EXECUTIVE OFFICE OF THE PRESIDENT OF THE UNITED STATES

Science and Technology for America's Oceans: A Decadal Vision

A Report by the

SUBCOMMITTEE ON OCEAN SCIENCE AND TECHNOLOGY

COMMITTEE ON ENVIRONMENT

of the

NATIONAL SCIENCE & TECHNOLOGY COUNCIL

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About the Subcommittee on Ocean Science and Technology

The purpose of the Subcommittee on Ocean Science and Technology (SOST) is to advise and assist on national issues of ocean science and technology. The SOST contributes to the goals for Federal ocean science and technology, including developing coordinated interagency strategies and fostering national ocean science and technology priorities.

About this Document

This document was prepared by the SOST. This document serves as the second U.S. ocean science and technology decadal plan, following *Charting the Course for Ocean Science for the United States for the Next Decade: An Ocean Research Priorities Plan and Implementation Strategy* (2007) — which was updated in 2013 with the release of *Science for an Ocean Nation: An Update of the Ocean Research Priorities Plan.*

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List of Acronyms

AIS – Automatic Identification System

AUV – Autonomous Underwater Vehicle

eDNA – Environmental DNA

EEZ – Exclusive Economic Zone

EOV – Essential Ocean Variable

GDP – Gross Domestic Product

HAB – Harmful Algal Bloom

IARPC – Interagency Arctic Research Policy Committee

IDSS – Impact-based Decision Support Services

IMO – International Maritime Organization

IUU – Illegal, Unregulated, and Unreported

MSI – Marine Safety Information

MTS – U.S. Marine Transportation System

NAIS – Nationwide Automatic Identification System

NOPP – National Oceanographic Partnership Program

R&D – Research and Development

ROV – Remotely Operated Vehicle

S&E – Science and Engineering

S&T – Science and Technology

SES – Social-Ecological System

SOCCOM – Southern Ocean Carbon Climate Observation and Modeling

STEM – Science, Technology, Engineering, and Math

Executive Summary

America's unrestricted access to the Atlantic and Pacific Oceans, Gulf of Mexico, rivers, Great Lakes, and Arctic region powers domestic and global commerce. The ease of moving cargo and people beyond our coasts fuels the Nation's competitive advantage, advances trade, generates capital, and drives the domestic economy forward, in turn projecting strength abroad and safeguarding our national interests. Similarly, the biological diversity and productivity of the ocean sustains the health of coastal communities and promotes a vibrant national economy. The ocean also plays a fundamental role in the Earth system. Ensuring responsible ocean stewardship with science and technology (S&T) breakthroughs depends on a strategic Federal portfolio supported by foundational basic research. *Science and Technology for America's Oceans: A Decadal Vision* identifies pressing research needs and areas of opportunity within the ocean S&T enterprise for the decade 2018-2028.

This vision identifies five goals to advance U.S. ocean S&T and the Nation in the coming decade: (1) Understand the Ocean in the Earth System; (2) Promote Economic Prosperity; (3) Ensure Maritime Security; (4) Safeguard Human Health; and (5) Develop Resilient Coastal Communities. Each goal is supplemented with specific objectives and actionable priorities to achieve those objectives. Throughout this document, priorities across goals are interlinked and interdependent. The objectives for the five goals as well as an additional section that outlines areas of immediate ocean research and technology opportunities are summarized below:

Goal I. Understand the Ocean in the Earth System:
1) Modernize Research and Development (R&D) Infrastructure;
2) Harness Big Data;
3) Develop Models of the Earth System;
4) Facilitate Research to Operations

Goal II. Promote Economic Prosperity:
1) Expand Domestic Seafood Production;
2) Explore Potential Energy Sources;
3) Assess Marine Critical Minerals;
4) Balance Economic and Ecological Benefits;
5) Promote the Blue Workforce

Goal III. Ensure Maritime Security:
1) Improve Maritime Situational Awareness;
2) Understand a Changing Arctic;
3) Maintain and Enhance Marine Transportation

Goal IV. Safeguard Human Health:
1) Prevent and Reduce Plastic Pollution;
2) Improve Forecasts of Marine Contaminants and Pathogens;
3) Combat Harmful Algal Blooms;
4) Discover Natural Products

Goal V. Develop Resilient Coastal Communities:
1) Prepare for Natural Disasters and Weather Events;
2) Reduce Risk and Vulnerabilities;
3) Empower Local and Regional Decision-Making

Areas of immediate ocean research and technology opportunities include:

1. *Fully integrate Big Data approaches in Earth system science;*
2. *Advance monitoring and predictive modeling capabilities;*
3. *Improve data integration in decision-support tools;*
4. *Support ocean exploration and characterization;*
5. *Support ongoing research and technology partnerships*

Two cross-cutting topics that are relevant to each of the five goals are the modernization and management of ocean-related infrastructure, and an educated, diverse, and dynamic "blue" workforce. Continued investments in these two areas will contribute to U.S. global leadership within ocean S&T.

This document presents a decadal vision for an innovative and collaborative ocean S&T enterprise that promotes American security and prosperity while conserving the marine environment for present and future generations. Carrying out the research goals will require investments in and coordination of ocean S&T across all levels of government and private industry, academia, and nongovernmental organizations over the long-term. These goals will be achieved over years, working with Federal and non-Federal partners to direct and leverage the necessary resources. Additionally, while this document will provide important guidance to Federal agencies on ocean S&T priorities, implementation of this plan is dependent upon available resources and will vary year to year.

Introduction

The ocean, our coasts, and the Great Lakes are among the United States' most treasured resources. They are an integral part of our national identity and our Nation's future. The ocean[1] covers 71 percent of the Earth's surface and hundreds of millions of people rely on a viable ocean to sustain them.[2] A healthy, productive, and resilient ocean is inextricably linked to Earth's climate and weather patterns and contributes significantly to our quality of life. The ocean provides and creates jobs, gives mobility to our Armed Forces, helps feed our Nation, secures our borders, fuels our economy, enables safe movement of goods, and provides places for recreation. Understanding the physical, chemical, biological, and geological changes in the ocean is vital to the survival and prosperity of humanity.

In the United States, the ocean and its wealth of natural resources have played a critical role in fueling American prosperity and energy dominance, protecting our country, generating jobs, sustaining industries, and contributing to Americans' overall well-being. Our coastal ports and global waterways make up the epicenter of world trade, facilitating a thriving U.S. economy through the maritime enterprise. The biological diversity and productivity of the ocean sustains the health of coastal communities and promotes a vibrant national economy. At the same time, the coastal communities that take part in and benefit from the ocean economy are also vulnerable to events such as hurricanes and floods that are exacerbated by sea level rise. Many of these changes to the ocean and its services[3] are evident by human observation and traditional ecological knowledge,[4] exhibiting visible alterations to coastlines and ecosystems, navigation routes, water quality, species compositions, the timing and occurrence of pathogens, abundance of marine debris, and populations of commercially and ecologically important marine species.

The ocean science and technology (S&T) enterprise can provide the foundational knowledge needed to address many complex ocean-related challenges and inform decision-making that will ultimately strengthen our Nation and its communities. One essential objective of this document is to facilitate the integration of natural and social sciences. No single discipline can comprehensively address the complex and pressing problems facing the ocean, which can no longer be studied in isolation but must be considered as a part of a dynamic Earth system. This document recognizes the connections among the ocean, land, ice, and atmosphere. Humans are an important element of the Earth system as agents of change to Earth system processes. They are beneficiaries of Earth's natural resources and are at risk from Earth's natural hazards. The inclusion of human dimensions in ocean S&T ensures holistic understanding of the Earth system. The scientific understanding of the Earth system,[5] the need to

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[1] For the purposes of this document, "ocean" includes the open ocean, coasts, estuaries, coastal watersheds, and Great Lakes.

[2] Hoegh-Guldberg, O. et al. (2015) Reviving the Ocean Economy: the case for action - 2015. World Wildlife Fund International, Gland, Switzerland., Geneva, p. 60. https://www.wwf.de/fileadmin/fm-wwf/Publikationen-PDF/WWF-Report-Reviving-the-Ocean-Economy-Summary.pdf (accessed April 17, 2018).

[3] Ocean services are the benefits humans derive from different aspects of ocean structure and function. These can be partitioned into (1) Provisioning Services, (2) Supporting Services, (3) Regulating Services, and (4) Cultural Services. More information can be found at: NOAA (2017) Ecosystem Status Report for the Northeast Large Marine Ecosystem. https://www.nefsc.noaa.gov/ecosys/ecosystem-status-report/ecosystem-services.html (accessed June 12, 2018).

[4] U.S. Fish and Wildlife Service. (2018) Traditional Ecological Knowledge. https://www.fws.gov/nativeamerican/traditional-knowledge.html (accessed November 4, 2018).

[5] Cornell, S., I.C. Prentice, J. House, and C. Downing. (2012) Understanding the Earth system: Global change science for application. Cambridge: Cambridge University Press, p. 267. https://doi.org/10.1017/CBO9780511921155 (accessed June 15, 2018).

obtain, analyze, and manage Big Data,[6] and the relevance of dynamic feedbacks among socioeconomic, biophysical, and biogeochemical systems,[7] are key concepts that are evident throughout this document. As an ocean Nation and a global leader, the United States can advance the ocean S&T enterprise by fostering innovation and investing in basic and applied ocean research, technology, education, and workforce development—all key to increasing knowledge and understanding of the ocean system and maintaining our country's influence and leadership in an ever-challenging global arena.

Two cross-cutting topics emerged as critical components among all goals in this document. They include the modernization and management of ocean-related infrastructure, and an educated, diverse, and dynamic workforce that strengthens the "blue" economy. State-of-the-art research infrastructure provides the United States with unique competencies, allows for advances in discovery, minimizes potential economic and societal losses, and ensures the S&T workforce has the capabilities it needs to conduct world-leading ocean research. Infrastructure and advanced technologies such as airborne, marine, space- and land-based assets support U.S. ocean research and technology interests. Modernized technologies, including ocean-observing and modeling capabilities, and improvement in capabilities such as data acquisition and high-performance computing, are two related priorities relevant to all goals in this document. U.S. economic well-being and global leadership in S&T depend on an ocean-literate society and a well-trained blue workforce of the future. A strong blue workforce will enable the Nation to address tomorrow's ocean needs and contribute more jobs, enhanced production, and national prosperity.

The vision for the coming decade is a Nation that recognizes the importance of a science-based and technologically driven understanding of the ocean to American livelihoods, national security, and economic independence. This same knowledge enhances the conservation and stewardship of the ocean and its resources. Advancing the ocean S&T enterprise enables a better understanding of the past, enhanced opportunities to observe the present, and the ability to predict the future.

Science and Technology for America's Oceans: A Decadal Vision identifies research priorities and areas of opportunity within the ocean S&T enterprise for the decade 2018-2028. The aim of this document is not to prescribe policies, but to provide guidance for U.S. Federal agencies and non-Federal sectors to align their resources and areas of expertise, further build the scientific and technological foundation that will improve our knowledge and stewardship of the ocean, address issues of national and global importance, and inform decision-making for the coming decade.[8] This document considers the needs of researchers, resource managers, policymakers, educators, tribal, State, territorial, and local governments, and other stakeholders, and will rely on the continuous stream of information and knowledge derived from fundamental basic research by and for the ocean S&T community for the well-being of the Nation.

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[6] "Big data" refers to data sets so large and complex that commonly used or traditional data processing tools to capture, curate, and manage data within a tolerable elapsed time are inapplicable. Compared to traditional data, "Big Data" is characterized by high volume (enormous size of data), high velocity (timely response requirements), high variety (diversified data types), low veracity (uncertainties in the data), and high value (significance in knowledge and products). Jin, X., B.W. Wah, X. Cheng, and Y. Wang. (2015) Significance and challenges of big data research. *Big Data Research* 2:59-64. https://wah.cse.cuhk.edu.hk/wah/Wah/papers/J94/J96.pdf (accessed June 15, 2018).

[7] National Ocean Service. (2018) Socioeconomics. https://sanctuaries.noaa.gov/science/socioeconomic/ (accessed April 17, 2018).

[8] Prospectus: Ocean Research in the Coming Decade. (October 2016) https://www.nsf.gov/geo/oce/orp/orp-prospectus.pdf (accessed April 17, 2018).

This document builds on a number of initiatives outlined in the first comprehensive national ocean research decadal priorities plan.[9] Over the last decade, the ocean community has advanced novel ocean technologies, discovered new marine life and ocean-derived therapeutics, helped marine populations recover, tracked environmental changes, and answered important questions about how the ocean works. This document charts the course for the next decade.

A number of documents acknowledge complementary efforts, such as *Sea Change: 2015-2025 Decadal Survey of Ocean Sciences*.[10] *Sea Change* identifies strategic research priorities to advance scientific understanding of the ocean and recommendations for alignment of infrastructure and budgets with science priorities. This document does not intend to supersede *Sea Change*, but rather broadens its scope to wider government activities and includes all stakeholders and related entities involved in the ocean S&T enterprise.

Organization of this Document

This document presents five high-priority ocean S&T goals: (1) Understand the Ocean in the Earth System; (2) Promote Economic Prosperity; (3) Ensure Maritime Security; (4) Safeguard Human Health; and (5) Develop Resilient Coastal Communities. The first goal serves to improve the foundational understanding of the global ocean and is followed by the application of such scientific knowledge into more specific goals. Within each goal are S&T objectives, identified as key areas to advance the U.S. ocean S&T enterprise in the next decade. Subsections describe specific research and development (R&D) priorities to advance the U.S. ocean S&T enterprise. These priorities will likely evolve as the U.S. ocean S&T enterprise advances during the next decade. Many of these actions will produce short-term benefits that respond to immediate needs of communities, industries, ocean stakeholders, and the public. Others create building blocks to support key outcomes in the medium- to long-term. The goals, objectives, and priorities in this document were developed through a collaborative effort involving Federal agencies and stakeholders with interests and responsibilities linked to the ocean.

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[9] NSTC Joint Subcommittee on Ocean Science and Technology. (2007) Charting the Course for Ocean Science in the United States for the Next Decade. An ocean research priorities plan and implementation strategy, p. 85. https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/nstc-orppis.pdf (accessed April 17, 2018). This plan was updated in 2013 with the release of *Science for an Ocean Nation: An Update of the Ocean Research Priorities Plan*, p. 100. https://www.hsdl.org/?view&did=735388 (accessed October 22, 2018).

[10] National Research Council. (2015) *Sea Change: 2015-2025 Decadal Survey of Ocean Sciences*. Washington, DC: The National Academies Press, p. 86. https://doi.org/10.17226/21655 (accessed September 29, 2018).

Goal I. Understand the Ocean in the Earth System

The ocean is the largest habitat and is home to some of the most biologically diverse areas of the planet. To date, we have explored less than 15 percent of the global ocean floor.[11] The ocean is the predominant physical feature on our planet and drives the global climate through the absorption, retention, and transportation of heat, water, and carbon. The global ocean S&T enterprise has made significant progress in understanding the physical, geological, chemical, and biological aspects of the ocean system, but the dynamic ocean environment is changing in terms of ocean chemistry, temperature, sea-level, and currents, all of which affect marine biology.[12] Consequently, we must make observations, refine our models, and develop new predictive capabilities to be able to sustainably manage our ocean resources.

Scientific and technological advances have brought significant improvements in our understanding of the ocean. Exploration, discovery, and assessment of marine resources, processes, and ecosystem structure and function are vital to capitalize on economic and cultural opportunities, improve human health, and protect life and property at sea. Innovative laboratory techniques and biological tools allow us to identify and understand the contributions of the smallest organisms, while satellites, seafloor cabled arrays, and autonomous vehicles have revealed ocean behavior on temporal and spatial scales that were previously inaccessible. Developments in electronic technologies have opened new research and technological horizons. However, a combination of existing and emergent technologies and modeling capabilities are needed to further elucidate the ocean's behavior, its future trajectories, and its connections to other components of the Earth system. These technological capabilities will inform evidence-based stewardship, ensuring continued safeguarding of the air we breathe, the water we drink, and the food we eat.

The study and exploration of the ocean begins at the land-sea and atmosphere-sea interfaces and reaches to the deepest depths, where the ocean interacts with the seafloor and, further still, the deep biosphere found in the ocean sediments and crust beneath the seafloor. Changes in climate have altered important biogeochemical variables, such as pH and oxygen concentration, which have impacts on the biology and the ecology of the ocean. The deep and coastal oceans are regions of high carbon storage and rapid change, and are especially important to fisheries; coastal areas in particular can be subject to rapid change. Recent studies have demonstrated the increasing importance of the deep ocean for heat storage. The global ocean's stratification and heat content have increased, the latter of which accounts for most (over 90%) of the overall changes in the Earth's energy budget.[13]

To understand present conditions, determine rates of change, and make reliable projections of the future states of the Earth system and climate, we need to understand the past and present changes in the ocean environment. This first goal seeks to improve the foundational understanding of the global ocean, which is paramount to achieving the other four goals highlighted in this document.

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[11] Mayer, L., M. Jakobsson, G. Allen, B. Dorschel, R. Falconer, V. Ferrini, G. Lamarche, H. Snaith, and P. Weatherall. (2018) The Nippon Foundation—GEBCO Seabed 2030 Project: The Quest to See the World's Oceans Completely Mapped by 2030. *Geosciences*, 8(2), p. 63. https://www.mdpi.com/2076-3263/8/2/63/htm (accessed September 29, 2018).

[12] Lenton, T.M., H. Held, E. Kriegler, J.W. Hall, W. Lucht, S. Rahmstorf, and H.J. Schellnhuber. (2008) Tipping elements in the Earth's climate system. *Proceedings of the National Academy of Science* 105(6):1786-1793. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2538841/ (accessed June 15, 2018).

[13] IPCC Fourth Assessment Report: Climate Change 2007. Working Group I: The Physical Science Basis. 5.2.2.3 Implications for Earth's Heat Balance. https://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch5s5-2-2-3.html (accessed June 15, 2018).

Modernize R&D Infrastructure

Access to the sea has always been a fundamental hurdle for marine research as the ocean can be a harsh, unforgiving, and dangerous environment. Consequently, our research infrastructure is critical to our Nation's leadership role in ocean science, and plays a significant foundational role in each of the areas this document addresses. The infrastructure and technology necessary for successful ocean research includes ships, submersibles, aircraft, satellites, land-based radar, moorings and cabled buoys, and various unmanned underwater, surface, and airborne vehicles. Research infrastructure also includes land-based facilities, i.e., state of the art laboratories, to support deployed ocean assets and to receive, analyze, and manage incoming data using high-performance computing and communications networks that support wide access to and use of information. Additionally, investments in modern laboratories and affordable technologies are critical to conducting corresponding experiments that are essential to our understanding of the changes we observe in nature.

Box 1.1. Observing the Distant Ocean: An Example from the Southern Ocean

The Southern Ocean Carbon Climate Observation and Modeling (SOCCOM) project seeks to extend sparse physical and biogeochemical observations of the remote Southern Ocean by deploying a robotic observing system composed of some 200 autonomous profiling floats to provide greatly increased coverage in time and space of the Southern Ocean. The Southern Ocean plays an important role in regulating global ocean circulation and long-term climate patterns. The processes and changes occurring therein will be analyzed and used to improve the next generation of high resolution coupled Earth system models used to project the future changing paths of the Earth's climate and biogeochemistry. As well as SOCCOM's mission to transform scientific and public understanding, the education of a new generation of ocean scientists is needed to extend the SOCCOM float technology to a broader user community.

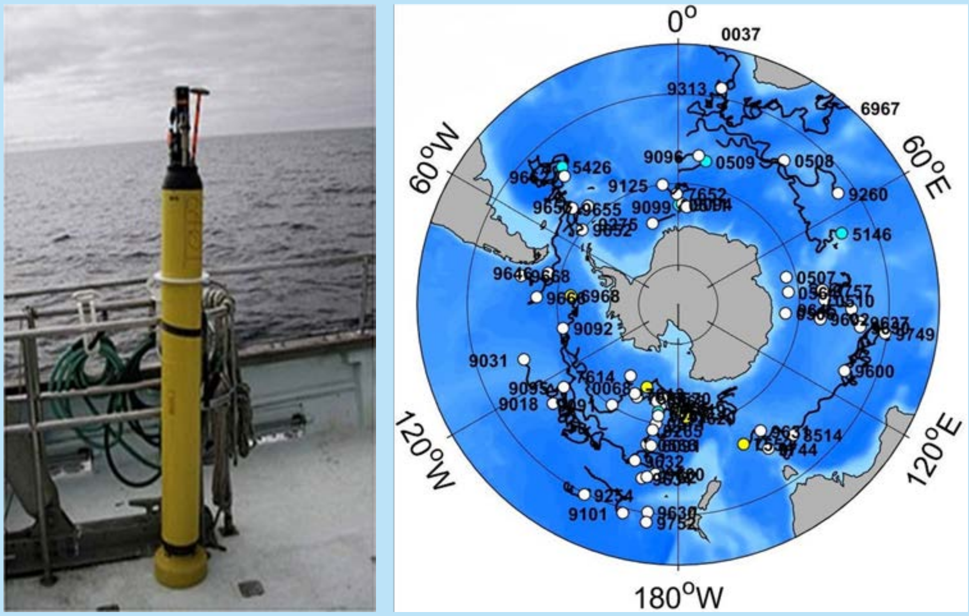

Figure 1.1. SOCCOM technology and map. SOCCOM floats in white. Pre-SOCCOM floats in yellow. Non- op. floats in cyan. From June 25, 2016. (Images courtesy of NSF)

Ocean observations, both remote and *in situ*, remain vitally important for advancing knowledge of and detecting changes in the ocean system over time, and for predicting weather impacts on community infrastructure, safety, and commerce (Box 1.1). Developing deployable unmanned technologies will advance our ability to explore hard to reach places such as the Arctic. Data from these new technologies will feed into tactical models and decision aids for marine operators, as well as critical information for economic and national security activities. Observations and regular surveys are supported by essential infrastructure, including ship and aircraft fleets, and ocean remote sensing assets. Networks of fixed monitoring stations and moorings, drifting floats, and cabled observatories also represent foundational infrastructure for ocean research.[14] Autonomous underwater vehicles (AUVs) and remotely operated aerial and surface vehicles are innovative technologies that are changing marine research and rapidly expanding and improving accessibility to the research and technology seascape. With precision navigation, high endurance, and multiple sensors, these vehicles now routinely launch from ships and land stations with the capability to efficiently collect and automatically send large volumes of valuable data.[15]

Presently, most observations occur in the upper few hundred meters of the ocean, and mostly take place in the Northern Hemisphere. However, ship-based observations, complemented by sustained deployment of subsurface floats, moored instruments, and autonomous vehicles (e.g., ocean gliders and other AUVs) have enabled significant expansion of our reach to observe biological, chemical, physical, and geological variables (Box 1.2) as well as energy resources throughout the ocean.

Box 1.2. Essential Ocean Variables

Ocean observations are often prioritized based on nationally and globally agreed upon Essential Ocean Variables (EOVs) that are key to assessing change and causes of change in the ocean.[16] These variables include physical, biogeochemical, biological, and acoustic measurements that influence societal needs such as ocean health, as well as short- and mid-term weather forecasting and longer-term changes in climate. EOVs can serve as input to numerical models and improve our ability to more quantitatively project changing ocean and atmospheric conditions. Emerging technologies should consider current EOVs and develop technologies to improve measurement of EOVs, while maintaining the quality required for sustained observational records that can capture events, as well as identify the emergence of longer trends through time.[17]

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[14] Programs such as the Ocean Observatories Initiative (OOI) have developed networks to involve academia and integrate infrastructure such as science-driven platforms and sensor systems, consolidate observing systems, and deliver a variety of ocean related data and data products to users.

[15] It is important to note that ships are needed with these autonomous technologies for uses such as launch, recovery, and unexpected retrievals.

[16] The Task Team for an Integrated Framework for Sustained Ocean Observing. (2012) A Framework for Ocean Observing. UNESCO, Washington, D.C. IOC/INF-1284 rev, p. 25. http://unesdoc.unesco.org/images/0021/002112/211260e.pdf (accessed June 15, 2018).

[17] Henson, S.A., C. Beaulieu, and R. Lampitt. (2016) Observing climate change trends in ocean biogeochemistry: when and where. *Global Change Biology* 22(4):1561-1571. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4785610/ (accessed June 15, 2018); Muller-Karger, F.E., P. Miloslavich, N. Bax, S. Simmons, M.J. Costello, I. Sousa Pinto, G. Canonico, W. Turner, M. Gill, E. Montes, B. Best, J. Pearlman, P. Halpin, D. Dunn, A. Benson, C.S. Martin, L.V. Weatherdon, W. Appeltans, P. Provoost, E. Klein, C. Kelble, R.J. Miller, F. Chavez, K. Iken, S. Chiba, D. Obura, L.M. Navarro, H.M. Pereira, V. Allain, S. Batten, L. Benedetti-Checchi, J.E. Duffy, R. Kudela, L-M. Rebelo, Y. Shin, G. Geller. (2018) Advancing marine biological observations and data requirements of the complementary Essential Ocean Variables (EOVs) and Essential Biodiversity Variables (EBVs) frameworks. *Frontiers in Marine Science* 5:211. https://doi.org/10.3389/fmars.2018.00211 (accessed September 4, 2018).

Ocean research infrastructure is one of the highest priorities of the ocean S&T community.[18] Our Nation's ocean research infrastructure needs to align capabilities with requirements, including the number and type of research vessels, to ensure that our assets are optimized through coordination and collaboration while also retaining the capacity to meet its goals. This includes satellite and other autonomous data collection efforts and related archive and data storage infrastructure. Many of these efforts rely on international collaboration including strong international partnerships and observing networks. The increase in autonomous data collection will depend on increased storage and processing of Big Data and improved analytical methods. Integrating these observations will enable a full understanding of how we can promote economic growth while conserving marine resources.

Next-generation and sustained observing systems could provide more robust and timely observations on the diversity and abundance of life in the sea along with physical and other environmental data. In addition, new systems could further our understanding of geohazards and weather events, providing information on the physical processes controlling their occurrence, timing, and magnitude. Fundamental understanding of Earth processes and basic research of subduction zone phenomena[19] will lead to the scientific understanding needed for robust forecasts of future geohazards and related events and can greatly assist risk mitigation. Technological advances in timing, power, shielding, underwater and satellite telemetry, and autonomous vehicles could improve the quality of seismic observations on the seafloor, and increase the frequency of data transmission to shore (Box 1.3). While hurricane track forecasts have improved dramatically, improvements in hurricane intensity predictions have lagged. At-sea observations of water column temperatures are essential for improving both hurricane track as well as hurricane intensity forecasts. With the advent of remotely sensed salinity measurements, recent studies emphasize the role of salinity in upper-ocean stratification and the potential to use satellite salinity data as a new resource to monitor storms and hurricanes.[20]

Priorities

- Sustain critical ocean monitoring, maintain time-series data collection, and support new observations and discovery in the world's ocean to provide the continuous information streams that inform research, advance forecasts, and support responsible resource management decisions.
- Prioritize new observing methods focused on processes that lack fundamental understanding, such as a modernized research fleet, gliders, and associated sensors, especially in areas identified as being important for human health, safety, and marine life.
- Identify and expand observations for unique processes and locations for extreme events, as well as in under-sampled areas of the global ocean, such as the deep-sea, offshore frontiers, the Southern Hemisphere, and key continental margins (Box 1.1).
- Support the development and accuracy of technologies in controlled environments at the interfaces: where land meets water, where water meets air, where water meets ice, and where water meets the ocean bottom.

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[18] As is supported by National Research Council. (2015) *Sea Change: 2015-2025 Decadal Survey of Ocean Sciences*. Washington, DC: The National Academies Press, p. 86. https://doi.org/10.17226/21655 (accessed September 29, 2018).

[19] Gomberg, J.S., and K.A. Ludwig. (2017) Reducing risk where tectonic plates collide: U.S. Geological Survey Fact Sheet 2017. 302:1-4. https://pubs.usgs.gov/fs/2017/3024/fs20173024.pdf (accessed May 9, 2018).

[20] Fournier, S., J. Vialard, M. Lengaigne, T. Lee, M.M. Gierach, and A.V.S. Chaitanya. (2017) Modulation of the Ganges-Brahmaputra river plume by the Indian Ocean dipole and eddies inferred from satellite observations. *Journal of Geophysical Research: Oceans*, 122(12): 9591-9604. https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2017JC013333 (accessed October 12, 2018).

- Utilize data from local hydrographic, geophysical, and atmospheric variables, and bathymetric maps of the ocean floor to serve as boundary conditions for observations and models and to advance early tsunami and earthquake warning systems.
- Extend the Argo Program to include full-ocean depth coverage (Deep Argo), dynamically complete (ArgoMix which adds turbulence sensors to Argo floats), and inclusion of biogeochemical sensors[21] (BGC Argo).

Box 1.3. CubeSats and Other Readily Available Sensing Technologies

Satellites once exclusively operated by nation states now have the simplicity to be built by high-school students.[22] As launch opportunities grow, the ocean science community is better poised to rapidly enhance global observations of the world's oceans. Similarly, autonomous and remote-controlled air vehicles can now be equipped with sophisticated sensors suitable for shipboard and coastal studies. Multi- or hyper-spectral electro-optical sensors can now routinely measure ocean biological parameters over wide areas. Day-night, all-weather sensing of the ocean surface using radar allows measurement of ocean winds and waves, as well as detection of vessels. Transmission of data from satellites to users will soon be significantly enhanced by Wi-Fi satellites, so that high fidelity data can be readily transmitted without regard for bandwidth limitations. Likewise, data from drifters, gliders, and unmanned surface vessels can be rapidly routed to users.

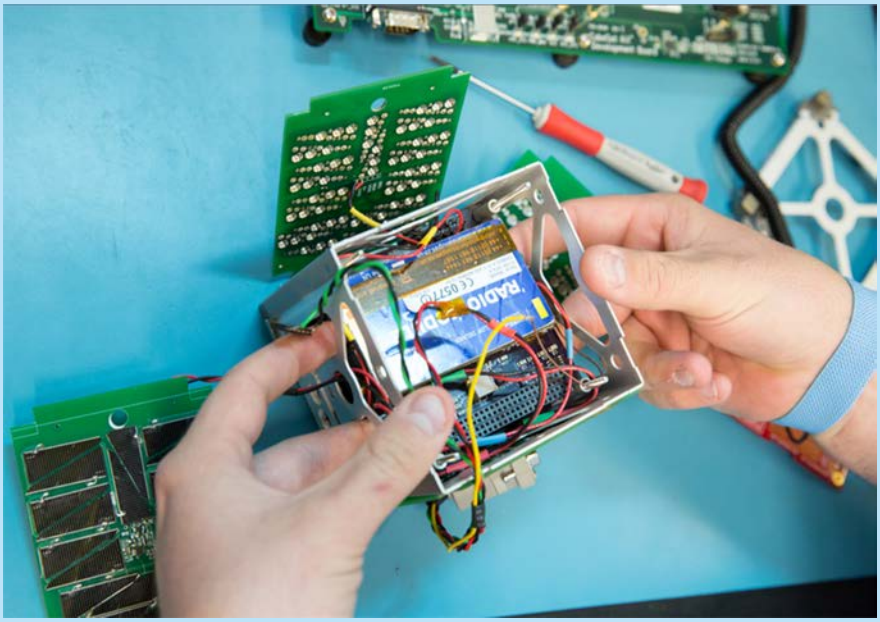

Figure 1.2. Students contribute to collecting Earth observations while getting hands-on experience building CubeSats: inexpensive, small, 3-pound satellites. (Image courtesy of NASA)

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[21] Tollefson, J. (2016) Massive network of robotic ocean probes gets smart upgrade. *Nature* 531:421–422. http://dx.doi.org/10.1038/531421a (accessed June 15, 2018).

[22] Buck, J. (2013) NASA Helps Launch Student-Built Satellites as Part of CubeSat Launch Initiative. NASA Public Release 13-343. https://www.nasa.gov/press/2013/november/nasa-helps-launch-student-built-satellites-as-part-of-cubesat-launch-initiative (accessed April 20, 2018).

Harness Big Data

Equally important to ocean R&D infrastructure is the ability to maximize data utility. In the coming decade, the United States can upgrade four-dimensional data assimilation and improve analysis of currently available data that can be useful for many products and as initialization for models that make predictions on all space and time scales. Big Data is revolutionizing our understanding of the ocean in the Earth system. Big Data allows scientists to measure and gain large amounts of information about the environment and directly translate that knowledge into enhanced scientific models and products to improve decision-making.[23] From a broad perspective, Big Data is the bond that connects and integrates the environment, human society, and cyberspace.[6] Big Data allows for the assessment of relationships between the ocean and other elements of the Earth system through rigorous, data-driven methods. Advancements in Big Data capabilities can improve general circulation models and integrated Earth system models, as well as improve dynamic, integrated and/or coupled biophysical models for future-condition forecasting. Two sources of Big Data in oceanography are: (1) large amounts of multi-dimensional data measuring a wide range of ocean variables collected by remote and *in situ* sensors across the globe, and (2) well-constrained and verified model simulations of ocean processes on global, regional, and local scales with high spatial and temporal resolution. Responsibly creating publicly available Big Data sets includes benefitting long-term public interests while also respecting intellectual property.

Critical to sustaining ocean biodiversity is a mixed set of research and applications including, but not limited to, sustained ocean observations, the infrastructure needed for those observations in support of Essential Ocean Variables (EOVs), and blending in new approaches such as "omics." Omics[24], a subset of molecular tools including genomics, proteomics, and metabolomics, is an emerging Big Data field with the potential to transform our ability to characterize the biological composition of the ocean efficiently, comprehensively, and at reduced costs (Box 1.4). For example, using metagenomics to inventory the microbiomes of various ocean habitats has allowed for a greater understanding of diverse microbial population structure and gene expression (i.e., behavior) over space and time. Metagenomics tools can be extended beyond bacteria to include the study of marine viruses (an emerging area of epidemiology), phytoplankton, zooplankton, and complex holobionts such as sponges and corals. A challenge for the coming decade is determining how microbial population structure and function vary with physical and chemical oceanographic parameters. Addressing such a challenge will enhance marine monitoring by measuring food web function, species biodiversity, prevalence of pathogens and pollution, and the rate at which microbes degrade materials. Such omics technologies can augment traditional observation programs and are being integrated into buoy-deployed and mobile AUVs.

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[23] McAfee, A., and E. Brynjolfsson. (2012) Big Data: The management revolution. *Harvard Business Review* 3-9. https://hbr.org/2012/10/big-data-the-management-revolution (accessed April 17, 2018).

[24] The term omics refers to fields of study in molecular biology with the suffix –omics, which aim to better detect, characterize, quantify, and understand pools of biological molecules [such as genes (genomics), mRNA (transcriptomics), proteins (proteomics), and metabolites (metabolomics)] in a given sample. More information can be found at: Horgan, R.P., and L.C. (2011) 'Omic' technologies: genomics, transcriptomics, proteomics and metabolomics. *The Obstetrician & Gynaecologist* 13:189–195. https://obgyn.onlinelibrary.wiley.com/doi/full/10.1576/toag.13.3.189.27672; Gilbert, J.A., G.J. Dick, B. Jenkins, J. Heidelberg, E. Allen, K.R. Mackey, and E.F. DeLong. (2014) Meeting report: Ocean 'omics science, technology and cyberinfrastructure: current challenges and future requirements (August 20–23, 2013). *Standards in Genomic Sciences* 9(3):1251. https://doi.org/10.4056/sigs.5749944 (accessed June 15, 2018).

Box 1.4. Big Data from Environmental DNA

As organisms move through the ocean, they leave in their wake a path of tiny particles which scientists can sample for DNA. Environmental DNA (eDNA) is an emerging omics technology that allows researchers to sample water, soil, or air in order to determine the species found in that area. eDNA is a cost-efficient and quick surveillance tool useful for assessing a habitat's biodiversity, monitoring for invasive species, and tracking the movements of threatened and endangered species. Informing on the presence, absence, and abundance of certain species has great potential for better understanding and managing vulnerable ocean habitats. Ensuring quality control of eDNA data, managing the massive amount of data generated from sampling eDNA, and applying eDNA data to support decision-makers will allow the Federal government to capitalize on the potential benefits of eDNA technology.

The ocean S&T enterprise must continue to support data repositories, cloud computing, and data-sharing efforts. Observing System Simulation Experiments (OSSE)[25] and Observing System Experiments (OSE)[26] used in parallel with ocean models and data assimilation strengthen the impact of observations and cost-effectively optimize remote and *in situ* ocean sampling. A unified national effort should aim to establish common frameworks across diverse computing systems and facilitate data integration. These efforts will establish a common structure for Big Data datasets and promote efficient data sharing and communication of data limitations such as uncertainties while minimizing costs and resources.[27]

Priorities

- Advance Big Data analytics and cloud computing platforms to identify and forecast changes in ocean circulation and heat and freshwater transport, ocean biogeochemical cycling, marine ecosystems and ecosystem services, and sea level rise.
- Increase and sustain the ocean community's access to usable Big Data, and strengthen the interactions between the ocean observing, research, and modeling communities.
- Strengthen high-performance computing to effectively process and use Big Data analytics and omics technologies that enhance the understanding of the ocean in the Earth system.
- Deploy and integrate recent technological advances such as environmental DNA (eDNA) and other omics approaches to ocean assessments.
- Promote collaborative platforms to integrate omics, biodiversity, economic, and environmental databases.
- Encourage unclassified, releasable data, particularly Big Data, to be easily accessible and usable to local and regional decision-makers and the public.

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[25] Masutani, M., T.W. Schlatter, R.M. Errico, A. Stoffelen, E. Andersson, W. Lahoz, J.S. Woollen, G.D. Emmitt, L-P Riishøjgaard, and S.J. Lord. (2010) Observing System Simulation Experiments. 647-680. In: Lahoz W., B. Khattatov B., and R. Ménard (eds.) Data Assimilation. Making sense of observations. Springer, Berlin, Heidelberg.

[26] Lord, S., G. Gayno, and F. Yang. (2016) Analysis of an observing system experiment for the Joint Polar Satellite System. *Bulletin of the American Meteorological Society* 97(8):1409-1425. https://doi.org/10.1175/BAMS-D-14-00207.1 (accessed June 15, 2018).

[27] For example, ongoing efforts by the National Oceanic and Atmospheric Administration, the U.S. Navy, and others are focusing on building a common ocean modeling framework merging Arbitrary Lagrangian Eulerian (ALE) ocean models by establishing a merged code-base permitting options for different spatial resolutions and temporal model integration extents.

Develop Models of the Earth System

The foundational research and technology needed to advance our understanding of the ocean within the Earth system includes modeling of the dynamics of the ocean, including climate, atmospheric, and weather-related influences on the ocean. The coastal and deep oceans require additional study to better understand how current changes in the coastal zone and deep-sea can be used to improve the capability to predict how the coastal ocean may respond to future changes, the associated impacts on marine ecosystem services, and the resilience of the communities that depend on them.[28] Advanced understanding of the ocean environment also plays a key role in improving understanding of geohazards associated with subduction zones, including earthquakes, tsunamis, volcanic eruptions, and landslides.[29]

Coastlines consist of distinct but tightly coupled systems that are connected to nearby terrestrial systems by the flow of water and materials from coastal and estuarine drainage areas to the ocean (Box 1.5). Understanding and quantifying the impacts and feedbacks of human and environmental influences on coastal ecosystems requires comprehensive, multi- and inter-disciplinary research, including steps toward development of predictive capabilities. Added emphasis should be placed on particularly vulnerable systems, such as bays, estuaries, coastal wetlands, marshes and mangrove systems, and high latitude regions such as the Arctic.

Adaptation to and mitigation of coastal change, and resilience to extreme events, requires understanding the vulnerability of coastal zones.[30] Reliable and validated models that integrate coastal processes, hydrography, and land use and change, and include biogeochemical processes and biodiversity, are essential to predict changes in ecosystem services.[31] Such models are also important to project potential impacts on public health, infrastructure, and the economy, and to provide communities and decision-makers with options and cost-benefit analyses. Understanding the interaction between land and ocean cannot be limited to the development of technologies or model improvement. In order to ensure the sustainability of ocean resources, studies of biological, chemical, geological, and physical process should consider applications that are useful to coastal managers, and should forge synergies across disciplines to put forward an integrated understanding of the coastal system.

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[28] Such research is supported by the National Academy of Sciences *Sea Change: 2015-2015 Decadal Survey of Ocean Sciences.* In particular, priority science question number two: "How are the coastal and estuarine ocean and their ecosystems influenced by the global hydrologic cycle, land use, and upwelling from the deep ocean?" National Research Council. (2015) *Sea Change: 2015-2025 Decadal Survey of Ocean Sciences*. Washington, DC: The National Academies Press, p. 86. https://doi.org/10.17226/21655 (accessed September 29, 2018).

[29] Such research is supported by the National Academy of Sciences *Sea Change: 2015-2015 Decadal Survey of Ocean Sciences.* In particular, priority science question number seven: "How can risk be better characterized and the ability to forecast geohazards like megaearthquakes, tsunamis, undersea landslides, and volcanic eruptions be improved?" National Research Council. (2015) *Sea Change: 2015-2025 Decadal Survey of Ocean Sciences*. Washington, DC: The National Academies Press, p. 86. https://doi.org/10.17226/21655 (accessed September 29, 2018).

[30] Adger, W.N., J. Barnett, K. Brown, N. Marshall, and K. O'Brien. (2013) Cultural dimensions of climate change impacts and adaptation. *Nature Climate Change* 3(2):112-117. https://www.nature.com/articles/nclimate1666 (accessed June 15, 2018).

[31] Such research is supported by the National Academy of Sciences *Sea Change: 2015-2015 Decadal Survey of Ocean Sciences.* In particular, priority science question number three: "How have ocean biogeochemical and physical processes contributed to today's climate and its variability, and how will this system change over the next century?" National Research Council. (2015) *Sea Change: 2015-2025 Decadal Survey of Ocean Sciences*. Washington, DC: The National Academies Press, p. 86. https://doi.org/10.17226/21655 (accessed September 29, 2018).

Priorities

- Enhance capabilities of Earth system models, including dynamic coupling of various components within the ocean-ice-land-atmospheric system.
- Engage various research communities, including academia, to enhance model success and provide continuous improvement and support.
- Improve biological and ecological modeling and the development of bioinformatic analyses to better predict effects caused by stressors on coastal and marine ecosystems.
- Examine quantitative precipitation forecasts (QPFs) and data assimilation resulting in more accurate coupled ocean-land-weather modeling.
- Increase studies of the air-sea interface to provide better understanding of the relationships between ocean characteristics, including mixing processes that transport surface momentum, and the ocean interior.
- Integrate new monitoring technologies into existing and emerging ocean observation systems (e.g., U.S. Integrated Ocean Observing System (IOOS); the United Nations Global Ocean Observing System (GOOS)), while ensuring quality assurance and data comparability.

Box 1.5. The Interconnected Earth System

The flow of water and constituents (dissolved and particulate) from land to the coastal ocean connect the terrestrial and marine systems. Natural and anthropogenic processes add and alter riverine constituents that flow to the coastal ocean; inputs are regulated by hydrology (precipitation and evaporation), land use, and the condition of the drainage network (including reservoirs and ecological condition of estuaries). Excess nutrient runoff can lead to oxygen depletion and associated acidification, affecting numerous living marine resources. In the coastal zone, physical and biogeochemical processes control the transport and fate of the discharged material, which may be recycled or removed (via export) from the system.

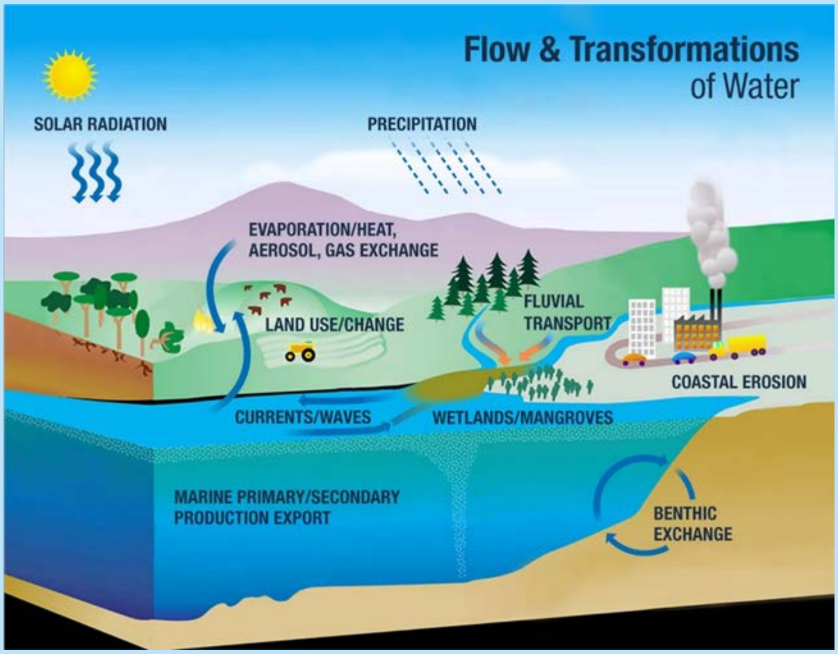

Figure 1.3. Water flow and transformations with the Earth system. (Image courtesy of NASA)

Facilitate Research to Operations

Applying R&D advancements to operation, commercialization, or other uses is fundamental to advance the United States in ocean S&T, and to enhance economic prosperity, maritime security, human health, and resilient coastal communities. Deploying such research concepts requires a comprehensive understanding of the ocean in the Earth system including the role of external factors. Research which adopts a social-ecological system (SES) lens and considers the whole system, particularly context-specific factors, is more likely to observe operational success. Coupled physical, biological, chemical, geological, and socioeconomic models support the systems based approach that many ocean S&T applications depend upon.

For example, much progress has been made in weather forecasting in the last decade, both with respect to more accurate modeling, and moving from forecasting (modeling) to Impact-based Decision Support Services (IDSS). Sustained progress in forecasting and IDSS will critically depend on a more holistic approach to environmental modeling, particularly on shorter "weather" time scales, by expanding coupled modeling experiences gained with seasonal forecasting, tropical cyclone, and weather-ice-ocean models to fully-coupled global and regional atmosphere-ocean-ice-land-aerosol-wave prediction for weather time scales.

Substantial fundamental advances have arisen from programs that cross traditional disciplinary boundaries, bringing together scientists and stakeholders from many fields, research institutions, Federal agencies, and other entities. In order for the United States to continue its leadership in ocean, coastal and Great Lakes research, we must utilize and encourage public-private partnerships, specifically regarding infrastructure such as marine laboratories and oceanographic research fleets. Such partnerships can better promote emerging technologies, and enable the transfer of ocean-related technologies from the lab to the market, broaden user accessibility to key advances, and bolster the ocean economy. To do so, coordinated investment in merit-based, competitive research, infrastructure, and education is key. One example that has documented numerous successes through public-private partnerships is the National Oceanographic Partnership Program (NOPP), which has provided the framework to rapidly foster such partnerships and tech transfer goals.

Priorities

- Integrate environmental observing and prediction systems with multi-use prediction and simulation systems to promote economically efficient, environmentally sound, and successful operations across the broad spectrum of marine operations.
- Support global operational modeling capabilities in order to improve the ability to protect operational forces, installations, and equipment from hazardous conditions of the physical environment.
- Develop programs that provide a more accurate, validated, longer-range, global ocean, atmosphere, and sea ice forecast system for decision support to enhance safety of flight, safety of navigation, and mission planning.
- Advance interagency collaborations in order to pursue goals such as the deployment of unmanned underwater gliders prior to hurricane season, which will provide better awareness of storm intensity leading to improved hurricane forecasts.

- Sustain forecasting capabilities, for example, by maintaining a network of drifting buoys in the Arctic Ocean, which collect sustained weather and oceanographic observations for 3-5 years and provide operational and scientific communities access to *in situ* data.[32]
- Encourage opportunities for public-private partnerships, particularly to leverage knowledge and resources, ensure the successful application of ocean research, avoid duplication of efforts, and improve communication between ocean researchers and ocean users.

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[32] As also supported by Performance Element 3.1.2 in the Interagency Arctic Research Policy Committee. (2016) Arctic Research Plan FY2017-2021. Washington D.C. p. 84. https://www.iarpccollaborations.org/plan/objective/3.1 (accessed April 17, 2018).

Goal II. Promote Economic Prosperity

Optimizing sustainable use of our exclusive economic zone (EEZ) and the high seas is vital to America's global economic leadership (Box 2.1). The U.S. ocean economy, which includes six economic sectors that depend on the ocean, is estimated to have contributed more than $320 billion to the U.S. Gross Domestic Product (GDP) and supported 3.2 million jobs directly dependent on these resources in 2015.[33] These economic sectors include: living resources, marine construction, offshore mineral extraction, tourism and recreation, ship and boat building, and marine transportation.

Our ocean is home to a vast array of living and non-living marine resources. Much of the ocean is underexplored, and offers great potential for advancing science, technology, and our growing economy. Our resources are central to the national economy and American quality of life, and thus we must balance our present use of ocean resources with a productive and healthy ocean for future generations. Characterizing the primary uses of the marine environment (including fisheries, aquaculture, transportation/shipping, energy, national security, land values, mineral extraction, recreation, and protected species habitats) and the goods and services, beneficiaries, and market and non-market values attributable to those uses, is key to understanding the ocean's potential.

Living marine resources serve critical roles in their ecosystems and in sustaining life on land; they are used for food, medicine, and cosmetics, and support services such as fisheries and tourism, as well as processes that may influence the climate (e.g., biologically-controlled marine processes absorbing excess atmospheric carbon dioxide and the absorption and transport of atmospheric heat). Non-living marine resources also serve multiple roles: in powering our communities, reducing our dependence on foreign sources of minerals, providing avenues for transportation, and controlling climate (e.g., through thermohaline adjustments). The ocean S&T enterprise can expedite and better inform the exploration, assessment, and sustainable management of America's living and non-living marine resources.

Emerging innovative technologies serve a critical role in capitalizing on marine resource economic opportunities while sustaining future options. S&T advancements will provide the necessary information to guide responsible future development and investment opportunities and allow resource-dependent communities to adapt to ocean changes. As resource identification and surveying progresses, S&T advancements can continue to ensure that multiple uses such as energy exploration and recreational activities successfully coexist. Ocean education will drive technological breakthroughs, will strengthen public understanding and engagement in best using and protecting ocean resources, and will provide a foundation for the Nation's growing blue workforce. Readily available data and user-friendly quality assured tools incorporating the best available environmental and social data will empower our resource managers and policy makers to harness America's resources responsibly.

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[33] NOAA. (2018) Report on the U.S. Ocean and Great Lakes Economy. Charleston, SC: NOAA Office of Coastal Management, p. 27. https://coast.noaa.gov/data/digitalcoast/pdf/econ-report.pdf (accessed May 31, 2018).

Box 2.1. The U.S. Exclusive Economic Zone

The U.S. Exclusive Economic Zone (EEZ) is one of the largest in the world, encompassing approximately 4.38 million square miles.[34] Coastal counties contain approximately 40% of the U.S. population, yet account for only 10% of the area within the U.S.[35] As the U.S. population is expected to surpass 400 million by the middle of this century,[36] it is important to understand how ocean changes will impact the Nation's economic security, safety, environment, and health:

- 42% of the U.S. labor force is employed in coastal watersheds.[37]
- In 2014, counties adjacent to the shore contributed to 43% percent of the U.S. GDP.[37]
- The offshore mineral industry contributed over 170,000 jobs in 2013 and $122 billion, the majority of which was predominantly from the oil and gas sector.[37]
- Approximately 88,000 square miles of the Nation's coastal wetlands provide nursery areas for commercially harvested fish and places of refuge for migrating birds.[37]
- In 2015, the commercial and recreational fishing industry supported 1.6 million jobs and contributed $208 billion in sales to the U.S. economy.[38]
- Ocean measurements, observations, and forecasting generate about $7 billion in revenues annually.[39]

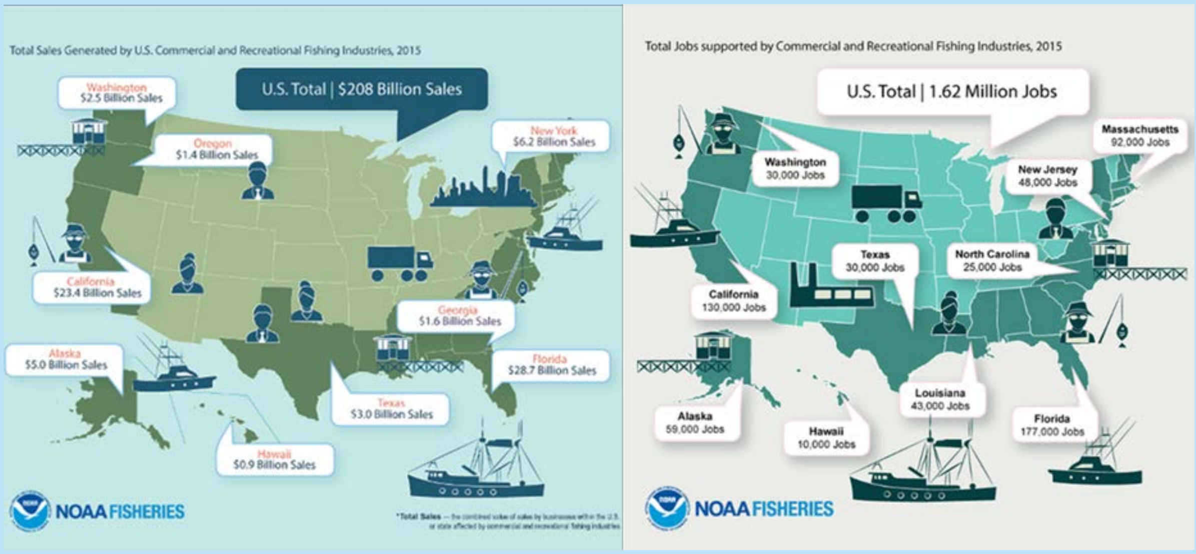

Figure 2.1. Total sales and jobs supported by commercial and recreational fisheries. (Images courtesy of NOAA)

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[34] NOAA. (2011) The United States is an Ocean Nation. https://www.gc.noaa.gov/documents/2011/012711_gcil_maritime_eez_map.pdf (accessed June 18, 2018).

[35] NOAA. (2013) National Coastal Population Report: Population Trends 1970 to 2020. http://oceanservice.noaa.gov/facts/coastal-population-report.pdf (accessed April 17, 2018).

[36] Colby, S.L., and J.M. Ortman. (2014) Projections of the size and composition of the U.S. Population: 2014 to 2060. Current Population Reports, P25-1143, U.S. Census Bureau. Washington, D.C. https://census.gov/content/dam/Census/library/publications/2015/demo/p25-1143.pdf (accessed June 18, 2018).

[37] NOAA. (2016) State of the U.S. Ocean and Coastal Economies 2016 Update. National Ocean Economics Program.

Expand Domestic Seafood Production

The United States currently imports 90% of its seafood, leading to a $14 billion seafood trade deficit.[40] Given that the World Bank projects a nearly 50% increase in worldwide fish consumption between 2006-2030,[41] the United States has an opportunity to meet this demand, ensure food security, create new industries, and accordingly provide jobs by maximizing sustainable wild and aquaculture harvest.

The United States leads the world in science-based sustainable fishery management, yet maximum sustainable harvests are not realized in all fisheries and changes in ocean temperatures threaten the stability of key populations. Advances in technologies such as underwater sensors (cameras, audio recorders, biochemical, etc.) to better survey and land target species and reduce bycatch[42] can lead to more efficient and effective fishing.[43] Electronic real-time reporting of landings and modern data management techniques for our commercial fisheries will lead to greater certainty in what is being caught and what is left in the water. Improving the accuracy and accessibility of seafood data will promote America's seafood industry by enhancing transparency and traceability.

To meet our Nation's seafood demands, narrow the seafood trade deficit, and reduce pressure on wild populations, the United States needs to complement wild fisheries with aquaculture, including mariculture.[44] Using sustainable and environmentally responsible marine aquaculture methods, the United States could change from being a net seafood importer to a net seafood exporter, using only a fraction of our EEZ. Improved and expanded research associated with environmental monitoring, in addition to promoting emerging aquaculture technologies, will help mitigate risks associated with land-based and open water practices and make aquaculture a financially feasible industry while ensuring the health of our ocean and its biodiversity.

Sustainable aquaculture requires improved understanding of environmental risks, technical infrastructure, and active collaborations between Federal, State, territorial, and tribal governments and the private sector to streamline the permitting process. Federal partnerships and extramural research opportunities for academia and aquaria will contribute to U.S. aquaculture being a science-based, environmentally responsible, financially viable, and sustainable business.

National Marine Fisheries Service. http://midatlanticocean.org/wp-content/uploads/2016/03/NOEP_National_Report_2016.pdf (accessed April 19, 2018).

[38] National Marine Fisheries Service. (2016) Fisheries Economics of the United States, 2015. U.S. Department of Commerce, NOAA Tech. Memo. NMFS-F/SPO-163, p. 237. https://www.fisheries.noaa.gov/feature-story/fisheries-economics-united-states-2015 (accessed June 15, 2018).

[39] ERISS Corporation, the Maritime Alliance. (2016) The Ocean Enterprise. A study of U.S. business activity in ocean measurement, observation and forecasting. https://ioos.noaa.gov/project/ocean-enterprise-study/ (accessed April 19, 2018).

[40] NOAA. (2016) Fisheries of the United States. https://www.fisheries.noaa.gov/resource/document/fisheries-united-states-2016-report (accessed April 17, 2018).

[41] World Bank. (2013) Fish to 2030: Prospects for Fisheries and Aquaculture. World Bank. Washington, D.C. Report 83177-GLB. http://www.fao.org/docrep/019/i3640e/i3640e.pdf (accessed April 17, 2018).

[42] Bycatch refers to discarded catch of marine species and unobserved mortality due to a direct encounter with fishing vessels and gear. More information can be found at: https://www.fisheries.noaa.gov/insight/bycatch (accessed May 31, 2018).

[43] Hazen, E.L., K.L. Scales, S.M. Maxwell, D.K. Briscoe, H. Welch, S.J. Bograd, H. Bailey, S.R. Benson, T. Eguchi, H. Dewar, and S. Kohin. (2018) A dynamic ocean management tool to reduce bycatch and support sustainable fisheries. *Science Advances 4*(5):eaar3001. http://advances.sciencemag.org/content/4/5/eaar3001.full (accessed June 15, 2018).

[44] Mariculture is a subset of aquaculture, referring to aquaculture activities within the open ocean. The term aquaculture refers to the breeding, rearing, and harvesting of animals and plants in all types of water environments. More information can be found at: NOAA Aquaculture. (2018) https://www.fisheries.noaa.gov/topic/aquaculture#overview (accessed June 5, 2018); National Ocean Economics Program. (2007) http://www.oceaneconomics.org/LMR/Aquaculture/ (accessed June 5, 2018).

Public acceptance for aquaculture products will be essential for market success and should be a key focus of education. Key research infrastructure includes test beds for industry and researchers to try new ideas, and technology and development of key inputs to production such as feed and fingerlings. Support industries such as animal health, processing, manufacturing, and engineering will create more jobs.

Priorities

- Support development and deployment of sensors to detect, identify, and quantify target and protected species.
- Employ real-time data techniques and modern data management to reduce uncertainty in fishery management.
- Leverage and evolve scientific tools and information to support a clear road map for aquaculture permitting including effective siting, water quality, genetics, and other science-based computer tools to aid industry with applications for aquaculture sites and compliance with government mandates.
- Develop and test genetic approaches that safeguard wild genetic diversity while allowing for genetic improvement of resources such as farmed shellfish stocks, and use the hatcheries to develop such genetic selection programs for a range of commercially valuable resources such as mollusks.
- Advance ocean-based biomass research and technologies to better produce food, fiber, biofuel, and other products from sources such as seaweed farms, and transfer technology to industry.

Explore Potential Energy Sources

America's coastline and extensive EEZ contains vast untapped renewable (wave, tidal, wind, thermal) and non-renewable (oil and gas) energy sources to help power the Nation (Box 2.2). In addition to generating electricity for use on-shore, power generated at sea (from waves, currents, or wind) could be used to serve the needs of other existing or emerging ocean industries (aquaculture, ocean mineral mining, oceanographic research, or military missions). Aligning energy innovation with emerging developments in ocean science, security, and maritime technology could provide dynamic opportunities to further drive coastal economic development. The development of domestic energy resources should be achieved in concert with enabling military operations, training, and testing.

The Federal government has an interest in harnessing American energy sources safely and efficiently through new and innovative technologies. In particular, improving technology transfer could increase U.S. competitiveness in the global market, such as in offshore wind. Also, the United States can use emerging technologies to rapidly increase seafloor mapping and further assess the ocean's potential as an energy source. New acoustic technologies will expand ocean exploration and discovery, and provide a better understanding of energy development impacts on the marine environment.

Box 2.2. Potential Untapped Sources of Energy

There are many promising and undeveloped sources of energy available in ocean and coastal areas. In particular, harnessing the wind to produce electricity for society has grown exponentially on land and is moving out into the ocean where wind resources are greater and more consistent. Wind turbines introduce structures in the water column that will create an artificial reef system, not dissimilar to the Gulf of Mexico oil and gas structures. These structures could potentially become a part of an observing network to host monitoring equipment like temperature sensors, current profilers, or cameras to support continuous observations while generating electricity from a clean, renewable source. The durability of these structures depend on sound engineering design specific to the varying geology and wind, wave, and ocean current conditions of the U.S. offshore environment.

While wind, waves, and tides are relatively well understood sources of energy, gas hydrates and hydrothermal systems in the marine environment represent untapped yet poorly understood categories left to be explored. Gas hydrates are present on both coastal shelves and the deep ocean, often in permafrost. Understanding the biogeochemistry and geomorphological change associated with permafrost thaw as well as risks associated with shelf and slope destabilization that accompany thaw will demand significant scientific attention. Similarly, untapped energy that exists in deep ocean hydrothermal systems requires improved science that integrates magmatic, tectonic, geochemical, fluid flow, heat and mass flux, mineral formation, circulation, and biological processes. These hydrothermal systems also produce deep-ocean mineral deposits, seafloor massive sulfides, and contribute to ferromanganese crusts and nodules through fluxes of metals to seawater.

Figure 2.2. Wind turbines on land, which far exceed the number of at-sea wind turbines. (Image courtesy of NSF)

The ocean floor is similar to the terrestrial environment; it has mountains, canyons, channels, and hills. Most of these features are unmapped and unexplored, with less than 15% of the ocean floor currently mapped.[11] Detailed bathymetric mapping is important to better understand climate, earthquakes, tsunamis, weather forecasting, ocean habitats, and biodiversity, as well as ocean resource use and exploration. "Seabed 2030" is an international collaboration of public and private partners focused on compiling a high-resolution[45] map of the global ocean over the coming decade.[46] The Federal government will continue to map and better characterize America's EEZ, particularly through advancements in the oceanographic fleet and other assets. Bathymetric data will provide the necessary information to identify energy sources, and will also have cascading benefits for fisheries management, mineral extraction, cable and pipeline routing, natural hazard preparedness, and military and defense applications.

Priorities

- Continue mapping the U.S. EEZ and the global seafloor and perform surveys and characterizations of ocean resources and habitats, data tools, and logging platforms to provide temporal and spatial coverage, and assessments of classification, condition, and valuation mapping.
- Develop efficient and cost-effective at-sea power generation (wave, methane, solar, wind, etc.) for ocean observation platforms.
- Study contaminant releases (e.g., oil spills, natural seeps, pollutant loading) and benthic disturbances to improve understanding of their effects on coastal communities and transportation routes, and advance technologies to limit negative impacts.
- Support new technologies to measure underwater noise levels and acoustic conditions in coastal and open ocean environments in order to quantify long-term trends in ocean noise levels, monitor changes in acoustic habitats and in interference with underwater technologies, and assess the impacts of increases in human produced noise.

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[45] The ultimate goal is to complete 100 meter horizontal grid mapping resolution, but at least a resolution which falls in a grid cell found in a range of 35 to 768 footprint for a 2° × 2° system deep water system, as per described in Table 2 of this paper: Mayer, L., M. Jakobsson, G. Allen, B. Dorschel, R. Falconer, V. Ferrini, G. Lamarche, H. Snaith, and P. Weatherall. (2018) The Nippon Foundation—GEBCO Seabed 2030 Project: The Quest to See the World's Oceans Completely Mapped by 2030. *Geosciences*, 8(2), p.63. https://www.mdpi.com/2076-3263/8/2/63/htm (accessed September 29, 2018).

[46] Seabed 2030 is a collaborative partnership between the General Bathymetric Chart of the Oceans (GEBCO) and the Nippon Foundation aimed to facilitate the complete mapping of the ocean floor by 2030. More information can be found at: https://seabed2030.gebco.net/ (accessed May 8, 2018).

[47] Pratson, L.F., and W.F. Haxby. (1996) What is the slope of the U.S. continental slope? *Geology* 24(1): 3-6. https://pubs.geoscienceworld.org/gsa/geology/article-abstract/24/1/3/206427/what-is-the-slope-of-the-u-s-continental-slope (accessed April 15, 2018).

Assess Marine Critical Minerals

U.S. offshore and deep-sea areas remain mostly unexplored and unused. Especially important for American independence and prominence in the global market is access to critical minerals in the marine environment. Given that China is the top supplier of many of the 35 critical minerals identified in the U.S. 2018 list of critical minerals,[48] the United States needs policies, infrastructure, and technologies to produce and maintain supplies of critical minerals. A recent Executive Order highlighted the importance of "identifying new sources of critical minerals" and "increasing activity at all levels of the supply chain, including exploration, mining, concentration, separation, alloying, recycling, and reprocessing critical minerals."[49] Such efforts can be supported by exploration of the outer continental shelf to the abyssal plains and hydrothermal vents and seamounts along the mid-ocean ridges for valuable resources including manganese nodules, cobalt-rich crusts, and polymetallic sulfides.

In the past, the harsh environment and inaccessibility of potential extraction sites have meant that the marine environment was often discounted as a source for critical minerals. In the coming decade, the ocean S&T enterprise can support the United States in the discovery and assessment of marine resources. Basic mapping, baseline data, and ocean condition observations are foundational for understanding these resources and planning how to best use them.

Priorities

- Identify and quantify the location, size, and nature of important deep-sea minerals through sediment characterization and geochemical signals to better understand the complexity and scalability of resource use.
- Conduct basic and applied research to characterize the effects of deep-sea mining on vulnerable marine ecosystems, including the impact of light, heat, rock debris, underwater sediment plumes, noise, and biodiversity loss. Such research should include documentation of deep-sea biodiversity, and improved prediction of the scale and extent of environmental impacts from deep-sea exploration.
- Study the physical conditions at environmentally sensitive and important areas using surveys and gap analyses to assess effectiveness of current monitoring efforts and platforms.
- Continue involvement in global endeavors and organizations to both further our knowledge of and protect the ocean environment, such as the SeaBed 2030 Initiative and the International Seabed Authority.

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[48] Department of Interior. (2018) Final list of critical minerals 2018. https://www.gpo.gov/fdsys/pkg/FR-2018-05-18/pdf/2018-10667.pdf (accessed June 15, 2018).

[49] See Executive Order 13817, issued on December 20, 2017, A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals. https://www.federalregister.gov/documents/2017/12/26/2017-27899/a-federal-strategy-to-ensure-secure-and-reliable-supplies-of-critical-minerals (accessed June 18, 2018).

Balance Economic and Ecological Benefits

Proper stewardship of the ocean is critical to the long-term vitality of the United States. We must promote economic growth while protecting our marine environment for current and future generations. The United States benefits from its wide range of coastal ecosystems, from the cold Arctic waters of Alaska to the temperate Gulf of Mexico to the tropical reefs of southern Florida. Management of these unique ecosystems requires location-specific data and information to be included in adaptive management strategies.

Adaptive management allows U.S. managers and decision-makers to effectively oversee America's ocean resources according to new information and changes in context, while considering both short-term gains and long-term objectives. To balance economic and ecological goals, adaptive management relies on systems-based decision-support tools that incorporate socioeconomic data, including stakeholder knowledge, and better link physical and chemical ocean changes with corresponding biological responses. Tools that include regionally-specific information are likely to lead to more effective outcomes, as context is key to successful adaptive management of marine resources.

Decision-makers rely on research on the changes in resource and habitat conditions, as well as up-to-date information on human uses (e.g., frequency, duration, and intensity of use). Research on how organisms and marine populations respond to environmental changes will enable better predictions of economic and societal effects from environmental changes, especially for industries such as fisheries, ocean recreation, and marine tourism. These industries will also benefit from a better understanding of both top down (e.g., shark finning) and bottom up (e.g., coral bleaching) trophic pressures.

Integrating socioeconomics and building the knowledge to inform ecosystem-based management can facilitate adaptive management. Ecological and economic tools to evaluate natural capital[50] and ecosystem services can enable more accurate and timely decisions. Further understanding of ecological and economic relationships can better support effective valuation methods (e.g., for food, transportation, land values, extraction of minerals and other natural products, ecotourism, and recreation).

Understanding cumulative impacts is also critical to improving adaptive management and to optimizing objectives. Ocean resources are exposed to many different stressors, such as eutrophication, marine debris, and ocean noise. Our Nation will rely on research to evaluate cumulative impacts of multiple human influences as well as data on how changes in natural environmental stressors exacerbate stressor impacts. Recent developments in R&D have led to the increased use of advanced technologies to address this need, such as DNA-probes and biosensors. Monitoring and forecasting efforts will be enhanced through state-of the-art passive acoustic observing capabilities by the national Ocean Noise Reference Station Network.[51]

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[50] "Natural capital is defined as the Earth's stock of natural assets. Those assets are part of the world's ecosystems, 'a geographically specified system of organisms (including humans), and the environment and the processes that control its dynamics' according to the Millennium Ecosystem Assessment. Ecosystem services are the flow of benefits provided by these systems." Department of Commerce. What is Natural Capital? https://www.commerce.gov/naturalcapital (accessed November 4, 2018).

[51] Gedamke, J., J. Harrison, L. Hatch, R. Angliss, J. Barlow, C. Berchok, C. Caldow M. Castellote, D. Cholewiak, M.L. DeAngelis, R. Dziak, E. Garland, S. Guan, S. Hastings, M. Holt, B. Laws, D. Mellinger, S. Moore, T.J. Moore, E. Oleson, J. Pearson-Meyer, W. Piniak, J. Redfern, T. Rowles, A. Scholik-Schlomer, A. Smith, M. Soldevilla, J. Stadler, S. Van Parijs, and C. Wahle. (2016) Ocean Noise Strategy Roadmap. NOAA, p. 144. https://cetsound.noaa.gov/Assets/cetsound/documents/Roadmap/ONS_Roadmap_Final_Complete.pdf (accessed April 17, 2018)

Priorities

- Develop biological and ecosystem indicators and determine their efficacy for understanding cumulative impacts and assessing the overall vulnerability of marine resources and ecosystem services to human influences at all trophic levels, particularly in light of shifting baselines.
- Identify evaluation and performance criteria that managers can use to gauge effectiveness of management strategies.
- Continue quantitatively monitoring coastal and open ocean biogeochemical trends to characterize changes in ocean acidification, assess impacts of sea level rise[52] on ocean resources, and quantify cumulative effects.
- Explore "intervention" science and techniques[53] that recognize and leverage the inherent resistance and adaptive qualities of species under the threat of degradation or mortality with changing environmental conditions.
- Explore low impact, alternative fuel sources for maritime and port-related uses, balancing stewardship with energy efficiency, cost-effectiveness, and marine safety.[54]

Promote the Blue Workforce

The United States has excelled as a leader in scientific research and technological innovation, but today's world and environmental-related challenges continue to evolve. Meeting these challenges requires enhancing our knowledge about the ocean. It is essential to our economic well-being that we create and support an ocean-literate society focused on the development of an educated and diverse workforce. This workforce would ensure that the United States maintains a competitive advantage in our understanding of the oceanic environment by capitalizing on a strong knowledge base, and would support Executive Order 13845.[55] Studies reveal that advances in science, technology, engineering, and math (STEM) are central to our Nation's ability to create new jobs, improve quality of life, and maintain our position as a global leader in S&T.[56] STEM fields are also vital for national defense purposes to build ocean models, create systems that protect our Nation, and maintain tactical advantages.

A well-trained, diverse, and dynamic workforce capable of addressing tomorrow's career needs has long been identified as a priority for our Nation.[57] There is a growing need for a dynamic workforce to address national ocean challenges focusing on Big Data analysis, computational modeling, offshore renewable energy, and instrumentation operation and maintenance. It is imperative that we bridge the

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[52] Such research is supported by the National Academy of Sciences *Sea Change: 2015-2015 Decadal Survey of Ocean Sciences.* In particular, priority science question number one: "What are the rates, mechanisms, impacts, and geographic variability of sea level change?" National Research Council. (2015) *Sea Change: 2015-2025 Decadal Survey of Ocean Sciences*. Washington, DC: The National Academies Press, p. 86. https://doi.org/10.17226/21655 (accessed September 29, 2018).

[53] Hobbs, R.J., L.M. Hallett, P.R. Ehrlich, and H.A. Mooney. (2011) Intervention ecology: applying ecological science in the twenty-first century. *BioScience*, 61(6): 442-450. https://doi.org/10.1525/bio.2011.61.6.6 (accessed September 4, 2018).

[54] Such efforts can be enhanced through interagency initiatives, such as through the CMTS-led Maritime Energy and Air Emissions Working Group. https://www.cmts.gov/topics/energy_and_air_emissions (accessed June 14, 2018).

[55] See Executive Order 13845, issued on July 19, 2018, Establishing the President's National Council for the American Worker. https://www.federalregister.gov/documents/2018/07/24/2018-15955/establishing-the-presidents-national-council-for-the-american-worker/ (accessed October 11, 2018).

[56] National Science Board. (2010) Preparing the Next Generation of STEM Innovators: Identifying and Developing our Nation's Human Capital. NSB-10-33. https://www.nsf.gov/nsb/publications/2010/nsb1033.pdf (accessed June 15, 2018).

[57] National Science Board. (2018) A Policy Companion Statement to Science and Engineering Indicators 2018. NSB-2018-7. Alexandria, VA. National Science Foundation. https://nsf.gov/nsb/sei/ (accessed October 11, 2018).

gap between identified challenges and the workforce training required in order to effectively pursue S&T that may be relevant to the ocean enterprise. The development of cutting edge, advanced training opportunities will give the present ocean workforce the ability to make educational advancements outside of the traditional training opportunities. Investments in people, basic and applied research, and facilities are key to a strong workforce, professional development, and growing economic prosperity.[58] These opportunities and investments will foster the workforce's ability to adapt to dynamic technological advancements made within the S&T enterprise.

American capabilities begin with discoveries made in S&T, and our future competitiveness relies on a continuous supply of talented scientists and engineers. The security of the Nation and the quality of lives across the country also rely on strong science literacy in our communities. We need to ensure that all levels of academic programs are supported to fully prepare students to enter the workforce with the knowledge and experience they need to fuel the American ocean enterprise. Additionally, we must provide formal and informal research and training opportunities for students at both the K-12 and collegiate levels of education and beyond. This will ensure a technically qualified and diverse workforce capable of solving problems related to the protection, restoration, and management of coastal and ocean ecosystems, climate variability, and other societal challenges and needs. One example where students can gain place-based hands-on education and training involving all disciplines is U.S. marine and freshwater laboratories. Such training helps prepare the Nation's youth to address complex ocean, coastal, and Great Lakes challenges, and ensures U.S. leadership and competitiveness in the global market.

The ocean S&T enterprise offers workforce opportunities for workers at all education levels—not just those with advanced degrees—and across demographic groups. America's skilled technical workforce, which consists of individuals who may use STEM knowledge and skills in their jobs but don't have a four-year degree, are important to U.S. economic competitiveness. In addition, unemployment rates of skilled technical workers in science and engineering (S&E) and S&E-related jobs were significantly lower than those of workers in non-S&E jobs without bachelor's degrees, and their earnings were significantly higher.[59] The Federal government is well positioned to encourage courses and programs in marine technology and coastal engineering and to facilitate student-led missions related to the ocean workspace, such as through remotely operated vehicle (ROV) competition challenges.[60]

Community and technical colleges can help expose a more diverse body of students to job opportunities in the blue workforce. Special degree programs geared toward ocean work, hands-on experience, and professional development offered through these institutions can prepare students for marine occupations, including marine forecasters, ocean instrument technicians, and underwater ROV developers. Investment in all levels of education is critical for ensuring U.S. leadership and that the next generation of Americans remains competitive in the growing international field of ocean R&D.

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[58] The White House. (2015) National Security Strategy. Washington, D.C. p. 35. http://nssarchive.us/wp-content/uploads/2015/02/2015.pdf (accessed June 15, 2018).

[59] National Science Board. (2018) Science and Engineering Indicators 2018 Digest. NSB-2018-2. Alexandria, VA: National Science Foundation, p. 28. https://www.nsf.gov/statistics/digest/ (accessed June 15, 2018).

[60] National Science Foundation. (2013) Underwater Robotics Competition Helps Students Build Skills for Ocean Occupations. https://www.nsf.gov/discoveries/disc_summ.jsp?cntn_id=128911 (accessed June 1, 2018).

Priorities

- Develop and enhance programs between agencies and educational institutions that provide certification in Unmanned Maritime Systems. These programs would enable students to participate in short (e.g., 3-month) training cycles where they study nautical science, 3-D positioning, ocean policy, autonomous systems, and the interfaces of all aspects of unmanned maritime systems.
- Share resources to support surveys and unmanned system operations, allowing operators from multiple agencies' oceanographic fleets to identify best practices and apply lessons learned through joint cooperation.
- Improve and support cooperation among the Federal government, State governments, the private sector, and academic universities to successfully recruit researchers and ocean policy experts into the ocean science workforce, including the Federal component.[61]
- Support coastal communities to provide them with the latest skills necessary to conserve coastal resources, protect traditional livelihoods, and capitalize on future opportunities (e.g., offshore renewables, etc.).
- Develop and expand programs to equip educators pre-K through post-secondary, both formal and informal, to represent ocean science with fidelity and to intrigue their students as a means of preparing the future workforce.

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[61] This cooperation includes the Knauss Sea Grant Marine Policy Fellowship Program. More information can be found at: https://www.seagrant.noaa.gov/knauss (accessed May 28, 2018).

Goal III. Ensure Maritime Security

Maritime security is essential to the Nation's ability to defend the homeland and to sustain military advantages, both globally and in key regions.[62] Our Nation's investments in ocean observations, data management, and modeling and prediction (to include undersea acoustics and other underwater detection and avoidance technologies) must be applied to preserve and enhance the myriad of strategic, operational, and tactical advantages for U.S. Armed Forces in the maritime arena.

Maritime security also ensures the Nation's economic prosperity and U.S. global leadership. Approximately 80% of global trade by volume is transported across the ocean.[63] An efficient, safe, and secure maritime environment enables commerce, including marine public transportation, tourism, merchant ship traffic, aquaculture to improve nutrition and food security, and economic activities in the Nation's EEZ, the U.S. extended continental shelf, and on the high seas. Given that the Nation's coastal ocean and inland waterways act as gateways of commerce and that the United States has one of the most extensive maritime transportation systems in the world,[64] the ability to effectively navigate, map, chart, and predict ocean variability is critical for maritime security.

The rapid global growth of information dissemination and evolving technologies, including artificial intelligence and satellite remote sensing, has added immense complexity to both national defense (military) and homeland security (law enforcement and safety) challenges, as well as to the emergence of new operations such as automated cargo and naval vessels. An agile, rapid, and economical approach to ocean S&T investment will continue to contribute to national security.

Maritime security for national defense and law enforcement must be strengthened by continued scientific and technological advancement to keep America competitive in an increasingly complex global maritime environment. Developing the next generation of ocean S&T capabilities is a tremendous challenge that must be undertaken to ensure not only the Nation's maritime security, but its maritime superiority.[65]

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[62] Department of Defense. (2018) National Defense Strategy of the United States of America: Sharpening the American Military's Competitive Edge, p. 14. https://www.defense.gov/Portals/1/Documents/pubs/2018-National-Defense-Strategy-Summary.pdf (accessed June 19, 2018).

[63] United Nations Conference on Trade and Development (UNCTAD). (2017) Review of Maritime Transport, p. 130. https://unctad.org/en/PublicationsLibrary/rmt2017_en.pdf (accessed November 5, 2018).

[64] National Chamber Foundation. (2003) Trade and Transportation: A Study of North American Port and Intermodal Systems. U.S. Chamber of Commerce. Washington, D.C., p. 7. https://ftp.dot.state.tx.us/pub/txdot-info/library/projects/la_entrada/portstudy.pdf (accessed June 18, 2018).

[65] United States Navy. Chief of Naval Operations. (2016) A Design for Maintaining Maritime Superiority. p. 10. http://www.navy.mil/cno/docs/cno_stg.pdf (accessed June 19, 2018).

Improve Maritime Situational Awareness

Maritime domain awareness and security operations require continuous, near-real-time monitoring of the ocean and its changing conditions. The rapid growth of a range of sensing capabilities can be leveraged for the benefit of ocean sciences and other vital purposes. Increased understanding of the ocean enhances environmental protection, safe navigation of the ocean, and other uses, while providing essential information required for maritime security and military operations. In concert with this is the need to acquire situational awareness and context to better interpret the totality of data.

While an immense amount of data is collected in the physical, chemical, geological, acoustical, and biological observations of the ocean, we can improve the way we both model ocean environments and spark new innovations through the use of newly enabled machine learning and artificial intelligence algorithms. Both advanced hardware and software are required to assimilate and understand new observations, analyze the vast existing amounts of ocean data, and run the integrated models that are used to predict the maritime environment for operational decision-making. Ship-based seafloor and sub-seafloor surveys are now being supplemented by autonomous and remotely operated vehicles to assess the ocean (Box 3.1). Continued development of not only vehicles but autonomous behaviors and technologies is needed to reduce the need for human intervention. The United States should take better advantage of its technological workforce to develop systems for Earth system models, which have unique architecture requirements.

A thorough understanding of a range of oceanographic parameters and their interactions is critical for homeland security and commercial operations to safely operate and deploy in the marine environment. Direct observations of ocean currents, waves, tides, sound propagation, ocean temperature, and salinity provide robust predictive models. Safety at sea for commercial, security, and defense operations is also influenced by factors such as wave height and period, winds over water, and the sudden onset of hazardous conditions compounded by lack of open sea, *in situ* weather observations.

Remote sensors[66] are unable to observe the ocean depths and existing *in situ* observation systems are sparse.[67] More diversification in maritime observing systems will better help us establish trends in the maritime environment that are significant to our Nation's security needs. Accordingly, an important component of this strategy is to maintain and enhance the existing profiling and drifting sensor arrays, expanding capabilities through the addition of sensors, and more flexible and capable platforms. Comprehensive datasets provide essential inputs into ocean models to increase their fidelity, which can be achieved through a more diversified maritime observing sensor suite.

A diverse suite of space-based sensors capable of taking ocean measurements across the usable electromagnetic spectrum will support a wide range of ocean research, ocean models, and help improve forecasts of winds, waves, currents, species distributions, significant weather events, and seasonal to longer-term ocean variability. Measurements must be effectively communicated and aggregated in coupled data assimilative global models of the ocean, atmosphere, and ice to support maritime operations in nearshore and deep-ocean environments.

Such computational capabilities can address the considerable vulnerability to detrimental activities that exist in unobserved locations. Illegal, unregulated, and unreported (IUU) fishing is a risk to marine species and ecosystems, undermines sound management of sustainable fisheries, and poses significant

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[66] Referring to electromagnetic sensing from altitude.

[67] Akbari, E., S.K. Alavipanah, M. Jeihouni, M. Hajeb, D. Haase, and S. Alavipanah. (2017) A review of ocean/sea subsurface water temperature studies from remote sensing and non-remote sensing methods. *Water* 9(12):936 https://www.mdpi.com/2073-4441/9/12/936 (accessed November 8, 2018).

commercial, humanitarian, and security risks. The connection between human trafficking and IUU fishing is already strong, and the Federal government continues to assess the risk of such unmonitored transport for the smuggling of people and materials for criminals and terrorists.

Box 3.1. Tactical Advantage

Less than 15% of the world's ocean floor has been explored.[11] Unmanned underwater vehicles (i.e., gliders) allow researchers to explore more of the ocean, and faster, at a fraction of the cost of a manned submersible or a ship. Gliders are propelled by ocean currents and navigate with fins by diving and surfacing. These gliders have no active propulsion system and can operate to depths of 1,000 meters, for up to four months before retrieval and servicing. Gliders have the ability to provide hundreds of profiles per month, thus freeing oceanographic ships to perform missions in other areas.

The temperature and salinity data collected by the gilders are used by ocean modelers to forecast future environmental ocean conditions. The model forecasts are provided in near-real-time to support strategic, operational, and tactical fleet requirements and activities. These forecasts allow better prediction of ocean currents, density, sea states, and tides, which provide physical battlespace awareness and a common operational picture for U.S. Armed Forces.

Figure 3.1. An unmanned underwater vehicle is deployed from a Naval Oceanographic Office (NAVOCEANO) survey vessel. (Image courtesy of U.S. Navy)

Populations reliant on their coastal waters and lacking sufficient modern infrastructure are at risk for loss of food security if IUU fishermen poach fish populations on which these populations depend for sustenance, or if ocean acidification and warming leads to the loss or migration of staple fish stocks. Additional research is needed to understand the scale of both of these problems, develop monitoring and mitigation technologies, and identify effective interventions and policies.

Priorities

- Support the maritime observing framework that ensures diverse sensing capabilities for a range of U.S. end users.
- Sustain oceanographic sensors and autonomous monitoring technologies to enhance data collection under the ocean's surface and at the surface in all weather conditions to support high-spatial-resolution and near-real-time forecasting of the Earth system (terrestrial and oceanic).
- Pursue new methodologies and/or observing technologies and use of distributed networks of organic, tactical sensors[68] for collection of maritime environment variables.
- Develop inexpensive sensors with low environmental impact for remote sensing studies that enable observations across the electromagnetic spectrum and for full-ocean-depth sensors that exploit the emerging technology that integrates electronics and soft materials (conductive polymers).[69]
- Establish national glider coordination and standards to provide ocean sampling in coastal regions, strong oceanographic currents, and other regions where drifters and floats are impractical.
- Develop advanced computational capabilities to analyze vessel, operator, cargo, and infrastructure data to identify anomalous behaviors in the maritime domain, such as IUU fishing, human migration, at-sea smuggling, transnational maritime criminal activities, etc., to better support appropriate security responses.

Understand a Changing Arctic

Many nations are interested in understanding the Arctic's harsh environment and its resources. Research into the Arctic is motivated by scientific curiosity and longer-range commercial considerations.[70] Arctic dynamics influence global geophysical and biochemical systems, including freshwater storage and export, ocean-ice-atmospheric interactions, weather and climate dynamics, primary production, and the ocean's response to acidification, while also shaping human activities in the region. Opinions on the future of Arctic shipping and related activities within the Northwest Passage, the Northern Sea Route, and a potential transpolar route vary. Overall, the changing conditions of the Arctic, particularly the diminishing sea ice, are resulting in increased vessel traffic and extraction of natural resources. These developments impact homeland and national security

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[68] Shipboard or *in situ* sensors that are incorporated into a larger body, and are used to collect and present integrated situational awareness data.

[69] For example, the National Oceanographic Partnership Program (NOPP) funded soft materials integration laboratory explores such technology applications for oceanographic sensor development. http://sml.me.cmu.edu/?page_id=44 (accessed September 29, 2018).

[70] Interagency Arctic Research Policy Committee. (2016) Arctic Research Plan FY2017-2021. Washington D.C. p. 84. https://www.iarpccollaborations.org/plan/ (accessed April 17, 2018).

operations such as search and rescue, oil spill preparedness and response, and the overall domain awareness necessary to ensure that the Arctic region does not become a seam through which illegal activities can occur undetected.

Accurate operational forecasts of the environment, such as the location of the ice edge, the characteristics and evolution of sea ice, and the wind and wave conditions at the surface, will be critical to safe and efficient operations (defense and commercial) in the Arctic.[71] To achieve this, Earth system models need to better integrate Arctic ocean, ice, and atmospheric data and incorporate the physical processes, interactions, and feedbacks involved in the seasonal evolution of ice extent, area, thickness, and volume. Improved incorporation of Arctic conditions and processes in coupled Earth system models will help constrain predictions of future conditions. Observational technologies that are specifically designed to function in the Arctic environment will help provide better inputs into these models.

Space-based observation of oceanographic parameters and cryospheric parameters in the Arctic can supplement *in situ* measurements in the harsh polar environment. Such observations will be increasingly important to understand processes in the marginal ice zones as ice coverage diminishes and the Arctic becomes a commercially viable transportation route. To achieve this, a change in how we approach Earth system models that better integrate Arctic ocean, ice, and atmospheric data must occur, for example, through the use of evolutionary computation[72] and artificial intelligence. Many of these priorities will be addressed in collaboration with the United States Global Change Research Program (USGCRP) and the Interagency Arctic Research Policy Committee (IARPC).

Priorities

- Support integration of pan-Arctic/global knowledge and activities, including validated coupled ocean-ice-atmosphere models for improved Arctic prediction at multiple time scales.
- Improve models for enhanced forecasting and prediction of Arctic weather.
- Promote collaborative networks of researchers, communities, and native peoples to advance and disseminate knowledge and prediction of the sea ice and Arctic weather systems.
- Support domestic and international R&D focused on innovative response technologies and procedures suitable for the Arctic environment.
- Study the use of dispersants and the impacts of petrochemicals and other hazardous materials in order to provide better oil spill response options and protection for Arctic native communities, sea life, and migratory marine mammals.

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[71] This objective aligns with IARPC Research Goal 9: Enhance Frameworks for Environmental Intelligence Gathering, Interpretation, and Application toward Decision Support. Interagency Arctic Research Policy Committee. (2016) Arctic Research Plan FY2017-2021. Washington D.C. p. 84. https://www.iarpccollaborations.org/plan/research-goal/environmental-intelligence (accessed April 17, 2018).

[72] Eiben, A.E., and J. Smith. (2015) From evolutionary computation to the evolution of things. *Nature* 521:476-482. https://www.nature.com/articles/nature14544 (accessed June 18, 2018).

Maintain and Enhance Marine Transportation

The U.S. Marine Transportation System (MTS)[73] is critical to the economy and national security (Box 3.2). Vital commercial, government (including military), and recreational traffic rely on a safe, secure, and efficient transportation system. The Nation's maritime critical infrastructure–ports, inland waterways, and systems and structures supporting maritime commerce—contributes some $4.6 trillion in economic activity and millions of jobs each year.[74] This includes about $1.5 trillion of cargo annually through U.S. seaports to and from international trading partners.[75] Ocean S&T can support improved waterway management and safety, expanded shipping infrastructure and vessel capabilities, cyber resilience, and enhanced port operations and productivity. Understanding of cyber vulnerabilities in the maritime domain–both ashore and shipboard, mapping and predicting cyber-threats, as well as developing cyber-resilient options for maritime systems–would support mitigation strategies to manage cyber risks in the MTS.[76]

The maritime community relies on critical data during voyage planning and while transiting through U.S. navigational waterways (e.g., data from the Nationwide Automatic Identification System (NAIS),[77] the Physical Oceanographic Real-Time System (PORTS),[78] and Marine Safety Information (MSI)[79]). Such technologies allow for tracking and monitoring of vessel movements using systems along the coast or, when out of range of terrestrial networks, through a growing number of satellites equipped with automatic identification system (AIS) receivers. The International Maritime Organization's (IMO) International Convention for the Safety of Life at Sea (SOLAS) requires AIS to be equipped aboard vessels of 300 or more gross tons engaged in international voyages, and all passenger ships regardless of size. The IMO also requires a similar global system, Long-Range Identification and Tracking (LRIT) for applicable vessels, to provide global identification and tracking in the maritime domain.

In addition to technological advances, the ability to effectively communicate and maintain connections across ocean networks enhances safe navigation, search and rescue operations, and domestic and global trade. This can be achieved through advancing knowledge of the impact of invasive species on maritime transportation, electronic information to support cargo risk assessments, capability to screen cargo at loading, techniques to prevent smuggling of weapons, enhanced container security technologies, and other measures to ensure cargo integrity and in-transit visibility through maritime domain awareness.[80]

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[73] Consists of ocean, coastal, and inland waterways, intermodal connections, and vessels.

[74] U.S. Coast Guard. (2018) 2018 State of the Coast Guard. Admiral Zukunft. March 1, 2018. https://www.uscg.mil/SOTCG2018/ (accessed May 15, 2018).

[75] The National Ocean Service. (2018) How important is our ocean economy? https://oceanservice.noaa.gov/facts/oceaneconomy.html (accessed April 15, 2018).

[76] U.S. Coast Guard. (2017) Cyber Risks in the Marine Transportation System. p. 10. https://www.dco.uscg.mil/Portals/9/CG-FAC/Documents/USCG_Paper_MTS_CyberRisks.pdf?ver=2017-07-19-070403-473 (accessed April 19, 2018).

[77] The NAIS is an automatic tracking system used by ships, Vessel Traffic Services (VTS), and other maritime community users.

[78] PORTS is a program of NOAA's National Ocean Service that supports safe and cost-effective navigation by providing accurate real-time information required to avoid groundings, allisions, and collisions. The information provided at key hubs (currently 31 locations) includes tide/water level, current, wave, meteorological, and bridge clearance information.

[79] MSI is currently provided by the U.S. Coast Guard through "Local Notice of Mariners" and via Very High Frequency-Frequency Modulated (VHF-FM) marine band broadcasts.

[80] U.S. Department of Agriculture. (2015) A Reliable Waterway System is Important to Agriculture. https://www.ams.usda.gov/sites/default/files/media/Importance%20of%20Waterways%2010-2015.pdf (accessed June 15, 2018).

Box 3.2. America is a Maritime Nation

- Our Nation enjoys tremendous geographic advantages in its unhindered access to the Atlantic and Pacific Oceans, the Gulf of Mexico, and the Arctic region.
- America possesses a vast network and thousands of miles of navigable rivers, canals, and other waterways on which ships and barges carry massive amounts of commodities and products both within the United States and to and from the world market, taking advantage of 360 major ports. For example, 60% of U.S. grain exports are moved by barge for at least part of the journey.[80]
- The MTS is the economic lifeblood of the American and global economy, and plays an essential role in U.S. national security and economic interests. It enables critical national security sealift capabilities, where it supports U.S. Armed Forces logistical requirements around the globe.
- Any disruption to the MTS, whether man-made or natural, would have a potentially devastating impact on the domestic and global supply chain.
- New technologies can enhance safety and reduce threats, but also often add complexity to vessel designs, propulsion systems, operations, automation, robotics, networked systems, and new methods for offshore natural resource exploration, production, and transportation, which can make the MTS even more vulnerable to disruption.
- The Federal government, in its enduring role of promoting safety, security, and stewardship, safeguards the MTS and helps ensure the uninterrupted flow of maritime commerce.

Priorities

- Modernize the delivery of Marine Safety Information by experimenting with transmitting enhanced MSI (eMSI) via AIS technology for display on integrated bridge systems.
- Support ocean/maritime information sharing and cybersecurity to deploy maritime surveillance and communications in remote regions.
- Support and validate field detection equipment to detect nuclear, chemical, disease, biological, and other threats at ports of entry.
- Develop and validate systems to identify and track vessels failing to transmit required identification signals (e.g., AIS).
- Examine the vulnerabilities and dependencies between national security and sustainable national and international commerce (e.g., stable currency value, safe ship transit, reliable transportation, and enhanced infrastructure).
- Improve port security through diversified monitoring systems (e.g., use of autonomous platforms, monitoring of undersea cables, and improvement of detection technologies at the entrance to the Nation's ports and other navigable waterways for counter-terrorism evaluation and enhanced maritime security).
- Develop detection/avoidance and low noise technologies for ships to reduce interactions between vessels and marine life (e.g., whales).

Goal IV. Safeguard Human Health

The ocean provides a vast array of resources, natural products, and ecosystem services that impact human health and support our quality of life. It also provides safe and nutritional sources of food and drinking water, and natural products that ameliorate health issues and offer safer alternatives to cosmetics, anti-fouling agents, pharmaceuticals, and other products. More than 28,000 biochemicals have been isolated from marine species; many are important pharmaceutical products and hundreds of new compounds from the marine environment are discovered each year.[81] Moreover, marine organisms are responsible for approximately 50% of the oxygen in the atmosphere. [82]

Despite these benefits, the ocean also has hazards such as marine pathogens and harmful algal blooms (HABs),[83] both of which can produce toxic chemicals detrimental to human health, and pose a threat to our growing economy. [84] For example, the seafood, restaurant, and tourism industries lose about $82 million dollars every year due to the impacts of HABs.[85] In addition, knowledge gaps impede decision-makers from effectively mitigating emerging threats to human health, such as microscopic plastic (microplastics) debris found in the ocean. Advances in ocean S&T to improve seafood quality and safety, and harness the health benefits of seafood consumption, can benefit communities home and abroad.

Recent advances in ocean S&T have led to discovering new products derived from nature and improving risk management. There is still a need, however, to increase our understanding of ocean dynamics and resources, spur technological innovations, and improve the discovery and responsible use of ocean products and services. This can be accomplished by expanding exploration and discovery into unexplored ocean regions, collecting and studying natural products, and developing improved resource management practices, which can reduce the strain on known resources. Prediction, monitoring, and mitigation capabilities can also allow for a more strategic approach for how we use the ocean.

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[81] Blunt, J.W., B.R. Copp B.R., R.A. Keyzers, M.H.G. Munro, and M.R. Prinsep. (2015) Marine natural products. *Nature Product Report* 32:116–211. https://doi.org/10.1039/c4np00144c (accessed June 18, 2018).

[82] Marine phytoplankton are responsible for roughly half of global net primary production. Field, C.B., M.J. Behrenfeld, J.T. Randerson, and P. Falkowski. (1998) Primary production of the biosphere: Integrating terrestrial and oceanic components. *Science,* 281(5374):237-240. http://science.sciencemag.org/content/281/5374/237 (accessed October 4, 2018).

[83] HABs are hyper-proliferating colonies of algae that produce toxic or harmful effects on people, animals, and surrounding ecosystems. More information can be found at: Interagency Working Group on Harmful Algal Bloom and Hypoxia Research and Control Act. (2018) Harmful Algal Blooms and Hypoxia in the United States. A report on interagency progress and implementation. Washington D.C. p. 153. https://cdn.coastalscience.noaa.gov/page-attachments/research/FINAL_USEC%20signed%20-%20Progress%20and%20Implementation%20Report_HABHRCA.pdf (accessed June 15, 2018).

[84] Chen, C.Y., C.T. Driscoll, K.F. Lambert, R.P. Mason, L.R. Rardin, C.V. Schmitt, N.S. Serrell, and E.M. Sunderland. (2012) Sources to seafood: Mercury pollution in the marine environment. Maine Sea Grant College Program. Orono, Maine. p. 26. http://www.dartmouth.edu/~toxmetal/assets/pdf/sources_to_seafood_report.pdf (accessed April 17, 2018); Evers, D.C., J.G. Wiener, C.T. Driscoll, D.A. Gay, N. Basu, B.A. Monson, K.F. Lambert, H.A. Morrison, J.T. Morgan, K.A. Williams, and A.G. Soehl. (2011) Great Lakes mercury connections: The extent and effects of mercury pollution in the Great Lakes region. Biodiversity Research Institute. Gorham, Maine. Report BRI 2011-18, p. 44. http://www.briloon.org/uploads/BRI_Documents/Mercury_Center/Mercury_Connections/GLMC_FinalReport.pdf (accessed April 17, 2018).

[85] National Ocean Service. (2017) Why Do Harmful Algal Blooms Occur? https://oceanservice.noaa.gov/facts/why_habs.html (accessed April 19, 2018).

Prevent and Reduce Plastic Pollution

Plastics provide important benefits to our society and are used to make many everyday products, from medical devices to automobile airbags, to cell phones and computers. However, too many plastics—especially single-use plastics—are not properly disposed of and find their way into our oceans and waterways. Other items are lost, abandoned, or discarded at sea, such as derelict fishing gear and other items from vessels or stationary platforms. Once in the marine environment, these plastics are considered to be marine debris. This marine debris leads to wildlife entanglement, animal mortality from ingestion, habitat destruction, water contamination, flooding from clogged drainage systems, impediments to transportation and commerce, and impacts on human health.

Plastic debris is ubiquitous in all marine and freshwater environments, and has been documented globally from rivers and lakes, inland seas, shorelines, the ocean's surface and water column, coastal and deep-sea sediments, sea ice, and biota. It exists throughout the global ocean due to its durability, global usage, and ease of transport by ocean currents and wind. Marine plastic debris threatens the healthy functioning of coastal, freshwater, and ocean ecosystems, along with the societies and economies reliant upon them. A better understanding of the sources, transport, fate, and impacts of marine plastics will be essential to identifying effective, globally-translatable solutions for marine plastic debris.

Marine plastic debris originates from land-based and sea-based activities. It is estimated that more than half of the plastic in the global ocean originates from five countries: China, Indonesia, Philippines, Vietnam, and Sri Lanka.[86] Research suggests that mismanaged plastic waste, including materials from inadequate waste management systems, is the most significant pathway by which land-based sources of debris can reach the ocean.[86] Plastics do *not* mineralize (i.e., chemically break down) once they enter the environment, but instead physically break apart into smaller pieces called microplastics (Box 4.1). Consequently, plastic material remains in marine and freshwater environments for a long period of time, posing a threat to ecosystems, wildlife, humans, and economies across the globe.

Plastic debris can have widespread economic, ecological, and human health impacts. Marine debris can affect several economic sectors including aquaculture, fisheries, coastal tourism, commercial shipping, recreational boating, local coastal governments, and emergency response services. The costs associated with marine debris can be direct (e.g., beach cleanups, fishing gear replacement) or indirect (e.g., reduced revenue for coastal tourism industries, impacts to biodiversity and ecosystem services). Marine debris encounters have been documented for nearly 700 species,[87] from coastal vegetation, to plankton, invertebrates, fish, cetaceans, sea turtles, and seabirds. Common wildlife impacts include ingestion, entanglement, transport of non-native species, and habitat damage. Finally, plastic marine debris contains, and can possibly transfer, chemicals having known toxicological effects on humans and wildlife through pathways including ingestion, inhalation, and contact.[88] However, the actual

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[86] Jambeck J.R., R. Geyer, C. Wilcox, T.R. Siegler, M. Perryman, A. Andrady, R. Narayan, and K.L. Law. (2015) Plastic waste inputs from land into the ocean. *Science* 347 (6223): 768-771. http://science.sciencemag.org/content/347/6223/768.full (accessed October 2, 2018).

[87] Gall S.C., and R.C. Thompson. (2015) The impact of debris on marine life. *Marine Pollution Bulletin* 92: 170–179. https://www.sciencedirect.com/science/article/pii/S0025326X14008571?via%3Dihub (accessed October 2, 2018).

[88] Smith M., D.C. Love, C.M. Rochman, and R.A. Neff. (2018) Microplastics in seafood and the implications for human health. *Current Environmental Health Reports* 3: 375-386. https://link.springer.com/article/10.1007%2Fs40572-018-0206-z (accessed October 2, 2018); Koelmans A.A., E. Besseling, E. Foekema, M. Kooi, S. Mintenig, B.C. Ossendorp, P.E. Redondo-Hasselerharm, A. Verschoor, A.P. van Weze, and M. Scheffer. (2017) Risks of plastic debris: unravelling fact, opinion, perception, and belief. *Environmental Science & Technology* 51: 11513-11519. https://pubs.acs.org/doi/abs/10.1021/acs.est.7b02219 (accessed October 2, 2018); Koelmans A.A., A. Bakir, G.A. Burton, and C.R. Janssen. (2016) Microplastics as a vector for chemicals in the

ecological and human health risks associated with different plastics and their associated chemicals remain largely unknown.[89]

In order to effectively address marine plastic debris, additional research is needed in a number of areas. One area includes scalable waste management technologies that allow for appropriate containment and safe reuse of plastic waste. Equally important, S&T can support ongoing monitoring, modeling, and research in order to more fully characterize the scope and scale of the marine plastic debris problem. Domestic and international efforts to prevent plastic debris must occur alongside research to understand, and ultimately mitigate, its effects on marine and freshwater ecosystems, humans, and the ocean. Public-private partnerships and collaborative efforts by the public, academia, nongovernmental organizations, non-profit organizations, and government agencies can address this man-made problem to achieve a cleaner future by both preventing and reducing plastic pollution.

Priorities

- Establish reliable and reproducible methods for monitoring marine debris, including the collection, extraction, characterization, and quantification of plastics across various environmental compartments (e.g., shoreline, sea surface, water column, seafloor, and biota) in both marine and freshwater systems.
- Improve understanding of the transport and fate of marine debris within and among environmental compartments as a result of oceanographic processes and the variable processes of degradation, fragmentation, biofouling, and bioaggregation among polymer types.
- Support development of next-generation biodegradable plastics to reduce marine debris impacts on marine life and coastal communities.
- Estimate the risks associated with microplastic exposure for commercial seafood resources and humans to improve the understanding of potential exposure pathways, toxicological mechanisms, and public health concerns.
- Collaborate with industry to evaluate current (and if necessary, develop new) innovative, cost-effective technologies and methodologies to gather, recycle/reuse, and treat plastic waste.

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aquatic environment: critical review and model-supported reinterpretation of empirical studies. *Environmental Science & Technology* 50: 3315-3326. https://pubs.acs.org/doi/10.1021/acs.est.5b06069 (accessed October 2, 2018).

[89] Koelmans A.A., E. Besseling, E. Foekema, M. Kooi, S. Mintenig, B.C. Ossendorp, P.E. Redondo-Hasselerharm, A. Verschoor, A.P. van Weze, and M. Scheffer. (2017) Risks of plastic debris: unravelling fact, opinion, perception, and belief. *Environmental Science & Technology* 51: 11513-11519. https://pubs.acs.org/doi/abs/10.1021/acs.est.7b02219 (accessed October 2, 2018).

Box 4.1. Microplastics Accumulation in the Food Chain

Microplastics are particles of plastic that range in size from 1 nanometer to < 5 millimeters.[90] They can be manufactured for household products or result from larger pieces of marine debris breaking down over time into smaller pieces. It is estimated that 269,000 metric tons of microplastics are floating at or near the surface of the ocean, affecting over 700 marine species.[91] Depending on the material, microplastics may float or sink, contaminating both coastal and deep-sea sediments.[92] Ingestion of microplastics by marine organisms at all trophic levels is well documented. However, there is limited evidence to suggest that microplastics are a relevant exposure pathway for the transfer of persistent organic pollutants into organisms.[93] The transfer of microplastics from marine organisms to humans through seafood consumption may present a risk to human health, yet research is lacking.[94] Likely, plastic-mediated contaminants accumulate due to the preferred binding of persistent organic pollutants (including polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs)) to plastic particles.[95] However, the scientific community is still investigating whether microplastics themselves leach into the tissue of marine organisms that consume them.[93] For the coming decade, we should learn how these processes and direct exposure of microplastic chemicals through the food chain ultimately impact human health. In addition, further research is necessary to determine the extent to which microbes in the ocean environment consume persistent plastics and what might be done to enhance the success of such natural processes.

Figure 4.1. Accumulation of microplastics on a shoreline. (Image courtesy of NOAA)

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[90] Joint Group of Experts on the Scientific Aspects of Marine Environmental Pollution. (2015) Sources, fate and effects of microplastics in the marine environment: a global assessment. International Maritime Organization 90, p. 98. http://www.gesamp.org/publications/reports-and-studies-no-90 (accessed November 7, 2018).

[91] Eriksen, M., L.C.M. Lebreton, H.S. Carson, M. Thiel, C.J. Moore, J.C. Borerro, F. Galgani, P.G. Ryan, and J. Reisser. (2014) Plastic pollution in the world's oceans: More than 5 trillion plastic pieces weighing over 250,000 tons afloat at sea. *PloS one* 9:e111913. https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0111913 (accessed June 18, 2018); Gall S.C., and R.C. Thompson. (2015) The impact of debris on marine life. *Marine Pollution Bulletin* 92: 170–179. https://www.sciencedirect.com/science/article/pii/S0025326X14008571 (accessed October 2, 2018).

Improve Forecasts of Marine Contaminants and Pathogens

Ocean chemistry can enhance human well-being by supplying healthy compounds in our food, but it can also put human health at risk, such as by exposing people to toxins. Through state-of-the-art forecasting capabilities of ocean chemicals and conditions, researchers and managers have been able to reduce the risk of threats such as seafood-borne illness (e.g., shellfish and finfish poisoning). Through monitoring levels of known toxins and pathogens, the seafood industry works with local, State, and Federal agencies to provide healthier products and guard against potential human health risks from the ocean.[96] Predictive capabilities depend on research in ocean hydrodynamics, chemical fate and transport, and human reactions to toxins and pathogens. For example, continuous monitoring of temperature and salinity in coastal regions can help predict overgrowth of *Vibrio vulnificus*, the bacterium responsible for 95% of seafood-related death in the United States.[97] Bacterial infections can result from ingestion of contaminated seafood or enter via the bloodstream by way of open wounds exposed to tainted seawater. Toxin-associated illnesses occur in a similar fashion via ingestion of animals (namely shellfish) that have been feeding on several species of toxin-producing algae.

There are also large uncertainties in contaminant emission rates and ocean-mediated biogeochemical cycling mechanisms. An increased understanding of such processes can better inform consequences such as that of halogens and isoprene emissions from the ocean that can exert significant influences on atmospheric chemistry, including ozone levels. Forecasting ocean biogeochemical and physical cycling is done at multiple spatial and temporal scales. For example, forecasting of waterborne pathogen levels might be necessary over a time scale of days for a specific recreational area, whereas forecasting of contamination levels in fish in a large area such as Lake Superior might change over years to decades. Forecasting tools require accurate estimates of contaminant sources and how these sources change over time, and need to be based on validated models (Box 4.2).

Priorities

- Improve predictive mathematical models of the sources, transport, fate, and degradation of constituents immediately relevant to human health.
- Understand the pathways of human and animal exposure to waterborne pathogens, toxic chemicals, and algal toxins, including oral, dermal, and airborne routes via drinking water, food, recreational water, and aerosols.

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[92] Woodall, L.C, A. Sanchez-Vidal, M. Canals, G.L.J. Paterson, R. Coppock, V. Sleight, A. Calafat, A.D. Rogers, B.E. Narayanaswamy, and R.C. Thompson. (2014) The deep sea is a major sink for microplastic debris. *Royal Society Open Science* 1:140317. http://rsos.royalsocietypublishing.org/content/1/4/140317 (accessed June 18, 2018).

[93] Lohmann, R. (2017) Microplastics are not important for the cycling and bioaccumulation of organic pollutants in the oceans—but should microplastics be considered POPs themselves? *Integrated Environmental Assessment and Management* 13(3): 460-465. https://setac.onlinelibrary.wiley.com/doi/abs/10.1002/ieam.1914 (accessed November 7, 2018).

[94] Smith M., D.C. Love, C.M. Rochman, and R.A. Neff. (2018) Microplastics in seafood and the implications for human health. *Current Environmental Health Reports* 3: 375-386. https://link.springer.com/article/10.1007%2Fs40572-018-0206-z (accessed October 2, 2018).

[95] Seltenrich, N. (2015) New Link in the food chain? Marine plastic pollution and seafood safety. *Environmental Health Perspectives* 123(2):35-123. https://www.ncbi.nlm.nih.gov/pubmed/25643424 (accessed April 17, 2018).

[96] McMichael, A.J., C.D. Butler, and J. Dixon. (2015) Climate change, food systems and population health risks in their eco-social context. *Public Health* 129(10):1361-1368. https://www.ncbi.nlm.nih.gov/pubmed/25896548 (accessed June 15, 2018).

[97] National Centers for Coastal Ocean Science. (2017) Chesapeake Bay Vibrio Pathogen Forecast. https://coastalscience.noaa.gov/project/chesapeake-bay-vibrio-pathogen-forecast/ (accessed May 30, 2018).

- Advance knowledge of the exchange of chemical contaminants and nutrients between the ocean and the atmosphere, the impacts of the changing ocean, and other contributors to the occurrence, frequency, and severity of human health impacts from constituents relevant to human health.
- Support computational modeling capabilities for bioaccumulation research, especially in pharmacokinetic simulations[98] of contaminants threatening water quality and food safety (e.g., per- and polyfluoroalkyl substances).

Box 4.2. Building Forecasting Tools for Human Health

- Contaminants produced *in situ*, such as biotoxins, require accurate estimates of generation or production rates under different conditions.
- Understanding toxic chemicals requires knowledge of loading rates from direct discharges, nonpoint sources, and indirect pathways such as watershed processes and atmospheric surface exchange, as well as the legacy distribution and amounts of the pollutant within the system resulting from past loading.
- Forecasting of atmospheric deposition requires understanding of atmospheric emissions as well as atmospheric fate and transport processes. Once the loading and/or generation rates are understood, knowledge of the dynamic behavior of the contaminant in the oceanic ecosystem is required.
- Advanced research and technologies require more effective measuring of biological variables and indicators.

Combat Harmful Algal Blooms

Understanding the incidence, severity, and persistence of hazards to human health from oceanic, estuarine, and freshwater areas requires increased observations at multiple spatial and temporal scales. This includes arrays and networks of monitoring sites, *in situ* measurements from buoys and instrumented moorings, and remotely-sensed data and imagery from aircraft and satellites. An example for this need to enhance monitoring capabilities is the increasing occurrence and spread of HAB events worldwide, including recent highly impactful HAB events in the United States.[83]

HABs are created by a small subset of naturally occurring microscopic or larger plant-like cyanobacteria or algal species. However, over the past several years in particular, their "blooms" (rapid growth periods) have become more prevalent and severe. The physical, chemical, and biological conditions that influence HAB development and persistence are myriad and may include changes in water temperature, extreme weather events, and precipitation patterns due to climatic changes; runoff and pollution from wastewater systems, urban areas, and agricultural sites; and invasive organisms.

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[98] "Pharmacokinetic simulations demonstrate the fate of a chemical inside of the body, from initial exposure to elimination, and how the body's absorption, distribution, etc. may alter the chemical compound." Environmental Protection Agency. (2018) Research on Per- and Polyfluoroalkyl Substances (PFAS). https://www.epa.gov/chemical-research/research-and-polyfluoroalkyl-substances-pfas (accessed September 4, 2018).

HABs have been reported in every U.S. coastal State and can produce a toxic threat to humans and their local environment.[99] This threat to the seafood and tourism industries calls for improved HAB toxin sensors, monitoring protocols, and quantification of toxins and their chemical structures. Better understanding the source, fate, and spatial and temporal scales of land-based nutrient runoff in relation to HABs will help mitigate these events in coastal and oceanic environments. New technologies based on immunoassays, enzyme inhibition, optical biosensors, nucleic acid amplification, and other novel approaches continue to evolve under government and private funding. Federal leadership is needed on the provision and quality of reference materials (e.g., specimens, toxin standards, and molecular probes) as well as data management and data visualization tools for increased awareness of public health risks and effective response and mitigation strategies.

Policy-makers, public health authorities, and communities need the best available information to minimize current and future exposure to HABs and other known and potential ocean related health threats. Ongoing R&D should focus on analytical measurements, process understanding, and modeling to provide more reliable, useful, timely, and policy-relevant information.

Priorities

- Develop guidelines, testing methods, and rapid response strategies for accurate assessment and mitigation of pathogens, eutrophying chemicals, toxic chemicals, and algal toxins.
- Enhance and transfer new tools and technologies such as omics and bioinformatics into management programs that promote human health and protect humans from HABs and other ocean-related issues.
- Generate data for computational and mathematical model evaluation and improvement to develop risk assessments of HABs and other known and emerging threats to human health.
- Document human and animal exposure, illness, disease, and death related to HABs and other water quality risks.
- Emphasize public access to monitoring data, create user-friendly data formats, and ensure readily available metadata of parameters related to health risks.
- Develop socioeconomic measures to estimate societal costs from exposure to HABs and other ocean-related human health hazards, and share that information with State, local, and tribal groups.

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[99] Environmental Protection Agency. (2017) Nutrient Pollution: Harmful Algal Blooms. https://www.epa.gov/nutrientpollution/harmful-algal-blooms (accessed June 12, 2018).

Discover Natural Products

While many promising pharmaceutical candidates are produced through synthetic approaches, approximately half of all new pharmaceutical approvals still trace their structural origin to natural products,[100] illustrating the unique structural and chemical diversity found in the ocean environment. A substantial number of natural products with applications in medicine (anti-cancer, anti-viral, anti-fungal, antibiotics), nutrients (dietary supplements, food additives), energy (biofuels), and other beneficial materials (e.g., antifoulant, diagnostics tools, and cosmetics) derive from marine hosts.[101] For example, the Alaskan deep-water green sponge produces molecules that target and kill pancreatic cancer cells in the laboratory.[102] Microbial (bacteria and archaea) and eukaryotic (fungi) symbionts of various marine hosts also produce a wide variety of compounds with potential for drug discovery. The rich diversity of the ocean presents enormous economic and biological potential (Box 4.3). Advances in ocean exploration and non-invasive discovery technologies (e.g., acoustic tools, digital imaging, remote vehicles, deep-diving submersibles, and improved environmental sensors) will enable Americans to leverage such potential, while also mitigating environmental impacts.

Advances in molecular approaches such as metagenomics, metatranscriptomics, and metabolomics will improve the discovery, optimize production, and increase understanding of the mechanisms for how chemicals influence our bodies. Increased computational capabilities and improvements in bioinformatics analyses, as well as open access knowledge and sharing of raw data, will open new doors for harnessing marine natural products.

Priorities

- Continue responsible exploration and discovery of oceanic habitats and associated species, including bacteria, archaea, fungi, microbes, and viruses, to discover natural products and processes that improve human health and the environment.
- Contribute to research on sensors and collection devices for extreme and hostile ocean environments, such as the deep-sea, to facilitate expanded sustainable ocean exploration and discovery.

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[100] Stratton, C., D.J. Newman, and D.S. Tana. (2015) Cheminformatic comparison of approved drugs from natural product versus synthetic origins. *Bioorganic and Medicinal Chemistry Lett*ers 25(21):4802–4807. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4607632/ (accessed June 15, 2018).

[101] Food and Drug Administration. (2011) Fish and Fishery Products Hazards and Controls Guidance, Fourth Edition. Florida Sea Grant College Program. Gainesville, Florida. p. 468. https://www.fda.gov/downloads/food/guidanceregulation/ucm251970.pdf (accessed April 17, 2018).

[102] Alaska Fisheries Science Center. (2017) Small, deep-water Alaska sponge has molecules that selectively target and kill pancreatic tumor cells. https://www.afsc.noaa.gov/News/Green_Sponge.htm# (accessed April 17, 2018).

[103] Lawson, K. (2011) Global Markets for Marine-Derived Pharmaceuticals. BCC Research. https://www.bccresearch.com/market-research/pharmaceuticals/marine-derived-pharma-markets-phm101a.html (accessed April 17, 2018); Blasiak, R., J-B. Jouffray, C.C.C. Wabnitz, E. Sundstrom, and H. Osterblom. (2018) Corporate control and global governance of marine genetic resources. *Science Advances* 4(6): eaar5237. http://advances.sciencemag.org/content/4/6/eaar5237 (accessed October 22, 2018).

[104] Vierros, M., C.A. Suttle, H. Harden-Davies, and G. Burton. (2016) Who owns the ocean? Policy issues surrounding marine genetic resources. *Limnology and Oceanography Bulletin* 25(2):29–35. https://aslopubs.onlinelibrary.wiley.com/doi/full/10.1002/lob.10108 (accessed April 17, 2018).

[105] Mayer, A.M.S. (2018) Marine Pharmaceuticals: The Clinical Pipeline. http://marinepharmacology.midwestern.edu/clinical_pipeline.html (accessed November 7, 2018).

[106] Malve, H. (2016) Exploring the ocean for new drug development: Marine pharmacology. *Journal of Pharmacy and BioAllied Sciences* 8(2): 83-91. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4832911/ (accessed June 18, 2018).

- Support the infrastructure (e.g., analytical methods, computer data mining technology, bioinformatics, computational capabilities) to screen, identify, and make sustainable use of beneficial natural products.
- Understand opportunities for increasing macroalgae culturing for use as raw material for beneficial algal bioproducts such as foods and biofuels.
- Accelerate partnerships with private industry and academia to support biosynthetic assembly lines and incubation beds (i.e., demonstration projects) to more rapidly move products to market, and improve mariculture techniques to assure the supply of natural products for R&D.

Box 4.3. Economic Potential of Marine Natural Products

- Ocean-derived pharmaceuticals are rapidly expanding in the global market, from $4.8 billion in 2011 to a projected global market of marine biotechnology at $6.4 billion by 2025.[103]
- Patent applications related to marine genetic material are increasing at a rate of 12% each year, with over 5,000 genes derived from marine organisms already patented.[104]
- The Global Marine Pharmaceuticals Clinical Pipeline[105] reveals over 30 natural products, which have been Food and Drug Administration (FDA)-approved or are in Phase III, II, or I of pharmaceutical development.
    - 59% of these compounds are isolated from bacteria associated with marine mollusks or sponges.
    - 80% of these compounds target various cancers.
- Approximately 1,340 new marine natural product compounds were isolated from various marine microbes, invertebrates, and algae in 2015.[81]
- There are currently over 20 marine natural products in FDA preclinical trials that target various diseases including bacterial and fungal infections, malaria, tuberculosis, diabetes, cystic fibrosis, and cancer.[106]

Goal V. Develop Resilient Coastal Communities

In 2017, the United States experienced the most expensive year on record in terms of natural disasters, causing $306 billion in total damage, of which $265 billion came from hurricanes.[107] Changing climatic conditions can affect the Earth's hydrological cycle, atmospheric water vapor concentrations, clouds, precipitation patterns, and runoff and stream flow patterns.[108] Flooding and coastal storms can have huge direct costs related to damaged local infrastructure[109] as well as other indirect economic and social costs[110] that affect people throughout the country (Box 5.1).[111] To protect coastal populations and infrastructure, the Nation must find ways to encourage innovation while mitigating risk from storms and other hazards. It is critical to prepare communities for extreme weather using scientific information, adaptive management strategies, and enhanced communication to promote a more resilient weather-ready Nation.

Our coasts and associated communities are economic engines that provide transportation, recreation, tourism, and energy for the millions of people that visit and reside in coastal as well as inland areas. Comprehensive understanding of the coastal and marine ecosystems, forecasting shifts of community vulnerability due to human and natural processes, and embedding that knowledge in decision-making processes that reduce risk and vulnerability and enhance economic prosperity of U.S. communities are long-standing scientific and technological challenges. Science-based information and tools can help coastal communities respond and adapt to a changing ocean.

The economic strength and sustainability of U.S. communities depends on services the ocean provides. Identification and measurement of communities' strengths and vulnerabilities allow managers and other decision-makers to assess management strategies to build and maintain resilient and prosperous communities, while promoting sustainable economic growth and healthy ecosystems. This baseline information also enables temporal and geographic comparisons of social-ecological systems and associated ecosystem services to understand and forecast the impacts of environmental change on the well-being of human communities for generations to come.

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[107] National Centers for Environmental Information. (2018) U.S. Billion-Dollar Weather and Climate Disasters. https://www.ncdc.noaa.gov/billions/ (accessed April 17, 2018).

[108] NASA. (2018) The Water Cycle and Climate Change. https://earthobservatory.nasa.gov/Features/Water/page3.php (accessed April 17, 2018).

[109] Padgett, J., R. DesRoches, B. Nielson, M. Yashinsky, O.S. Kwon, N. Burdette, and E. Tavera. (2008) Bridge damage and repair costs from Hurricane Katrina. *Journal of Bridge Engineering* 13(1):6-14. https://ascelibrary.org/doi/abs/10.1061/(ASCE)1084-0702(2008)13%3A1(6) (accessed June 15, 2018); Kunz, M., B. Mühr, T. Kunz-Plapp, J.E. Daniell, B. Khazai, F. Wenzel, M. Vannieuwenhuyse, T. Comes, F. Elmer, K. Schröter, and J. Fohringer. (2013) Investigation of superstorm Sandy 2012 in a multi-disciplinary approach. *Natural Hazards and Earth System Sciences* 13(10):2579. https://doi.org/10.5194/nhess-13-2579-2013 (accessed June 15, 2018).

[110] Morris, K.A., and N.M. Deterding. (2016) The emotional cost of distance: Geographic social network dispersion and post-traumatic stress among survivors of Hurricane Katrina. *Social Science and Medicine* 165:56-65. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5003656/ (accessed June 15, 2018).

[111] Shen, G., and S.G. Aydin. (2014) Highway freight transportation disruptions under an extreme environmental event: the case of Hurricane Katrina. *International Journal of Environmental Science and Technology*, 11(8):2387-2402. https://link.springer.com/article/10.1007/s13762-014-0677-x (accessed April 15, 2018); Becker, A.H., P. Matson, M. Fischer, and M.D. Mastrandrea. (2015) Towards seaport resilience for climate change adaptation: Stakeholder perceptions of hurricane impacts in Gulfport (MS) and Providence (RI). *Progress in Planning* 99:1-49. https://www.sciencedirect.com/science/article/pii/S0305900614000427 (accessed April 15, 2018).

Box 5.1. The Cost of Extreme Events

- In 2017 alone, there were 16 weather and climate related events from drought, flooding, freeze, severe storm, tropical cyclone, or wildfire events in which, for each event, economic damage exceeded $1 billion.[112]
- Estimated damages from Hurricane Harvey, including property damage, lost wages, and disrupted business, were as much as $125 billion.[113]
- Superstorm Sandy made landfall on October 29, 2012, devastating coastal communities and causing over $70 billion in property damage and at least 147 direct deaths across the Atlantic basin.[114]

Figure 5.1. Satellite photos of Ortley Beach, New Jersey, before (top) and after (bottom) Superstorm Sandy. (Images courtesy of NOAA and Google)

Prepare for Natural Disasters and Weather Events

The United States has experienced more than 219 weather and climate disasters since 1980, resulting in the total cost of more than $1.5 trillion[115] which is about $45 billion per year. Disasters are generally focused and have a disproportionately larger impact on specific locations and communities. Building a weather-ready Nation, where society is prepared for and responds appropriately to extreme weather, water, climate, and environmental threats is critical. Ensuring community resilience in the face of increasing vulnerability requires collaboration across all levels of government, industry, nonprofits, and academia (Box 5.2). Decision support services, along with physical, natural, and social science data and information, can help coastal communities mitigate the impacts from these threats.

Whether on a fair, sunny, and mild day or during an extreme-weather event with potential for loss of life and property destruction, improved decisions contribute to better prepared communities. Nowhere is this more important than in the coastal environment, where there is a need for continued research, support, and data for informed decision-making. Connections to the marine enterprise require relationship building, gathering and streamlining of requirements, and a coordinated approach to decision-support tools. Decision-support tools help build resilience and reduce adverse consequences. This all results in safer and more secure maritime transportation and enhances safe, enjoyable coastal recreation. The goal is a future with minimal weather-related losses of life and property at sea, along our coasts, and within our watersheds.

Box 5.2. Hurricane Harvey

Hurricane Harvey in 2017 resulted in major impacts to lives and property due to extensive flooding from storm surge, unrelenting rainfall, and heavy riverine discharge. Model predictions are not yet able to quantitatively link these three sources of coastal inundation, highlighting a critical gap in capabilities. Addressing the "Harvey-gap" in total coastal water-level prediction and Impact-based Decision Support Services (IDSS) capabilities requires coupled atmosphere-ocean-land-wave models. To address this, efforts are underway to develop a total coastal water plan to conduct modeling in a single estuary beginning in 2018 and expanding to a full national operational capability in 5-10 years. Initial capabilities will focus on water levels with 2-D ocean models; "end products" in the 10-year time frame will have to address navigation and water quality issues with 3D ocean models.

IDSS requires both accurate modeling and an accurate assessment of model uncertainties. Stochastic atmospheric physics and developing strategies for coupled ensemble generation (particularly for non-weather coupled components) are active fields of research that will enhance operational improvement over the next 5-10 years.

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[112] National Centers for Environmental Information. (2018) U.S. Billion-Dollar Weather and Climate Disasters: Table of Events. https://www.ncdc.noaa.gov/billions/events/US/1980-2018 (accessed April 17, 2018).

[113] Office for Coastal Management. (2018) Hurricane Costs. https://coast.noaa.gov/states/fast-facts/hurricane-costs.html (accessed April 17, 2018).

[114] Hurricane Research Division. (2017) Costliest mainland United States tropical cyclones 1900-2017. Unadjusted for inflation. http://www.aoml.noaa.gov/hrd/tcfaq/costliesttable.html (accessed April 17, 2018).

[115] United States Global Change Research Program. (2014) National Climate Assessment. USGCRP. Washington, D.C. http://nca2014.globalchange.gov/highlights/report-findings/extreme-weather (accessed June 15, 2018).

Priorities

- Conduct needs assessments to determine status of prediction tools and information already provided, identify existing gaps and enhance the capacity and capability to offer, integrate, display, and disseminate data and information.
- Support and disseminate tools for understanding and translating science to promote resilience-based approaches in ocean and coastal communities, waterborne recreational users, and those experiencing drought and flooding.
- Identify needs, areas for coordination, methods for technology transfer, and develop and implement a suite of integrated marine weather products to provide earlier warning and better highlight hazardous weather conditions at sea, fortify water quality efforts underway,[116] and reduce risk to coastal residents unaware of extreme weather events and storm surge.
- Produce and implement communications and outreach strategies with associated milestones, training tools and media relations platforms delivering technology, resilience, and commerce-related success stories to showcase products and services, increase awareness, educate, and enable adaptation strategies.

Reduce Risk and Vulnerabilities

While natural disasters and weather events are major threats, coastal communities are also at risk because of many other disturbances. In particular, many communities depend on coastal and marine resources for commercial and recreational uses, and changes to those resources provide both risks and opportunities to those industries and activities engaged in those uses. For example, fish populations may migrate along coasts, disrupting areas historically dependent on those populations, and providing new opportunities for other communities. Similarly, coastal economies and ecosystems are often dependent on their beaches and research into pollution discharge, sea level rise, and sediment transport and resulting changes in geomorphology is critical.

The ability of communities to overcome these disruptions depends on reducing risk, and where possible, capitalizing on opportunities by understanding community dependencies, forecasting resource responses to environmental change, and providing options for resource managers and industries to plan for the future. Because our Nation's security and prosperity is affected by our communities' access and use of coastal resources (e.g., fisheries, energy, recreation, and cultural heritage), it is important to understand the factors that affect the ability of communities to respond to, and recover from, natural and manmade disturbances. Vulnerability assessments for communities can lead to further risk reduction.

There is interest in better understanding the current state of resilience at multiple scales—from national to local—and the various determining factors that influence community resilience. Community resilience is affected by economic stability and the ability for communities to survive and rebuild in response to diverse challenges and impacts. Coastal communities recognized as highly resilient will attract investment and strengthen the ocean economy.

Understanding how communities change over time requires baseline information to assess vulnerability and resilience historically and into the future. This effort requires collaborative efforts between local community, State, and Federal governments to determine past conditions, current trends, and future projections. Thus, accurate observations, mapping, and ecosystem condition data

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[116] More information can be found at: https://www.epa.gov/aboutepa/about-office-water (accessed June 12, 2018).

must be available for modeling and analyses across the entire coastal area.[117] This baseline information leads to a better understanding and measure of community vulnerability and resilience.

Whether it be a coastal city planner developing a new 50-year infrastructure plan, or a fisherman preparing for the next season, individuals and communities are often presented with a myriad of choices, some which reduce risk and some which augment risk. Understanding the economic or social drivers that lead to support, opposition, or indifference to specific risk-reduction strategies or community enhancement actions could lead to increased effectiveness and reduced cost for local economies and response entities.

Priorities

- Examine community-driven resilience planning that uses the experience, concerns, and needs of industry and stakeholders, and incorporates their perspectives in conjunction with conventional science-supported, public-sector planning efforts.
- Identify and document baseline conditions (e.g., biophysical, economic, ecological, social, and cultural) and biophysical indicators for use in assessments of environmental and natural hazards, catastrophic events, cumulative effects, and community vulnerability and resilience.
- Examine how environmental hazards, including a changing climate and rising sea level, along our coasts are affecting American communities (e.g., economic, ecological, social, and cultural) at varied scales, resulting in questions concerning financial and social vulnerabilities to certain populations.
- Understand, describe, and quantify where possible, social vulnerability and the factors that contribute to the resilience of communities that depend upon and engage with coastal and marine resources.
- Assess how future conditions and changes to the environment could interact with hazards and catastrophic events, and affect community vulnerability, resilience, and continuity.
- Describe and evaluate effects of key drivers on community and economic resilience (e.g., presence/absence, application, consistency, compliance, and effectiveness of planning and construction laws, regulations, ordinances, codes, and practices; barriers and effectiveness of incentive mechanisms, and existing socioeconomic conditions of populations).
- Research the risks of ocean acidification and other ocean changes as they relate to at-risk populations, food security, and the implications for humanitarian crises.

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[117] Interagency Arctic Research Policy Committee. (2016) Arctic Research Plan FY2017-2021. 8.4 Improve observations, mapping, and charting to support research across the coastal interface. Washington D.C. 46-47. https://www.iarpccollaborations.org/plan/objective/8.4 (accessed April 17, 2018).

Empower Local and Regional Decision-Making

For a coastal community to be resilient, it must build capacity to respond to disturbances. This requires a better understanding of the particular characteristics of the community and industries, as well as information to support dynamic risk assessment and cost-benefit analysis of local and regional trade-offs. The Organization for Economic Cooperation and Development defines capacity development as the "process by which individuals, groups, organizations, institutions, and societies increase their abilities to: (1) perform core functions, solve problems, define, and achieve objectives; and (2) understand and deal with their development needs in a broad context and in a sustainable manner." In alignment with the other national initiatives (e.g., National Preparedness Goal[118]), research, technical assistance, and capacity development actions should be fostered to understand existing conditions and address deficiencies for coastal community and economic resilience across multiple scales.

There is no "one size fits all" to understanding, measuring, or developing capacity for community resilience. Rather, developing capacity is context and location specific and depends on a community's physical, social, economic, and cultural characteristics, which vary from place to place, by region, and through time. Access to local and regional specific data, including traditional, indigenous, or local knowledge, and data tools can assist effective decision-making when planning for the future of coastal communities.[119]

Arising coastal issues, including management towards sustainable fisheries and ecosystems, are often best addressed holistically. There is a growing body of case studies where both Western science and traditional ecological knowledge have effectively been applied to the marine realm, including coastal regions employing partnerships with local and regional tribal organizations. Federal agencies should develop best practices for such partnerships and seek to expand partnerships in the coming decade.

The complex interconnections between humans and marine ecosystems also require a better understanding of their spatial and temporal scales. Research that considers all the drivers influencing a resource is better equipped to provide government, industry, nonprofits, and academia a more accurate understanding of marine resource-based economies and their challenges and opportunities for growth. Such greater understanding will provide more realistic situational awareness of our coastal and marine resources so that coastal communities and marine industries can appropriately prepare for and adapt to changes. Capacity building depends on incorporating stakeholders who are dependent on marine resources into resilience planning.

Incentive programs can aid in the acceptance of program requirements by offsetting real or perceived costs, but may not be adopted for reasons that are still not understood. Applied economics, psychology, and decision science can help determine what makes something acceptable and why, how opinions are formed and influenced by others, and ultimately which decision made by an individual or a community is refused or adopted.

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[118] FEMA. (2018) National Preparedness Goal. https://www.fema.gov/national-preparedness-goal (accessed April 17, 2018).

[119] Such local and regional data, tools, and technical support is available through integrated marine information systems such the Digital Coast Partnership (https://coast.noaa.gov/digitalcoast/), the Marine Cadastre (https://marinecadastre.gov/), and Regional Ocean Partnership (ROP) portals (e.g., the Northeast Ocean Data Portal, https://www.northeastoceandata.org/), some of which are supported by Executive Order 13840, issued on June 19, 2018, Ocean Policy To Advance the Economic, Security, and Environmental Interests of the United States. https://www.federalregister.gov/documents/2018/06/22/2018-13640/ocean-policy-to-advance-the-economic-security-and-environmental-interests-of-the-united-states (accessed October 12, 2018).

Priorities

- Examine incentives and successful adoption of specific programs or concepts across segments of a community (e.g., by population characteristics, such as age, gender, profession, income, and education). Identify and inform decision-makers of specific incentives and disincentives related to actions to further improve community recovery and adaptation capabilities.
- Assess and evaluate existing and potential community-level adaptations to environmental variability and change to understand what elements are most effective in mitigating impacts and what factors are most important in adoption of those adaptation measures.
- Develop capacity to deliver research results and culturally relevant products to all communities at risk (e.g., translating scientific jargon, evaluating and communicating risk).
- Determine methods and incentives for increasing capacity for communities to effectively evaluate and improve their resilience in alignment with their own specific needs and objectives.
- Develop observation and monitoring systems, tools, and delivery mechanisms to evaluate scenarios, and to enable better decisions, in terms of social, ecological, cultural, and economic health and well-being taking into consideration the probabilities of the scenarios.

Moving Forward

This document establishes a vision for the Federal ocean S&T enterprise, in partnership with the broader ocean community, for the 2018-2028 decade. The outlined priorities are intended to guide the development of future Federal ocean research implementation plans within each agency. It also encourages Federal agencies' collaboration with State and local governments, academia, private industry, and nongovernmental organizations to leverage non-Federal resources and support related non-Federal efforts. Its success will require an engaged, informed, and coordinated ocean community as a concerted effort is essential to advancing ocean S&T and improving application of that understanding for the benefit of the Nation.

This document does not prescribe metrics and agency-specific tasks. Instead, it offers direction in the form of priorities. These priorities were designed to promote research that contributes to greater understanding of ocean issues and variability, addresses relevant needs of resource managers and mandates of governing entities, encourages partnerships to expand the Nation's capabilities, and positively impacts national and economic security.

Advancing national ocean R&D priorities requires a coast-to-coast effort. These priorities vary across regions, as do the ways in which different regional organizations address them. This document acts as a guide to identify areas requiring national attention, while recognizing the need for flexibility.

Learning from the Last Decade

This 2018 vision for U.S. ocean S&T builds off the 2007 plan, aiming to advance the achievements and progress developed during the past 10 years. For example, the prior plan identified the need to forecast ocean and ocean-influenced processes and phenomena to produce better decision-making tools. This document advances such efforts to strengthen decision-making processes by incorporating socioeconomic and regionally specific data. A significant area of growth in the last decade is the establishment of a coordinated national and international network of observations[120] with associated data transmission, data management and communications, and data analyses and modeling capabilities. We have collected an enormous amount of data about our oceans and coasts, and this document addresses the need to obtain, analyze, and manage such Big Data.

Some identified research priorities in the previous plan remain as continued objectives, while many of the priorities are even more relevant today. For example, the 2007 plan called for advancing modeling capabilities to improve "understanding and forecasting the response of natural and constructed landscapes and ecosystems to extreme weather events, natural disasters, and changing ocean conditions to inform hazard mitigation and response plans, support navigation safety." In light of 2017's hurricanes Harvey, Irma, and Maria, their aftermath, as well as the continued rise in Presidential Federal Emergency Management Agency (FEMA) Disaster Declarations in response to extreme weather and hazardous events, this priority remains just as crucial to continue the momentum toward improved predictions and proactive measures such as expedited warning and response time.

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[120] Interagency Ocean Observation Committee. (2017) Integrated Ocean Observing System. http://www.iooc.us/ocean-observations/integrated-ocean-observing-system/ (accessed April 17, 2018).

Areas of Immediate Opportunity

Managing ocean S&T innovation is a long-term pursuit. There is, however, a need for balancing short-term research to address immediate needs or potential concerns, with long-term R&D efforts to understand the fundamental ocean system and inform major challenges and decision-making. As technologies advance and research priorities shift, it is important to ensure that a balanced approach is taken between longer-term goals and areas of immediate opportunity.

Five recurrent topics emerged from the goals and objectives described in this document that provide focus for initial research and technology opportunities. These areas surfaced from Federal agencies with interest and responsibilities linked to the ocean, and thus represent synergy across Federal agencies and immediate areas of coordination and collaboration. They are not exclusive of other efforts directed to the full suite of longer-term research and technology activities. These areas resulted from criteria that include impact of the work, urgency of the research and technology, availability of funds, and partnerships and collaborations across agencies and the broader scientific community.

1. *Fully integrate Big Data approaches in Earth system science*

Big Data is revolutionizing the way scientists and the public approach and study the ocean in the Earth system. However, scientific communities often use Big Data for research objectives and require their data to be in a specific format, or the data is not made publically available in due course. As a result, many long-term measurements and models are not accessible to non-academic institutions and businesses. Sources of ocean-related Big Data in ocean sciences include the large amounts of multi-dimensional measurements on a wide range of ocean variables collected by remote and *in situ* sensors across the globe. Big Data can also include biological information in the form of genetics as well as high-resolution, verified model simulations of global, regional, and local ocean processes. Full accessibility and use of Big Data capabilities provides opportunities for new and strong collaborations between the observational, modeling, scientific, and technological communities, resulting in novel findings through deployment of cloud infrastructure, data-analytic tools, data-mining algorithms, and scalable workflow frameworks. For example, certain Big Data analyses can be used to combat illegal fishing by increasing enforcement efficiency through rapid identification of illegal vessels, and complementing concrete resources such as manpower, ships, and planes.[121]

2. *Advance monitoring and predictive modeling capabilities*

Advances in understanding coupled and nonlinear ocean, atmosphere, land, and ice phenomena and variations are required to monitor the environment and predict future changes. These models, and the expanded ocean observing data on which they rely, are significantly enhanced by improving computational resources and enabling ensemble simulation approaches to forecasting. Recent hurricane events clearly illustrate that research efforts aimed at improving coupled ocean-coastal-hydrology models for total water and storm surge prediction capability is of high priority and critical to the preparedness of the Nation. A combination of existing and emergent technologies and modeling capabilities is required to further elucidate oceanographic systems, future trajectories and uncertainties, and the connections among Earth system components. For example, building a weather-

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[121] Command, Control, and Interoperability Center for Advanced Data Analysis. (2013) Fisheries Enforcement: U.S. Coast Guard is Sharpening Enforcement Tools with Big-Data Help from CCICADA. http://ccicada.org/2013/12/20/fisheries-enforcement-us-coast-guard-is-sharpening-nforcement-tools-with-big-data-help-from-ccicada/ (accessed April 23, 2018).

ready Nation requires ports and open ocean transit systems to continuously include weather, water, climate, and environmental data and information into decision-making and planning to ensure safe, secure, and efficient maritime commerce. Unified efforts should target the establishment of common and interoperable frameworks that allow for efficient model execution on scalable computing systems, as well as interdisciplinary application and standardized interface with Earth system observations.

3. *Improve data integration in decision-support tools*

Understanding and managing the interactions of the human dimensions within the Earth system needs to be enhanced in the coming decade. Decision-making pertaining to ocean use and conservation issues is challenged by increasing complexities of economic variability, ecosystem features, and community diversity. The situation is becoming more challenging as the number and types of ocean users increase, while interdependencies between the ocean's ecosystems and human well-being continue to grow.[122] Decisions will need to directly address the role of humans as shaping modern seascapes and coastal landscapes. For example, physical, biological, and socioeconomic models can be coupled with various Earth system models of potential impacts or benefits to people, industry, and the surrounding ecosystems to evaluate alternative management approaches.[123] Science, research, and technology will be most useful for citizens if the results and the implications of those results are broadly understandable and communicated, and made easily accessible. Decision-support tools and allied approaches will help both individuals and their communities ensure their viability now and in the future.

4. *Support ocean exploration and characterization*

Advances in ocean S&T within the coming decade will allow us to better explore our ocean and better understand our environment, such as improved seafloor mapping to better inform maritime transportation operations. While ocean exploration includes assessing physical and ecological characteristics, recent technological advancements in molecular tools collectively referred to as omics, has the promise to revolutionize our ability to explore, sample, and efficiently characterize the biodiversity of the ocean. Through omics it has been possible to characterize and quantify the distribution and function of several organisms in ocean ecosystems through space and time, and explore organisms for natural products discovery. The declining cost and rapid increase in omics technologies offer new opportunities to address pressing needs in ocean science. Further development of eDNA and other omics approaches to interpret the marine environment are likely to provide a high return on investment. Although there are sampling and cyberinfrastructure challenges for the coming decade, it is currently possible to address critical questions from managers and stakeholders. One example is how omics data can be used and/or coupled with models to effectively monitor and predict ecosystem changes and their consequences, as well as to manage marine resources such as fisheries. eDNA is one technology that can be better developed to help facilitate fine-scale geographic and

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[122] Levin, P.S., and M. Poe. (2017) Conservation for the Anthropocene Ocean. Academic Press. London. p. 530. https://www.sciencedirect.com/science/book/9780128053751 (accessed June 15, 2018); Plagányi, E.E., and E.A. Fulton. (2017) The Future of Modeling to Support Conservation. 423-446. In: Levin P.S., and M. Poe (eds) Conservation for the Anthropocene Ocean. Academic Press. London. https://eprints.utas.edu.au/25751/ (accessed June 15, 2018).

[123] Holsman, K., A. Hollowed, A. Haynie, S. Kasperski, J. Ianelli, K. Aydin, W. Cheng, A. Hermann, T. Kristiansen, and A. Punt. (2016) A stress test for fisheries management: using coupled physical-biological-socioeconomic models to evaluate alternative management approaches in Alaska. NOAA Fisheries. p. 42. https://cpo.noaa.gov/sites/cpo/MAPP/Webinars/2017/11-21-16/Holsman.pdf (accessed April 21, 2018).

temporal mapping of fish populations to assess fisheries management effectiveness.[124] The discovery of natural products is essential for the development of new therapeutics, nutrients, energy, ecological processes, and other beneficial products and technologies derived from a variety of marine hosts. Exploration, discovery, and assessment of marine resources, processes, and ecosystem structure and function, are vital to capitalize on economic opportunities, human health, and environmental resilience, among others.

5. Support ongoing research and technology partnerships

Advancing the Nation's ocean S&T enterprise described in this document requires effective collaboration of all organizations involved in ocean science. Participation of local, tribal, State, and regional governance entities will ensure that national ocean priorities incorporate the needs of specific areas or groups. Involvement of academic institutions provides scientific innovation and peer review, helps identify and address pressing research questions, and shapes society's interaction with the ocean by communicating ocean science directly to the public. Increasing partnerships across government, nongovernment, international, and the private sectors prevents duplicative efforts, strengthens resources and opportunities, helps prioritize ocean science, and promotes an ocean-literate public. For example, programs have successfully used partnerships with Federal agencies, academia, industry, State, local, and tribal governments, and nongovernmental organizations to increase ocean-related knowledge for the purposes of promoting national security, advancing economic development, protecting the marine environment, enhancing quality of life, and strengthening science education and communication.[125]

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[124] Stoeckle, M.Y., L. Soboleva, and Z. Charlop-Powers. (2017) Aquatic environmental DNA detects seasonal fish abundance and habitat preference in an urban estuary. *PLoS ONE* 12(4):e0175186. https://doi.org/10.1371/journal.pone.0175186 (accessed June 15, 2018).

[125] An example of such collaborative programs is the National Oceanographic Partnership Program (NOPP). More information can be found at: http://www.nopp.org/ (accessed June 1, 2018).

Summary of Stakeholder Engagement

Multiple writing teams contributed in the drafting of this document. Additionally, many mechanisms were used to solicit feedback from outside stakeholders. In addition to the public input period, the SOST presented the prospectus during Town Halls of five widely-attended conferences in 2017. The input gathered by these outreach efforts assisted in crafting the overall content of the document.

SOST collected input from the public on the draft report following the June 2018 Federal Register Notice for public comment. SOST incorporated changes, as appropriate, to reflect those public comments into the final report. A total of 50 public comment submissions were received from individuals and groups from academia, private industry, non-profit organizations, Federal and State governments, and the public. Reviewers considered all comments and incorporated the feedback as appropriate into the final document.