation between these variables in their long-term trends (Figure 2.2). These observations provide strong support for theory and models of CO_2 exchange with the ocean and are an essential component to understanding climate change and the global carbon budget. Additional datasets illustrate similar patterns (e.g., Tamburri et al., 2011; Bates et al., 2014).

Ocean carbon distributions show regional variation, and comprehensive in

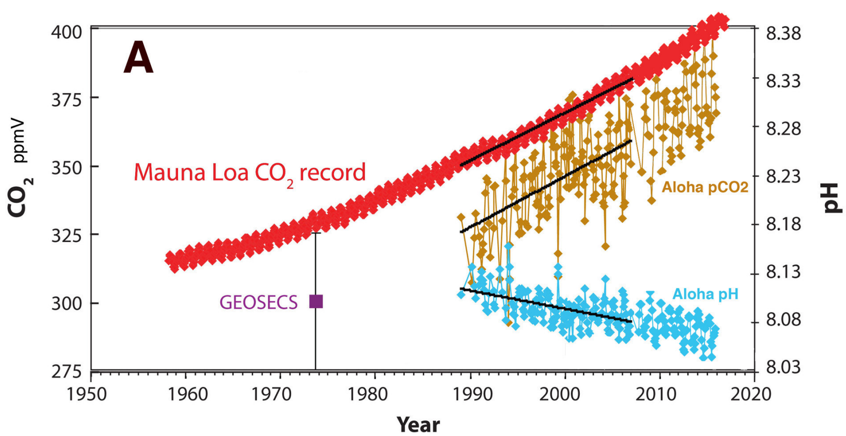

FIGURE 2.2 In situ observations of the partial pressure of CO_2 (labeled as Aloha pCO_2) and pH (Aloha pH) (1989-2016 time period) in the ocean compared to atmospheric CO_2 concentration (Mauna Loa CO_2 record). Black lines are trend lines from 1989 to 2007. SOURCE: Doney et al., 2009 and sources cited therein, modified with data from Bates et al., 2014.

situ sampling is needed to capture this spatial variability. In contrast, atmospheric CO_2 measurements have been made for decades at some locations around the globe under the World Meteorological Organization's Global Atmospheric Watch (WMO, 2001), such as at Mauna Loa (Figure 2.2; see also Keeling, 1998); because the atmosphere is relatively well mixed, sampling at a small number of locations is representative of the full atmosphere. Ocean CO_2 and pH measurements have been principally made in the historic WOCE and JGOFS and the current GO-SHIP programs, at time-series stations at single points (Station Aloha at Hawaii as seen in Figure 2.2, and Bermuda Atlantic Time-Series, both starting carbon observations in the late 1980s), and as underway surface pCO_2 measurements. Although automated systems on research and merchant vessels have collected millions of surface pCO_2 measurements, winter season and spatial coverage in some regions (e.g., Southern Ocean) is sparse. Depth coverage of CO_2-system properties is limited to GO-SHIP (and previously WOCE) transient tracer measurements, which provide insight into ocean carbon uptake and distribution. Currently there are 32 pCO_2 moorings that are deployed by the United States in the U.S. coastal oceans and in the open ocean, and earliest pCO_2 data can trace back to the early 2000s in the equatorial Pacific and U.S. West Coast. The data collected from these moorings have enabled us to study the changes of surface pCO_2 and CO_2 fluxes on timescales ranging from daily cycles to interannual variabilities (e.g., see synthesis reports by Hales et al., 2008; Najjar et al., 2012; Benway and Coble, 2014). These data form the backbone to quantify the U.S. coastal carbon budget for the last decade, and long-term (decadal and longer) studies of changes in surface pCO_2 and CO_2 fluxes can be conducted as the data record expands and lengthens.

The development of moored and unattended shipboard sensors for CO_2 and pH has seen great progress in recent years and now provides sufficiently frequent observations for some locations. The National Oceanic and Atmospheric Administration's (NOAA's) Pacific Marine Environmental Laboratory is working toward growing the OceanSITES global flux mooring network to provide widespread, global collection of ocean and atmospheric CO_2 measurements (NOAA, 2017c). A global network of underway ocean surface CO_2 measurements has been implemented and organized under the Surface Ocean CO_2 Atlas (known as SOCAT), which specifies data quality control standards and provides data access. SOCCOM (Southern Ocean Carbon and Climate Observations and Modeling), a National Science Foundation (NSF)-funded project, is currently deploying biogeochemical-Argo (BGC-Argo) profiling floats throughout the Southern Ocean, equipped with pH sensors as well as nitrate, oxygen, and the standard temperature and salinity sensors. Recent inclusion of new sensors on profiling BGC-Argo floats and moored platforms now provides good resolution of the seasonal cycle, which had for the most part never been measured, but because these instruments are only beginning to be deployed, spatial coverage is still inadequate. Using empirical relationships between carbon parameters, alkalinity and dissolved inorganic carbon can be computed from the observed measurements. The first full annual cycles of dissolved inorganic carbon, pCO_2, and air-sea fluxes of carbon are now being collected (Williams et al., 2017). Sensor development is advanced enough to be in commercial production, and expansion to global year-round profiling is now possible. With these improved capabilities and increased deployments that expand spatial coverage to the entire globe, understanding of the carbon budget will be enhanced and better predictions of how much CO_2 will be dissolved into the ocean versus remain in the atmosphere can be made. Significant international coordination and financial resources will be needed to achieve this observational network expansion.

Although the ocean carbon dataset currently available is limited relative to other ocean variables, it provides important information about human impacts on ocean carbon dynamics. Figures 2.2 and 2.3 synthesize data from Ocean Time-Series stations and WOCE and GO-SHIP research cruises that sample lines across the ocean basins approximately every 10 years. This example shows the large variations in water column CO_2 in the deep sea that are driven by differences in the ventilation of the interior ocean by currents sinking from the surface. The comparison of CO_2 concentrations before and after the rapid CO_2 increase attributed to human activities shown in Figure 2.3 also provides important insights into where on Earth the oceans may be changing most quickly.

These relatively sparse observations do not, however, illuminate the processes that transfer CO_2 between the atmosphere and ocean. For example, do short-lived events such as storms that impart energy at the surface of the ocean also contribute greatly to CO_2 exchange? Do eddies in the upper ocean play a role in air-sea carbon transfer? Or are deep winter surface mixed layers the primary

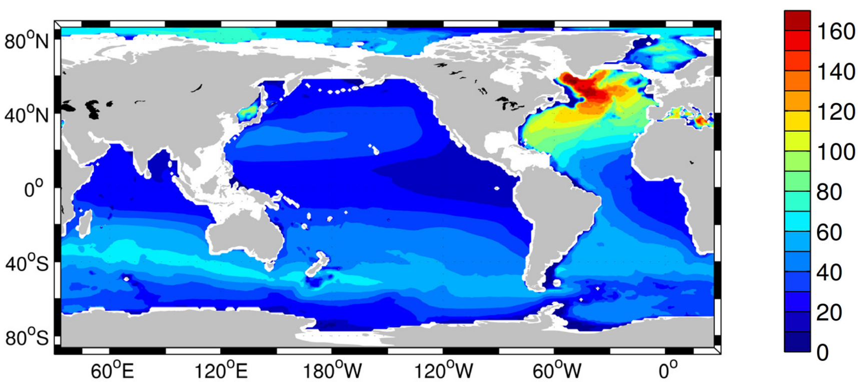

FIGURE 2.3 Map of the global distribution of oceanic water column inventories (moles m^{-2}) of estimated anthropogenic CO_2 (determined from data from WOCE and GO-SHIP hydrographic expeditions). SOURCE: Khatiwala et al., 2013.

mechanism for larger absorption of CO_2? If so, this may explain the high values in the North Atlantic and Antarctic Circumpolar Current region in Figure 2.3, which are areas rich in eddies and also of very deep winter surface mixed layers. Knowledge of the spatial and temporal variability of the processes at work is needed to close the budget through the development of improved models. Improved sampling and prediction of CO_2 exchange and pH also have other benefits. In more acidic waters, for example, organisms that build shells and other structures from calcium carbonate will require more energy to do so and have less success (NRC, 2010). Thus, managers of shellfish hatcheries have a strong interest in the variability and change in the pH of the water drawn from the ocean for use in the hatchery. Looking ahead, a better ocean carbon observing system is necessary to sample from local (coasts) to global scales and resolve variability in much the same way that coastal observing platforms and the Argo array do today. As with the heat budget, some processes in the carbon budget that influence carbon transport, are not yet routinely observable; and ocean research and process studies are important to build the understanding and capabilities needed to enable sustained observing of these processes.

Fresh Water Budget

The ocean holds about 97 percent of the water on Earth (Gleick, 1996). The "fresh water" in the ocean refers to the amount of water (by weight) in sea water, which consists of both water and salts, with salts accounting for about 3 percent of the mass. Ocean salinity is the measure of the salt content of sea water; it is decreased by dilution (through fresh water input from precipitation, river outflows and surface runoff, or ice melt) and increased by evaporation or rejection of salts from sea water during sea ice formation. Ocean surface salinity is lower in regions of excess precipitation (P), and higher in regions of excess evaporation (E) (Figure 2.4b, d). Because of the direct linkage between salinity and fresh water content, measurements of ocean salinity provide information about how fresh water is redistributed globally (e.g., Gordon, 2016). As the climate warms, the atmosphere holds more water vapor (Figure 2.4a; see also Schneider et al., 2010) and this excess water vapor capacity is associated directly with patterns of increased evaporation from the ocean and increased precipitation (Figure 2.4b) that maintain a new equilibrium in atmospheric water vapor content.

Evaluation of the global fresh water budget requires observations of salinity, temperature, sea ice, velocity of ocean currents, diffusivity within the ocean, and the fluxes of fresh water into and out of the ocean in the form of precipitation, continental and ice sheet drainage (through runoff, melting, and calving), and evaporation. Ocean salinity measurements provide a record of changes in the hydrological cycle over the past 50 years, showing that on the whole, regions of high surface salinity have become increasingly saline, while regions of lower surface salinity have become fresher (Figure 2.4c). This has been observed through

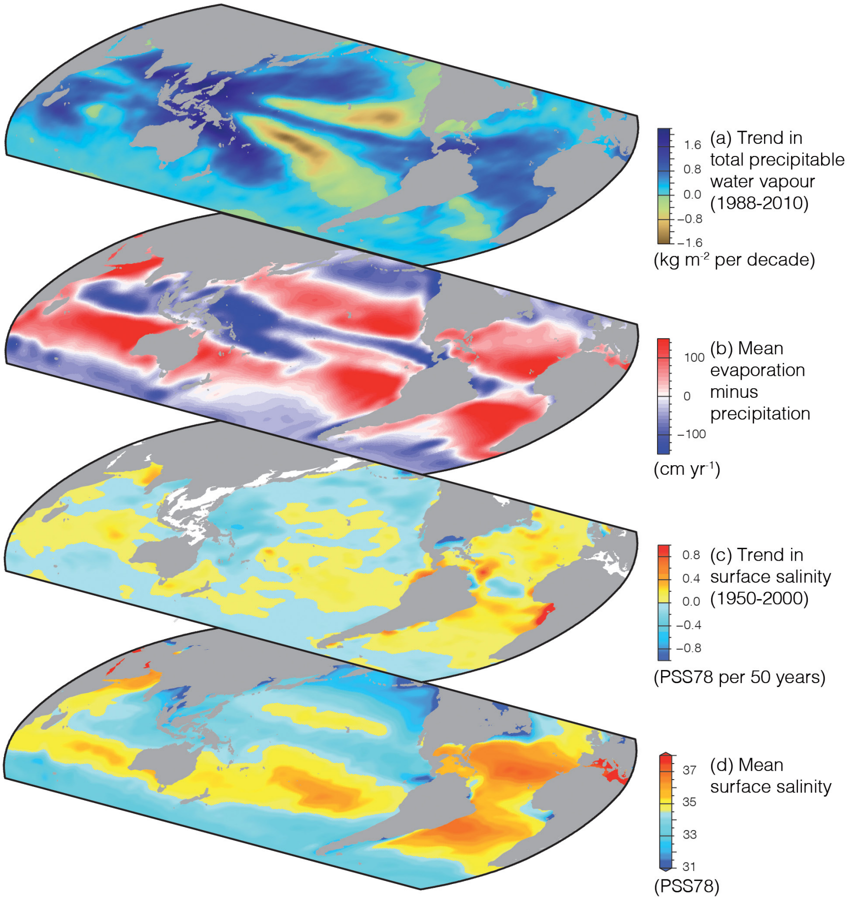

FIGURE 2.4 Changes in sea surface salinity are related to the atmospheric patterns of evaporation minus precipitation (E – P) and trends in total precipitable water. (a) Linear trend (1988-2010) in total precipitable water (water vapor integrated from the Earth's surface up through the entire atmosphere) from satellite observations (blues, wetter; yellows, drier). (b) The 1979-2005 climatological mean net E – P from meteorological reanalysis (reds: net evaporation; blues: net precipitation). (c) Trend (1950-2000) in surface salinity (blues, freshening; yellows-reds, saltier). (d) The climatological mean surface salinity (PSS78) (blues, <35; yellows–reds, >35). SOURCE: Rhein et al., 2013.

the network of opportunistic research ship expeditions over many decades, plus the much more intense observing provided by the Argo profiling float network since the early 2000s. While pre-Argo observations provided evidence of such hydrological changes only through spatially averaged trends in salinity (Boyer et al., 2005), Argo observations over the past 10 to 15 years have allowed the trends to be mapped (Figure 2.4; Durack and Wijffels, 2010), showing that indeed, at the largest spatial scale, regions with high evaporation rates are becoming more saline and high rainfall regions are becoming fresher. Averaged over the globe, the surface salinity difference between saltier and fresher surface regions has increased by almost 0.09 parts per thousand, which is about 1 percent of the total range of salinity but as high as 5 percent when looking at the range in a given hemisphere of an ocean (see also Rhein et al., 2013). Changes in salinity also impact ocean circulation and the heat and carbon exchanges between the ocean and the atmosphere, making this a critical component of understanding Earth's changing climate.

Observing ocean salinity on a global scale informs us about the global hydrological cycle and adds to understanding that will be used in prediction of drought and flood conditions (Durack et al., 2012). At the same time, observing ocean temperature and salinity is the primary way in which climate-related change in the ocean is tracked, including changes in ocean circulation. Combined temperature and salinity distributions reflect the large-scale circulation patterns as well as the changes caused by heating and cooling, and evaporation and precipitation. An important part of the global ocean circulation, referred to as the overturning circulation, or in earlier usage as the thermohaline circulation, is associated with density differences stemming from the differing temperature and salinity of different water masses. Higher density water created at high latitudes, especially in the Antarctic and subpolar North Atlantic, spreads through the deep oceans, returning to the sea surface through both wind-driven upwelling in the Southern Ocean and through downward mixing (diffusion) of heat in the warm low latitudes. Freshening of surface waters in some regions at high latitudes can cause even cold surface water to be more buoyant, thereby reducing the ability of surface waters to become dense enough to sink to great depth and altering the pathway of surface water into the interior of the ocean. By tracking salinity and temperature properties of water in the ocean interior, change in the overturning circulation and in how those waters are generated can be better understood. A description of the overturning current and the observations needed to understand its climate-relevant process is found in Box 2.1.

New developments in remote sensing have added the capability of measuring and mapping sea surface salinity (SSS) from satellites such as Aquarius and SMOS (Soil Moisture and Ocean Salinity) (Lagerloef et al., 2008; Reul et al., 2014). In situ sampling of SSS in field experiments is being used to calibrate and support the remote sensing effort, thereby increasing the extent of reliable measurement coverage (Lindstrom et al., 2015). Fresh water fluxes into the ocean are increasingly better observed, through improvements in satellite observations of precipitation and ocean mass, in-stream gauge networks operated by the U.S. Geological Survey, and in coupling coastal models with NOAA's new integrated water (hydrological) model. Fresh water changes due to formation and movement of sea ice, as well as melting of glaciers, ice sheets, and ice shelves, are

BOX 2.1
Atlantic Meridional Overturning Circulation: How the Frequency and Geographic Distribution of Ocean Observations Influences Our Understanding of Climate

Ocean observations have been essential to unraveling the complex pathways of the overturning circulation of the ocean; these pathways are a critical property of the climate system because of their major role in redistributing and storing heat and carbon absorbed from the atmosphere (Lozier, 2015). Ocean currents carry heat that enters the ocean preferentially in tropical waters toward the poles and transport cooler waters from higher latitudes beneath the warmer upper ocean to form the interior and deep waters of the ocean basins. The transfer of cold surface water (which absorbs more CO_2 than warm surface water) to the deep ocean transfers CO_2 absorbed at the surface to the deep ocean, where it is "stored" away from exchange with the atmosphere, as evident in the large inventory of anthropogenic carbon in the North Atlantic where deep water formation is especially vigorous (Figure 2.3).

Periodic ocean surveys from sampling by ship transits, as far back as the eighteenth century, contributed to the notion that a dominant pattern of ocean circulation took the form of a simplistic "conveyor belt" of water movement from the North Pacific, down to the Southern Ocean, westward to the Atlantic, up to the North Atlantic, and back (Broecker, 1987). Initially, the vertical branch of this circulation was hypothesized to be mainly driven by the sinking of higher density sea water at the poles, due to meridional (north-south) differences in temperature and salinity, termed the thermohaline circulation. The horizontal component is dominated by the wind-driven circulation. Because climate affects both temperature and salinity, the "conveyer belt" is susceptible to climate change, which could reduce the transfer of heat from lower to higher latitudes, which moderates the climate in northern latitudes. For example, the relatively temperate weather in northern Europe could arguably become considerably colder if the circulation weakened. This concern was heightened by the discovery of "abrupt climate changes" on the scale of years to decades in the analysis of Greenland and Antarctic ice cores that were attributed to a slowdown in the ocean's thermohaline circulation, resulting primarily from large increases in low-salinity surface waters in the high-latitude North Atlantic that weakened the formation of deep water (Alley et al., 1997). With historical precedence for such an abrupt change seen in the paleorecord, scientists raised concerns that the modern increase in greenhouse gases could result in abrupt changes in climate, albeit arising from a multitude of different causes in addition to high-latitude freshening (NRC, 2002).

These concerns led to increased study and more systematic observations of ocean circulation, particularly the dominant Atlantic portion of the system, the Atlantic Meridional Overturning Circulation (AMOC), characterized by net northward flow (in both hemispheres) of heat carried by warm upper-ocean water and southward flow of deeper, cool water. The Rapid Climate Change–Meridional Overturning Circulation and Heat Flux (RAPID) Array is a system of moorings and cables across the subtropical North Atlantic basin that provided the first continuous observations of the AMOC at that latitude, starting in 2004. These regular observations from RAPID showed that the AMOC can vary as much as sixfold in a period of months, whereas previously, scientists had assumed that the circulation only varied on longer timescales (Cunningham et al., 2007; Srokosz and Bryden, 2015), with serious implications for required temporal sampling to infer trends. In fact, the evidence from the earlier, infrequent hydrographic surveys appeared to indicate that a slowdown in the circulation could already be detected. With the additional data from RAPID it became clear that the apparent slowdown could be an artifact of natural variability that could only be detected with continuous monitoring. Additional studies have challenged the notion of a simple Atlantic "conveyor belt" (e.g., Bower et al., 2009; Mielke et al., 2013; Wunsch and Heimbach, 2013), including its deficiencies in depicting the global overturning circulation that includes the Southern Ocean (See Figure and Marshall and Speer, 2012; Talley, 2013). The global overturning circulation instead is a more complex system of pathways whose strength varies in time. Observations and studies on the pathways through which water circulates between the surface and ocean depths and around the ocean basins also contribute to our understanding of the carbon budget. The size of the ocean's carbon reservoir and the length of time it stays in deep water are both essential measures for determining the ocean's capacity for carbon storage.

Sustained and systematic observations in the past decade have revealed the complexity and variability of the global overturning circulation, but knowledge gaps remain. The mechanistic causes of the observed variability are not well

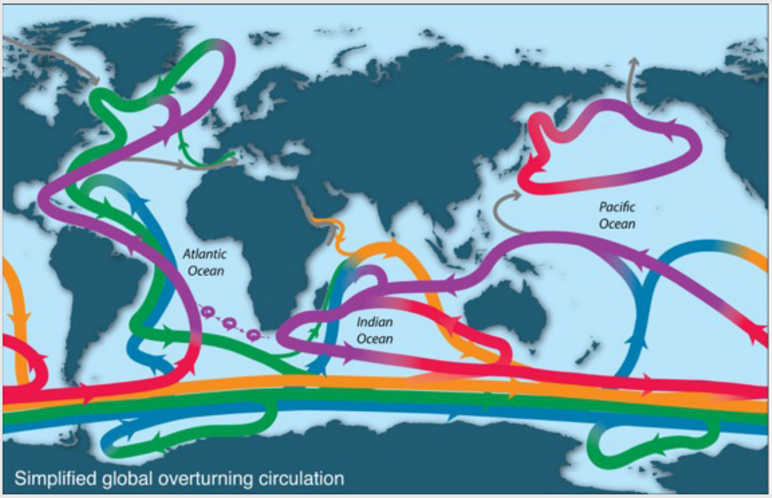

Figure Depiction of the Meridional Overturning Circulation as a "conveyor belt" has been replaced by a more complex understanding of a multipathway system that varies in time and space. Purple = upper ocean and thermocline. Red = denser thermocline and intermediate water. Orange = Indian Deep Water and Pacific Deep Water. Green = North Atlantic Deep Water. Blue = Antarctic Bottom Water. Gray = Bering Strait components and Mediterranean and Red Sea inflows. SOURCE: Talley, 2013.

continued

BOX 2.1 Continued

understood. For example, it had been assumed that changes in convection in subpolar regions would influence the strength of the current flow in the AMOC, but that has not been observed to be the case (Pickart and Spall, 2007; Fischer et al., 2010). Variability in the strength of the overturning circulation influences sea surface temperature and subsequent weather patterns, sea-ice extent, and carbon storage, and is therefore critical for improving our understanding of the climate system and anticipating future changes in Earth's climate. Expansion of long-term AMOC measurements to the subpolar North Atlantic where deep water is formed and carbon and heat are sequestered (such as the Overturning in the Subpolar North Atlantic Program, or OSNAP, using moorings, hydrography, and subsurface floats), and to the South Atlantic where the AMOC connects with the rest of the global ocean (South Atlantic MOC or SAMOC or SAMBA), continuation of GO-SHIP global decadal surveys, and expanding observing platforms such as Deep Argo and the network of carbon measurements will provide better understanding of the overturning circulation and its changes, and hence the climate system (CLIVAR, 2017; Lozier et al., 2017).

increasingly better observed as a result of extensive satellite remote sensing of the cryosphere. As with the heat and carbon budgets, some processes that redistribute fresh water in the ocean are not yet routinely observable; and research and process studies are important to build the understanding and capabilities needed to enable sustained observing of these processes.

Through expansion of the existing Argo program into the deep ocean, polar waters, and coastal regions (along with GO-SHIP repeat hydrography, remote sensing of SSS, and deep moored temperature and salinity measurements) and improvements in observing ice mass balance, precipitation, land runoff, and evaporation, it should become possible to close the fresh water budget and hence improve our understanding of the global water cycle. Further, this information will help quantify change and variability in the ocean's water masses and global overturning circulation. In addition to improving understanding of the physics of climate, this information is needed for ecosystems management and forecasting of species adapted to live in specific temperature and salinity conditions.

OBSERVATIONS OF GLOBAL AND REGIONAL SEA-LEVEL CHANGE

Knowledge of sea level has an immediacy of value for the large fraction of the population located near coasts and on low-lying islands. Sea level is impacted by—and thus integrates—a large range of geophysical processes, involving ocean and atmosphere dynamics, changing land ice, the Earth's lithosphere and its response to ocean mass and land-ice loading, and the Earth's rotation characteristics (Stammer et al., 2013). Thus, discussion of sea level and the observations needed to improve our understanding and predictive capabilities for future change provides a complement to the previous discussions of heat, carbon, and fresh water budgets, particularly since ocean heat and mass changes affect sea level. Monitoring ocean heat content changes provides estimates of rates of thermosteric sea-level rise. The net fresh water input to the ocean, which increases when higher temperatures cause glaciers and land ice sheets to melt and run off (or calve) into the ocean, also contributes to sea-level rise. To assess these components of the heat and fresh water budgets, in situ measurements of temperature and salinity are needed throughout the water column to complement satellite observations. Moreover, ocean current observations are required to evaluate the transport of heat and salt and their contributions to regional sea-level change. Refining the calculations of these budgets based on a comprehensive set of in situ measurements will advance our understanding of causes of global and patterns of regional sea-level rise, as will be necessary to assess risks to coastal communities and infrastructure in the United States, and to low-lying regions worldwide. Because some measurement techniques target absolute sea level, whereas others measure relative (local) sea level, care must be taken in properly accounting for their differences in observing strategies.

Global Sea-Level Rise

Sea-level rise is one of the leading indicators of a warming climate. The increase in global mean sea level (GMSL) over the past century has been approximately 15 cm, as estimated from tide gauges and satellite altimetry. This rise in GMSL has occurred during a dramatic increase in global average surface temperature and is nearly equal to the increase in sea level over the past millennium (Figure 2.5). Climate model projections suggest that sea-level rise will continue to accelerate dramatically over the next century and beyond (Church et al., 2013), causing profound societal impacts around the world (Wong et al., 2014). To understand the drivers of sea-level rise, both globally and on regional scales, and to validate and improve climate model projections, a sustained satellite and in situ observing effort is required. As an illustration of current capabilities, the recent trend and year-to-year variations in GMSL (measured by satellite altimeters) are well described by the combined contributions to GMSL from melting land ice (measured from satellites) and ocean warming (thermosteric sea level estimated from in situ Argo data) (Figure 2.6 and, e.g., Leuliette and Willis, 2011; Chambers et al., 2017). The agreement of these intercomparisons suggests that the attribution of sea-level rise is achievable on a global scale. An expanded heat and fresh water monitoring effort in the deep ocean and in polar regions, as discussed earlier in this chapter, will enhance our understanding of GMSL.

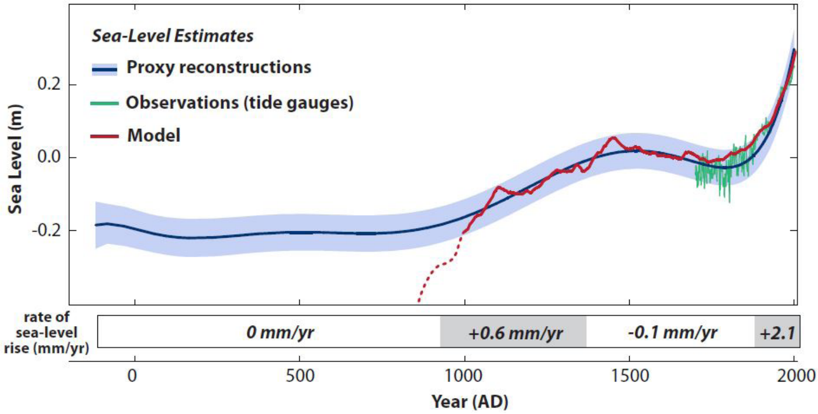

FIGURE 2.5 Sea-level estimates for the past 2000 years, adjusted for land height changes caused by glacial coverage and melt (known as isostatic effects), from proxy (geological) evidence (blue), tide gauge observations (green), and statistical model estimates based on observations (red). The dotted red line shows where the model estimate deviates from the proxy record. The lower panel shows rates of sea-level change in millimeters per year based on proxy reconstructions. SOURCE: NRC, 2012b and sources cited therein.

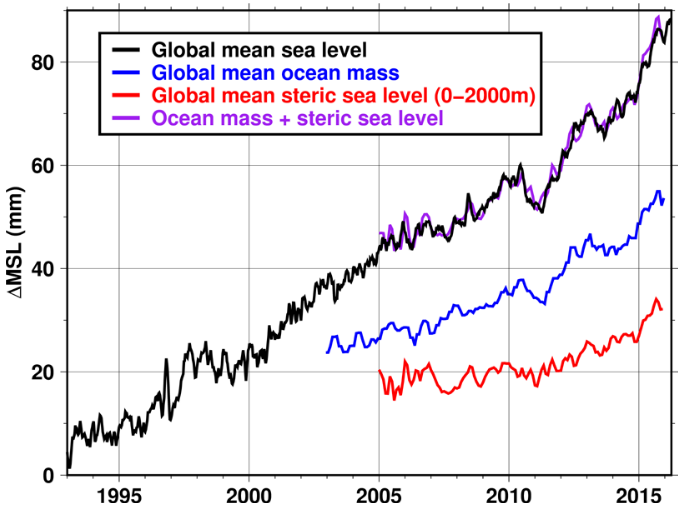

FIGURE 2.6 (Black) Monthly averaged global mean sea level observed by satellite altimeters (1993–2016) from the Copernicus Marine and Environment Monitoring Service. (Blue) Monthly averaged global ocean mass (2003–August 2016) from the Gravity Recovery and Climate Experiment (GRACE). (Red) Monthly averaged global mean steric sea level (2004–2016) from the Argo profiling float array. (Purple) Mass plus steric. SOURCE: Leuliette and Nerem, 2016.

Regional Sea-Level Change

Sea-level change is not uniform across the global ocean, but instead varies in different regions. Research efforts have focused on determining this spatial variability to better explain the drivers of regional change and the impacts of sea-level rise at specific locations. The satellite and in situ observing system elements that provide the integrated measure of GMSL also monitor the rich variations in regional sea-level change. Satellite altimeters have provided near-global coverage of the oceans since the early 1990s which can be used to evaluate regional change. Tide gauges provide validation for satellite measurements and complementary information at multidecadal-to-centennial timescales, and include measurements of the coastal zone. Both systems indicate regions of the ocean that have been rising faster than the global average over the altimeter era, particularly in the Southern Hemisphere, while in other areas sea level has fallen (Figure 2.7). These patterns largely represent variations in the upper ocean circulation in response to surface winds that change on decadal and longer timescales. For example, recent changes in Pacific wind patterns associated with a shift to the Pacific Decadal Oscillation warm phase (Hamlington et al., 2016; NASEM, 2016a), have led to a sea-level increase at the eastern tropical Pacific and a decrease at the western side over the past 5 years (Figure 2.7b), which is counter to the longer term trend since 1993 (Figure 2.7a). Similarly, the observed slowdown of the North Atlantic subpolar gyre circulation since the mid-1990s has been attributed to changes in the wind field over the North Atlantic sector (Häkkinen and Rhines, 2004, 2009).

Regional sea-level patterns are also influenced by vertical land motion, with rates that are often comparable to absolute sea-level changes. Mass loss from the Antarctic and Greenland ice sheets results in distinctive regional sea-level patterns, or "fingerprints" (Mitrovica et al., 2011), the reduced weight of the ice sheet causing the land below it to uplift (or rebound) as well as other far-field solid Earth deformations. The reduction of mass concentrated in frozen form on the ice sheet leads to a change in the global gravitational field, and the global mass redistribution causes changes in the Earth's rotation, which in turn impacts the sea level's dynamic topography. Land can also rise or fall locally due to the loss of ice mass from the last glacial period (glacial isostatic adjustment), earthquakes, land water storage, land subsidence from groundwater withdrawal, soil compaction, variations in sedimentation rates, wetland submergence, or oil extraction (Church et al., 2013; Wöppelmann and Marcos, 2016). These processes underscore the need for sustained regional measurements to identify the contribution from vertical land motion to relative sea-level change (e.g., Khan et al., 2016). Understanding, quantifying, and distinguishing the drivers of sea-level change and the associated coastal impacts requires a continued, broad interdisciplinary monitoring approach, involving ocean, atmosphere, land ice, and land observing components. Monitoring the sea surface height, the ocean circulation, changes of land-ice masses and vertical land motion, and air-sea fluxes of heat, fresh water, and momentum all contribute to improved understanding of pro-

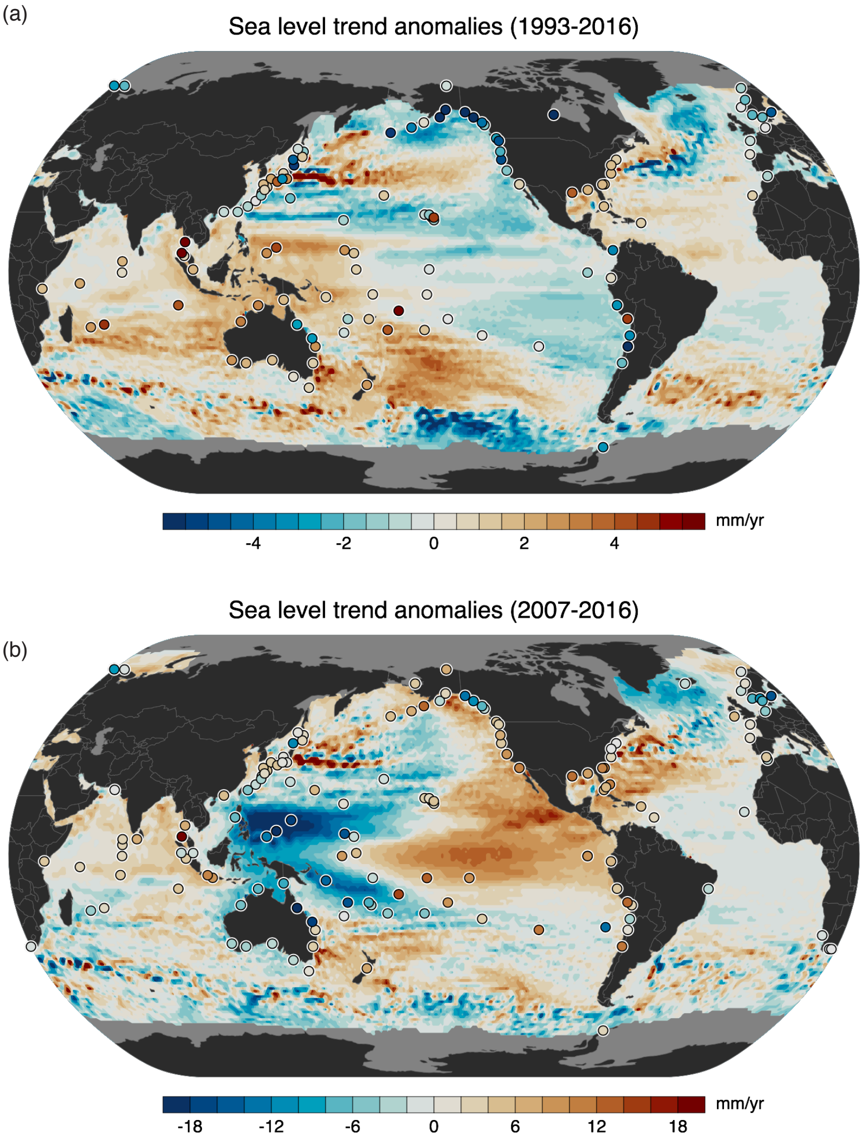

FIGURE 2.7 (a) Linear sea-level trends from altimetry during 1993–2016. (b) Linear sea-level trends from altimetry during 2012–2016. Trends were calculated using tide gauge data from the University of Hawaii Sea Level Center Fast-Delivery database, and Ssalto/Duacs altimeter products that were produced and distributed by the E.U. Copernicus Marine and Environment Monitoring Service. SOURCE: University of Hawaii Sea Level Center with data from Caldwell et al., 2015, and Copernicus Marine Environment Monitoring Service (http://marine.copernicus.eu/).

cesses driving sea-level change. The temperature and salinity observing efforts, with the improvements discussed earlier in this chapter, are also essential to improving knowledge of sea-level change processes.

> *Finding: The current ocean observing system has made significant contributions to better understanding the ocean's role in the Earth system, including its heat, carbon, and fresh water budgets, and to better understanding global and regional sea-level change. Sustaining, optimizing, and increasing ocean observing capability will further improve understanding of the ocean's role in climate.*

INTEGRATING DATA FROM MULTIPLE OBSERVATION SYSTEMS TO UNDERSTAND CLIMATE

In situ data collected with different observing systems are commonly linked to each other and to data collected with external observing systems, such as satellites and atmospheric observations. By integrating datasets from multiple observing platforms, more detailed knowledge of specific aspects of the system can be gained, and improved understanding of the ocean and its role in the broader climate system can be achieved. Remote sensing methods provide incomparable spatial coverage that complements in situ sampling. Key ocean observations made from satellites include sea surface height, surface winds, sea surface temperature, sea surface salinity, ocean bottom pressure, sea state (surface waves and swell), and ocean color. Over polar regions, satellites measure characteristics of sea-ice extent, drift, age, and, increasingly, thickness. Often, in situ sampling also provides important means to calibrate and validate remote sensing products. Tide gauges, for example, have proven essential to identify drift in satellite altimeters (Mitchum, 2000; Chen et al., 2017). Atmospheric observations at the sea surface of surface wind, near-surface air temperature, surface rainfall, and near-surface air humidity, together with the sunlight (shortwave radiation) and infrared (longwave) radiation falling on the sea surface, are required to compute the exchange of heat, fresh water, and momentum between the ocean and atmosphere (momentum is the effect of surface wind on surface water, to accelerate water movement). Such observations are possible at a small number of in situ surface buoys (OceanSITES and DBCP) and from ships (SOT).

Combining and interpreting diverse sets of variables with heterogeneous spatial and temporal sampling patterns is challenging. This has long been recognized in numerical weather prediction, where computational frameworks, generally known as data assimilation (DA), have been developed in which numerical models are used to combine data and connect the different variables through known equations (Lahoz et al., 2010). Experience from weather forecasting shows that development of robust DA methodologies (e.g., Bauer et al., 2015) is critical for increasing the usability of ocean observing data for a broader array of data consumers. Atmospheric observations are routinely incorporated in the large weather forecasting models, and in "reanalysis" methods used for climate purposes (defined below). Ocean observations similarly have become essential for constraining the ocean component of these forecast models, for stand-alone systems in operational oceanography (Edwards et al., 2015; Martin et al., 2015), as well as ocean observation–climate modeling systems (Stammer et al., 2016). Many of the ocean observing programs described in this report are integral to these models, and disruption or discontinuity of the observations would exact a large toll.

DA is increasingly being used in so-called coupled model "initialization" efforts, where formal methods are deployed to derive optimal initial states based on available satellite and in situ observations to improve seasonal-to-decadal Earth system predictions (Meehl et al., 2014; NASEM, 2016b). A challenge is that the observed initial state may not be the model's preferred state, potentially leading to "initialization shocks" that may confound the forecast. One role of DA is to reduce such shocks and the dependence of the initialization technique on the (incomplete) observing system. DA also enables Observing System Experiments (OSEs) as well as Observing System Simulation Experiments (OSSEs). These frameworks are employed to assess the impact of existing observing networks on a specified climate metric, and to quantify the optimal enhancement of such networks by new observations (what observations have the most impact, where should they be placed, and at what sampling rate), thereby prioritizing or guiding the evolution of the observing system design.

The oceanographic community is gradually adopting DA frameworks; however, the sparsity of ocean observations compared to atmospheric ones presents a challenge in implementing these frameworks to reconstruct the ocean's past climate. Multiple data assimilation methodologies have been developed, including state estimation and reanalysis, the uses of which vary depending on the data analysis needs (e.g., the need to interpolate conditions of the recent past based on limited observations or to extrapolate into the future; see Thacker and Long, 1988; Wunsch and Heimbach, 2013; Stammer et al., 2016). A state estimate represents a statistical fit of a dynamical model to the available observations and uses interpolation-based DA both forward and backward in time. Reanalysis is the collection through time of optimized initial states that have been generated for forecasting purposes. Whereas these states represent good fits to available observations and are similar to state estimates, considered as time-evolving states they do not adhere to strict conservation laws on timescales relevant to climate variability and change. State estimation is thus essential for closing the climate budgets, and is slowly becoming more commonly used in oceanography. Ocean state estimates and reanalyses are increasingly being explored to provide optimal initial conditions for seasonal-to-decadal climate prediction. Atmospheric reanalysis fields are used in ocean models to infer the ocean surface's boundary conditions, such as the air-sea fluxes of momentum, heat, and fresh water ("surface forcings"), essential information for driving the ocean component of the models and for estimating heat, carbon, and fresh water budgets in the ocean.

DA usually requires a (state-of-the-art) general circulation model (ocean, atmosphere, or coupled), a serious effort to collect available data streams, uncertainty estimates for observations and the background state, a comprehensive assimilation scheme, and significant computational resources to put it all together. Common, simpler approaches for merging observations than DA, which requires a full numerical model, are blended products of different in situ, remotely sensed, and model inputs of one variable to create gridded fields (three-dimensional maps of observed variables). Temperature, salinity, and biogeochemical data are routinely treated in this manner, and are at the heart of many published and ongoing budgets for heat, fresh water, and carbon, as well as other biogeochemical parameters. Ocean velocity is a critical variable for budgets derived in this manner; because the useful parts of the velocity field for climate timescales are difficult to measure directly throughout the ocean, velocities are estimated using a combination of different types of observed variables. This is one of the outputs of DA, but estimating the ocean's velocity field is also routinely accomplished through "data integration," in which different observed variables are combined using an assumed underlying dynamical model, such as geostrophy or Ekman balance.

From a climate perspective, the ocean currents transport heat poleward from the equator and sequester waters from high-latitude surface oceans into the interior, and are thus a key component of the processes that govern heat, carbon, and fresh water uptake, transport, and storage. At the same time, knowledge of currents supports applications including improved maritime transportation, improved search and rescue capabilities, and improved oil spill prediction. Deriving ocean current velocities via approximate methods (for instance, geostrophic balance and Ekman transport) requires information about the ocean's density field and surface winds. Argo profiling floats measure temperature and salinity profiles, which are used to calculate sea water density. Incorporating satellite measurements of sea surface height (altimetry) improves estimation of the geostrophic flow. Finally, the wind-driven, or Ekman, component of the ocean velocity field can be added by using wind data from satellite remote sensing. Taken all together, the estimates of the sum of the wind-driven and density-driven flows are key to building basin-by-basin budgets of inflow, outflow, and storage of heat, carbon, and fresh water.

BENEFITS OF OCEAN OBSERVATIONS BEYOND CLIMATE

A sustained and integrated suite of ocean observations designed to contribute to a better understanding of future changes in Earth's climate also benefits many other areas of science, commerce, and human safety. Among the most apparent and important benefits are daily to weekly weather forecasting and seasonal climate prediction. Modern weather forecasting relies on the same satellites and in situ measurements used for observing the oceans. Increasingly, observations of ocean temperatures, patterns of sea surface warming and cooling, and even sea-ice extent are used with numerical circulation models to reliably forecast hurricane intensities and tracks as well as seasonal precipitation and storminess, which influence large portions of the United States. Seasonal prediction of Arctic Ocean ice cover will become increasingly valuable as reduction of the seasonal ice pack may open the Arctic to increased commercial activities and tourism (NRC, 2014).

The Tropical Pacific Observing System (TPOS) has been operating for decades and is a valuable part of the monitoring network for measuring long-term changes in ocean-atmosphere heat exchange and ocean heat content. This system was originally designed, in large part, to better understand and predict the occurrence and impacts of the El Niño–Southern Oscillation (ENSO) phenomenon. The system has been highly successful in achieving these goals and today's operational ENSO forecasts, with lead times of 3 to 9 months, are highly dependent on data from the array. These forecasts impact many areas of American commerce, influencing farmer crop decisions, grain and electricity futures, and insurance rates among others, because of the profound and often predictable influence of ENSO on seasonal weather patterns in the United States and beyond (Haigh et al., 2015; Tack and Ubilava, 2015; Anderson et al., 2017; Ubilava, 2017). Specifically, agricultural enterprises use ENSO-dependent seasonal forecasts as an aid to plan the timing of planting, fertilizing, and harvest, as well as livestock grazing strategies (see Klemm and McPherson, 2017). The U.S. investment in TPOS has paid for itself many times over, and ENSO experts expect these benefits to become even more important as the climate continues to change. A redesign of the TPOS is being undertaken to modernize and improve the system with the view of extending ENSO forecast ability and broadening the TPOS objectives to include climate (Cravatte et al., 2016).

A study by Scharroo et al. (2005) provides compelling examples on how combined sea surface temperature (SST) and sea surface height observations could have significantly improved forecasting the intensification of Hurricane Katrina prior to landfall (see also Goni and Trinanes, 2003; Morrow and Le Traon, 2012). Sea surface height anomalies were measured related to anomalously thick layers of warm waters associated with warm core eddies in the hurricane's path. Such features developing over longer timescales provide a source for prediction of hurricane intensification. Similar results were found for Northwestern Pacific typhoon intensity (Mei et al., 2015). Altimetry also measured elements of developing storm surge in the wake of the hurricane. In 2012, Superstorm Sandy caused over $65 billion dollars in damages in the United States, second only to Hurricane Katrina (NOAA, 2014). Lau et al. (2016) simulated Superstorm Sandy under warmer ocean conditions expected with a doubling of atmospheric CO_2 levels and estimated that the storm's Power Destructive Index may increase as much as 50 to 160 percent, depending on the extent of Atlantic warm pool warming and the storm's exposure time to it. Taken together these studies reinforce the importance of both surface and subsurface ocean observations to improve and extend forecasting of the world's most destructive storms.

Tide gauges that provide information on sea-level rise are also used to track changes in water level resulting from storms, and the potential for coastal inundation. Tide gauges can be used to monitor changes in water height in navigable channels, information that has become more important as merchant ships have increased in size and draft. Additionally, observations of the tides and the height of the tide, as well as observations of the salinity and temperature of the water in ports are also being used to estimate the buoyancy of large vessels, to gain small advantages in bringing loaded ships directly to docks rather than unloading offshore or using smaller vessels.

Ocean observations are also important for optimizing fisheries management and promoting sustainable use of marine resources (Nicol et al., 2013; Evans et al., 2015). Ultimately, sustainable ocean harvests and aquaculture require sustained ocean observations, ranging from knowledge of changes in the location and amount of oceanic primary productivity that fuels all trophic levels including commercial species; to changing ocean currents, temperatures, and salinities that influence where and when fish breed and feed; to the locations and activities of illegal and unregulated fishing vessels. Multiple elements of the existing and future ocean observing system can provide important datasets that support the development and maintenance of sustainable fishing practices worldwide.

Ocean acidification is a natural and predictable consequence of CO_2 uptake from the atmosphere and is now decreasing global ocean pH with substantial regional variability. Declining pH is already impacting marine food webs and causing negative impacts within specific sectors of U.S. shellfish aquaculture (Washington State Blue Ribbon Panel on Ocean Acidification, 2012; Cooley et al., 2015; Feely et al., 2016). Projections of future impacts include significant losses to coral reef habitats and some fish stocks (Branch et al., 2013; Speers et al., 2016). Many of the assets now being used for ocean climate observations are needed for understanding future changes in ocean acidification as discussed in the carbon budget section of this chapter. Additionally, platforms such as Argo are already being outfitted to make pH and O_2 measurements through the BGC-Argo program discussed above. Attention to ocean acidification and its impacts on food security is likely to increase in the next decade. Future research depends on a healthy and sustained ocean observation system.

The data and products from the ocean climate observing system have also enabled services provided by private companies in multiple sectors such as marine forecasts for shipping, seasonal forecasts for agriculture and water resource management, and tailored services based on sea surface temperature and other factors for commercial fisheries operations. For example, multiple companies (e.g., BigOceanData, StormGeo) provide ocean climate information in their data products designed for optimal shipping safety and routing.

Finding: The ocean observing system contributes not only to our understanding of climate variability and change, but also to a wide variety of other services including weather and seasonal-to-interannual forecasting, living marine resource management, and marine navigation. This understanding of climate variability and change and other services underpins national defense, economic, and social policy decisions.

TECHNOLOGY CHALLENGES OF OCEAN CLIMATE OBSERVING

Although great progress in ocean observing has been made, many technological and computational challenges remain and new obstacles are likely to arise as systems expand and new data needs emerge. The observing system deployed to collect in situ ocean climate observations exists in the context of the Earth observing system, which is the combination of in situ and remote sensing observations, and in the context of model-based syntheses and predictions. The integration of in situ data with that from remote sensing is essential to gaining the most comprehensive understanding of the ocean and climate system, as discussed earlier in this chapter. This integration, however, presents unique challenges. Most in situ sensors sample at a point location, while satellite sensors look down and average over a spatial footprint using a property of the ocean surface, such as emissions of thermal radiation at a specific frequency. This spatial footprint is then related to the desired observed metric, such as sea surface temperature. The satellite observation needs to be calibrated, algorithms need to be developed to apply to the remote sensing observations, and platform-to-platform continuity and comparability need to be established as successive satellites are flown. Developing and sustaining formal data-model synthesis in the form of formal estimation is a complex undertaking, akin to, albeit different from, DA for the purpose of numerical weather prediction. These activities are key to integrating the disparate and heterogeneous observational data streams in a consistent manner.

Measuring environmental variables in situ in the ocean is also technologically and logistically complex. Sea water is corrosive to deployed instrumentation and it is opaque to radio frequencies, making communication of data from within the ocean by telemetry difficult. Instruments and sensors deployed in the ocean are subject to biofouling, with marine growth either interrupting sampling or affecting the calibration of the sensors. Surface waves, currents, and winds challenge structures designed to work at or near the sea surface while in the deep ocean, instrument cases must withstand cold temperatures and high pressure. Because of the cost and limited availability of ships required to deploy and maintain equipment, deployed instrumentation has to be designed robustly, using low-powered but reliable and accurate electronics. Data are often recorded internally, to be collected when instruments are recovered, or data are telemetered via satellite in the case of platforms that are not recovered. In addition, moored and untethered platforms are subject to vandalism at sea, damage by fishing gear, or theft.

It is attractive to consider adding new sensors to existing platforms; however, this raises costs, increases power consumption, and adds to data telemetry or recording requirements. Adding sensors thus must be done with consideration of negative impacts on the data currently delivered by a platform. New technological approaches may yield more cost-effective approaches to sampling, but phasing out an existing sampling methodology to be replaced by a new approach requires a period of overlapping sampling and analyses of both datasets to document and prove the comparability that is required to preserve a continuous long-term record of a given variable.

Current and near-future technological advances have helped and will continue to help address ocean observing challenges, an important element of advancing the ability to sustain ocean observations as noted in the committee's statement of task. Improved batteries allow greater lifetime, hosting of more sensors, and higher sampling rates. Increased power availability also allows implementation of strategies to address biofouling (e.g., opening and closing shutters, in situ generation of chlorine) and use of higher rate telemetry systems. Shifting from limited-bandwidth telemetry system to higher data rate Iridium and Inmarsat systems has increased the ability to send more data in real time and also allows two-way communication to support system maintenance and adjustment of sampling. Autonomous systems such as gliders and Saildrones allow deployment of platforms that navigate themselves to the desired site or region and are less subject to the vandalism and damage seen at fixed observing platforms in heavily fished areas. In addition to human impacts, biofouling at and near the surface continues to be a challenge, and technical improvements to mitigate biofouling impacts (e.g., sensor drift, flow, and light blockage) continue to be needed. The inherent challenges to sustaining ocean observing in the wide-ranging and physically harsh environment of the ocean can be overcome with these advances in technology, but ultimately require prioritization and sustained investments in these efforts.

FUTURE EVOLUTION OF THE OCEAN CLIMATE OBSERVING SYSTEM

Building and improving our understanding of climate requires continued and expanded observations of the ocean that are adaptable over time to address emerging opportunities and data needs. The heat budget example made clear the need for deep temperature data. The carbon budget illustrates the need for more space and time resolution in sampling. The fresh water budget shows how new remote sensing capabilities greatly augment in situ sampling, while expansion of salinity sampling in concert with temperature sampling would be extremely valuable. Shaping the evolution of the sustained observing system includes considerations of global coverage of data collection, uninterrupted long time series that allow for data collection across the wide range of timescales associated with climate variability, and additional sampling to fill gaps in either the coverage in space and time or in the variables being observed. The extent of global coverage needs is increasing as ice-free summers in the Arctic Ocean add to the surface area and volume of open ocean to be sampled; additionally, sampling the ocean beneath polar ice shelves presents an even greater challenge. There are also data-sparse regions, such as the Southern Ocean and Southeastern Pacific, that play a significant role in the Earth system, where improved understanding and predictive capabilities are needed, in particular given the potential role of Southern Ocean circulation changes in future Antarctic ice-sheet mass loss (e.g., Joughin et al., 2012; Alley et al., 2015). Additionally, there are many patterns of natural variability that act on varying timescales and influence the ocean's role in the climate system where greater information is needed. These patterns include the periodicity of ENSO, the decadal and multidecadal modes of coupled ocean-atmosphere variability, and the slow (millennial) timescale implied in the overturning of the deep ocean. These sources of natural variability are also influenced by the changes in the oceans and global climate system from anthropogenic emissions of CO_2. To the extent that modes of climate variability have distinct spatial patterns and timescales, long and detailed enough observations may help disentangling their respective roles and provide robust estimates in detection and attribution studies (e.g., Hasselmann, 1993, 1997).

The ocean observing programs have evolved to address emerging questions and utilize technological advances in measurement techniques, and this will continue into the future. New programs and observing system components currently in major pilot experimental stages intended to fill existing sampling gaps include the Deep Argo and BGC-Argo programs (Zilberman and Maze, 2015; Biogeochemical-Argo Planning Group, 2016), increased observation of sea surface salinity through the SMOS and Aquarius satellite missions, and improved quality of time-varying gravity measurements over the ocean by GRACE to constrain ocean mass transport (e.g., Wouters et al., 2014; Landerer et al., 2015). There is ongoing development of new sensors. In particular, nonphysical sensors that measure nutrients, pH, biomass of oceanic organisms, dissolved oxygen, fluorescence, optical properties, and genetic material have reached or are reaching technical readiness for inclusion in the sustained ocean observing system (Riser et al., 2016). Additional types of sampling will also likely emerge through new prioritizations made within the international community framework (see Chapter 3) and in response to modeling needs as the scientific understanding of the ocean's role in climate advances.

The broader ocean observing community will also contribute to the evolution of the system through various related efforts. Models provide the ability to examine the impacts of withdrawing or adding sampling platforms and to assess requirements for sampling density in space and time. Oceanographic research programs carrying out regional or local field programs that find modes of ocean variability and improve understanding of and parameterization of ocean processes are important contributors to consideration of how to evolve the observing system. National and international research programs have foci on assessing the efficacy of basin-scale observing (e.g., AtlantOS in Europe) and on the ability of the observing system to quantify key processes such as basin-scale meridional overturning in the Atlantic (e.g., AMOC).

3

International Frameworks for the In Situ Ocean Observing System

Achieving continuous in situ measurements and the subsequent analyses of collected data relies on national and regional research organizations and extensive international coordination. While a relatively small number of nations currently engage in sustained ocean observations, capacity-building efforts encourage new nations to join the sustained observing enterprise. The ocean observing frameworks developed by these international structures have identified priorities and requirements for the end-to-end ocean observation enterprise. The task for the committee was to consider "processes for identifying and characterizing the most critical, long-term observations" required to understand future changes in Earth's climate. In doing this, the committee was asked to discuss considerations of (1) sampling specifications (accuracy, precision, frequency, and spatial resolution), (2) duration, (3) value and/or trade-offs of increasing multidisciplinary sampling on existing platforms compared to fielding new platforms to make those measurements, (4) complementarity of an observation to another set of observations, and (5) introduction of new technology enabling more cost-effective observing. These foci are not new topics for dialog in the ocean and climate observing communities, but instead are discussed within an active international framework for climate observations where an ongoing process has been established for identifying variables that should be observed for climate, specifying the sampling and accuracy required, identifying the primary platforms for these observations, and spearheading improvements in technology. This chapter describes the international frameworks for developing observing requirements, long-term coordination, data sharing, and capacity building. The committee also points out international opportunities and challenges for sustaining the in situ ocean observing system.

INTERNATIONAL COORDINATION UNDER GCOS AND GOOS

The Global Climate Observing System

The Global Climate Observing System (GCOS) is a joint undertaking of the World Meteorological Organization (WMO), the Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational, Scientific, and Cultural Organization (UNESCO), the United Nations Environment Programme (UNEP), and the International Council for Science. Its goal is to provide comprehensive information on the total climate system, involving a multidisciplinary range of physical, chemical, and biological properties and atmospheric, oceanic, hydrological, cryospheric, and terrestrial processes. GCOS includes both in situ and remote sensing components, with its space-based components coordinated by the Committee on Earth Observation Satellites (CEOS) and the Coordination Group for Meteorological Satellites. It is intended to meet the full range of national and international requirements for climate and climate-related observations. As a system of climate-relevant observing programs, GCOS constitutes, in aggregate, the climate observing component of the Global Earth Observation System of Systems (Houghton et al., 2012). The GCOS program does not directly make observations or generate data products. Instead it stimulates, encourages, coordinates, and otherwise facilitates the collection of the needed observations by national or international organizations in support of common goals and their individual requirements. GCOS provides an operational framework for integrating, and enhancing as needed, observational systems of participating countries and organizations into a comprehensive system focused on the requirements for addressing climate issues (GCOS, 2017). Climate monitoring principles have also been developed that address practices for moving to new collection systems for existing variables, metadata needs, prioritization for new datasets, and data management, among others (GCOS, 1999).

GCOS has a process for developing implementation plans to articulate and address what have been identified as the Essential Climate Variables (ECVs) to measure across the Earth system. The program also provides an assessment of progress toward these plans. Over the past decade, the GCOS Implementation Plan for the Global Observing System for Climate has guided U.S. and international investments in the global observing system, focusing primarily on physical climate variables. In 2016, GCOS released its new implementation plan that has four long-term overarching targets: closing the carbon budget (greenhouse gases), closing the global water cycle, closing the global energy balance, and explaining changing conditions to the biosphere (GCOS, 2016). All targets have ocean dimensions and the first three map directly to the heat, carbon, and fresh water budgets discussed in this report. The plan also addresses gaps and areas of improvement that had hindered progress toward about a quarter of GCOS's goals, including those related to shortfalls in deployment and maintenance of some in situ ocean observing platforms and slow progress toward increased involvement of developing countries (GCOS, 2015). The implementation plan further highlights the relevance and important contribution of sustained ocean observing to meet the climate data collection goals.

The Global Ocean Observing System

The IOC created the Global Ocean Observing System (GOOS) in March 1991 in response to calls from the Second World Climate Conference in Geneva in 1990. GOOS was developed to meet research and operational requirements for sustained ocean observations, both in situ and remote. GOOS coordinates observations around the global ocean for three critical themes: climate, ocean health, and real-time services (e.g., ocean hazard early warnings or weather forecasting). These themes correspond to the GOOS mandate to contribute to the United Nations Framework Convention on Climate Change (UNFCCC), the United Nations Convention on Biological Diversity, and the IOC and WMO mandates to provide operational ocean services, respectively. An essential element of GOOS is an active capacity development program that ensures that all nations are invited to participate.

GOOS implementation is supported by three discipline-based GOOS Expert Panels that provide scientific oversight on Physics, Biogeochemistry, and Biology and Ecosystems. Of the three panels, the Physics and Biogeochemistry Panels were built on existing structures—the Physics Panel on the Ocean Observations Panel for Climate (OOPC) and the Biogeochemistry Panel on the International Ocean Carbon Coordination Project (IOCCP). The Biology and Ecosystems Panel was formed more recently and draws on the experience from the last decade of research best practices in this field. These panels draw members from the major international ocean research programs and major ocean institutions based on building teams of experts in each discipline that are aware of both the state of technology of observing and the science and societally driven needs for ocean observing. These panels have developed the lists of, and detailed specifications for, Essential Ocean Variables (EOVs; see Table 3.1), which are judged to be the priority variables to be observed in the ocean, and which reflect information needs and technical readiness to collect variable data (See the "Establishment of the Framework for Ocean Observing" section for further detail).

GOOS has succeeded in coordinating a collaborative system of sustained observations unified by principles outlined in the late 1990s (IOC, 1998). The "Design Principles" are general rules for how a GOOS system should be designed, including the need to serve users, be long term, and solve global problems. The "Principles of Involvement" guide participation in the system, including requirements for compliance with the Design Principles and GOOS data policy, and a commitment to sustain observations. With its unique status within the United Nations, GOOS has been able to marshal the resources of the UNESCO/IOC Member States to build a network around independently managed and indepen-

TABLE 3.1 GOOS Essential Ocean Variables (EOVs)

Physics	Biogeochemistry	Biology and Ecosystems
Sea state	**Oxygen**	**Phytoplankton biomass and diversity**
Ocean surface stress	**Nutrients**	**Zooplankton biomass and diversity**
Sea ice	**Inorganic carbon**	**Fish abundance and distribution**
Sea surface height	**Transient tracers**	**Marine turtles, birds, mammals abundance and distribution**
Sea surface temperature	**Suspended particles**	**Live coral**
Subsurface temperature	**Nitrous oxide**	**Seagrass cover**
Surface currents	**Stable carbon isotopes**	**Macroalgal canopy**
Subsurface currents	**Dissolved organic carbon**	**Mangrove cover**
Sea surface salinity	**Ocean colour**	
Subsurface salinity		
Ocean surface heat flux		

NOTE: The technical readiness of EOVs (as of March 2017) is classified as mature (green), pilot (orange), or concept (red). SOURCE: GOOS, 2017.

dently funded observing elements. The current in situ ocean observing system (a portion of which is shown in Figure 3.1) contains internationally coordinated networks that sample the space and time variability of EOVs.

The WMO-IOC Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM) offers ongoing technical coordination, oversight, and operational support for a range of observational, data management, and service activities conducted under GOOS. JCOMM Observations Coordination Group (OCG) is a forum for the leadership of all the networks to come together to identify synergies and opportunities to ensure that the observing system functions better as a system. OCG also has a work plan with thematic foci on areas such as metrics and standards/best practices. The JCOMM In-Situ Observing Programmes Support Centre (JCOMMOPS) provides observing implementation support and monitoring capabilities for a large cross section of the in situ ocean network. Through these functionalities, JCOMM is an important element in sustaining the observing system.

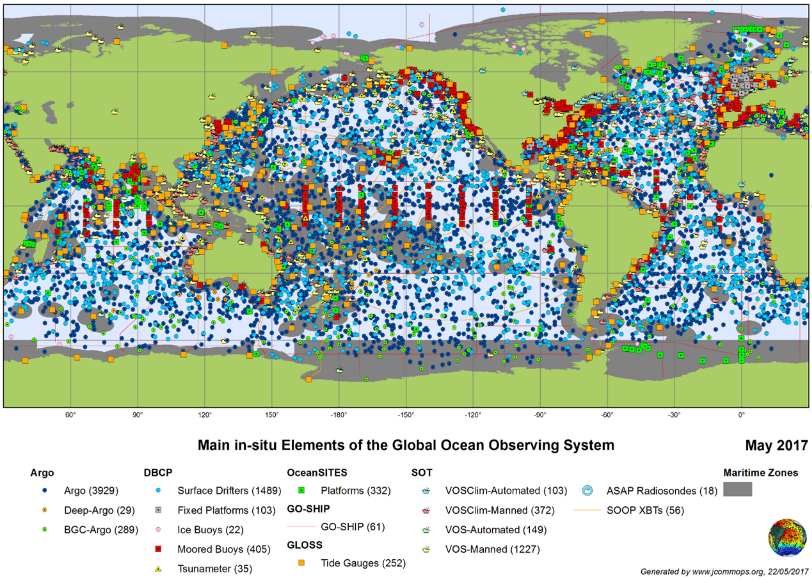

FIGURE 3.1 Distribution of deployed instrumentation for select in situ ocean observing programs implemented under GOOS. Maritime zones, including Exclusive Economic Zones (EEZs), are identified in gray. SOURCE: JCOMMOPS, 2017.

ESTABLISHMENT OF THE FRAMEWORK FOR OCEAN OBSERVING

Decadal "OceanObs" meetings that bring together the international community to discuss and plan have played a pivotal role in the development of today's ocean observation structures and priorities. The first International Conference for the Ocean Observing System for Climate, OceanObs'99, was held to build understanding and consensus around GOOS. In this workshop, groups developed white papers describing components proposed as elements of GOOS, and the workshop took under consideration the readiness of these components and their success at supplying observations seen as essential for GOOS. OceanObs'99 laid the foundational plan that was followed by many nations in moving forward to contribute to GOOS. In the United States, the National Oceanic and Atmospheric Administration (NOAA) Climate Program Office took steps to support key elements presented at OceanObs'99, including the Argo floats, the surface drifters, the moored time-series sites, and the repeat hydrographic cruises. It thus formalized for the first time its approach to contributing to GOOS.

The second International Conference, OceanObs'09 (http://oceanobs09.net) held in 2009, established that ocean observing plans needed to address deployment and maintenance of a more comprehensive, multidisciplinary GOOS that addressed the needs of many stakeholders. This led to the development of the Framework for Ocean Observing ("the Framework"; Lindstrom et al., 2012), which articulates the requirements and technical readiness of a multidisciplinary ocean observing system tailored to meet both scientific and societal needs. GOOS utilizes the Framework to guide its implementation of an integrated and sustained ocean observing system by identifying the science-driven requirements resulting from societal issues and the observations deployment and maintenance needed to produce impactful and relevant tools to address those issues. To maintain an ocean observing system that is fit for purpose, the outputs (publications, products, ocean services) are intended to properly address the issues that drove the original requirements. This system evaluation creates a constant feedback loop such that requirements are always science driven and informed by societal needs.

The Framework was built around the critical quantities to be observed, which would be called EOVs (Table 3.1). To build the Framework, an international steering group worked with international ocean observing panels, including the previously mentioned OOPC and IOCCP, the GOOS Panel for Integrated Coastal Observations, and those implementing ocean observing. The Framework document states the key guiding principles for development, including "deliver[ing] an observing system that is fit for purpose […] focused on both scientific inquiry and societal issues … balancing research and innovation with the need for stability [… and] providing maximum benefit to all users from each observation," that "appl[ies] a systems approach for sustaining global ocean observing" by using "Essential Ocean Variables (EOVs) as a common focus […,] define[s] a system based on Requirements, Observations, and data and information [… and] recognize[s] and develop[s] interfaces among all actors," and that facilitates "transformation of observational data organized in EOVs into information […] that serve[s] a wide range of science and societal needs […]" (Lindstrom et al., 2012). Further coordination across terrestrial, atmospheric, and oceanic observations addressing climate is being carried out internationally under GCOS to identify the ECVs and their specifications. For the physical variables, EOVs have also been identified as ECVs. However, because GOOS planning addresses requirements in addition to climate, the EOV list contains an expanded set of biogeochemical and biological and ecosystem variables compared to the ECVs.

Following OceanObs'09, the Framework Steering Group, the international observing panels, and the expert teams formed for each of the EOVs have been working to identify and describe the EOVs in depth. Selection of EOVs is motivated by scientific and societal needs, with technical readiness also being considered. At present, the physical EOVs important for climate identified by the OOPC are sea state, ocean surface stress, sea ice, sea surface height, sea surface temperature, subsurface temperature, surface currents, subsurface currents, sea surface salinity, subsurface salinity, and ocean surface heat flux. All but the last are considered to be obtainable by technically mature methods, while ocean surface heat flux is judged be in a pilot stage of technical readiness. Additionally, inorganic carbon, a biogeochemical EOV, is an important variable for climate, described by the IOCCP. The EOVs for climate agree well with the variables identified by the committee in Chapter 2 as those necessary to close the climate budgets. Table 3.2 specifies the EOVs that contribute to each budget.

The committee determined that the Framework for Ocean Observing and identification of the EOVs and their detailed descriptions effectively address the five bulleted items identified in its statement of task. For each of the EOVs, detailed specification documents have been developed by the expert panels, which outline the necessary observing platforms and sampling requirements to sufficiently measure each variable. Each variable is defined in detail in a "Variable Information" table which identifies the subvariables and derived variables

TABLE 3.2 Priority Variables for Ocean Observations for Climate

	Budget Metric	Relevant Essential Ocean Variable
Heat Budget	Ocean heat content	Sea surface temperature Subsurface temperature
	Air-sea heat exchange	Ocean surface heat flux
	Heat transport by ocean currents	Surface currents Subsurface currents Subsurface temperature Ocean surface stress
	Mixing (temperature)	Surface currents (derived variable upper-ocean turbulent mixing) Subsurface currents (derived variable turbulent mixing) Surface temperature Subsurface temperature (derived variable turbulent mixing and basic field) Subsurface salinity (derived variable turbulent mixing)
Carbon Budget	pH	Inorganic carbon (subvariable pH)
	Alkalinity	Inorganic carbon (subvariable total alkalinity)
	Dissolved inorganic carbon	Inorganic carbon (subvariable dissolved inorganic carbon)
	Air-sea carbon flux	Inorganic carbon (subvariable pCO_2) Sea state Ocean surface stress
	Ocean carbon inventory	Inorganic carbon (subvariable dissolved inorganic carbon)

continued

TABLE 3.2 Continued

	Budget Metric	Relevant Essential Ocean Variable
Fresh Water Budget	Ocean fresh water and salinity content	Sea surface salinity Subsurface salinity
	Ocean heat content	Sea surface temperature Subsurface temperature
	Sea-ice budget	Sea ice Surface currents
	Air-sea and land-sea fresh water flux (precipitation, evaporation, runoff)	Ocean surface heat flux (subvariable latent heat flux) (Precipitation and river discharge are important ECVs)
	Fresh water and salinity transport by ocean currents	Surface currents Subsurface currents Subsurface salinity Ocean surface stress
	Mixing (salinity)	Surface currents (derived variable upper-ocean turbulent mixing) Subsurface currents (derived variable turbulent mixing) Surface salinity Subsurface temperature (derived variable turbulent mixing) Subsurface salinity (derived variable turbulent mixing and basic field)
Sea-Level Change	Sea surface height	Sea surface height
	Ocean heat content	Sea surface temperature Subsurface temperature
	Heat transport by ocean current	Surface currents Subsurface currents
	Salinity (from melting land ice)	Sea surface salinity Subsurface salinity

NOTE: The table compares the budget components identified by the committee to those identified (and terminology used) as Essential Ocean Variables.

for each EOV (as well as supporting variables and the expert groups working on the EOV). For example, pH, identified by the committee as an important component of the carbon budget, is a subvariable of the inorganic carbon EOV. The specification documents also identify the temporal and spatial sampling requirements for the EOV, requirements that are dependent on the phenomena being captured (all found in the "Requirements Settings" table). The observing elements capable of measuring the EOV are described in the documents, with details about the sensor(s) used, the phenomena they measure, their spatial and temporal sampling, and random uncertainty. There is also recognition of near-future pilot-stage technology ("Future observing elements") relevant to the EOV. A "Data and Information Creation" table lists data products, their readiness, who provides technical oversight and coordination, readiness of metadata, the relevant data center, and sources from which the data may be obtained.

The sampling requirements listed in the EOV specifications, such as those specified in this committee's task (e.g., accuracy, precision, frequency, spatial resolution, and duration) typically depend on the phenomenon being addressed. For example, the EOV sea surface temperature (SST),[1] is associated with measuring coastal shelf exchange processes, air-sea fluxes, fronts and eddies, and upwelling, and the sampling requirements for each of these calls for varying spatial resolutions ranging from 1 to 100 km, and temporal resolutions ranging from hourly to weekly. Diverse, complementary observing methods are identified for measuring SST, including microwave and infrared remote sensing from satellites and ships, volunteer observing ships, moorings, surface drifters, profiling floats, and tagged animals. For each, the specification document describes what is measured with each sensor, the ocean phenomenon being addressed, the technical readiness level, the spatial and temporal sampling, any special characteristics, and random uncertainty. Temporal- and spatial-scale capabilities of each observing platform vary, but there is overlap in their capabilities that allows the networks to complement each other and meet the requirements driven by each phenomenon. The SST specification also identifies future observing elements, in this case, next-generation drifters, infrared radiometers on autonomous vehicles, and ocean gliders. Data products also vary, and are coordinated and stored by different entities.

The development of the EOVs is an ongoing process and the lists in Table 3.1 will evolve with time. The selection of EOVs is based on their need to support improved scientific knowledge as well as societal needs. At the same time, the Framework process defines the maturity of a particular EOV based on an evaluation of the technical readiness and feasibility of the observing methods. New scientific challenges may arise, as may societal needs. Observing technology will also improve. Thus, the EOV lists will change with time to reflect need and technical readiness. For example, there is an international science focus on the large-scale heat budget of the Earth, called "Concept HEAT," articulated by the CLIVAR (Climate and Ocean: Variability, Predictability, and Change) Decadal Climate Variability and Predictability Panel. Quantifying the heat budget requires, among other things, observation of the exchange of heat between the atmosphere

[1] The SST specification document can be viewed at: http://goosocean.org/index.php?option=com_oe&task=viewDocumentRecord&docID=17466.

and ocean at the sea surface. The need for this observation was brought to the attention of the OOPC, and that expert panel worked to assess capability and readiness and, in recognition of the scientific need, recently added ocean surface heat flux as a pilot EOV. Similarly, several communities (the Deep Ocean Observing Strategy initiative, tsunami monitoring agencies, and CEOS) have pointed to emerging capability of constraining ocean mass transports via time-varying satellite gravity measurements, with the variable of interest being ocean bottom pressure, and its importance in monitoring large-scale ocean circulation changes.

The ocean science community plays a critical role in identifying and evaluating additional new variables and developing and demonstrating the capability to observe them. An illustrative example arose during the development of the budget sections in Chapter 2 of this report. Progress toward developing budgets for heat, carbon, and fresh water would be strengthened through improved measurements of vertical mixing, particularly at the spatial and temporal scales of the overturning circulation. Diffusivity, which is used to quantify how heat or molecules, for example, spread through a fluid, has demonstrably important regional and temporal variability as they arise from turbulence associated with internal wave breaking, which has spatial and temporal dependence. The highest standard for measuring diffusivity is to measure microstructure fluctuations of temperature, salinity, and velocity, but these measurements are difficult and specialized and cannot be done at present in a global monitoring fashion. Instead, they are estimated using parameterizations of dissipation and diffusivity that use high-resolution (1- to 10-m vertical resolution) profiles (profiles from ships and Argo floats, velocity profiles from ships and moorings) of temperature and salinity, and preferably also in situ vertical profiles of velocity. There are experimental global measurements of temperature microstructure presently on U.S. GO-SHIP lines. Moving forward, the ocean science community will advance additional variables, make the case for maturing sampling specifications and observational methods.

The Framework for Ocean Observing and the identification of EOVs under GOOS pinpoint and characterize the ocean observations most critical to understanding future changes in Earth's climate. The committee was very aware of this extensive, long, and ongoing effort by international experts and judged that the committee could not, with its small membership and limited duration of report development, recreate a prioritization process that would improve upon the activities conducted under the Framework. The committee is fully supportive of the Framework process and in agreement with the resulting selection of the EOVs and detailed specifications attached to each. At the same time, the committee anticipates further evolution of the EOV lists that recognize that addressing the three budgets discussed in this report will require additional ongoing observations.

Planning is now under way for OceanObs'19 (http://oceanobs19.net), to be held in 2019. This meeting will provide an opportunity to assess progress on the Framework and identify challenges and opportunities. The major themes for OceanObs'19 will be the ocean-based ("blue") economy; ocean hazards and opportunities; climate variability and change; water, food, health, and energy securities; ecosystem health and biodiversity; and ocean acidification.

Finding: The GOOS efforts are effective at promoting international cooperation to sustain the ocean climate observing system. Its guiding document—Framework for Ocean Observing—and the associated procedures for establishing priority observations—the Essential Ocean Variables—are constructive for defining ongoing requirements (precision, frequency, spatial resolution) for sustained ocean observations and provide a solid foundation for selecting and prioritizing ocean variables for sustained observing.

GOOS provides the framework under which nations can plan and prioritize their ocean observing activities. Through this framework, nations can combine resources to make their own ocean observing contributions to one global network. Specific opportunities exist to increase coordination in sharing of large ocean observing infrastructure such a ships and moored platforms. Support for some observing efforts, such as TPOS and GO-SHIP (see Box 3.1), includes use of ships from multiple nations. However, planning for the deployment of U.S. academic and government research vessels still proceeds largely as a stand-alone exercise, not working as part of an optimization across nations of which research vessel would be most effective at supporting observing platforms in a specific region at a specific time. In addition, when deploying moored and autonomous platforms, U.S. oceanographers are not formally encouraged by funding agencies to work to host additional sensors and instruments from oceanographers of other nations and to seek partners internationally or in the United States to add additional multidisciplinary instrumentation and/or to extend sampling to additional depths and locations. During transits between projects and to reach working areas, U.S. oceanographic research vessels could provide a means to extend spatial coverage of ocean sampling; yet, there is no coordination effort to maximize utilization of such transits or of voyages to sparsely sampled regions of the globe. Ultimately, neither GCOS nor GOOS provides a strong framework for the accountability of national commitments. This is handed down to the individual participating countries to organize.

Finding: Opportunities exist to increase the spatial coverage and multidisciplinary nature of sustained ocean observations through U.S./international (either bilateral or multilateral) coordination and sharing of resources.

GCOS AND GOOS CONNECTIONS TO RESEARCH PROGRAMS

The GCOS and GOOS frameworks draw on expertise from the ocean research and observations community to provide advice for international oversight

BOX 3.1
GO-SHIP: An Example of International Cooperation

The global network of ocean reference hydrographic sections is carried out under GO-SHIP (see Figure 3.1). The international GO-SHIP structure remains organizationally loose in that it is not governed by formal agreements, but the contributing nations, each of which has and maintains very highly accurate and comprehensive ocean observations, finds a way to fund and carry out its work. GO-SHIP requires all of its contributing nations to provide global climate quality data. While autonomous sampling, principally in the Argo program, is now expanding to most of the water column (Deep Argo) and biogeochemistry (BGC-Argo), these autonomous measurements require systematic reference data of highest quality for validation and quality control, and this is provided by GO-SHIP. GO-SHIP therefore remains critical to the success of autonomous sampling, providing the highest reference standards to complement the high temporal resolution and global mapping capability of autonomous measurements.

GO-SHIP arose in modern form in WOCE, which continued a long historical practice of basin-scale, ship-based surveys of ocean water properties and ocean circulation. The quasi decadally repeated GO-SHIP hydrographic sections are currently the only way to track the significant fraction of heat going into the deep ocean, and the only way to track changes in ocean carbon, as well as nutrients and oxygen. WOCE was a fully international program, with agreements for sampling, accuracy, and data management between all of the nations that participated. The WOCE Hydrographic Programme (WHP) was one of the more visible observational networks of WOCE. Long hydrographic sections from coast to coast crisscrossed each of the ocean basins, with mesoscale-resolving stations to reduce aliasing, from surface to ocean bottom. All WHP survey lines included biogeochemical tracers. With its highly accurate temperature and salinity measurements, and full-basin carbonate system measurements along with tracers that provide age information, the WHP provided the first global budgets of carbon, and a baseline for highly accurate estimates of full-ocean-depth heat and fresh water.

At the end of WOCE, it was well understood that the climate was likely changing in response to anthropogenic forcing, and that the ocean absorbs not only most of the excess heat of the changing climate but also a significant fraction of the excess anthropogenic carbon. As the only means to quantify changes in ocean carbon, as well deep-ocean heat changes, the WHP was continued in a reduced form through the 2000s, under CLIVAR and the international carbon programs. The program remained fully international, loosely organized from the United Kingdom and with continued full data management in place, in the United States, as a legacy of the WHP. It was clear from surveys of the 2000s that the data were extremely valuable in tracking ocean heat, carbon, and fresh water changes, but the loose management of the program meant that continuation into the 2010s was tenuous. Therefore at the OceanObs'09 meeting, the nations contributing to the CLIVAR CO_2 repeat hydrography survey agreed to a tighter international structure, under the rubric GO-SHIP. It is agreed that GO-SHIP observations must adhere to a very high and well-defined standard of accuracy, and that GO-SHIP datasets must include a minimum set of parameters that cover both physical and biogeochemical processes.

and implementation of GOOS. These programs have also contributed to the innovation and evolution of the ocean observing system by increasing the readiness level of the observing networks. The primary international programs that provide expertise and guidance for ocean observing for climate are CLIVAR and the IOCCP, both of which are organized under UNESCO. CLIVAR is one of the four core projects of the World Climate Research Programme. CLIVAR's mission is to understand "the dynamics, the interaction, and the predictability of the coupled ocean-atmosphere system" (CLIVAR, 2017). To this end it facilitates observations, analyses, and predictions of changes in the Earth's climate system. The CLIVAR Scientific Steering Group consists of core panels, some of which are organized jointly with GOOS. In the United States, there are three CLIVAR panels, with the Global Synthesis and Observations panel being most relevant to ocean observations. CLIVAR also carries out short-term, intense sampling during process studies. Process studies heavily sample a site or region of the ocean, testing hypotheses about the cause of observed variability and the role of different processes at work there. Two recent such examples are the Climate Process Team on improving oceanic overflow representation for deep water formation in climate models (Legg et al., 2009), and the Climate Process Team on internal wave-driven ocean mixing (MacKinnon et al., 2017). The IOCCP promotes and coordinates the diverse set of ocean carbon observations in support of the biogeochemistry EOVs (see Table 3.1) by facilitating dialogue within the scientific community and national and international organizations (IOCCP, 2017). IOCCP works with observing programs to provide technical coordination for methodologies, practices, and standards. The OOPC draws on the international CLIVAR basin panels and the IOCCP to stay up to date on information about ocean space and time variability and on the scientific research requirements for ocean sampling.

GCOS AND GOOS CONNECTIONS TO OPERATIONAL OCEANOGRAPHY

The requirements of the ocean observing system are determined by priority scientific and societal goals that are both long and short term. Recognizing the need for developing near-real-time ocean analysis and forecasting capabilities as practiced by the numerical weather prediction community, the international Global Ocean Data Assimilation Experiment (GODAE) was launched in 1998 as a 10-year effort (Smith and Lefebvre, 1997; Bell et al., 2009). Its goal was to demonstrate the feasibility and utility of high-resolution short-term open-ocean predictions based on state-of-the-art ocean and data assimilation systems, to extend the predictability of coastal and regional subsystems, and to produce optimal initial conditions for seasonal-to-decadal climate forecasts. GODAE boosted the establishment and improvement of operational ocean prediction systems in a number of countries. It drastically enhanced capabilities for the robust, real-time collection and processing of measurements, and the generation and dissemination of analyses and forecasts. It demonstrated that forecasting of open-ocean mesoscale phenomena is feasible in many regions, and GODAE products showed real benefit for a number of applications (see Bell et al., 2009).

Based on GODAE's success, the international GODAE OceanView (GOV) program was launched in 2010 to "define, monitor and promote actions aimed at coordinating and integrating research associated with multi-scale and multi-disciplinary ocean analysis and forecasting systems, thus enhancing the value of GODAE OceanView outputs for research and applications" (GODAE, 2010). A key component of GOV is the assessment of the contribution of the various components of the observing system and the scientific guidance for improved design and implementation of the ocean observing system (Bell et al., 2015). The GOV systems and their important societal benefits depend critically on the GOOS satellite and in situ observation components. Observational data must be accessible and readily available for near-real-time assimilation by GOV partners. Through the development, operation, and improvement of Observing System Experiments, GOV contributes to comprehensive, effective, and scientifically robust advocacy of the case for and prioritization of the components of the GOOS, in collaboration with JCOMM and CEOS. Another core component of GOV is the advancement and operation of data assimilation systems that are at the core of near-real-time analysis and forecasting (see "GODAE Ocean View Part 1," 2015).

DATA MANAGEMENT

The GOOS principles address the need to manage, process, and distribute data from the ocean observing system. Much of the heritage for ocean data management in the United States stems from WOCE, and its data management practices have continued largely intact under GOOS. The unprecedented quantity and scope of in situ and satellite measurements collected during WOCE necessitated a new approach to data management that interweaves various data streams into a unified system. The dependence on Data Assembly Centers (DACs) organized by instrument type (e.g., surface drifters, moored instruments, sea-level gauges, gliders, Argo floats), spreads responsibilities for quality assessments, metadata support, and distribution among groups with expertise with data from those instruments. Data quality assessment responsibilities largely rest with investigators connected to measurement collection, which has improved the overall quality of the database. Open access to data and the requirement that investigators submit data within a reasonable period after collection ensure that the scientific community has timely access to the entire data stream. Near-real-time data distribution, championed under WOCE, has developed new stakeholders for in situ ocean data such as those involved in the calibration and validation of satellite data, data assimilation into numerical circulation models, and other operational oceanographic pursuits. Data collected under GOOS programs are publicly available in near real time, and in delayed mode as climate quality measurements. Many

GOOS elements, such as Argo, GO-SHIP, surface drifters, and OceanSITES have data management plans and funded DACs. OceanSITES, for example, uses a common data format, NetCDF developed by NCAR/Unidata, which is supported by metadata, and has Global Data Assembly Centers (GDACS) for data archiving and distribution at the National Data Buoy Center (NDBC) in the United States and Coriolis at Ifremer in France. U.S. funding agencies now require data management plans and have historically required submission of ocean data to federal archives.

The global distribution of real-time and delayed-mode ocean data is currently limited. There are a few global ocean data centers and a large number of regional ones; many coastal states are mandated to have national data centers. Yet there are many users who would benefit from ocean data who traditionally are not users of archives of NetCDF or ASCII text files. Thus, there is tremendous opportunity to network and connect these efforts to provide improved open and equitable access to ocean data and ocean information. For example, the Research Data Alliance provides a forum through its working groups and interest groups for the development of infrastructure to promote data sharing. Another organization, ESIP (Earth Science Information Partners), works with agencies, universities, and nonprofit and commercial organizations to improve the management of their data for mainstream use (ESIP, 2017).

INTERNATIONAL LEGAL REGIMES FOR FREELY DRIFTING OBSERVING PLATFORMS

About 30 percent of the area of the global ocean lies inside the Exclusive Economic Zones (EEZs) of coastal nations or within other maritime zones such as the region governed by the Antarctic Treaty System (see Figure 3.1). Because of the large ocean area of the EEZs, it is critical for a global ocean observing system to ensure governance arrangements that allow for deployment and drift of instruments inside and across EEZ boundaries. International regulation of such observing system activities falls under one of two regimes, depending on whether they are marine science research (MSR, under the United Nations Convention on Law of the Sea) or operational meteorological and related data (under WMO Resolution 40, which includes ocean temperature and salinity profile data). Observations made by research vessels, including hydrographic transects and mooring deployments, are subject to the well-established permitting process for MSR. The most successful models are bi- or multilateral partnerships between those who might have the resources (Organisation for Economic Co-operation and Development countries) and less developed coastal states. Many of these partnerships include training, capacity building, and assistance to use ocean information in support of the needs of the coastal state. A more complex situation is that of drifting or partially mobile platforms such as profiling floats (Argo) and gliders which may move in and out of EEZs (Bork et al., 2008). No international consensus has been achieved on the question of whether the Argo program's global float array is primarily MSR or operational oceanography (e.g., Mateos and Gorina-Ysern, 2010). The differing rules followed by different national Argo programs have resulted in wasted effort on conflict avoidance, occasional protests, and decreased Argo coverage in some EEZs. **The issue of access within EEZs for deploying observing system elements, or for the drift of mobile platforms such as Argo floats, remains a challenge and can act as a disincentive to deployment in some regions of the global ocean.**

The IOC has adopted two resolutions concerning the deployment of Argo floats on the high seas and their drift into EEZs. The first of these, Resolution XX-6 (IOC, 1999), noted and supported the use of Argo float data in global ocean data assimilation models and required that "concerned coastal states must be informed in advance, through appropriate channels, of all deployments of profiling floats which might drift into waters under their jurisdiction, indicating the exact locations of such deployments." The JCOMMOPS Argo Information Center (AIC) was created to carry out the deployment notification mandated by IOC Resolution XX-6 as well as to track the locations of all Argo floats. The second IOC resolution on Argo (IOC, 2008) established a set of guidelines for floats drifting into EEZs. The guidelines, which include notification of some coastal states by float-providing nations when a float approaches the EEZ, have, in some cases had a negative effect on deployments in EEZ-contiguous regions. More importantly, because of national differences over the question of MSR versus operational oceanography, there has been no IOC action taken regarding deployment of floats inside of EEZs.

Thus, while deployments inside EEZs are critical for global ocean and climate observation, the procedures for carrying out such deployments vary from nation to nation. Three ad hoc strategies are presently in use. First, since drift of floats into EEZs is permitted under IOC Resolution XLI.4, many floats presently inside EEZs have been deployed on the high seas. The opportunistic drift of floats into EEZs is an attractive option but float trajectories remain difficult to predict. Second, many coastal nations have stated their concurrence with deployment of Argo floats inside their EEZs. For those nations, all that is required is the standard deployment notification via the AIC and free access to the data, as is provided for all Argo data. A third procedure is the donation of instruments by an Argo National Program to a coastal nation that takes responsibility for deploying the instruments within their EEZ. In such cases, specific arrangements are needed for data communications and data management. For the Argo program, it is hoped that once the high value of Argo data to all nations is recognized, many more nations will concur with EEZ deployments. This hope has not yet been realized. Moreover, new sensors in addition to temperature and salinity, such as those already being implemented in the growing BGC-Argo program (Biogeochemical-Argo Planning Group, 2016) may increase national sensitivities around this issue in the future, because of the usefulness of the sensors for monitoring the environment for living marine resources, unless multilateral partnerships can be successfully forged.

INTERNATIONAL AGREEMENTS SUPPORTING OCEAN INFORMATION

Although a broad range of activities benefit from ocean observations, there is a need for more international and national coordination between the various ocean actors. As reflected by the diverse themes planned for OceanObs'19 mentioned earlier, there are a number of economic, societal, and scientific drivers for ocean observing and therefore a complex network of existing international activities that are in need of specific ocean information. A good example of where improved interagency coordination at the international level would have provided more impact is the World Ocean Assessment (WOA). The WOA, is a regular process for the global reporting and assessment of the marine environment, including socioeconomic aspects, is mandated by the UN General Assembly and was administratively delegated to the Division for Ocean Affairs and the Law of the Sea (DOALOS) with technical and scientific support from the IOC-UNESCO, UNEP, the International Maritime Organization and the Food and Agriculture Organization of the United Nations, and the International Atomic Energy Agency. A more collaboratively executed WOA with adequate resources (no additional staff was allocated specifically for this work; the secretariat function has been provided by the existing DOALOS staff) could become a more impactful and fully scientifically vetted product akin to the Intergovernmental Panel on Climate Change. Recommendations have been made by the science ministers of the G7 in support of the development of a global initiative to sustain and enhance ocean observing and the development of a global assessment through the UN to inform sustainable management strategies.[2]

The most recent addition to the international agreements that foster and depend on global ocean observations and information are the Sustainable Development Goals (SDGs) articulated under the UN 2030 Agenda for Sustainable Development. There is a goal around climate (SDG13) and one for the ocean (SDG14). The oceans also provide services for several other goals that have to do with food security (SDG2), jobs (SDG8), sustainable cities (SDG11), and renewable energy (SDG7) (Le Blanc et al., 2017; Schmidt et al., 2017). Other societal drivers for ocean observing that are included in Agenda 2030 are associated with climate, biodiversity, shipping, ocean pollution, remote sensing, and regional fisheries. However, there is no clear mandate given to a single UN organization for the Agenda 2030 as a whole. Instead, support for each goal is undertaken by existing relevant coordination bodies.

[2] Attachment 2 to Tsukuba Communiqué: Recommendations – G7 expert workshop on future of the oceans and seas (http://www.g8.utoronto.ca/science/2016-tsukuba2.html).

CAPACITY BUILDING

Many lessons are learned in sustained ocean observing by experience, by carrying out observations at sea, finding and fixing problems, and by working with the instrumentation, sensors, and data. Thus, capacity-building and training activities are important components to address within the international community of actors. Capacity building allows more investigators, operators, and countries to increase capabilities and contribute to a global sustained ocean observing system. Numerous organizations and programs are concerned with capacity-building efforts related to ocean observing, such as the IOC (2016), notably through the Global Sea Level Observing System (GLOSS) and JCOMM, with particular success through the Data Buoy Cooperation Panel (DPCP), SysTem for Analysis, Research, and Training (START), which promotes capacity building to advance knowledge on global environmental change in Africa and the Asia-Pacific region, the UN Regional Seas Programme, CLIVAR, Argo, and many others.

One example of the type of programs that have been effective in supporting capacity building for ocean observing is the Partnership for Observation of the Global Oceans (POGO). POGO is an organization of the directors and leaders of major oceanographic laboratories around the world. It holds that the "Lack of trained personnel is considered to be a major obstacle to development of a global ocean observing system. Therefore, a central element of the POGO agenda is capacity building and training. POGO has developed an extensive array of training and education activities targeted primarily at scientists from developing countries and those with economies in transition" (POGO, 2017). These activities include the Visiting Fellowship Programme, the Visiting Professorship Programme, the Nippon Foundation-POGO Centre of Excellence in Ocean Observations, and shipboard training programs. These activities are funded through partnerships with the Nippon Foundation and with the Scientific Committee on Oceanic Research. Through 2011, around 450 young scientists from 63 developing countries had received training through a POGO capacity-building initiative (Seeyave and Platt, 2012).

Finding: Capacity building enhances international support for the sustained ocean observing system and is valuable for increasing international use of the information and sharing of observing responsibilities.

4

Sustaining Global Ocean Observations in the United States

The priority setting and coordination that occur internationally are structured such that funding and implementation of sustained ocean observations occurs at the national level. Within the United States, government agencies, academic institutions, and philanthropies plan, fund, and implement the U.S. share of the global observing system, as well as regional observing programs. As seen in Table 2.1, the United States is a leader in participation in global observing programs; the support of the United States is instrumental in establishing globally distributed observing programs and cooperatively building the framework for other countries to invest in the observing system, adding to the value of the U.S. investment (for an example of the U.S. role in the development of the Argo program, see Box 4.1). U.S. observing activities span the end-to-end range (described in Chapter 1), from technology development, to operations of observing programs, to global data management and analysis. While the U.S. involvement in ocean observing activities is substantial today, issues related to flat or declining funding and reduced workforce capacity are already causing U.S. leadership in ocean observations to decline and creating challenges in maintaining long-term, ocean climate observations. Continued agency-specific involvement as well as the activities of interagency bodies provide an opportunity for sustained and coordinated ocean observing in the United States, but require consistent leadership to be effective.

FEDERAL COORDINATION, PRIORITY SETTING, AND FUNDING

In the United States, climate-related ocean observations mainly come under the purview of three federal agencies: the National Oceanic and Atmospheric Ad-

BOX 4.1
Argo: A Long-Term Observing Success Story

In late 1997, as WOCE was winding down, the global potential of profiling float technology had become apparent. A small group of U.S. scientists advocated for a global array of 3,000 profiling floats (meant to take measurements between 0 and 2,000 m), termed the ARGO[a] Project, to NOAA Administrator D. James Baker. Argo was also promoted internationally at the same time, acquiring endorsements from the Global Ocean Data Assimilation Experiment (GODAE) and the CLIVAR Upper Ocean Panel (UOP). Dr. Baker saw the potential in Argo and agreed that NOAA would support the U.S. component of Argo as its highest priority for new observations. NOAA Deputy Chief Scientist W. Stanley Wilson coordinated Argo's international growth, beginning with the entrainment of NOAA's partner agencies in many nations. The Argo Science Team (AST, chaired by Dean Roemmich, and later to become the Argo Steering Team) was formed by GODAE and the CLIVAR UOP to build the scientific consensus for Argo. The AST published the Argo Design Document (AST, 1998) and subsequently held its first meeting in Easton, Maryland, in early 1999 to scope the global implementation of Argo. In the ensuing few years, Dr. Wilson and the AST organized Argo Implementation Workshops for the Pacific, Atlantic, and Indian Oceans, collecting commitments and creating plans for completing the global array.

Argo's rapid acceptance and early growth were due in no small part to the parallel coordination of the program at both the scientific and agency levels. Through efforts led by Drs. Wilson and Baker, an international partnership of agencies was forged to support Argo's growth, while at the same time the AST developed the scientific consensus on Argo's objectives and applications. Deployment of Argo floats began in late 1999 and the goal of a 3,000-float global array was achieved in 2007. Key aspects of the Argo program that contributed to its rapid acceptance and its early growth included the following, and Argo could not have succeeded unless all of these requirements were met:

- Valuable and easily understood objectives, including quantifying Earth's energy budget and fresh water cycle, and the steric contributions to regional and global sea-level change. The Argo array would provide the subsurface data needed for operational oceanography, including global ocean reanalyses and forecast modeling applications.
- Complementarity of Argo and many other sustained ocean observing programs—satellite sea surface height, temperature, salinity, and wind stress, plus in situ repeat hydrography, moored observations, XBT, surface drifter, and glider data. Argo's unique niche within the sustained observing system is the global subsurface ocean.
- Technical appropriateness, robustness, and readiness of profiling floats and CTD sensors (which measure conductivity, temperature, and depth) for the task of Argo implementation. The lifetime of Argo floats would prove long enough for global deployment and replenishment, and the sensor accuracy and stability sufficient for program objectives.
- The existence of multiuse satellite communications systems that serve as critical infrastructure for Argo: initially the unidirectional System ARGOS and later the bi-directional Iridium network.

- Capability of the international partnership to provide the necessary level of hardware, human resources, and logistics to support a global ocean program.
- Commitment to free and open data access through a comprehensive data management system that provides near-real-time data within 24 hours and climate-quality delayed-mode data.
- Buy-in of many individual scientists, agency managers, and engineers who believed that making Argo succeed was worth their effort and sacrifice.

Following Argo's creation and its early development, the completed Argo array has now been sustained for a decade. The key aspects that have and will continue to allow Argo to be sustained have evolved out of those that contributed to Argo's early growth:

- Argo has revolutionized global oceanography through its major contributions to basic research, climate assessment, education, and operational applications. These have gone far beyond what was anticipated at the start of the program.
- The continuing evolution of autonomous technologies has stimulated more accurate, more cost-effective, and more valuable Argo measurements.
- Scientists, engineers, and data managers in research institutions and government agencies have dedicated their careers to improving and sustaining Argo. Without these many individual contributions in about 30 nations, Argo could not be sustained.

The Argo revolution is not yet complete. The major enhancements of Deep Argo and BGC-Argo have yet to be implemented globally. Argo observations of the ocean interior cover the globe on large spatial scales but need complementary observations of oceanic boundary currents and other small-scale features. The simplicity of Argo's original design and the cost-effectiveness[b] of the Argo program are challenged by these major enhancements, as valuable as they undoubtedly are. Can the additional resources be found? Can the Argo data management system and international legal protocols cope with multidisciplinary complexities? Can a new generation of Argo leaders sustain the core Argo time series even while broadening the program? These are the challenges to continuing Argo through the coming years and decades.

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[a] The name ARGO was chosen to emphasize the complementary nature of subsurface ocean measurements and satellite sea surface height observed by the Jason series of satellite altimeters. ARGO was initially an acronym for "Array for Real-time Geostrophic Oceanography," but this was subsequently simplified to Argo.

[b] The cost of a U.S. Core Argo float profile (0-2,000 m) is defined by the total annual cost of U.S. Argo (~$11M) divided by the annual number of U.S. Argo profiles (~70,000), resulting in a cost of less than $200 per profile. The only alternative means of collecting such data is to use large research vessels. Research vessels obtain three or for stations per day, so the cost per station of the ship time alone, not including scientific personnel and equipment is ~$10,000. The large cost advantage of Argo float profiles comes from having instruments that operate autonomously and provide high-quality data every 10 days over float lifetimes in excess of 4 years.

ministration (NOAA), the National Science Foundation (NSF), and the National Aeronautics and Space Administration (NASA). Many other agencies contribute to ocean observing, but with less emphasis on long-term observing for climate. For example, the U.S. Navy and the Office of Naval Research's (ONR's) investments in technology and research vessels have contributed to ocean observing capabilities. A degree of coordination is required among agencies. For example, current expansion of Argo to Biogeochemical Argo (BGC-Argo) and Deep Argo, which are being led by NSF through a proposal-driven process, involve important contributions from NOAA and NASA.

Federal activities are coordinated through a constellation of subcommittees and interagency working groups under the National Science and Technology Council (see Figure 4.1). The National Plan for Civil Earth Observations (OSTP, 2014), produced by the U.S. Group on Earth Observations (USGEO) within the White House Office of Science and Technology Policy (OSTP), with expertise contributed by the agencies in the U.S. Global Change Research Program (USGCRP), addresses the value of long-term climate observations and states: "Long-time-series data derived from these observations contribute to more effective detection and diagnosis of climate change. Agencies should sustain the operations of established airborne, terrestrial, and marine observation platforms with ongoing attention to sufficient coverage and data quality." It is difficult in this plan to identify all of the U.S. components of the ocean climate observing system, although some key components are identified by name (e.g., Argo).

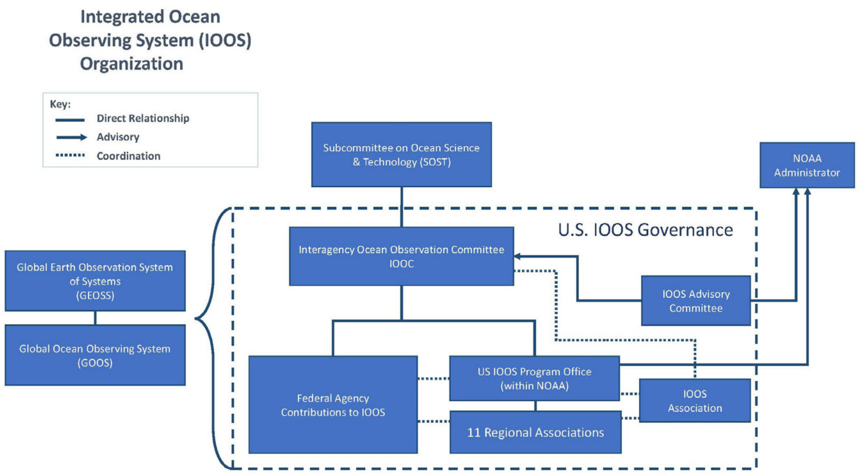

FIGURE 4.1 U.S. Integrated Ocean Observing System (IOOS) governance structure. SOURCE: Modified from IOOC, 2017.

In addition to coordination of observations through the climate-specific subcommittees, ocean observations are part of the portfolio of the National Science and Technology Council's Subcommittee on Ocean Science and Technology (SOST), co-chaired by representatives from NOAA, NSF, and OSTP. The SOST oversees the Interagency Ocean Observations Committee (IOOC), which was established under the Integrated Coastal and Ocean Observing System (ICOOS) Act of 2009 and chartered to "advise, assist and make recommendations on matters related to ocean observations."[1] Among its responsibilities, the IOOC will "establish required observation data variables to be gathered by both Federal and non-Federal assets and identify, in consultation with regional information coordination entities, priorities for System observations." The ICOOS Act authorized the establishment of the U.S. Integrated Ocean Observing System (IOOS) to organize the ocean observing activities of 17 federal agencies, with NOAA as the lead. Part of the IOOS vision is to provide NOAA and partner agencies with "improved ecosystem and climate understanding" (NOAA, 2017b), among other programmatic goals. Federal and nonfederal contributions to IOOS are organized by NOAA in consultation with the IOOC, which conducts the activities related to IOOS planning, policy, and coordination. The United States fulfills its contributions to GOOS through IOOS. Figure 4.1 outlines the connections between the interagency coordination bodies included in IOOS.

Over a decade before the ICOOS Act, Congress passed the National Oceanographic Partnership Act in 1996 (P.L. 104-201). This legislation created the National Ocean Partnership Program (NOPP) and the National Ocean Research Leadership Council (NORLC; under the National Ocean Policy, the National Ocean Council assumed the responsibilities of the NORLC) to help foster coordination among federal ocean agencies, provide leadership in ocean research and education, and implement partnerships among the federal agencies, academia, industry, and other members of the ocean science community. To advise the NORLC and NOPP, the Act called for the formation of a federal advisory committee, the Ocean Research Advisory Panel (ORAP), consisting of experts in marine science and policy and related fields.

NOPP has been instrumental in advancing the ocean observing system, including coordinating NOAA and Navy initial funding for Argo, as well as multiagency funding for HYCOM (HYbrid Coordinate Ocean Model), MISST (Multi-sensor Improved Sea-Surface Temperature), ECCO (Estimating the Circulation and Climate of the Ocean), and support for sea glider development, sensors, ocean models, and ocean data assimilation systems (Lindstrom et al., 2009). NOPP provided the funding to develop the pH sensors now being built and deployed on U.S. BGC-Argo floats, thus enabling the potential for global

[1] See the Charter of the IOOC at http://www.iooc.us/wp-content/uploads/2010/09/IOOC-Charter-Signed-02-13-13.pdf.

monitoring of the ocean carbon cycle. These sensors are also deployed on many coastal moorings that are part of the ocean acidification observing network.

At times, the agencies will separately or jointly seek guidance from the ocean science community on program priorities. This may be initiated to gather ideas through outreach to the community in dedicated meetings, town hall events at scientific society meetings, or through newsletters and other communications. After development of a draft plan, the agency or agencies may seek responses from the community through a public comment period. Alternatively, they may commission a review from an independent advisory committee, such as ORAP or a committee of the National Academies of Sciences, Engineering, and Medicine. The Consortium for Ocean Leadership (COL) and professional societies such as the American Geophysical Union, the American Meteorological Society, and the Oceanography Society also express their views on ocean priorities. There are similar opportunities to engage with advisory entities at the international level. For example, in the face of a serious decline in the capabilities of the Tropical Pacific Observing System (TPOS) infrastructure that supports El Niño–Southern Oscillation (ENSO) forecasts, which has been substantially supported by the Unites States and Japan, an international commission called TPOS 2020 was constituted under the GOOS Steering Committee to review and redesign the observing system to meet present and future needs, including consideration of possible new approaches to observing.

As described in this chapter, there exist several interagency bodies with responsibilities to coordinate activities associated with ocean climate observing. Though the responsibilities and prominence of various organizations may vary over time, the committee has described the structure as it stands during the writing of the report, and those that are founded by legislation are expected to be more stable over time. A particular issue is that the committee was not able to identify any plan with associated resource requirements to sustain or expand as needed the many components of the ocean climate observing system. Although Congress has recognized the need for sustained ocean observations in the ICOOS Act, budgets are subject to the annual appropriation process and have not been matching the increasing costs of sustaining the current system in terms of workforce, infrastructure, and data management. This leaves little available for investment in new technologies and approaches. **The absence of an overarching long-term (e.g., 10-year) national plan with associated resource commitments and lack of strong leadership presents a challenge for sustaining U.S. contributions to ocean observing, by inhibiting effective coordination and multiyear investments in the many components of the observing system.**

ACTIVITIES AND INVESTMENTS

Support in the United States comes from multiple agencies, where there are different funding mechanisms and missions dictating their activities. These are addressed here for the entities involved in ocean observing.

National Oceanic and Atmospheric Administration

NOAA has funded design, development, and implementation of a large portion of the current in situ global ocean observing system in cooperation with national and international partners and through its research laboratories, long-term support of cooperative institutes housed at universities, and competitive grants programs. Through NOAA's Climate Program Office, NOAA-funded observational systems include tide gauges, drifting buoys, tropical moored buoys (including TPOS), surface and subsurface moorings, ship-of-opportunity expendable bathythermograph probes (XBTs), Argo, GO-SHIP hydrography, and surface carbon flux surveys (NOAA, 2017a). The sustained large-scale measurements supported by these platforms are sea surface temperature and currents; ocean heat content and transport; air-sea exchanges of heat, momentum, and fresh water; sea level; and ocean carbon uptake and content. The Climate Observations Division Strategic Plan 2015-2020 (NOAA, 2015) lays out a bold vision for, "A sustained, comprehensive, and responsive global climate observing system that seamlessly delivers information and products to our partners and users within and beyond NOAA, and that provides a critical foundation for climate, weather, and environmental decision-making."

In addition to global ocean observations, NOAA's National Ocean Service also supports coastal observations, including those critical to the heat, carbon, and fresh water budgets, through the IOOS program office.[2] These include long-term NOAA observing programs as well as observations supported by the 11 regional associations that form the coastal component of IOOS. These associations guide the development of regional observations, based in part on stakeholder input. Nonfederal funds supplement the support provided to these regional networks by NOAA. Many of these coastal and regional observing programs are critical for operational applications such as navigational safety, management of marine ecosystems, and search-and-rescue, but through their coverage, data quality, and continuity, they also have important climate applications.

As with other federal agencies, funding available to sustain global ocean observing is subject to annual appropriation and has been flat for about a decade. Flat funding for ocean observing is putting a strain on NOAA-supported systems that need to not only maintain their coverage, but to grow, such as the expansion of Argo into biogeochemical and deep ocean sampling. For example, decreasing

[2] A list of the core variables observed by the IOOS associations can be found at http://www.iooc.us/ocean-observations/variables/core-ioos-variables/.

deployments of Argo floats will lead to a smaller array, reducing global coverage (Durack et al., 2016).

National Science Foundation

NSF funds large-scale ocean observing programs, their development, and their instrumentation, primarily within the Geosciences directorate through two fundamentally different mechanisms: (1) principal investigator (PI)-initiated grants system similar to, but of much larger scope than, standard PI grants, and (2) the Major Research Equipment and Facilities Construction account.

The first is the traditional NSF funding stream through peer-reviewed proposals to a given directorate. Large coordinated scientific programs may be funded in this manner following years of community discussion, project formulation, and a proposal that is fully peer reviewed. These programs can be the genesis of long-term ocean observations including methods and instrumentation. For instance, NSF supports development and implementation of new observation technologies and has funded several long-term time series (e.g., the Bermuda Atlantic Time-Series and the Hawaii Ocean Time-Series) through competitive grants. NSF also provided funding for WOCE in the 1990s, which spawned many of the modern technical approaches and sampling strategies for long-term physical and chemical observations that have evolved into sustained observing programs supported by NOAA or other agencies. In the 2000s, NSF PI-driven funding of large programs was directed toward more narrowly focused process experiments with strong ties between observations and modeling. One example of a current research project funded with this structure is the SOCCOM project, which extends Argo profiling float observations to include biogeochemical sensors and to take measurements under Antarctic sea ice. Through demonstration of the viability of the sensor technology and capability of mapping biogeochemical parameters, SOCCOM can serve as a prototype for global BGC-Argo observations. SOCCOM is formulated around modeling and thorough scientific analysis. Another example of a long-term observing program funded through a series of PI-originated proposals is the decadal repeat hydrographic survey of the global oceans, GO-SHIP, which repeats a chosen subset of the WOCE hydrographic survey. A significant difference from other NSF grants based on PI proposals is that GO-SHIP (funded by both NSF and NOAA) is funded as a data collection effort with minimal support for scientific analysis. Each funding increment has a limited duration of 6 years, with funding for data collection and archiving, setting an early example for rapid public dissemination of in situ data.

At NSF, large pieces of infrastructure have been funded using the MREFC account. These items draw on MREFC support for their design and construction, and this support comes to an end as operations begin. Examples of MREFC items in other fields include telescopes and research aircrafts and in the ocean sciences, support for research ships built by NSF has been provided, including the construction of the *R/V Sikuliaq* ice-hardened global research vessel. An example of an MREFC-funded observing program is the Ocean Observatories Initiative (OOI). Years of community planning, including guidance from National Research Council study committees (NRC, 2000, 2003), led to the development of a plan for a combination of cabled, coastal, and open-ocean observing arrays, with supporting infrastructure. Construction for the OOI was funded by the MREFC account, but further operations of the system must come from a division's core funding as per current NSF policy. A decadal survey conducted by the NRC for the Division of Ocean Sciences at NSF to prioritize scientific investments identified a need to reduce investments in infrastructure that have come at the expense of core research programs, given expectations of flat or declining budgets (NRC, 2015). NSF is seeking to reduce the operating costs of OOI by restructuring its management and removing two observing arrays (NSF, 2015; Murray, 2017).

National Aeronautics and Space Administration

Through NASA's Earth Science Division, the agency has coordinated and maintained a series of dedicated ocean observing platforms for short-term operational, long-term climate, and basic science discovery purposes. NASA supports the sequence of satellite altimeters, flown since 1992 (initially TOPEX/POSEIDON, now Jason series) that provide quasi-global continuous coverage of sea surface height measurements pertaining to sea level and upper ocean currents. It also contributes to the constellation of missions measuring sea surface temperature through a series of low-orbiting satellites (Aqua/MODIS, AMSR-E, TRMM/TMI). Other *Climate Continuity Missions* key for sustained ocean observing include the Orbiting Carbon Observatory (OCO-2; since 2014), the Gravity Recovery and Climate Experiment (GRACE; since 2002) and its follow-on mission which measures the time-varying mass redistribution by ocean currents, and the Plankton, Aerosol, Cloud, ocean Ecosystem (PACE; launch expected 2022) mission that will contribute to establishing a long-term chlorophyll record. Among NASA's *Foundational Missions* relevant for sustained ocean observing were sea surface salinity measured by Aquarius (2011-2015). *Decadal Survey Missions* relevant for sustained ocean observing include ICESat (2003-2010) and its follow-on ICESat-II (launch expected 2018), measuring sea-ice properties in the polar oceans, and the Surface Water and Ocean Topography (SWOT) altimetry mission (launch expected 2020).

NASA's Earth Science Division is pursuing a strategy that aims to balance several requirements: advance Earth system science, deliver societal benefits through applications development, provide essential global spaceborne measurements in support of science and operations, complement and coordinate activities with other agencies and international partners, and develop new remote observational capabilities. Its execution strategy over the last decade has been heavily informed by the 2007 National Research Council's report *Earth Science* *and Applications from Space*, ESAS2007 (NRC, 2007) and the 2012 *Midterm Assessment of NASA's Implementation of the Decadal Survey*, MA2012 (NRC, 2012a). In generating a set of consensus recommendations from the earth and environmental science communities, the ESAS2007 study laid out a new agenda for Earth observations from space with practical benefits for society.

ESAS2007 was organized along seven themes,[3] with oceanography identified as a key discipline that was represented in all thematic panels. Of relevance to the present study, an urgent need was identified for renewed investment in and careful stewardship of the U.S. Earth observations enterprise. The need for contributing to long-term observational records of Earth was one of eight criteria used by the ESAS2007 panels to create relative rankings of satellite missions. ESAS2007 called for the development of a science and implementation plan by OSTP for achieving and sustaining global Earth observations for research and monitoring. This plan has taken the form of the National Plan for Civil Earth Observations, referenced earlier (OSTP, 2014).

Both reports were created in an environment of diminishing resources, and the challenges in implementing the survey's recommendations are indicative of those facing implementation of sustained ocean observations as a whole. The MA2012 report stated that the 2007 "vision is being realized at a far slower pace than was recommended" and that "the nation's Earth observing system is beginning a rapid decline in capability as long-running missions end and key new missions are delayed, lost, or canceled." Failure by Congress to restore the Earth science budget to $2 billion in 2007 (FY 2006) was identified as "a principal reason for NASA's inability to realize the mission launch cadence recommended by the survey." Concerns about maintaining technological expertise and training the next generation of scientists and engineers were raised. The MA2012 report also pointed to potential implications for the accuracy of the nation's weather forecasting capabilities, a concern that has since been confirmed (Kramer, 2016). GRACE-FO (a follow-on mission to the Gravity Recovery and Climate Experiment), slated for launch in 2016 (according to MA2012) has been delayed to 2018 (OSTP, 2014), putting strains on the existing mission that is critical for quantifying land-ice contributions to global sea-level rise.

Ocean Observing Institutions

U.S. oceanographic institutions and laboratories have demonstrated significant commitment to sustained ocean observing. During a workshop held as part of the information gathering for this report, the committee heard from representatives of Scripps Institution of Oceanography (SIO) and the Woods Hole Oceano-

[3] (1) Earth science applications and societal benefits; (2) Land-use change, ecosystem dynamics, and biodiversity; (3) Weather; (4) Climate variability and change; (5) Water resources and the global hydrologic cycle; (6) Human health and security; and (7) Solid-Earth hazards, resources, and dynamics.

graphic Institution (WHOI), as well as from leadership from the NOAA Pacific Marine Environmental Laboratory (PMEL) and the Atlantic Oceanographic and Meteorological Laboratory (AOML), representing the university and private research institutions, and the government research laboratories that conduct sustained ocean observations. The input from SIO and WHOI represented the large number of U.S. academic and private research institutions that are central to sustained ocean observations. The government laboratories hold agreements with universities, which act as cooperative institutions in accomplishing the research activities of the laboratories.

These institutions have scientific staff, including faculty members and researchers, who are key leaders in elements of the U.S. contribution to sustained ocean observing. Further, these laboratories have the key technical and engineering staff and the facilities required to support these activities. Most of the fundamental advances in ocean observing technology have come from these institutions, supported by federal and sometimes philanthropic funding. Later technical transfer to private companies supports the long-term and larger-scale production needed for a major observing system. Space and facilities have been provided in support of ocean observing at these organizations. There is also an awareness of the merit of ocean observing that is demonstrated in hiring and promotion processes at these institutions.

Philanthropy

U.S.-based and international philanthropic entities have funded or are interested in ocean research and conservation. Organizations such as the Schmidt Ocean Institute and Schmidt Family Foundation, Gordon and Betty Moore Foundation, Packard Foundation, Vulcan Foundation, Waitt Foundation, Paul G. Allen Family Foundation, Pew Charitable Trusts, Alfred P. Sloan Foundation, Heising-Simons Foundation, and others, have made substantial investments in areas such as marine technology, ocean research, education and outreach, conservation, and exploration and discovery. Some foundation-funded activities map directly onto ocean observations relevant to understanding climate change, such as the Wendy Schmidt Ocean Health X-Prize to develop better and more affordable technologies to measure ocean pH and ocean acidification, and the Sloan Foundation-funded Census of Marine Life. Yet many foundations limit funding for basic research on the ocean environment or technologies, favoring instead targeted funding in support of areas such as marine conservation, ocean health, food security, and blue economy development.

Nongovernmental donor organizations have funded over $800 million for marine science in ocean and coastal waters globally since 2009.[4] Such support

[4] Data obtained from http://FundingTheOcean.org/FundingMap on September 6, 2017, by filtering for "Marine Science" projects funded by all entities that are not government or governmentally linked. Data are based on user-submitted information.

is often limited to 3-5 years; the funds may be suitable for the development of projects but not necessarily long-term funding of operations and maintenance of observing systems. Few philanthropic organizations have provided funding to sustain long-term projects such as ocean observing activities. Some foundations have announced publicly their willingness to partner with other entities to fund large initiatives and provide additional funding opportunities for the ocean research community in the face of reduced U.S. federal ocean research and observation support (announced by Schmidt, Packard, and Moore program managers at American Geophysical Union Ocean Sciences Meeting, 2015). Discussions with the committee and between invited participants from foundations at public sessions of the committee's meetings were encouraging and suggested that the diverse interests of the foundations could, if coordinated synergistically, provide opportunities in the ocean observing arena. Foundations that employ their own research and analysis divisions may also be able to offer guidance for structuring sustained observational programs, based on perspectives unique and different from those provided by federal agencies or members of academia.

Finding: Raising awareness of the importance and value of sustained ocean climate observations could increase support for the observing system from multiple sectors, including philanthropic organizations.

THE CHALLENGE OF SHORT-TERM FUNDING

Sustainment of ocean observations requires an ongoing source of funding, yet in the federal budget process, these investments are subject to annual review and appropriation. Continuous long-term climate datasets can be interrupted if the associated grant-making or operational government offices receive a reduction in their appropriations. Technical expertise can be lost if there is even a brief gap in funding. While the ocean research community has continually sought new and cost-saving technologies to reduce these costs—examples include ongoing work with unmanned ocean platforms and the expanded suite of observations that are being taken despite flat support—it is clear that new and expanded observations are needed to answer key research questions. There is a pressing need for more observations to support our knowledge of the global carbon budget; the BGC-Argo floats that are being deployed around the Southern Ocean as part of the SOCCOM project are one such highly effective and cost-efficient approach. In an annual appropriations process, the need for sustainment of observing capabilities must be continually justified.

Contributing further to this challenge, it is often difficult for program officials to point to a "recent" success of those aspects of the ocean observing system that are primarily intended to fill a sustained monitoring role. However, while the long-term nature of climate observing means that many results take time to appear, there are still numerous examples of vital information provided by the ocean observing system. The ocean observing system has already contributed to the understanding of the changing climate (see the examples related to heat, carbon, and fresh water in Chapter 2), as well as of more short-term subseasonal and seasonal predictions (NASEM, 2016b). The increasing cost-efficiency of the system due to technological progress, and the added value provided by participating in an international network of platforms also can be used to illustrate the strong return on investment of the system.

Finding: The continuity of ocean observations is essential for gaining an accurate understanding of the climate. Funding mechanisms that rely on annual budget approval or short-term grants may result in discontinuity of ocean climate measurements, reducing the value of the observations made to date and in the future.

OBSERVING SYSTEM OPERATIONS

The in situ ocean observing system is mainly operated by research institutions and the relevant experts therein. The key to maintaining climate-quality, long-term observing system elements is with this direct involvement by the researchers in all steps. This includes conducting the science, and providing oversight, including, where possible, actual operations of the observing system programs. Research institutions and their funding sources place a high priority on peer-reviewed, original research, necessitating useful and high-quality observations. The observing system elements with deep roots in research laboratories, led by scientists who conduct observations and utilize the data from the observing system, have demonstrably high success. An example of leadership of scientific teams in an observing program is the development of the Argo program led by the Argo Science Team, described in Box 4.1. The most expensive part of the ocean observing system, satellite remote sensing, is operated by NASA. Nevertheless, the success of the NASA missions includes reliance on strong scientific involvement from beginning to end of a mission, with long-term academic science teams and in-house expert scientific staff.

Finding: Direct scientific involvement in sustained observing programs, from design to implementation to analysis, synthesis, and publication, ensures that the ocean observing system will be robust in terms of data quality, incorporation of new methods and technologies, and scientific analyses; all are essential elements for realizing the value of long-term, sustained observations.

By being based in research and academic laboratories, each ocean observing effort has committed engagement by the same core group of scientists and technicians through much of the end-to-end process. For example, those who have developed mooring technology and the means to design moorings to survive harsh environments are also involved in deployment and maintenance of moorings and moored arrays. And those who have developed and/or oversee the instrumentation used on the moorings are in the same group. Data processors are also collocated with the team, fostering strong coherence among the groups and ensuring that observational requirements are met or exceeded. A further benefit is that through scientific analysis of the data, those in the group see immediately the problems and shortcomings that arise in the field and in the data, and it is these staff who are best equipped to address such issues. This important benefit can be lost when observational programs are funded without including support for analysis of the data by the scientists who are responsible for obtaining it.

Finding: To avoid data gaps and ensure the required data quality and the accessibility of the data for monitoring climate over decades, ocean observing initiatives will need to plan for the end-to-end scope of expenses associated with observing programs, including appropriate logistical planning and all processing including data analysis, data management, and scientific involvement.

CHALLENGES SUSTAINING THE OCEAN OBSERVING WORKFORCE

The U.S. ocean observing suite of activities depends on both institutional and individual expertise and commitment. For individual scientists, starting up and implementing an ocean observation activity is time-consuming and may be difficult without substantial institutional support and guarantees for long-term funding. By its very nature, observational science typically requires some years of data collection before results are publishable. This acts as a disincentive for early-career scientists contemplating participation in ocean observing activities beyond utilization of existing datasets. This leads to the concept of ocean observing "heroes"—those individuals who have the interest and ability to design and implement effective and valuable ocean observing programs and choose to do so as a service to science and the community. Typically, these individuals are later in their careers and in positions that allow them to engage in activities with long, or even uncertain, payoff timelines. The current ocean observing arrays owe their existence to a large number of such heroes, yet many of these thought leaders and creators are now reaching advanced stages of their careers or have already retired. This poses challenges for sustaining ocean observations as we look ahead several decades and beyond. The committee heard from community members that the current demographics of ocean observing experts cannot sustain long-term operations. Transformation of today's cohort of ocean observing experts to one with more balanced career demographics is essential for sustaining ocean observations long term.

The long-term investment required to develop and sustain the necessary

expert workforce of the future is a challenge due to limited professional rewards or career incentives at major institutions and laboratories to ensure intergenerational succession of scientists, engineers, and technical staff. Traditional measurements of career accomplishments do not align well with the activities of scientists conducting long-term observing. For many oceanographic positions, an impressive publication record is the primary metric by which accomplishments are judged, with both quantity of publications and impact (as measured by citation counts) factoring into such evaluations. Sustaining long-term observations is not an activity that maximizes publication metrics, especially when these observations are immediately made available in public databases to be analyzed and written about by people who may not have contributed to the acquisition of these data. Making ocean data public as quickly as possible is in the interest of the community as a whole, but it is also imperative that the community recognize and reward those scientists whose efforts generated those data in the first place, if for no other reason than to ensure that this long-term data acquisition continues. By far the most important steps that could be taken to incentivize participation in sustaining long-term observations are those that lead to stable and rewarding careers.

For oceanographic institutions, incentivizing career paths that help sustain long-term observations may require a broadening of the criteria by which career accomplishments are evaluated in the United States when promotion and tenure decisions are made. These criteria could include contributions to science that derive from the collection and maintenance of the observational datasets to which a scientist has contributed. For scientific societies, this could include the creation of new awards that specifically recognize early- to mid-career scientists who make substantial contributions to society through the acquisition of sustained high-quality datasets. For scientific journals, editors, and reviewers, incentives to participate in sustaining publicly available observations will require a greater emphasis on proper citation of critical observational datasets (e.g., Argo, drifters, or moorings) when evaluating papers. Ultimately, though, funding is critical for sustaining any scientific effort, and the federal agencies' funding decisions will play an important role in reinforcing the oceanographic institutions' efforts to reward participation in sustaining the ocean observations that will be necessary to monitor and understand climate changes.

Scientists are also hindered by the lack of research positions that provide long-term funding stability. Federal civil service scientific positions in U.S. government laboratories have traditionally provided more stable "hard-money" funding to enable scientists to plan, implement, and oversee long-term observational projects. However, the number of such hard-money positions has declined over time. Even in federal laboratories, many positions are dependent on a large fraction of soft funding, which may vary over time, making it difficult to stably sustain long-term ocean observational networks if grant proposals are not always funded. In addition, researchers today are typically employed in multiple postdoctoral positions before securing stable long-term positions. The lack of secure career positions in the community is cultivating a culture that emphasizes high-profile, short-term results over less visible but ultimately more fundamental long-term studies. Sustained funding for the highly trained technical staff such as chemists, electronics technicians, and data processors and managers is also an issue. With intermittent funding, it is difficult to maintain experienced staff able to develop new instrumentation or laboratory analyses. Various mechanisms for providing continuity of the highly trained, small corps of technicians have been attempted, but continuity and capability of staff can be lost when budgets are decreased.

THE RESEARCH FLEET

Research vessels are indispensable to the ocean observing system, providing direct observations and deployments of moored and drifting instruments. Research vessels are categorized by their size, which dictates the range of distances they typically travel. Three categories of research vessels are useful for ocean observations: global class vessels, the largest ships which have a global range; ocean class vessels, slightly smaller and which do not travel globally; and regional class vessels, which are even smaller and operate closer to coasts. The global and ocean class ships that are essential for the most distant sustained observing system components are operated by the member universities of the University-National Oceanographic Laboratory System (UNOLS), plus additional ships operated by NOAA and NSF. UNOLS is a consortium of 14 academic institutions that operate a fleet of 18 vessels constructed and owned by federal agencies. The largest UNOLS ships, the global class vessels, were built and are owned by the Navy and NSF and most of the operating costs of this fleet are paid by NSF, along with funding from the Navy and NOAA.

NOAA operates one global class research vessel, the *Ronald H. Brown*, which works in all oceans. It is a mainstay of mooring and float deployments, and provides up to half of U.S. ship support for GO-SHIP. In 2012, largely because of a reduction in the NOAA fleet and an inability to prioritize identification of viable ships for mooring deployments, a gap in TPOS, essential for ENSO description and forecasting, was permitted to grow (Cravatte et al., 2016). This gap resulted from decisions about NOAA fleet size and a shift in oversight of TPOS to an operational branch of NOAA and away from research laboratory oversight. As the negative consequences of the lack of observational data needed for forecasting the Earth's most vigorous natural climate variation became apparent, the observing system was restored. However, the vulnerability of long-term monitoring was clearly revealed in this several-year episode, and stands as an example to the rest of sustained ocean observations of the need for continuous assessment of funding and scientific needs. In the recent NOAA Fleet Plan, NOAA lays out a plan to build two new "Class A" ships, which are those capable of conducting "oceanographic monitoring, research, and modeling" (NOAA, 2016b).

The decreasing number of global and ocean class research vessels is creating a shortfall in the infrastructure required for sampling the global ocean and expanding collection into the polar regions. The importance of ships and the scope of the research fleet were examined in detail by the NRC in *Sea Change: 2015-2025 Decadal Survey of Ocean Sciences* (NRC, 2015). In that report, research vessels, especially global class vessels, were identified as essential infrastructure for serving the needs of the decadal science priorities. However, as noted earlier, that report also warns against spending funds on infrastructure at the expense of basic research and recommends that NSF build no more than two new regional class vessels. As U.S. ships reach the end of their lifetime (18 of the 35 current vessels by 2030), the federal government is frequently facing a need to "right size" the fleet to fit the existing budget and meet evolving research and survey demands (NRC, 2015; IWG-FI, 2016). This means making funding decisions regarding how many new vessels of each class could be built and which ships could go out of service or be upgraded, while still providing for operation and maintenance of existing ships. Opportunities to increase efficiency and leverage capacity will be important, such as the use of autonomous observing technologies, and national and international infrastructure coordination.

IMPORTANCE OF FUNDING TO ADVANCE TECHNOLOGICAL CAPABILITY

Looking ahead, there will be the need for more sustained ocean observations and sampling of more diverse ocean variables. In the face of this need and of limitations on funding, it is essential to develop new capabilities that are as effective and efficient as possible. Investment in advancing technological capabilities will have significant return over the lifetime of sustained observing platforms.

As described in Chapter 2, the ocean is a challenging physical environment for making sustained observations, driving the need for ongoing technological advances in the platforms and sensors. The maturation of sustained ocean observing benefited from the investments of U.S. agencies in the development of ocean observing platforms and sensors. In the later part of the twentieth century, the U.S. Navy's Office of Naval Research (ONR) was a major source of support for development of ocean observing platforms and was responsible for significant progress in the United States. For example, surface moorings, with an instrumented buoy supporting an instrumented mooring line beneath and anchored to the seafloor had long proved a challenge, especially outside calm, tropical waters. ONR support for ocean engineers and physical oceanographers led to new design techniques that treat surface moorings as dynamic systems and to new surface mooring designs and hardware. ONR also supported the development of new instruments for deployment on moorings. As a result, surface mooring deployments that yielded 1- to 3-month records in the 1970s are now followed by successful 1-year-long deployments of surface moorings in challenging mid- and high-latitude locations.

Both ONR and NSF historically supported research on and development of ocean sensors and instruments. Large programs in the 1980s and 1990s such as WOCE and the Tropical Ocean Global Atmosphere included strong observing system development efforts by U.S. scientists that helped build the foundation for today's activities, including the GO-SHIP program. For example, NSF funding for WOCE supported the development of the climate-quality surface meteorological packages now in use on surface moorings. Advances were made in the development of acoustic Doppler current meters and profilers and of surface and profiling drifters.

The present level of investment in technological development does not match that of earlier years. ONR is a less significant source of support and the NSF is constrained by other demands and the need to reduce support for infrastructure. **The limited investment in advancing technological capabilities is a challenge that, if addressed, will yield significant returns over the lifetime of sustained observing platforms through development of more robust and efficient sensors and platforms.** The NOPP, under its mandate to coordinate ocean research efforts, has worked to coordinate agency investment in technological development. Philanthropic institutions have also provided support, for example, in the form of the previously mentioned Wendy Schmidt Ocean Health X-Prize. Beginning in 2013, NOAA's IOOS program has provided a small amount of funding through its Ocean Technology Transition program to bring emerging observing technologies developed by institutions of higher education, nonprofit and for-profit organizations, and state, local, and tribal governments into operation.

SUSTAINED OPEN DATA

To realize the value of sustained ocean observing, the observations must be readily available to diverse users. This is essential to building user support for the investment in sustained ocean observing in the United States. The committee supports and reiterates the increasing consensus within the research and stakeholder communities to promote full and timely open data access. Open access spurs scientific discovery, innovation, and the extraction of maximum benefit from research investments. Specifically, the committee notes the Open Data in a Big Data World accord, spearheaded by the International Council for Science and adopted by four major international science organizations[5] that represent more than 250 national and regional science academies and scientific unions (Science International, 2015). The accord formulates open-data responsibilities for scien-

[5] The International Council of Science, the InterAcademy Partnership, the International Social Science Council, and The World Academy of Sciences for the advancement of science in developing countries (TWAS).

tists, research institutions, universities, publishers, funding agencies, professional associations, and scholarly societies. It addresses potential challenges and boundaries to openness and discusses enabling practices.

Core ocean climate data consist of measurements collected by a network of diverse in situ and remote observing platforms, which observe different parts of the ocean with different spatiotemporal sampling characteristics. The highest priority has been on data (1) quality control, (2) near-real-time dissemination, and (3) archiving. Quality control is typically performed by the individual observing program's team, thus ensuring a high level of expertise and vested interest devoted to this process. Real-time dissemination is achieved through WMO's Global Telecommunication System (GTS) network that is in charge of rapid collection, exchange, and distribution of observations and processed information within the framework of the World Weather Watch (WMO, 2016). For most in situ ocean observing programs, real-time dissemination is supported and coordinated by JCOMMOPS. Most countries mandate that collected data be submitted to their national data centers, such as the National Centers for Environmental Information (NCEI; which includes the former National Oceanographic Data Center) in the United States. NASA's Earth Observing System Data and Information System is a system of Distributed Active Archive Centers (DAACs, including PO.DAAC, the Physical Oceanography Distributed Active Archive Center) with the tasks of processing, archiving, documenting, and distributing data from NASA's past and current Earth-observing satellites. All of these foundational centers are charged with archiving and disseminating data to the wider community.

High-quality ocean and climate records demand an extra level of maintenance in terms of quality control, calibration, drift assessment, and analysis of adequate sampling. Various studies have shown that lack of these considerations will limit the scientific utility of these datasets for climate research, in particular signal detection and attribution (Abraham et al., 2013; Karl et al., 2015; Boyer et al., 2016).

With the increase of data sources and formats, new paradigms are emerging for best practices for data and information management as well as stewardship. In this context "data" refers not only to raw observations, but also to derived data products, algorithms, software tools, workflows, and metadata. Stewardship encapsulates long-term care of valuable digital information. New cyberinfrastructure initiatives aim to provide tools that promote these paradigms based on latest available information technology. Implementation of these new frameworks using newly developed tools is challenging. Furthermore, the goal is not to duplicate efforts or generate new repositories, but to enhance and promote existing well-established (i.e., well-curated), deeply integrated, and special-purpose foundational systems, such as NCEI.

A diverse group of stakeholders representing academia, industry, funding agencies, and scholarly publishers have created a set of principles for scientific data management and stewardship (Wilkinson et al., 2016). These FAIR Guiding

Principles promote data to be findable, accessible, interoperable, and reusable. Beyond individual discoverability and (re)usability, the principles are essential for increased automated access and use of the data. FAIR condenses a number of previous works by efforts such as the Concept Web Alliance, the Joint Declaration of Data Citation Principles, the Core Trustworthy Data Repositories Requirements, and the Data Seal of Approval. The committee is conscious that budget restrictions may place a premium on core data collection activities, but sees substantial benefits in adapting FAIR Guiding Principles and corresponding cyberinfrastructure frameworks in the management and stewardship of the sustained ocean observing system. Similar to these principles, the American Geophysical Union has adopted the position that data should be "Credited, Preserved, Open, and Accessible" in order to help future scientists understand the Earth systems and will adopt data management best practices for their own and other journals (AGU, 2017).

As one of the foundational oceanographic and climate data repositories, NCEI states that it "has implemented numerous interoperable data technologies to enhance the discovery, understanding, and use of the vast quantities of oceanographic data in their archives. Combined, these technologies enable NODC [now NCEI] to provide access to its data holdings and products through some of the commonly-used standardized Web services." (NOAA, 2016a). NCEI would be an appropriate entity in the United States to adopt the principles described above.

5

Overcoming Challenges and Identifying New Opportunities

The climate of the planet is changing and will continue to change in large and possibly unexpected ways over the coming decades and centuries. The role of the ocean in acting to moderate climate change by taking up both heat and carbon, and its physical and biogeochemical response as climate change continues, is consequential to how societies can plan to adapt to these changes. As discussed in the previous chapters, melting or dynamically unstable ice sheets provide an increasing source of fresh water input to the ocean and, among other impacts, raise global sea level. Yet key questions remain on how heat is distributed in the ocean, how carbon is exchanged with the atmosphere, and the impacts of more fresh water in the ocean. Natural climate variability, as represented in this report by the El Niño–Southern Oscillation, affects everything from monsoon strength in Asia to variations in mid-latitude storm tracks and winter weather. Sustained ocean observations are key to both understanding and improving natural climate predictability on seasonal-to-decadal timescales. Beyond climate, important decisions rest on improved understanding of the ocean to inform commercial activities such as fisheries management and coastal community planning. Sustained and expanded ocean observations are expected to continue to provide ancillary benefits such as improved ability to forecast and effectively respond to weather patterns.

The State of the Ocean Observing System: The committee has found that the current ocean climate observing system represents a significant scientific achievement that provides essential information for advancing our understanding of the climate system and other ocean processes and properties.

Finding: The current ocean observing system has made significant contributions to better understanding the ocean's role in the Earth system, including its heat, carbon, and fresh water budgets, and to better understanding global and regional sea-level change. Sustaining, optimizing, and increasing ocean observing capability will further improve understanding of the ocean's role in climate.

Finding: The ocean observing system contributes not only to our understanding of climate variability and change, but also to a wide variety of other services including weather and seasonal-to-interannual forecasting, living marine resource management, and marine navigation. This understanding of climate variability and change and other services underpins national defense, economic, and social policy decisions.

CHALLENGES

In assessing the current state of the ocean climate observing system and its expected evolution, the committee identified major challenges in sustaining ocean observing that guide the conclusions provided in this report:

- **The issue of access within Exclusive Economic Zones (EEZs) for deploying observing system elements, or for the drift of mobile platforms such as Argo floats, remains a challenge and can act as a disincentive to deployment in some regions of the global ocean.** International coordination and cooperation for ocean observing has been otherwise effective.
- **The absence of an overarching long-term (e.g., 10-year) national plan with associated resource commitments and lack of strong leadership presents a challenge for sustaining U.S. contributions to ocean observing, by inhibiting effective coordination and multiyear investments in the many components of the observing system.** Observing the global ocean on timescales from seasons to a century involves multiple entities within and external to the federal government.
- **The long-term investment required to develop and sustain the necessary expert workforce of the future is a challenge due to limited professional rewards or career incentives at research institutions and laboratories to ensure intergenerational succession of scientists, engineers, and technical staff.** Success to date in the development, deployment, and operation of ocean observing infrastructure has been enabled by a relatively small but dedicated group of scientists, engineers, and technical staff that have devoted their careers to this activity, though the long-term nature of the research is typically not rewarded in the academic community.

- **The limited investment in advancing technological capabilities is a challenge that, if addressed, will yield significant returns over the lifetime of sustained observing platforms through development of more robust and efficient sensors and platforms and through the maturation of observing methods to address existing and new scientific challenges.** The ocean is vast and the operating environment is harsh. Much of the success to date rests on technology sponsored by the Department of Defense prior to the 1990s.
- **The decreasing number of global and ocean class research vessels is creating a shortfall in the infrastructure required for sampling the global ocean and expanding data collection into poorly sampled regions such as the polar seas.** Ships require long-term planning and investment, and maintenance of a capable fleet of research vessels is an essential component of the U.S. effort to sustain ocean observing.

INTERNATIONAL COOPERATION

As described in Chapter 3, countries with interest in ocean observing for climate and other purposes participate in coordination activities of the Global Climate Observing System (GCOS) for climate observations and in the Global Ocean Observing System (GOOS) under the Framework for Ocean Observing. These efforts capture the needs of the United Nations Framework Convention on Climate Change for setting global climate mitigation and adaptation policies, the Intergovernmental Panel on Climate Change for scientific assessments of the state of the climate and the expected changes for different development scenarios, and the Global Framework for Climate Services (GFCS) of the World Meteorological Organization for real-time information on climate variability and change as it pertains to regional climate phenomena such as El Niño. These efforts have been effective in identifying global priority ocean variables, establishing global ambition and plans, facilitating national resource mobilization, and harmonizing observing efforts among countries. The United States has been a leader and strong supporter of GCOS and GOOS, and, as seen in Table 2.1, has supported a substantial portion of the global system.

International Coordination and Prioritization of Ocean Observations: GOOS provides the framework under which nations can plan and prioritize their ocean observing activities. And, although GOOS does not provide a mechanism for sustaining national commitments, this international coordination and cooperation for ocean observing is generally considered to be effective.

> *Finding: GOOS efforts are effective at promoting international cooperation to sustain the ocean climate observing system. Its guiding document—Framework for Ocean Observing—and the associated procedures for*

establishing priority observations (the Essential Ocean Variables) are constructive for defining ongoing requirements (precision, frequency, spatial resolution) for sustained ocean observations and provide a solid foundation for selecting and prioritizing ocean variables for sustained observing.

Since the early 1990s, the number of countries involved in ocean observing has increased due to the capacity-building efforts of the Partnership for Observation of the Global Oceans and other ocean observing programs. The increased participation in conducting ocean observations and research adds to the value of the investments made by the United States in ocean observing.

Finding: Capacity building enhances international support for the sustained ocean observing system and is valuable for increasing international use of the information and sharing of observing responsibilities.

Much effort has gone into harmonizing investments of multiple countries but the committee has identified untapped opportunities for further international cooperation. Specific opportunities exist in sharing of large ocean observing infrastructure such a ships and moored platforms. Entities charged with coordinating ocean science nationally, such as the National Ocean Research Leadership Council (NORLC), can explore these opportunities.

Finding: Opportunities exist to increase the spatial coverage and multidisciplinary nature of sustained ocean observations through U.S./international (either bilateral or multilateral) coordination and sharing of resources.

Conclusion on International Cooperation: The Global Ocean Observing System organization has effectively engaged countries and built capacity for ocean climate observing. A challenge remains in obtaining global access to national EEZs for drifting platforms which could be addressed by NORLC.

SUSTAINING THE U.S. CONTRIBUTION

The United States has been a leader in national and international investments and cooperation that have created ongoing global observing programs for priority ocean climate variables. Federal agencies, academic institutions, and, more recently, philanthropic organizations have played roles in establishing and maintaining the U.S. contributions to the ocean observing system for climate. The private sector is increasingly becoming a key in the production of observing system components, an innovator of technology, and developer of data platforms. The committee carefully considered the central question of the appropriate roles of these sectors. Given the significant contribution of these observations to national security, the economic and social outcomes that span the nation, and the intergovernmental negotiations, the committee found that the resources required for sustained observations are primarily a federal responsibility. Federal agencies have established observing programs, conducted research and development, and provided program management and financial support to academic institutions. Academic institutions have conducted basic research and technology development to bring observing programs to life and educated and sustained the requisite workforce. In recent years, the philanthropic sector has engaged in the support of ocean research and conservation, yet long-term observing is generally not funded by this sector. Federal funding has provided the vast majority of resources for climate/ocean observing to date but is subject to the annual fiscal cycle. Additionally, most academic projects are subject to 3- to 5-year funding cycles. This fundamental disconnect between short-term funding increments and the decadal commitment required for ocean climate observing requires ongoing education and awareness campaigns.

Further, the committee reviewed the past performance and future plans for sustaining ocean observations for climate and found ocean observing to be dependent on multiple federal agencies. There are two key legislative acts associated with ocean observing and interagency coordination mechanisms. The National Oceanographic Partnership Act created the National Ocean Partnership Program and NORLC to help foster coordination among federal ocean agencies. The Integrated Coastal and Ocean Observing System (ICOOS) Act of 2009 established the Interagency Ocean Observations Committee (IOOC) and seeks to promote a coordinated ocean observing system organized by federal agencies and nonfederal entities. Although the interagency bodies described above have responsibilities to coordinate activities associated with ocean climate observing, the committee has not been able to identify a clear leadership position for this intersection of ocean, climate, and observing although NORLC is the most likely. The NORLC could guide the development of a long-term plan and identify needed resources relying on the legislatively established IOOC focused on ocean observing and engaging the Ocean Research Advisory Panel (ORAP). Although there are active interagency coordination bodies, there is no long-term plan to guide development and establish investments in sustained ocean observing.

Sustaining the Ocean Observing System: The committee has found that the full value of ocean climate observations can only be realized through continuity of measurements to capture variability and change, and through a long-term commitment to observe processes on the extended time frames required to monitor variability and changes in the climate system.

> *Finding: The continuity of ocean observations is essential for gaining an accurate understanding of the climate. Funding mechanisms that rely on annual budget approval or short-term grants may result in discontinuity of*

ocean climate measurements, reducing the value of the observations made to date and in the future.

Finding: To avoid data gaps and ensure the required data quality and the accessibility of the data for monitoring climate over decades, ocean observing initiatives will need to plan for the end-to-end scope of expenses associated with observing programs, including appropriate logistical planning and all processing including data analysis, data management, and scientific involvement.

The committee has concluded that a focus on both long-term planning and building partnerships across public, private, and academic sectors as described below would be beneficial in this context for sustaining U.S. ocean observing contributions and aligning them with the long-term observational priorities of GOOS. The first approach is the development of a process for creating a decadal plan for ocean observing.

Conclusion on Planning: Because of the extended time frame required for climate observations, a decadal plan for the U.S. ocean observing system would be the most effective approach for ensuring critical ocean information is available to understand future climate. Consistency of the decadal plan with the Framework for Ocean Observing would optimize U.S. investments relative to contributions of the international community, with plan updates likely required to align with international activities during the 10-year period. Elements of a decadal plan include identification of requirements, assessment of the adequacy of the current system, components to be deployed over the 10-year period, potential for technological advancements, and an estimate of resources necessary to implement the plan. The NORLC has the mandate under the ICOOS Act to oversee development and adoption of a long-term plan and NORLC could be responsible for its periodic assessment and update, possibly utilizing the IOOC and the ORAP. Progress in implementing the plan would depend on the engagement of the broader stakeholder community and coordination with international partners in the global ocean observing system.

A high-level federal coordinating body such as NORLC would be able to provide program oversight and prepare budgets for a successful observing system. A key role of this coordinating body would be sponsoring the development and periodic review/update of a long-term strategy with associated resources for sustaining ocean observations for understanding climate change. This long-term strategy and periodic assessment would engage a broad representation of experts and stakeholders through an existing advisory group such as the ORAP or a new mechanism. Ideally the advisory group would be engaged in regular strategic planning, supporting decadal surveys, and be available for rapid-response analysis and decision making. This advisory group could also be charged by NORLC with periodic assessment of the effectiveness of the program and progress toward goals. Membership requirements would include a strong background in the science of ocean observing, oceans' role in climate change, ocean modeling, program management, and knowledge of critical methods, techniques, platforms, and programs involved in ocean observing.

A key aspect of the planning and assessment process would be the identification of resources needed to sustain the ocean observing system. This would include the development of suggestions for possible best practices in budgeting given the existing disconnect between the decadal mission and the annual budget cycle. Planning and budgeting would cover the entire end-to-end system of ocean observing, from technology development to support for open data usage and access. A critical component for success of the ocean observing enterprise is the ongoing involvement of the scientific community in observing programs that are maintained over long time periods. However, there is not a standardized approach or coherent policy for ensuring the engagement of scientists throughout the evolution of systems from research to operations. This shortcoming could be addressed as part of the decadal plan described in "Conclusion on Planning."

NONFEDERAL PLAYERS

While philanthropic organizations are not currently inclined to commit to the direct sustainment of observations, they can play a key role in technology development, building global capacity, and other areas. The committee found genuine interest among foundation representatives in supporting the goal of long-term ocean observing to further understand climate change. Philanthropists may be able to contribute to long-term ocean observing to understand climate change through the endowment of faculty or senior graduate billets at academic institutions or through continuing support of training and technology development programs. Given an interest by foundations in supporting ocean conservation initiatives and the trend of flat or reduced federal funding, particularly for ocean observations linked to understanding climate change, there may be opportunities to seek philanthropic support for sustaining key ocean observations and observing capabilities.

Finding: Raising awareness of the importance and value of sustained ocean climate observations could increase support for the observing system from multiple sectors, including philanthropic organizations.

Ocean observations for climate are at the root of a value chain that provides broad social and economic benefits. For example, seasonal forecasts of great importance to the U.S. agricultural enterprise depend directly on these observations. Skillful seasonal forecasting ability has been monetized by weather and climate companies that provide specialized services to businesses. Other companies (e.g., shipping, fisheries, insurance, and energy supply companies) benefit directly from these observations. Efforts could be made to entrain these commercial companies with the goal of gaining their support for the system. Types of support could range from advocacy for the system to federal decision makers or financial or in-kind support to accelerate technology improvements. The committee concludes that another effective approach for sustaining long-term ocean observations is the engagement of these partners.

Conclusion on Partnership: An Ocean-Climate Partnership (OCP) organization would be an effective mechanism to increase engagement and coordination of the ocean observation science community with non-nonprofits, philanthropic organizations, academia, U.S. federal agencies, and the commercial sector. Through their shared interests in the observational data and associated products, the OCP members could work together toward the goal of sustaining the ocean climate observing system.

The OCP's mission would be to communicate the ocean climate observing system's socioeconomic benefits to potential partners and policy makers with the goal of ensuring the long-term fiscal viability of the ocean observing enterprise. It would seek to demonstrate value for investment to federal funders and entrainment of nonfederal partners, including businesses and philanthropy to harmonize and leverage their contributions. The role of the OCP could be hosted in an existing entity, such as a nonprofit with experience conducting such activities.

Additional tasks of the OCP could include conceiving and seeking sponsorship of projects designed to

- Accelerate the implementation of new observing and data technologies, perhaps through prizes or a program modeled after the DARPA (Defense Advanced Research Projects Agency) program directed at ocean technology;
- Support workforce development by attracting and training qualified personnel through the establishment of engagement workshops, internships, and postdoctoral programs, endowed faculty positions, national/international scientist exchanges, and international recognition and reward mechanisms;
- Contribute to efforts to build global capacity;

OCP member requirements would include a strong background in communication and science outreach, knowledge of the ocean observing system and goals, experience working with public–private partnerships, and experience working with philanthropic entities. The structure and responsibilities of this entity can be further explored through a potential second phase of this study.

DEVELOPING AND SUSTAINING THE FUTURE WORKFORCE

The key to maintaining climate-quality, long-term observing system elements is direct scientific involvement and oversight, including, where possible, involvement in actual operations of the observing programs by academic or government scientists. Successful sustained ocean observing in the United States has relied on human resources in the form of strong individual performers holding leadership and program-level positions supported by capable technical staff. This requires individuals dedicated for a decade or more to these observing programs. For individual scientists, starting up and implementing an ocean observation activity is time-consuming and may be difficult without substantial institutional support and guarantees for long-term funding. By its very nature, observational science typically requires some years of data collection before results are publishable and this can be out of line with traditional career-advancement metrics. This acts as a disincentive for early-career scientists contemplating participation in ocean observing activities beyond utilization of existing datasets.

> *Finding: Direct scientific involvement in sustained observing programs, from design to implementation to analysis, synthesis, and publication, ensures that the ocean observing system will be robust in terms of data quality, incorporation of new methods and technologies, and scientific analyses; all are essential elements for realizing the value of long-term, sustained observations.*

One responsibility of the OCP would be to engage universities and sponsor activities to educate, attract, and retain the talent needed in sustained observations, whether carried out by government programs or within universities or the private sector. Institutions interested in retaining scientists engaged in ocean observing would need to recognize individual and team contributions to creating and sustaining observing programs that constitute original research, and reward them accordingly. This would help grow and maintain the ocean observing workforce.

Conclusion on Workforce: Direct scientific involvement in sustained observing programs, from design to implementation to analysis, synthesis, and publication, ensures that the ocean observing system will be robust in terms of data quality, incorporation of new methods and technologies, and scientific analyses. Thus, intergenerational succession of scientists is critical for sustaining the observations on climate timescales. The OCP could focus on improving career incentives for the scientific workforce as a priority.

NEW TECHNOLOGY

The ocean observing enterprise is an end-to-end system that not only relies on ocean climate observing scientists, but also on the development of technologies by engineers, the deployment and maintenance of observing platforms from ships, and the management and application of the processed data. The ocean presents significant physical challenges for ocean observing technology, as outlined in Chapter 2. New sensors, materials, and battery technology and more efficient electronics would allow optimizing ocean observing. Further, key processes and variables, such as vertical mixing, could be routinely observed and new scientific challenges could be addressed if new sensors and methods were developed and taken to maturity. Yet, the committee perceives a decline in investments for new technology, particularly given an overall flattening of funding for ocean observing over the last decade. Improvements to current technology may extend the lifetime of observing system elements where appropriate. For example, with attention to battery technology, sensor stability, and care in production, Argo float lifetimes might be extended from about 4 years at present to at least 6.

Conclusion on Technology: Declining investments have slowed the development of new technology, which is proven to expand the capability, the efficiency, and therefore the capacity of the observing system. Philanthropic efforts have in part filled this gap and the OCP could encourage more support there.

THE RESEARCH FLEET

While improving current technologies and developing new ones, such as autonomous ocean-going vehicles, holds promise for increasing the efficiency of observing system operations, ships and, in particular, global and ocean class vessels will continue to be required to deploy and maintain ocean observing platforms. These vessels are indispensable to the ocean observing system, providing direct observations and deployments of moored and drifting instruments. While there is a need to regularly evaluate the substantial investments made in research vessels and determine the "right size" of the fleet for contemporary research needs, it is vital to continuously consider the importance of global and ocean class vessels for ocean observing. The committee shared the concern motivating recommendation 5 of the NRC report, *Sea Change: 2015-2025 Decadal Survey of Ocean Sciences* (NRC, 2015): "NSF should reconsider whether the current RCRV [Regional Class Research Vessel] design is aligned with scientific needs and is cost-effective in terms of long-term O&M [operations and maintenance], and should plan to build no more than two RCRVs." The committee also supports the plan for two new NOAA vessels capable of conducting ocean monitoring (NOAA, 2016b).

Conclusion on the Research Fleet: While new technology holds promise for access to the ocean, a capable fleet of research vessels, including those with global reach, is essential to sustaining the U.S. contribution to ocean observing.

POTENTIAL NEW MODELS OF SUPPORT FOR SUSTAINED OCEAN OBSERVING

This report identifies the many benefits of sustaining and growing the capabilities of the global ocean observing system to advance climate science and improve capabilities to anticipate changes critical for decisions on mitigating and adapting to climate change. Because ocean climate data are needed to inform national security, economic, and societal decisions on climate change and other ocean-related issues and given the intergovernmental negotiations required for participating in a global system, responsibility for supporting the ocean observing system falls predominantly on the federal government in the United States. However, limited funding means there is a need to prioritize efforts and increase the efficiency of existing operations. In addition to prioritizing limited government spending, there is also an opportunity to create new models for partnerships of the government with the private and nonprofit sectors in order to accomplish shared goals for ocean observing and research.

A potential second phase of this study is a workshop to explore new models for sustaining ocean observations. The workshop could discuss a full range of potential options for aligning resources and governance structures to ensure continuity and quality of the most critical ocean climate observations over the long term. The workshop could include discussion of governance issues such as scientific oversight, coordination with U.S. and international observing initiatives, and multiyear financing structures. Opportunities for leveraging private and philanthropic support within these government structures would also be important to explore.

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Appendix A

Committee and Staff Biographies

COMMITTEE

Mary M. Glackin *(Co-chair)* is senior vice president, Public Private Partnerships, and Director of Meteorological Science and Services at The Weather Company, an IBM Business. In this role, she oversees the company's relationship with members of the international environmental community, including government agencies, academia and other private-sector providers. She is also responsible for the company's research agenda as well as forecast operations. Ms. Glackin is retired from the National Oceanic and Atmospheric Administration, where from 2007 to 2012 she was deputy under secretary of commerce for NOAA Operations in Washington, D.C. As such, she was responsible for the day-to-day management of operations for oceanic and atmospheric services, research, and coastal and marine stewardship. Before that, she was the assistant administrator for NOAA's Office of Program Planning and Integration. Between 1999 and 2002, she served as the deputy assistant administrator for the National Environmental Satellite, Data, and Information Service of NOAA. Ms. Glackin has twice received the Presidential Rank Award (2001 and 2009). She has also received the Charles Franklin Brooks Award for Outstanding Services to the American Meteorological Society (AMS), the NOAA Bronze Medal (2001), the Federal 100 Information Technology Manager Award (1999), the NOAA Administrator's Award (1993), and the United States Department of Commerce Silver Medal (1991). She is a Fellow of the AMS and the National Academy of Public Administration, as well as a member of the National Weather Association and of the American Geophysical Union. Ms. Glackin has a B.S. degree from the University of Maryland.

Robert A. Weller *(Co-chair)* is a senior scientist with the Woods Hole Oceanographic Institution, where he formerly served as director of the NOAA Cooperative Institute for Climate and Ocean Research and past Chair of the Physical Oceanography Department. His research focuses on atmospheric forcing of the upper ocean, observation and prediction of upper-ocean variability, and the ocean's role in climate. Dr. Weller has been a pioneer in developing tools and technologies that enable scientists to investigate upper-ocean processes on scales from meters to tens of kilometers and with accuracy never before available. Dr. Weller has been on multiple mooring deployment cruises and has practical experience with ocean observation instruments. He serves as chair of the U.S. Climate Variability and Change (CLIVAR) Scientific Steering Group and on the World Meteorological Organization/Intergovernmental Oceanographic Commission international Ocean Observing Panel for Climate, the NOAA Climate Observing System Council, and the NOAA Environmental Information Services Working Group. He co-chairs OceanSITES, a program under the international Joint Commission on Oceanography and Marine Meteorology that coordinates sustained time-series observations in the global ocean. He is chair of the Ocean Research Advisory Panel. He has served on several National Research Council (NRC) committees, including the Committee to Review the U.S. Climate Change Science Program Strategic Plan, the Committee on Implementation of a Seafloor Observatory Network for Oceanographic Research, the Committee on Utilization of Environmental Satellite Data, the Board on Atmospheric Sciences and Climate, and he chaired the NRC committee on the Assessment of Intraseasonal to Interannual Climate Prediction and Predictability and co-chaired the NRC committee on a Strategic Vision and Implementation Plan for the U.S. Antarctic Program. Dr. Weller received his A.B. in engineering and applied physics from Harvard University and Ph.D. in physical oceanography from Scripps Institution of Oceanography.

Edward A. Boyle is a professor of Ocean Geochemistry at MIT and Director of the MIT-Woods Hole Oceanographic Institution Joint Program in Oceanography. His research interests include a focus on ocean trace metal chemistry in relation to biogeochemical cycling, anthropogenic inputs, and as a tool for understanding the geological history of the ocean. He has worked on lead and other anthropogenic trace metals in Greenland ice cores and on trace metals in estuaries. Dr. Boyle discovered that iron in the deep southwest Pacific derives from distant hydrothermal vents. Additionally, he has shown that cadmium in some species of benthic foraminifera tracks the cadmium content of the bottom water they grow in, and has applied this finding to sediment cores to trace past changes in ocean deep water chemistry which is influenced by changing ocean circulation patterns and changes in biogeochemical cycling within the ocean, including mechanisms that influence atmospheric carbon dioxide levels. He is a member of the National Academy of Sciences, and his National Research Council experience includes membership on the Ocean Studies Board from 2010 to 2015, the 2013 Alexander Agassiz Medal Selection Committee, the Committee on Guidance for NSF on National Ocean Science Research Priorities: Decadal Survey of Ocean Sciences, the Committee on an Ocean Infrastructure Strategy for U.S. Ocean Research, and the Marine Chemistry Study Panel. Dr. Boyle received his Ph.D. from the MIT/Woods Hole Oceanographic Institution Joint Program in Chemical Oceanography.

Robert B. Dunbar is the William M. Keck Professor of Earth Sciences at Stanford University. Dr. Dunbar was the founding director of Stanford's Interdisciplinary Ph.D. Program in Environment and Resources. He directed the Stanford Earth Systems program for 9 years. He is also the first J. Frederick and Elisabeth B. Weintz University Fellow in Undergraduate Education and a Senior Fellow at Stanford's Woods Institute for the Environment. He served on the Board of Trustees of the U.S. Consortium for Ocean Leadership from 2009 to 2016, including as Board Chair for the last 3 years. Dr. Dunbar's research interests link climate dynamics, oceanography, and marine ecology with environmental policy and solutions. His research group works on topics related to global environmental change, with a focus on the hydrologic cycle, air-sea interactions, tropical ecosystems, and polar biogeochemistry and glacial history. His lab participated in the ANDRILL program as shore-based and field-based scientists exploring the history of Antarctic climate at Windless Bight (McMurdo Ice Shelf Drilling) and Southern McMurdo Sound. He has participated in over 100 oceanographic research expeditions, most recently to install ocean observing instrumentation in the Chagos Archipelago in April 2016. Dr. Dunbar received his Ph.D. in oceanography from the Scripps Institution of Oceanography.

Robert Hallberg is an oceanographer and the head of the Oceans and Ice-sheet Processes and Climate Group at NOAA's Geophysical Fluid Dynamics Laboratory (GFDL), and a lecturer on the faculty of Princeton University. He has spent many years developing isopycnal (density) coordinate ocean models to the point where they now are valuable tools for coupled climate studies, including extensive work on the robustness of the models' numerical techniques, and on the development or incorporation of parameterizations of a wide range of physical processes. The isopycnal coordinate ocean model that Dr. Hallberg developed provides the physical ocean component of GFDL's ESM2G comprehensive Earth System Model, which was used in the Intergovernmental Panel on Climate Change 5th Assessment Report, and its dynamic core is the basis for version 6 of the Modular Ocean Model (MOM6). Dr. Hallberg has used global-scale numerical ocean simulations to study topics as varied as the dynamics of Southern Ocean eddies and their role in the ocean's response to climate, sources of steric sea-level rise, and the fate of the deep plumes of methane and oil from the Deep water Horizon oil spill. Dr. Hallberg has been actively involved in three ocean Climate Process Teams, studying gravity current entrainment, eddy–mixed layer interactions, and internal-wave-driven mixing. These teams aim to improve the representation of these processes in climate-scale models, based on the best understanding that can be obtained from observations, process studies, and theory. He is currently working on coupling a dynamic ice-sheet and ice-shelf model with high-resolution versions of GFDL's coupled climate models for improved prediction of sea-level rise. He has a 1995 Ph.D. in oceanography from the University of Washington and a 1990 B.A. in physics from the University of Chicago.

Patrick Heimbach is associate professor at the University of Texas at Austin and fellow of the W. A. "Tex" Moncrief, Jr., Chair III in Simulation-Based Engineering and Sciences. His research focuses on understanding the general circulation of the ocean and its role in the global climate system. As part of the Estimating the Circulation and Climate of the Ocean (ECCO) consortium that originated under the National Oceanographic Partnership Program (NOPP), he and his group are applying formal inverse modeling techniques for the purpose of fitting a state-of-the-art general circulation model (the MITgcm) with much of the available satellite and in situ observations to produce a best possible estimate of the time-evolving three-dimensional state over the past few decades of the global ocean and seaice cover. ECCO products support global and regional ocean circulation and climate variability research on timescales of days to decades. Emerging research foci are understanding the dynamics of global and regional sea-level change, the provision of formal uncertainties along with these estimates and implications for improving the global ocean observing system for climate. Dr. Heimbach is a member of the National Academies' Ocean Studies Board. He earned his Ph.D. in 1998 from the Max Planck Institute for Meteorology and the University of Hamburg, Germany.

Mark Merrifield is a professor in the Department of Oceanography at the School of Ocean and Earth Science and Technology at the University of Hawaii at Manoa. His research interests include coastal oceanography, surface and internal waves, and sea-level variability. He is the director of the Joint Institute for Marine and Atmospheric Research and the University of Hawaii Sea Level Center. Dr. Merrifield received his A.B. in physics from the University of California, Berkeley and Ph.D. in oceanography from Scripps Institution of Oceanography.

Dean Roemmich is a professor of oceanography in the Integrative Oceanography Division and the Climate, Atmospheric Science, and Physical Oceanography Section at Scripps Institution of Oceanography, University of California, San Diego. He teaches courses on observations of large-scale ocean circulation and advises graduate students in the Physical Oceanography and Climate Science programs. He is a leader in the Argo program, a global array of 3,000 profiling floats providing data from the subsurface ocean that are necessary to complement and interpret satellite measurements of sea surface height and surface wind. He was a lead author of the IPCC 5th Assessment Report's chapter on Ocean Observations. Additionally, he is a member of the NOAA Climate Working Group, the international CLIVAR (Climate and Ocean: Variability, Predictability and Change) Global Synthesis and Observations Panel, and the NASA Ocean Surface Topography Science Team. Dr. Roemmich received his B.S. in physics from Swarthmore College and Ph.D. in oceanography from the Massachusetts Institute of Technology, Woods Hole Oceanographic Institution Joint Program.

Lynne D. Talley is a professor of oceanography at the Scripps Institution of Oceanography at the University of California, San Diego. Dr. Talley's expertise and research interests include general ocean circulation, hydrography, theory of wind-driven circulation, and ocean modeling. She is co-principal investigator for the U.S. GO-SHIP program, an international repeated decadal survey of the deep ocean's physical and chemical properties. She is head of the observational team in the SOCCOM program that is deploying a network of biogeochemical Argo profiling floats throughout the Southern Ocean. She was a lead author on the IPCC 4th and 5th Assessment Reports chapter on Ocean Observations, and on the 5th Assessment Report's Technical Summary and Summary for Policymakers. Dr. Talley has an extensive NRC committee background, having served previously on the Climate Research Committee, Global-Ocean-Atmosphere-Land System Panel, Panel to Review the Jet Propulsion Laboratory Distributed Active Archive Center (DAAC), and committees on Abrupt Climate Change, Climate Change Feedbacks, and Future Science Opportunities in the Antarctic and Southern Ocean. She is a member of the CLIVAR Southern Ocean Region Panel, and the US CLIVAR Southern Ocean Working Group. Dr. Talley was a National Science Foundation Presidential Young Investigator in 1987. Dr. Talley received her Ph.D. in physical oceanography from the WHOI/MIT Joint Program in Oceanography. She is a fellow of the American Academy of Arts and Sciences, American Geophysical Union, American Meteorological Society, and Oceanography Society.

Martin Visbeck is head of Research Unit, Physical Oceanography at GEOMAR. His current research is concerned with ocean and climate variability and change, with particular emphasis on the circulation of the subpolar North Atlantic, climate-biogeochemical interactions in the tropical ocean, observations of ocean circulation and mixing using modern robotic platforms including profiling floats and gliders, and development of ocean observatories for long-term observations in the water column. He is a member of the Joint Scientific Committee of the World Climate Research Programme (WCRP) and participated in the development of the Framework for Ocean Observing concept. Dr. Visbeck received his Ph.D. in physical oceanography from Kiel University. He is a fellow of the American Geophysical Union and the incoming president of the Oceanography Society.

STAFF

Susan Roberts became the Director of the Ocean Studies Board in April 2004. Dr. Roberts received her Ph.D. in marine biology from the Scripps Institution of Oceanography. Prior to her position at the Ocean Studies Board, she worked as a postdoctoral researcher at the University of California, Berkeley and as a senior staff fellow at the National Institutes of Health. Dr. Roberts' research experience has included fish physiology and biochemistry, marine bacterial symbioses, developmental cell biology, and environmentally induced leukemia. Dr. Roberts specializes in the science and management of living marine resources. She has served as study director for 18 reports produced by the National Research Council on topics covering a broad range of ocean science, marine resource management, and science policy issues. She is a member of the U.S. National Committee for the Intergovernmental Oceanographic Commission (IOC) and serves on the IOC panel for the Global Ocean Science Report. Dr. Roberts is a member of the American Association for the Advancement of Science, American Geophysical Union, and the Association for the Sciences of Limnology and Oceanography. She is an elected Fellow of the Washington Academy of Sciences.

Emily Twigg joined the Ocean Studies Board in October 2016 as an associate program officer. Prior to her time at the National Academies of Sciences, Engineering, and Medicine, she held positions at the National Science Foundation and at the U.S. Environmental Protection Agency. She has a Master's degree in environmental science and management from the Bren School at the University of California, Santa Barbara, and a Bachelor's degree in biology from the University of California, Berkeley. She has additional experience working in resource management at a national park, and in outdoor environmental education.

April Melvin is an associate program officer with the Board on Atmospheric Sciences and Climate. Her primary expertise includes climate change impacts in the U.S. Arctic and effects of pollution on environmental health. Prior to joining the National Academies, she was a Science & Technology Policy Fellow in the Climate Change Division at the U.S. Environmental Protection Agency, sponsored by the American Association for the Advancement of Science (AAAS). She has also held positions as a postdoctoral research associate at the University of Florida and was a Christine Mirzayan Science & Technology Policy Fellow with the Board on Atmospheric Sciences in Climate. Dr. Melvin received her Ph.D. in ecosystem ecology and biogeochemistry from Cornell University and holds a B.S. in ecology and evolutionary biology from the University of Rochester.

Allie Phillips graduated in May 2016 from Colby College in Waterville, Maine, where she received a B.A. in environmental studies, policy. As an undergraduate, she held internships at the Environmental League of Massachusetts (ELM) and the New England Aquarium. She joined the Ocean Studies Board as a program assistant in September 2016.

Appendix B

Workshop Agenda

Sustaining Ocean Observations to Understand
Future Changes in Earth's Climate
Workshop Agenda

National Academy of Sciences
2101 Constitution Avenue NW | Washington, DC 20418
NAS BUILDING
November 15-17, 2016

November 15, 2016
Meeting Location: NAS 120

OPEN SESSION

8:30 AM **Breakfast available**

9:00 AM **Welcome and Introductions:**
Mary Glackin and Bob Weller, *Committee Co-Chairs*
- Context and purpose of the study
- Objectives of the workshop

9:30 AM **Keynote Address:**
John Holdren, *Assistant to the President for Science and Technology, Director of the White House Office of Science and Technology Policy*

Introduced by:

Marcia McNutt, *President, National Academy of Sciences*

10:30 AM **Session 1—Defining and Supporting the U.S. Contributions to GCOS and GOOS**

Session Objective: To understand how major funding decisions are made and how funding can be sustained

Session lead: Bob Weller

Panelists:

Michael Freilich, *Director, Earth Science Division, Science Mission Directorate, NASA*

Craig McLean*, Assistant Administrator, Office of Oceanic and Atmospheric Research, NOAA*

Roger Wakimoto, *Assistant Director, Directorate for Geosciences, NSF*

Questions:

1. Given the long-term need for sustained, global, ocean observations to understand future climate change as outlined in IPCC, GCOS, and GOOS documents, how does the United States define and scope its role in developing and sustaining the global, ocean observing system? For years, the U.S. has played a leading role; will it continue as a leader, as a coordinator, as a participant? As a contributor, what levels of resources are projected in terms of funds, platforms, human resources?
2. What are the most effective means for the U.S. ocean science community to argue for and gain a high level of prioritization within the United States for U.S. support of sustained, global ocean observations?
3. How do U.S. agencies divide and coordinate U.S responsibilities and commitments to the development and support of sustained ocean observing among themselves?
4. What is (are) the process(es) by which funding is developed for sustained ocean observations in the budgets of NOAA, NASA, and NSF?
5. Is the United States able to make and subsequently meet long-term or ongoing commitments to sustained ocean observing?
6. Is there dialog and coordination with your peers in other countries directed at supporting sustained, global ocean observations?

12:00 PM *Lunch Break*

1:00 PM **Session 2—International Coordination and Sovereignty**

Session Objective: To understand the challenges and potential solutions to international coordination and collecting and sharing observations in the EEZ

Session lead: Dean Roemmich

Panelists:

Craig McLean*, Assistant Administrator, Office of Oceanic and Atmospheric Research, NOAA*

Michael Patterson, *Director, US CLIVAR Project Office*

Allison Reed, *Foreign Affairs Officer, Office of Ocean and Polar Affairs, Marine Science and Research, Department of State*

Questions:

1. Given that 30% of the deep ocean is inside an EEZ or maritime zone, what is needed to ensure that sustained ocean observations for climate can be made in the global domain that is required for such observations?
2. With ocean observing datasets being freely available, how can we entrain new contributions into the enterprise? In the present system, are the contributions distributed in an equitable manner?
3. Advances in technologies of sustained observations tend to come from a few nations. How can these advances be distributed among all interested global partners?
4. Are existing international coordination bodies, i.e., JCOMMOPS, carrying out the functions required of them?
5. Are the relationships, responsibilities, and functions between different international coordination bodies (such as IOC-GOOS, JCOMMOPS, GEO,) well defined and complementary?
6. What is the follow through in the U.S. on international agreements, like the Galway Declaration, to work toward growth in sustained ocean observing? Does the recent

interest at G7 ministerial summits on ocean observing indicate a growing international coordination to develop and support sustained ocean observing?

2:00 PM *Break*

2:30 PM **Session 3—Prioritizing and Coordinating U.S. Contributions to GCOS and GOOS**

Session Objective: To understand how the U.S. ocean research and observing efforts across the agencies and from remote sensing, to coastal, to open ocean are prioritized and coordinated

Session leads: Rob Dunbar and Patrick Heimbach

Panelists:

David Legler, *Division Chief, Climate Observation Division, Climate Program Office, NOAA*

Eric Lindstrom, *Physical Oceanography Program Scientist, Science Mission Directorate, NASA, and Co-Chair, Global Ocean Observing System*

Gary Mitchum, *Associate Dean and Professor, College of Marine Science, University of South Florida*

Rick Murray, *Director, Ocean Sciences Division, Directorate for Geosciences, NSF*

Questions:

1. International planning is advancing a framework for ocean observing that includes identification of essential ocean variables. How do U.S. agencies select what they will support, develop priorities, and coordinate investments?
2. The coastal observing system, IOOS, is comprised of regional components. How are these IOOS observing efforts coordinated with global ocean observing?
3. Across the agencies' investments in the open ocean and the coastal ocean, is there agreement on, or movement toward, common best practices for observing and for data sharing?

4. How would one prioritize what observing to support across both open and coastal ocean?
5. Does the greater proximity of regional coastal observing efforts to stakeholders and the U.S. population suggest a different perspective will be formed on developing support for sustained coastal ocean observing than for sustained open ocean observing?

4:00 PM **Session 4—Prioritizing and Coordinating Science at the International Level**

Session Objective: To understand the challenges in prioritizing ocean observations as seen from U.S. and international science planning and oversight groups and from intergovernmental planning perspectives

Session leads: Lynne Talley and Ed Boyle

Panelists:

Molly Baringer, *Deputy Laboratory Director and Supervisory Oceanographer, Atlantic Oceanographic and Meteorological Laboratory, and Co-Chair, NOAA Climate Observing System Council, NOAA*

Annalisa Bracco, *Co-Chair, CLIVAR Scientific Steering Group and Professor, Georgia Institute of Technology*

Katy Hill, *GCOS-GOOS Scientific Office, IOC, WMO*

Gregory Johnson, *Co-Chair, NOAA Climate Observing System Council, Pacific Marine Environmental Laboratory, NOAA*

David Legler, *Division Chief, Climate Observation Division, Climate Program Office, NOAA*

Questions:

1. What is WCRP's mechanism for evolving its science plan and incorporating new technologies?
2. Does WCRP, JCOMMOPS have sufficient buy-in/support/authority to support long term ocean obs.?

3. What is GOOS/GCOS's mechanism for evolving its implementation plan in terms of defining essential ocean variables and in optimizing across observational platforms to achieve the essential ocean variables' specifications?
4. What are the essential ocean variables that need to be observed over the long term?
5. To what extent are the recommendations described in the GCOS/GOOS plans implemented by different nations? Are there mechanisms for commitment? Legally binding? What is their role in planning for system resilience (e.g., if one country's contribution declines are they ensuring other countries provide additional resources)?
6. Is it conceivable, based on experience working at international level, to create a CERN-like institution that would deal with sustained ocean observations, where countries commit resources, but decisions be made by the institution?
7. Is international coordination hampering implementation plans because of "minimum common denominator"/ national interests/priorities, incompatible funding structures?
8. (How) can GOOS/GCOS support the specific goal of longevity, evolution, preservation of know-how?

5:30 PM **Meeting adjourns for the day**

6:00 PM **Committee Dinner**

November 16, 2016
Meeting Location: NAS 120

OPEN SESSION

8:00 AM Breakfast available

8:30 AM **Session 5—Institutional Support to Sustaining Ocean Observations**

Session Objectives: To understand the budget constraints and challenges to coordinate the contributions to GCOS and GOOS and explore opportunities for improvement

Session leads: Mark Merrifield and Bob Hallberg

Panelists:

Rick Lumpkin, *Deputy Director, Physical Oceanography Division, Atlantic Oceanographic and Meteorological Laboratory, NOAA*

Kathleen Ritzman, *Assistant Director, Scripps Institution of Oceanography*

Chris Sabine, *Director, Pacific Marine Environmental Laboratory, NOAA*

Sophie Seeyave, *Executive Director, Partnership for Observation of Global Oceans (POGO)*

John Trowbridge, *Senior Scientist, Woods Hole Oceanographic Institution*

Robert Winokur, *Deputy Oceanographer, Navy (ret.), and Senior Advisor, Michigan Tech Research Institute*

Questions:

1. What experience does your institution have in the area of sustained ocean observations in support of climate research?
2. What do you see as the host institutional role in supporting various phases of sustained observations, such as: proposal support or idea development, technical support (facilities, technicians), research support (students, postdocs, FTE compensation), database management (IT specialists)?
3. What role should the host institution play in making participation in sustained observations an attractive career path? How can institutions ensure multigenerational support of sustained observation facilities?
4. What role does your institution play in advocating for ongoing financial support for sustained observations?
5. Given the long time on sustaining the need observations, do you have concerns about the mismatch between the typical promotion milestones and career time lines at your institution?

6. Do you encourage and facilitate staff utilization of the sustained ocean observing efforts you support? At times the PIs involved say they get just enough funding to do the observing but none to do science with the observations; should it be an institution's role to address this by helping raise support for the utilization of the observations?

10:30 AM *Break*

11:00 AM **Session 6—Illustrating the past success and future challenges of a global observing system: Argo (past, future)**

Session Objectives: To show, using the example of the Argo profiling float array, the efforts to deploy and sustain one element of the sustained ocean observing system and to also summarize challenges of responding to observing more different variables over more of the ocean

Session lead: Dean Roemmich

Panelists:

Jim Baker, *Director, Forest and Land-Use Measurement, Clinton Climate Initiative, Clinton Foundation*

Molly Baringer, *Deputy Laboratory Director and Supervisory Oceanographer, Atlantic Oceanographic and Meteorological Laboratory and Co-Chair, NOAA Climate Observing System Council, NOAA*

Gregory Johnson, *Co-Chair, NOAA Climate Observing System Council, Pacific Marine Environmental Laboratory, NOAA*

Dean Roemmich, *Professor, Scripps Institution of Oceanography*

Stan Wilson, *Assistant Administrator, National Ocean Service, NOAA (ret.)*

Nathalie Zilberman, *Project Scientist, Climate, Atmospheric Science and Physical Oceanography, Scripps Institution of Oceanography*

Questions:

1. Do you see ways where the contributions of the Argo Program could be better articulated to policy makers to ensure future investments of this critical program?
2. Argo's creation and development sprung from flexibility that academic institutions provided to researchers to explore science and emerging technology. How do we ensure this continued support into the future for sustainment and investment in new technologies and science exploration?
3. In today's fiscal and political climate, do you think it is feasible to use Argo's past successes to more effectively make the case for the increases needed to meet today's growing needs to invest in long term climate observing?
4. What mechanisms might we use to make the work of long term climate observing to be attractive to young scientists?
5. How might we optimize/prioritize the future Argo program with the addition of BioArgo, DeepArgo, Arctic, etc. in a flat budget environment?

1:00 PM *Lunch Break*

2:00 PM **Session 7—New Models and Solutions for Sustaining Ocean Observations**

Session Objectives: To explore and initiate the discussion of new models for sustaining ocean observations

Session leads: Mary Glackin and Rob Dunbar

Panelists:

Andrew Clark, *Vice President of Research Industry Technology, Marine Technology Society*

Adena Leibman, *Ocean and Coastal Policy Advisor, Office of Senator Sheldon Whitehouse*

Rick Spinrad, *Chief Scientist, NOAA*

Questions:

1. Both the Pew Ocean Commission and the U.S. Ocean Commission proposed various mechanisms to increase funding for ocean activities including long-term ocean observing. Since that time, we have seen increasing requirements for long-term ocean observing and largely flat or declining federal investments in this area. Over the past few decades, we have seen business grow by leveraging environmental information and access to the ocean. What have we learned from these experiences? How might you suggest this community better engage the private sector?
2. There has been sustaining efforts to raise awareness of ocean issues and promote more investments as a result of the Pew Ocean Commission and U.S. Ocean Commission reports. How do you recommend the community that is stewarding long term ocean observing for climate change engage in these broader ocean efforts?
3. It has been suggested that either Foundations or philanthropic funding could be a source of support for these long term ocean climate measurements. Do you see opportunities there? Is it reasonable in your opinion to rely on such funding sources for these very long term needs?
4. Awards or endowed position (chair) for dedicated effort to long-term records?

3:00 PM **Workshop discussion and wrap up** by **Jim Baker** (*Director, Forest and Land-Use Measurement, Clinton Climate Initiative, Clinton Foundation)* and **Ray Schmitt** *(Senior Scientist, Woods Hole Oceanographic Institution)*

Wrap up will include comments based on the information gained during the workshop and a discussion of how to develop a report that has impact and makes a meaningful contribution to the current dialog. How do we capitalize on the growing international support for sustained ocean observing? This session is also intended to help set the stage for the second phase of this NAS effort.

5:00 PM **Open session adjourns**

Appendix C

Acronyms

AMOC	Atlantic Meridional Overturning Circulation
CEOS	Committee on Earth Observing Satellites
CLIVAR	Originally the Climate Variability and Predictability project, but renamed the Climate and Ocean Variability, Predictability, and Change project
DA	Data Assimilation
DBCP	Data Buoy Cooperation Panel
ECV	Essential Climate Variable
EEZs	Exclusive Economic Zones
ENSO	El Niño–Southern Oscillation
ENSO OS	El Niño–Southern Oscillation Observing System
EOV	Essential Ocean Variable
FOO	Framework for Ocean Observing
GCOS	Global Climate Observing System
GLOSS	Global Sea Level Observing System
GMSL	Global Mean Sea Level
GODAE	Global Ocean Data Assimilation Experiment
GOOS	Global Ocean Observing System
IOC	Intergovernmental Oceanographic Commission
IOCCP	International Ocean Carbon Coordination Project

IOOC	Interagency Ocean Observation Committee
IOOS	Integrated Ocean Observing System
JCOMM	Joint Technical Commission for Oceanography and Marine Meteorology
JCOMM OCG	JCOMM Observations Coordination Group
JCOMMOPS	JCOMM In-situ Observing Programmes Support Centre
JGOFS	Joint Global Ocean Flux Study
MSR	Marine Science Research
NCEI	National Centers for Environmental Information
NODC	National Oceanographic Data Center
NORLC	National Ocean Research Leadership Council
OceanObs	International community process for review of the Ocean Observing System for Climate
OCP	Ocean-Climate Partnership
OOPC	Ocean Observational Panel for Climate
POGO	Partnership for Observation of the Global Oceans
SOOP	Ships of Opportunity Program
SOT	Ship Observation Team
TOGA	Tropical Ocean Global Atmosphere program
UNFCCC	United Nations Framework Convention on Climate Change
UNOLS	University National Oceanographic Laboratory System
WCRP	World Climate Research Program
WHP	WOCE Hydrographic Programme
WMO	World Meteorological Organization
WOCE	World Ocean Circulation Experiment
XBT	eXpendable Bathy-Thermograph