CHARTING THE COURSE FOR OCEAN SCIENCE IN THE UNITED STATES: RESEARCH PRIORITIES FOR THE NEXT DECADE

NSTC JOINT SUBCOMMITTEE ON

OCEAN SCIENCE AND TECHNOLOGY

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

Over the last two decades, our nation has again acknowledged that proper stewardship of the ocean and Great Lakes is critical to the long-term vitality of the United States. The ocean provides food and recreation, contributes to the nation's economic engine, is an element of national security, and is a major player in the global climate system. Despite its vast extent, the ocean is finite and cannot indefinitely absorb all the stresses being placed on it by the growing human population. The United States must commit to protecting the ocean through wise stewardship and sensible management. Scientific research provides the information necessary to support these efforts. This document highlights ocean research priorities for the next decade. By addressing pressing national and global ocean-related issues, society can ensure a healthy ocean for this generation and the generations to follow.

In 2000, Congress tasked the U.S. Commission on Ocean Policy to investigate and provide recommendations for a "coordinated and comprehensive national ocean policy." After extensive hearings, written input, and public comment, the Ocean Commission published *An Ocean Blueprint for the 21st Century* with more than 200 recommendations. Upon consideration of these recommendations, the Bush Administration developed the U.S. Ocean Action Plan, a broad plan that proposed a fundamental restructuring of ocean governance, research, and management intended to "engender responsible use and stewardship of ocean and coastal resources for the benefit of all Americans."

The Ocean Action Plan called for the National Science and Technology Council's Joint Subcommittee on Ocean Science and Technology to prepare an Ocean Research Priorities Plan and Implementation Strategy using a transparent process that included input from the ocean research community. This document, *Charting the Course for Ocean Science in the United States: Research Priorities for the Next Decade,* outlines the national ocean research priorities and presents the foundation for the Ocean Research Priorities Plan and Implementation Strategy. The Ocean Research Priorities Plan and Implementation Strategy is scheduled for release in December 2006. The final document will provide guidance on how the various ocean science sectors (government, academia, industry, and non-government entities) can and should be engaged, individually or through partnerships, to address the areas of greatest research priority and opportunity.

As pointed out by the U.S. Commission on Ocean Policy, "America is a nation intrinsically connected to and immensely reliant on the ocean." Given the importance of our waterways - including the open ocean, coasts, coastal watersheds, and Great Lakes - to societal well-being, quality of life, and the economy, the research priorities of this document are developed along six societal themes: Stewardship of Our Natural and Cultural Ocean Resources, Increasing Resilience to Natural Hazards, Enabling Marine Operations, The Ocean's Role in Climate, Improving Ecosystem Health, and Enhancing Human Health.

Within these societal themes, twenty-one research priorities are identified that address the most compelling issues in these key areas of interaction between society and the ocean. These research priorities focus on understanding critical processes and interactions and applying that understanding toward responsible use of the ocean environment, and include the following:

Stewardship of Natural and Cultural Ocean Resources

- Understand the status and trends of resource abundance and distribution through more accurate, timely and synoptic assessments
- Understand interspecies and habitat/species relationships as a basis for forecasting resource stability and sustainability
- Understand human-use patterns that may influence resource stability and sustainability
- Apply advanced technologies to enhance the benefits of various natural resources from the open ocean, coasts, and Great Lakes

Increasing Resilience to Natural Hazards

- Understand the initiation and evolution of hazard events and apply that understanding to improve forecasts of future hazard events

- Understand the response of coastal and marine systems to natural hazards and apply that understanding to assessments of future vulnerability to natural hazards
- Apply understanding to develop multi-hazard risk assessments and to support development of model, policies, and strategies for hazard mitigation

Enabling Marine Operations

- Understand the interactions between marine operations and the environment
- Apply understanding of environmental factors to characterize and predict conditions in the maritime domain
- Apply understanding of human behavior to develop the information and tools necessary to carry out effective, safe, and secure marine operations
- Apply understanding of marine operations to enhance the marine transportation system

The Ocean's Role in Climate

- Understand ocean-climate interactions across regions
- Understand the impact of climate variability and change on the ocean, including its biogeochemistry and ecosystems
- Apply understanding of the ocean to help project future climate changes and their impacts

Improving Ecosystem Health

- Understand and predict the impact of natural and anthropogenic processes that govern the overall level of ecosystem productivity
- Apply understanding of ocean-related socio-economic activities to assess the ability of marine ecosystems to provide essential goods and services
- Apply understanding of marine ecosystems to develop appropriate indicators and metrics for their sustainable and effective management

Enhancing Human Health

- Understand, forecast, and reduce ocean-related risks to human health from pathogens, biotoxins, and chemical contaminants
- Understand human health risks associated with the ocean and the potential benefits of ocean resources to human health

- Understand how human use and valuation of ocean resources can be affected by ocean-borne human health threats and how human activities can influence these threats
- Apply understanding of ocean ecosystems and biodiversity to develop products and biological models to enhance human well being

The independent development of the research priorities in the six theme areas led to the identification of some common scientific and technical threads. These threads form a "pattern of opportunity," whereby advances achieved by seizing opportunities in a few areas can be leveraged to achieve advances across the breadth of the enterprise. Acting upon this pattern of opportunity would provide the United States with the scientific and technical means to redefine its relationship with the ocean over the next decade. For that relationship to change for the better, advances in three key areas of science and technology must be pursued: (1) increasing understanding and capability to forecast ocean processes; (2) developing scientific information to facilitate ecosystem-based management of resources, especially those found in coastal and nearshore ecosystems; and (3) deploying ocean observing technologies that will, in turn, accelerate forecasting and management capabilities.

Understanding and Capability to Forecast Ocean Processes— The understanding and capability to forecast certain ocean and ocean-influenced processes and phenomena will change how society takes action in the future, much like weather forecasts do today. Forecasts of El Niño and La Niña phenomena that are now used routinely by governments and the private sector demonstrate the significant potential of this capability. These forecasts currently influence the buying and selling of energy resources, and help reduce agricultural loss by adapting agricultural processes using early estimates of the magnitude of El Niño-related weather hazards. These forecasts have emerged from investments in the basic understanding of equatorial Pacific Ocean circulation and its relation to weather, in observing systems capable of providing key data, and in model and simulation capability. Developing the understanding and capability to forecast key processes related to hurricane and severe storm formation, ocean currents, fish stocks, and human health hazards, to name a few, would expand the economic, societal, and environmental benefits of ocean forecasts.

Enhanced Scientific Support for Ecosystem-Based Management— Components of the ocean environment work like an interlocking system. But managing resources in ways that recognize and account for the complex interactions between those resources and other parts of the marine environment—including humans—is a substantial challenge. Ecosystem-based management is now widely recognized as the one of the most effective ways to cope with a variety of increasing natural and human-induced pressures. Implementing ecosystem-based management requires determining which interactions are most critical, as well as the natural and human factors affecting those interactions, and the way those factors will change in the future.

Targeted Deployment of an ocean observing system—A robust observing system that can describe the actual state of the ocean will revolutionize the view of the ocean environment and provide the data necessary to advance the research efforts outlined in this document. As described in the societal themes, observations underpin fundamental knowledge of the open ocean, coasts, coastal watersheds, and Great Lakes. Although much work remains, mature plans for many components of an integrated, global ocean observing system have been developed by the communities interested in ocean research and ocean management. Deploying the priority elements of the observing system will allow the ocean community to enable the promise of ocean forecasting and ecosystem-based management, while supporting other societal goals such as a strong economy during the next decade.

Near-term Priorities

Near-term (2-5 years) priorities were developed from the 21 research priorities identified in this document. The near-term priorities incorporate aspects of each of three overarching opportunities (understanding and capability for forecasting ocean processes, scientific support for ecosystem-based management, and targeted deployment of elements of an ocean observing system). Advancing the three overarching opportunities through these near-term priorities supports the efforts of all of the societal themes outlined in this document, ranging from stewardship of our natural and cultural resources to enabling marine operations to enhancing human health. These near-term priorities, each with equal priority, were identified using the criteria outlined for the general research priorities, with an added focus on impact (i.e., why the work would be of value), urgency (i.e., why a concentrated effort should be pursued over the next 2-5 years rather than a modest effort over 10 years), and partnerships (i.e., will the effort maximize collaborations among agencies and sectors).

Forecasting the Response of Coastal Ecosystems to Persistent Forcing and Extreme Events—Understanding the response of natural and constructed landscapes and ecosystems to extreme weather events, natural disasters and changing ocean conditions, and forecasting the frequency, intensity, and impact of those events is integral to constructing more resilient structures and communities, and protecting the natural environment. This effort will integrate and enhance regional observing systems and models, yielding improved understanding and better forecasts of coastal system responses to extreme events, persistent natural processes, and human influences across the coastal zone. These data will be made widely available to diverse end-users through the national ocean observing system. Results from this effort will inform hazard mitigation and response plans, provide forecasting data to support navigation safety, and assist regional resource managers in sustaining ecosystem health and promoting hazard resilience.

Comparative Analysis of Marine Ecosystem Organization— Management of marine ecosystems can be improved by elucidating their underlying dynamics at a variety of scales. Forecasting marine ecosystem responses to management strategies requires an understanding of the complex dynamics that control and regulate ecosystem processes. This effort will provide a greater basic understanding of these processes, and practical tools for evaluating the effectiveness of local and regional ecosystem-based management efforts.

Sensors for Marine Ecosystems— New, improved sensor capabilities are necessary to realize the full potential of *in situ* ocean observing networks and satellite-based observations to enhance understanding of marine ecosystems. Immediate improvements can be made to *in situ* instrumentation in eco-genomics, interdisciplinary ocean observing, and sensors in support of satellite-derived "ocean color" and new biological and biogeochemical observations. These improvements will enable expanded and more accurate information on the ocean environment to better define management options, help understand processes that influence ecosystem productivity, serve as the basis for forecasting ocean-related risks to human health and safety, and shed light on the impact of climate variability and change on the ocean, marine life and humans.

Assessing Meridional Overturning Circulation Variability: Implications for Rapid Climate Change—The ocean plays a central role in many of the mechanisms that impact global climate. Thus, incorporating ocean observations and understanding into an integrated Earth system analysis capability is needed to assess the current state of the climate system. Specifically, the meridional overturning circulation (MOC) of the Atlantic Ocean, an element of the global scale ocean circulation responsible for long-term climate variations, has been identified as a key process related to rapid or even abrupt climate change (i.e., changes over a few years to a few decades). Understanding how to monitor, detect, and analyze rapid changes in this key component of the ocean conveyer belt could have implications for many significant changes in climate.

INTRODUCTION

Throughout history, humanity has interacted with and prospered from the ocean.[1] As a nation, we began dedicated study of the ocean in the late 1800s. Ocean science and technology were bolstered significantly in the 20th century due, in part, to the major world wars. Major advances followed during and after the Cold War, and were highlighted by the International Geophysical Year (1957-1958) and the International Decade of Ocean Exploration (1971-1980), leading to the growth of *in situ* and satellite observations of the global ocean. The U.S. claim to an Exclusive Economic Zone (EEZ) in 1976[i] extended the national ocean domain to 200 nautical miles from shore, providing new areas for resource exploration and use. The result of these activities is a greatly improved understanding of the physical, chemical, biological, and geological properties of the global ocean. At the same time, the waters of the open ocean, coasts, coastal watersheds, and Great Lakes have been impacted by human activities and natural events. These impacts to the ocean environment have ecological, economic, and societal ramifications that society is only now beginning to understand.[ii] Ultimately, much remains to be done to improve understanding of ocean processes, describe the ocean's role in the Earth system, develop and manage society's interactions with the ocean, moderate impacts on it, and help ensure that the United States maintains a leadership role in the global ocean community.

As the nation's scientific and technological capacity has grown, responsibility for ocean research has expanded beyond the boundaries of any single funding entity. Such research now covers nearly all geographic regions, many academic disciplines, most environmental processes, many agency missions, and a large number of regulatory responsibilities. In 2000, in recognition of these multiple, sometimes overlapping interests, Congress tasked the U.S. Commission on Ocean Policy (USCOP) to investigate and provide recommendations for a "coordinated and comprehensive national ocean policy." In July 2004, the USCOP published *An Ocean Blueprint for the 21st Century* with more than 200 recommendations, developed based on extensive hearings, written

[1] The term "ocean" throughout this document includes a broad set of environments, including open ocean, coasts and estuaries, Great Lakes, and coastal watersheds. Where appropriate, these components of the global ocean may be specified.

input, and public comment. In December 2004, upon consideration of these recommendations, the Bush Administration released the U.S. Ocean Action Plan (OAP). This broad plan proposed a fundamental restructuring of ocean governance, research, and management intended to "engender responsible use and stewardship of ocean and coastal resources for the benefit of all Americans."

In order to help identify the most important research challenges and opportunities, and to develop a coordinated response strategy, the OAP called for the National Science and Technology Council's Joint Subcommittee on Ocean Science and Technology (JSOST) to prepare an Ocean Research Priorities Plan and Implementation Strategy, using a transparent process that included input from the ocean research community. This document, *Charting the Course for Ocean Science in the United States: Research Priorities for the Next Decade,* outlines the national ocean research priorities and presents the foundation for the Ocean Research Priorities Plan and Implementation Strategy. The Ocean Research Priorities Plan and Implementation Strategy is scheduled for release in December 2006. The final document will provide guidance on how the various ocean science sectors (government, academia, industry, and non-government entities) can and should be engaged, individually or through partnerships, to address the areas of greatest research priority and opportunity.

The purpose of this document is to develop and present ocean research priorities that address key interactions between society and the ocean. If acted upon, these priorities will result in considerable strides toward enhancing the quality of life and safeguarding the health of the open ocean, coasts, coastal watersheds, and Great Lakes.

The strength of this document is that it was developed through a collaborative effort involving all federal agencies with interests and responsibilities linked to the ocean, as well as representatives of academia, industry, and non-governmental organizations. Addressing the national and global challenges outlined in this document also requires the collaboration and coordination of national research efforts with international initiatives. This document takes a fresh approach in considering the ocean as a dynamic system rather than attempting to identify research needs based on historical academic disciplines or independent activities such as resource distributions, fisheries assessments, ocean currents. Future research efforts must take an interdisciplinary approach to exploring and understanding the ocean's role in many of society's most pressing challenges, such as climate change, sustainable resources, public health, and hazard mitigation. This document is also unique in that it recognizes the important relationship between society and the ocean and, therefore, places high emphasis on understanding the interactions between humans and ocean ecosystems – the human dimension of ocean issues. Finally, this document recognizes the unprecedented capabilities in the areas of advanced *in situ* and remotely sensed data acquisition, information management, computer simulation and visualization.

The nation's ocean research portfolio is, in essence, being re-balanced to take advantage of new interdisciplinary research approaches, sophisticated research and computational tools, and the availability of shared assets such as personnel and research platforms. An appropriately balanced research portfolio will provide insight into ocean processes that will enable better policy and resource management decisions. These decisions will help ensure appropriate use and protection of the ocean, particularly the coastal margins, where so much of America lives, works, and plays, and which contributes so heavily to the nation's economy. This interdisciplinary approach will require careful coordination among state, regional and local government agencies as well as academic, industrial, and non-governmental entities. The ocean research priorities presented in this document are national in scope yet reflect the need to provide benefits at the local, state, regional, and national levels, while involving all parties in the enterprise.

FOCUSING THE NATION'S OCEAN RESEARCH ENTERPRISE

PROTECTING LIVES, ENHANCING LIVELIHOODS, AND IMPROVING QUALITY OF LIFE

The basic necessities for protecting lives, enhancing livelihoods, and improving quality of life are derived, in no small measure, from functioning ocean ecosystems, available ocean resources, and a safe and secure maritime domain and associated marine-based economic sectors. The ocean provides abundant food, recreation, and other forms of enrichment, but at the same time, presents risks that, if not understood and respected, pose serious threats to lives and livelihoods. Research is essential to understand and manage the benefits and risks of society's interactions with the ocean, from the nation's watersheds to the polar regions. Wise management will prevent or minimize the risks of illness and disease, bolster the resilience of coastal communities and regions to natural hazards that arise from the marine environment, and ensure the economic productivity of the open ocean, coasts, coastal watersheds, and Great Lakes.

With thousands of miles of coastline, the United States depends on a secure maritime domain. A vigorous ocean science research agenda, combined with the most advanced technologies, must be a component of any plan to address national security. At the same time, society has benefited in numerous ways from the scientific and technological advances wrought from the demands of national security. The security of the nation encompasses not only military missions abroad, but also homeland and economic security. The nation depends heavily on the shipment of goods through coastal ports; ocean science and technology will continue to contribute to the efficient and safe movement of ships in coastal waters and the U.S. EEZ, as well as in the global ocean.

Understanding society's impact on the ocean and its impact on us forms the basis for ensuring a clean, healthy and stable ocean environment that can be responsibly used and enjoyed by generations to come. This productive relationship depends on wide public access to information that will enable informed public discourse and decision-making.

The research priorities presented in this document are challenging to address because society interacts with the open ocean, coasts, and Great Lakes in numerous ways. The task for government at all levels is to effectively manage these varied demands, expectations, and uses with the least possible negative impact to the ocean environment as a whole. Perhaps the biggest challenge is to engender within society a stewardship ethic to value and protect, based on the best scientific information available, ocean and coastal ecosystems while facilitating access to them so these ecosystems will be available for future generations to enjoy.

FRAMING THE APPROACH

The scope of this effort is to promote *discovery* that will provide new insights and perspectives on the ocean environment; impart greater *understanding* of ocean properties and processes; and expand opportunities to *apply* that knowledge in a safe, prosperous, and sustainable manner. As the three interlinked components of the research enterprise, discovery, understanding and application serve as the foundation for the research priorities developed in this document.

Discovery:

Discovery entails both the pursuit of the unconstrained fundamental science questions that drive the imagination and the exploration of new phenomena and terrain, remote geographies, and unique marine systems. Discovery provides the foundation upon which society builds comprehension of life; it has the potential to fundamentally shift our understanding of the ocean, its role in the Earth system, and society's place in that system.

Understanding:

An understanding of ocean processes is required to predict the consequences of interactions between humans and the ocean, and manage those interactions. Supported by discovery efforts, the need to understand often focuses on those processes that cascade through spatial and temporal scales (global/local, abrupt events/long-term change), describe the interactions between ecosystem components (physical/ecological, human/natural), and/or cross thematic boundaries (hazards/ecosystem health, resource use/ecosystem health). Enhancing understanding is an ongoing task that requires continuous innovation in both ideas and technology. The benefit of this understanding is that new knowledge can then be applied to promote responsible use and stewardship of the marine environment.

Application:

A critical component in the research process is to apply the knowledge gained from discovery and understanding to serve the public interest. Application includes efforts to translate information so that policy-makers, managers, and the public will be able to understand and use the knowledge to make informed decisions. Application also includes developing new tools, new techniques, and new approaches to address complex issues.

EXPANDING THE SCIENTIFIC FRONTIER: THE NEED FOR FUNDAMENTAL SCIENCE

Many of the research priorities outlined in this document focus on solving specific problems of great importance to society. Society addresses these problems based on the current understanding of the ocean. But if that understanding is incomplete because the intricacies of important processes or relationships have yet to be unraveled, the limited data available may point toward faulty conclusions. Thus, a critical aspect of understanding the ocean environment is expanding the scientific horizon through innovative research that does not directly respond to specific products or societal requirements, but addresses key, underlying science questions and poorly understood processes.

Scientific discovery, driven by competitive, merit-based investigations, is the foundation of the nation's research enterprise, and is an intrinsic and highly valued component of the ocean research portfolio. Fundamental research that expands the scientific frontier will provide a deeper and more comprehensive understanding of the ocean and its role in the Earth system. It is essential that the nation continues to cultivate and investigate new ideas about the ocean and new approaches for exploring the marine environment that may challenge existing interpretations. In doing so, society should also recognize and even encourage risk-taking in supporting the most exciting and promising ideas for making progress in understanding the ocean. Progress requires the continued support of both systematic measurements of the ocean's properties and the freedom to pursue new ideas and technology. The path ahead as presented in this document necessarily includes "room for creative individuals to pursue the kind of fundamental scientific research that can lead to unforeseen breakthroughs."[iii]

The ability to access all aspects of the ocean environment, made possible by fostering scientific and technological innovation, will enable breakthroughs in basic understanding of ocean biology, chemistry, geology, and physics and the connections among these disciplines. Improved access to the open ocean, coasts, Great Lakes and associated watersheds depends on advances in infrastructure and technology, from advanced sensors (e.g. for genomics) to satellites and unmanned vehicles. The development of innovative tools, ranging from remotely operated and autonomous vehicles, to molecular techniques, to physical, chemical and biological sensors, will facilitate novel experiments and permit the measurement of processes ranging from isolated episodes to global cycles. In addition to platforms that enable ever-expanding temporal and spatial access to the ocean, such as *in situ* and remote global, national, and regional observing systems and a robust research fleet (including manned submersibles), land-based marine laboratories enable multidisciplinary research programs and support specialized equipment and instrumentation. A workforce eager to expand the limits of scientific knowledge and technological innovation will support the scientific discoveries necessary to address fundamental scientific questions.

The fundamental science research community identifies many promising areas for scientific investment through scientific workshops and other planning activities. The National Research Council and other community groups also publish analyses of promising new directions in fundamental ocean research that are used by funding agencies to guide investments.[iv] Attempting to prioritize research efforts driven by new ideas and the desire for discovery would constrain these fundamental and critical activities. By definition, unforeseen breakthroughs and paradigm shifts cannot be planned nor should they be, as such planning would be inherently limited by current understanding. Therefore, this document focuses on underscoring – rather than defining and enumerating - the fundamental research efforts that provide the foundation for understanding the ocean.

IDENTIFYING OCEAN RESEARCH PRIORITIES

This document focuses national attention on six themes that represent key areas of human interaction with the ocean.

- Stewardship of Our Natural and Cultural Ocean Resources
- Increasing Resilience to Natural Hazards
- Enabling Marine Operations
- The Ocean's Role in Climate
- Improving Ecosystem Health
- Enhancing Human Health

These themes were developed through the combined efforts of federal agencies involved in ocean science and technology pursuits. Although described separately in this document, these societal themes are deeply connected. The ocean comprises one global marine ecosystem, linked by physical, chemical, biological, and geological processes to terrestrial habitats and the atmosphere. The processes occurring in the open ocean cannot be divested from impacts felt along the coasts and throughout vast watersheds and vice versa. Understanding the scale and scope of these connections is vital to effective research, which itself must be adapted by cutting across traditional disciplinary boundaries. Elements of research essential to multiple themes are highlighted in the Opportunities for Progress section to underscore their importance to the overall research initiative. These pervasive, cross-cutting elements present many opportunities for economy, efficiency and, ultimately, success.

The research priorities address the most compelling questions under the six societal themes. The document does not encompass the vast diversity of research in these areas, but **focuses on essential research efforts that must be undertaken in the coming decade.** The priorities necessarily cover a broad portfolio of research efforts because of the many ways society uses the ocean. The research priorities encompass physical and natural sciences as well as those disciplines focusing on the human dimension, such as social sciences (e.g., sociology, anthropology), economics, and public health.

The following questions were used to identify the most compelling research priorities for each theme, recognizing that the prioritization criteria for one theme may not be equally applicable to another:

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

STEWARDSHIP OF OUR NATURAL & CULTURAL OCEAN RESOURCES

The resources of the open ocean, coasts, coastal watersheds and Great Lakes generate tremendous benefits and opportunities. The ocean is a source of food, minerals, and energy, and is used for transportation, recreation, and tourism. The ocean preserves a record of the past in the form of drowned cultural sites. The ocean also provides substantial but more intangible benefits through its ability to produce oxygen, sequester carbon, fix nitrogen, and neutralize toxins. The ocean remains a vast, unexplored realm with the capacity to provide new pharmaceuticals, industrial products, and energy sources. At the same time, its resources are subject to many pressures, such as overfishing, habitat destruction, and competition with invasive species. To unlock the full resource potential of the open ocean, coasts, coastal watersheds, and Great Lakes, society must improve understanding of these systems and balance their use and sustainability.

RATIONALE

U.S. waters are the source of many of the resources society uses daily. The United States has the largest EEZ of any nation.[v] Fishery production within the EEZ and contiguous inshore waters supports a $60 billion annual seafood industry and a $20 billion recreational industry.[vi] Recent advances in aquaculture are providing an increasing contribution to the seafood supply. The total current market value of the oil and gas inventory is approximately $8 trillion, consisting of $1 trillion in discovered remaining reserves and $7 trillion in undiscovered technically recoverable resources.[vii] Estimates for offshore wind energy suggest a potential of 900 gigawatts within 50 nautical miles of the coast.[viii] Approximately 200,000 trillion cubic feet is present in gas hydrate deposits on land and the U.S. outer continental shelf (OCS).[ix,x] The Great Lakes are the largest source of freshwater in the world.[xi] Healthy ocean and coastal natural and cultural resources provide the foundation for a huge coastal tourism and recreation industry that is the fastest growing area of the ocean economy.[xii] Relict prehistoric landscapes, shipwrecks, and historic and living waterfronts along the nation’s coasts and Great Lakes all contribute to the national cultural heritage.

The scale and diversity of ocean resources is immense, however, resource use and development sometimes compete with other societal needs and values. Balancing environmental impacts of resource use and extraction with the economics of resource development can help mitigate some of the pressures being placed on coastal ecosystems, enable restoration of degraded habitats, and ultimately, support robust and coordinated ecosystem-based management[xiii] and governance strategies for sustainable resource use.

RESEARCH PRIORITIES

Central to the effective management of natural and cultural resources is the ability to accurately assess the current condition of these resources, and to determine the likely impacts of various management alternatives. A better understanding of the complex relationships between living and non-living resources and the impacts of human activities is also necessary. Research into these issues will enable society to prevent major impacts to a specific species or system, maintain ocean populations, and support management efforts that focus on restoring depleted populations.

Understand the status and trends of resource abundance and distribution through more accurate, timely and synoptic assessments. Measuring the abundance and distribution of biota and non-living resources in the open ocean, coasts, coastal watersheds, and Great Lakes is challenging, particularly for living resources, because of their complex movement patterns. Capabilities necessary for these measurements include the ability to: monitor living resources nearly continuously over wide swaths of ocean at appropriate levels of species resolution; assess the spatial and temporal variability (both natural and use-induced) of resources (biota, energy, minerals, and pharmaceuticals, among others), particularly in deep-water settings; and provide long-term and sustained monitoring and mapping, using diverse and robust sensors. The development and implementation of these capabilities will provide the data necessary to enable adaptive approaches to the management of natural and cultural resources and improved decision-support.

Understand interspecies and habitat/species relationships as a basis for forecasting resource stability and sustainability. Understanding the cumulative impacts of an ever-widening array of human activities (e.g., transportation, recreation, land development, fishing, energy exploration and development, and increased food production from aquaculture) on water and habitat quality and the ocean's ability to support marine life is necessary for enabling ecosystem-based management approaches to ocean resource use. Often the data necessary for these assessments are difficult to obtain because of practical limitations of controlled experimentation and replication in natural systems. There is a need to invest in data collection, experimentation, and advanced modeling to help identify crucial data and process-understanding gaps so that the proper resource management techniques can be developed and implemented. Priorities for natural-resource modeling that would enable better forecasting include: (1) development and validation of broad, large-scale, ecosystem models and detailed, small-scale models of species interactions that incorporate feedback mechanisms among higher trophic levels; (2) development of regional and local models of environmental changes (e.g., responses to annual, decadal, and longer-term climate drivers; rapid regime shifts; hydrodynamic circulation; watershed discharge) to enable assessments on how these changes impact resources; (3) development of models to understand the specific and cumulative impacts of various natural-resource policies on living resources and human communities; and (4) collection of additional data (observational and experimental) to support model robustness.

Understand human-use patterns that may influence resource stability and sustainability. Determining the "worth" (i.e., consumptive and non-consumptive valuation) of natural and cultural resources and evaluating effects of alternative management scenarios requires considering economic, sociological and cultural factors, and potential competing uses. Integrating socio-economic factors into resource management will help cultivate a better-engaged public that views information supporting management as accurate, credible, and unbiased. Human-use data can be acquired through expanded surveys of the economic and sociological factors associated with a broad range of open ocean, coastal, watershed and Great Lakes resource activities.

Human behavior and economic research, and modeling of resource use will potentially enable the forecasting of effects of various management options on resource use and sustainability.

Apply advanced technologies to enhance the benefits of various natural resources from the open ocean, coasts and Great Lakes. Key technological developments are required to facilitate long-term and effective resource management and to make more responsible use of available sustainable and non-sustainable resources, such as energy, minerals (including sand) and pharmaceuticals. Areas of focus include: development of sustainable approaches to aquaculture that consider implications for surrounding ecosystems, wild genetic resources, and impacts on coastal economies; advancement of new sustainable energy technologies from the ocean, including efficient methods for power generation, and scientific information to fully consider impacts on marine life; development of new generations of military subsurface detection systems or other mitigation methods that are potentially less deleterious to species sensitive to acoustic emissions in certain sound ranges; development of bycatch reduction technologies for fisheries and protected resources, enabling sustainable resource use; and use of advances in exploration technologies (e.g., geospatial, biooptical) to map and characterize the EEZ and the U.S. continental shelf, and to establish the outer limits of the U.S. continental shelf where it extends beyond the limits of the EEZ.

NECESSARY TOOLS

Technologies and procedures will be needed to enable rapid, efficient, and synoptic assessment of ocean resources (including inventories and alterations). Current estimates indicate that the fleet of ships available is only about one-third of the capacity needed to provide essential information on the status of managed populations and ecosystem effects of human activities.[xiv] Additionally, improved remote-sensing tools are needed to obtain necessary biological (e.g., biomass) and physical (e.g., current direction, wave height) parameters, and to survey deep waters, particularly as energy exploration moves to the edges of the OCS. In addition to monitoring and assessment with existing technologies, new and improved technologies and protocols are needed to expand the capabilities of fixed and mobile platforms to include biological and chemical sensors, and advanced acoustics and mapping capabilities.

Enhanced information technology and data support infrastructure is essential. Comprehensive environmental databases with appropriate spatial and temporal resolution that integrate information from local, regional, national, and global sources are key to understanding ecosystem interactions, and providing the necessary information for effective and adaptive resource management. Information systems using geographic information systems can integrate diverse data sets (e.g., physical, biological, social, cultural) to promote spatial analysis and modeling. This integration will, in turn, expand understanding of interrelationships among the physical environment, ecosystems and human activities.

Implementation of these new approaches requires more technical and scientific personnel for the operation, maintenance and interpretation of information. Investments in training and maintaining this workforce are a key priority for next generation natural resource decision support systems, improved resource management, and decision-making.

INCREASING RESILIENCE TO NATURAL HAZARDS

Recent hurricanes and tsunamis have clearly demonstrated the potential for natural disasters to have economic, environmental, social, and public-health impacts on regional, national, and global scales. Communities, maritime operations, cultural resources, social services, and ecosystems are vulnerable to coastal and marine hazards. While society cannot eliminate natural hazards, their impacts can be reduced. Persistent and coordinated investment in research and technology will provide the knowledge and information base needed to assess and reduce risk, save lives and property, ensure more rapid recovery and effective mitigation, and develop informed and effective responses to future hazard events.

RATIONALE

With over 50 percent of the U.S. population living in coastal counties, and that number rising each year,[xv] the United States must be adequately prepared for coastal disasters. Even as the nation continues to direct significant federal funding toward science and technology to assist in reducing the impacts of natural hazards, the United States still faces enormous losses each year from ocean and coastal hazards, including:

- Severe storms, hurricanes, and tornados, and the associated coastal and offshore wind, wave, and current damage;
- Coastal inundation and flooding from storms, tsunamis, and regional meteorological events; and
- Earthquakes, landslides, and volcanic eruptions along the coast and offshore, and resulting tsunamis.

The costs of these events are signficant and will likely increase. In 2005, Hurricane Katrina devastated the Gulf Coast and is estimated to be the costliest natural disaster yet to strike the United States.[xvi] The potential short-term and long-term human and economic costs to at-risk regions from tsunamis (Pacific Northwest, Alaska, Hawaii, southeastern United States, Caribbean) are substantial. A sound scientific and technological basis for decision-making must include improved models of hazard impacts, more accurate and timely forecasts, and comprehensive assessments of future hazard potential, vulnerability and risk. This scientific foundation will support cost-effective strategies designed to increase resistance, enhance resilience, and help promote avoidance (e.g., "smart growth").

RESEARCH PRIORITIES

Effective response to natural hazards is impeded by limitations in the ability to comprehensively assess hazard potential, vulnerability and risk. Hazard assessments must be thorough and reflect multiple hazards, impacts that span diverse economic, social, and ecosystem sectors, and human and natural processes that constantly alter system vulnerability and risk. Research communities that address hazards currently focus on single hazards, single elements of the hazard cycle (generation, impact, policy), or single research disciplines (physical, ecological, social, and engineering sciences). These diverse communities must be coordinated and integrated to inform and evaluate mitigation strategies with the broadest consideration of costs and effectiveness. If society is to reduce the social and economic impact of natural hazards, the public and policy-makers must be educated on the risks and associated costs of natural hazards so that decisions and responses are effective. Assessment, effective research translation, communication and education are essential to help develop a "risk-wise" population and mitigate the impacts of natural hazards.

Understand the initiation and evolution of hazard events and apply that understanding to improve forecasts of future hazard events. Quantifying future hazard potential requires understanding hazard generation (storms, submarine and coastal landslides, tsunami, flooding) and past hazard occurrence. Enhanced hazard forecasts, particularly storm formation, track, intensity and associated waves, surge, and flooding, will support more effective responses to developing hazard events. Research in this area should focus on the development of improved models of hazard generation (e.g., tsunami source modeling, seafloor stability modeling, storm formation) and evolution (e.g., tsunami propagation, storm and inundation modeling), and the process studies and necessary data to validate these models. Probabilistic models and assessments of hazard potential should include effects of land subsidence and future climate change (e.g., changes in storm intensity or frequency, sea-level rise) on hazard potential and vulnerability.

Understand the response of coastal and marine systems to natural hazards and apply that understanding to assessments of future vulnerability to natural hazards. Natural hazards impact infrastructure directly through alterations to the underlying landscape and through secondary processes (e.g., slope failures, shoreline change, inlet formation, and flooding). Hazards also have significant impacts on coastal features such as wetlands and shorelines, as well as cascading impacts throughout ecosystems, both during and after the hazard event. Understanding altered ecosystem processes will improve our ability to facilitate recovery of ecosystem functions and undertake appropriate restoration efforts. Models based on observations of pre-event conditions and post-event impacts are required to forecast the magnitude and nature of impacts, the changing vulnerability of the altered landscape, and the long-term impacts on ecosystem functions and health. Priorities include understanding and modeling landscape change (including impacts/influences across the adjacent watershed) associated with coastal hazards and structure and infrastructure resilience, and assessing vulnerability of coastal communities, infrastructure, marine operations, and ecosystems.

Apply understanding to develop multi-hazard risk assessments and to support development of models, policies, and strategies for hazard mitigation. To mitigate hazard impacts and reduce risk associated with individual and multiple hazards, research efforts must identify vulnerable ecosystem functions and infrastructure components and the potential for cascading component failure, and assess the efficacy of natural (e.g., barrier islands, coastal wetlands) and engineered systems (e.g., levees). Integration of observations, data, and models (including comprehensive characterization of vulnerable systems) will enhance understanding of hazard potential and vulnerability, and improve risk assessments for coastal communities, infrastructure, marine operations, and ecosystems. These risk assessments will help guide the creation of effective and affordable systems, materials, and technologies for hazard-resilient and resistant communities, infrastructure, and ecosystems. Development of economic and social models of consequence, resilience, and resistance, and integration of assessments and models into decision-support tools for emergency and development planning and policy will inform long-term and short-term public and policy response that promotes "risk-wise" behavior and minimizes economic, social, and environmental costs of hazards.

NECESSARY TOOLS

Meeting the broad requirements necessary to reduce hazard impacts and increase hazard resilience will require continued expansion of existing observational systems, data-delivery systems, and modeling capabilities at regional, national, and global scales. Sustained marine and coastal observations, including technological improvements in remote and *in situ* sensing of multiple time-sensitive parameters (oceanographic, geophysical, hydrological, chemical, biological, geographic) are required. Comprehensive geospatial characterization combined with sustained and reactive deployment modes of operation are required to acquire baseline (pre-impact) and post-hazard data. Deployments must be capable of assessing diverse hazard processes and impacts, such as coastal and inland inundation and water quality. These deployments would support development of improved models of, for example, storm evolution and coastal response. The capability to provide up-to-date characterization of coastal vulnerability and pre-storm conditions (including topography and bathymetry, land-use/land-cover, monitoring of riverine and coastal water levels) must be maintained.

Multi-hazard assessments will require information infrastructure supporting development of an "all-hazard" geographic information system (GIS) resource with defined standards supporting information integration and application. Advanced computational resources and the establishment of community computational standards are required for data assimilation systems, coupled earth/ocean/atmosphere models, and data management and delivery systems. The design and implementation of robust, reliable, and widely available notification systems will help enable more effective communication of warnings.

A comprehensive understanding of hazard costs and impacts will require a work force capable of linking physical, ecological, engineering and social science disciplines. An integrated approach will lead to more effective translation of research results and development of tools for informed and comprehensive decision-making.

ENABLING MARINE OPERATIONS

Marine operations are essential components of the global economy and vital elements of national competitiveness, national security, and homeland defense.[xvii] Marine operations[xviii] encompass international and national coastal and ocean transportation. Marine operations require freedom of navigation in the global ocean, and the ability to conduct mapping and charting activities, gather tide and current information, and use U.S. ports, harbors, estuaries, and the Great Lakes. Marine operations also deal with issues such as bridge clearance, dredging, navigation aids, and ice coverage. Forward-thinking, innovative basic and applied scientific research, coupled with technological advances, will permit marine operations to meet challenging requirements for increased levels of transportation and commerce in the maritime domain and to address security concerns, while balancing sustainable use and protection of the environment.

RATIONALE

Marine operations oversee a broad array of essential activities, including commercial fishing, recreational boating, passenger ferries, military operations, oil and gas exploration and production, merchant ship traffic, and numerous portside processes. Even a brief interruption in marine operations can have serious consequences for many sectors of society, national security, and the U.S. economy. The broad scope and far-reaching impact of marine operations requires expanding knowledge in several key areas.

Marine Safety: Up-to-date maps and charts, and reliable weather and sea-state forecasts are necessary to ensure safe and effective navigation of harbors, ports, and waterways by various users. With more than 95,000 miles of shoreline, 25,000 miles of navigable waterways, and 3.4 million square miles of open water (30 percent larger than the U.S. land area) within the U.S. EEZ, and with increased volume of open-sea shipping (potentially through an ice-reduced or ice-free Arctic[xix]) and short-sea shipping,[xx] research will be necessary to achieve more effective collection, processing, and modeling of environmental data to ensure safe and secure operations.

Marine Protection: Projections state that trade will increase, ships will become larger, and population along coasts will grow, all of which will have impacts on the marine environment and the nation's ability to conduct marine operations. Knowledge about those impacts and how to mitigate them, gained through incorporating research on ecosystem health, will be necessary to ensure a balance of operations and environmental protection.

Marine Industry*:* There are numerous other commercial but non-transportation uses of the maritime domain, including offshore aquaculture, energy extraction/harnessing (i.e., facilities for oil, gas, and wind), seabed and mineral rights uses, and laying of sub-sea communications and cables, all of which greatly affect the environment and use of the maritime domain. Interactions among the numerous existing and emerging uses of the maritime domain represent a challenge. There is a need to integrate natural resource requirements, data products, technological advances, and operations in a manner that will facilitate safe, efficient, and sound current and future marine operations.

RESEARCH PRIORITIES

Given that the majority of the nation's commerce (by weight) travels through U.S. ports and is anticipated to expand, the capacity of the U.S. marine transportation system must be enhanced.[xxi] Increasing understanding of environmental impacts and conditions affecting marine transportation is necessary as the transportation system integrates new modes of operation. Many of the research priorities that will enable marine transportation will also support other commercial uses, such as energy extraction and sub-sea communications, and ship movements and military operations required to ensure national and homeland security. To properly address the research priorities outlined below and to use that research effectively requires improved communication and collaboration among the diverse stakeholders involved in marine operations, including industry, local, state, and federal government, and researchers.

Understand the interactions between marine operations and the environment. Central to enabling marine operations is understanding how marine operations (including port development and vessel maintenance and operations) affect the environment, and how environmental conditions affect operations. This understanding will be particularly important in environmentally sensitive areas such as the Great Lakes, coastal areas with low tidal exchange, and coral reef systems. Areas of study include air, water, and sediment pollution (e.g., release, dispersion, cycling and cumulative impacts); interactions with marine life (e.g., ship strikes and ocean acoustics); and factors contributing to the introduction and persistence of invasive species (e.g., ballast water). These research areas will also inform the development of mitigation strategies and technologies. Research is needed to address the effect of environmental conditions on marine operations. Such research includes refining sediment transport models to enable rapid, efficient, and environmentally sustainable dredging and improved dredged material management, and investigating climate-change effects (e.g., sea-level rise, sea-ice abatement,[xxii] lake-level decreases) that may impact marine operations, such as the development of alternative transportation routes, changes to ports and harbors, and the stability and safety of energy-extraction platforms.

Apply understanding of environmental factors to characterize and predict conditions in the maritime domain. Enhancing environmental observation, characterization, and forecasting of ocean conditions (e.g., currents, turbidity, surface waves, sea-ice extent, lake levels, biogeochemical conditions) across the global ocean is necessary for safe and efficient marine operations, as well as national security. Increased precision in forecasting marine conditions will promote safe operations both at sea and in port, and minimize negative impacts on marine operations and the environment. Technologies must be developed to enhance data collection in all weather conditions, which will support high-spatial resolution and near real-time forecasting throughout the open ocean and coastal zone.

Apply understanding of human behavior to develop the information and tools necessary to carry out effective, safe, and secure marine operations. A priority is to use socio-economic indicators and educational research (e.g., developing and enhancing information transfer capacity and capability; developing accessible information sources) to address social and economic issues involving changes in marine operations, such as port development, expansion, or modification. Additionally, it is necessary to train operators and users of complex and automated ship systems, and educate the public to ensure safe and secure operations.

Apply understanding of marine operations to enhance the marine transportation system. Research should focus on improving waterway traffic mobility and safety, enhancing port operations and productivity, and reducing congestion. Research in this area will focus on integrating seaport planning and changes in modes of operation into coastal development by incorporating environmental, social, economic, and operations conditions and drivers into assessments and models. Additionally, mechanisms to expand operational capacity (e.g., short-sea shipping, higher-capacity vessels) must be assessed in conjunction with operational efficiency and environmental factors.

NECESSARY TOOLS

Achieving safe, effective, efficient, and secure marine operations balanced with environmental protection requires a diverse suite of infrastructure and technology ranging from assessment methodologies (e.g., rapid-assessment methods for detecting marine contaminants/pollutants and harmful, non-indigenous species) to observing systems and information networks. Providing accurate and comprehensive environmental information will require expanding observational networks to monitor, record, and present real-time surface-monitoring data (e.g, high-frequency coastal-based radars); advancing sensor and technology development, particularly for autonomous and persistent observations, as well as for long-term observing systems; and enhancing automated and autonomous bottom mapping capabilities for change detection to improve rapid, full-scale survey scheduling.

Data collected by the observing systems must be accessible and archived in a comprehensive national database.[xxiii] Developing this database will require designing methodologies to address gaps in data collection and sharing, and interoperability of technologies, and should permit integration of existing research into operational systems (e.g., systems providing real-time navigation data to vessels). This database should be able to be integrated with other databases, such as those focusing on ecosystem data. The national database will also provide the data needed for models simulating "what if" scenarios to better understand potential impacts of various situations (such as weather events or man-made disruptions) on marine operations, and to support operations restoration plans.

ENSURING NATIONAL AND HOMELAND SECURITY

The coast and open-ocean are critical domains for the security of the United States, both at home and abroad. National security operations in the ocean take place globally, and often require continuous, near-real-time monitoring of environmental conditions using tools such as autonomous sensors, targeted observations, and adaptive modeling. Expanded awareness of the ocean environment for security operations requires improved capabilities in:

- Autonomous monitoring of desired ocean parameters in any location for extended time periods
- Integration of multi-sensor data
- Numerical models to provide nowcasts and forecasts for critical parameters.

These capabilities, combined with improved understanding of the ocean environment enabled by other ocean science research activities, will support accurate ocean state assessments and allow future forces to conduct joint and combined operations in nearshore and deep-ocean operating environments, anywhere and at anytime.

THE OCEAN'S ROLE IN CLIMATE

The ocean plays a fundamental role in governing climate through its capacity to store and distribute heat and carbon. The challenge is to understand the ocean's past and present role in climate, and society's influence on this role, and to improve predictions and projections of climate change. Incorporating ocean observations into integrated Earth system models will improve the ability to project future conditions. These predictions and projections will improve society's ability to respond to climate-related hazards, to adapt to climate change and variations (e.g., sea-level rise), and to inform management and policy decisions addressing human and environmental impacts.

RATIONALE

The ocean covers more than 70 percent of the planet and has a much higher capacity to store heat than the atmosphere. Imbalances of the planetary energy budget are manifested in changing ocean temperatures and ice conditions. Because water expands with rising temperature, a warmer ocean leads to rising sea levels, as does runoff from melting of ice sheets and glaciers. The decision by human populations to live in low-lying coastal regions combined with rising sea level necessitates a more complete understanding of the rate of sea-level change, particularly at regional and local levels.

The ocean has an important influence on the path and intensity of major storm systems, such as hurricanes, mid-latitude winter storms, and intraseasonal atmospheric oscillations. Improved understanding of the drivers of these systems, and resulting predictive capability will enhance society's ability to prepare and adapt cities and other public infrastructure for the inevitable arrival of severe events and to take advantage of opportunities presented by climate predictions.

The tropical ocean is a vital component of seasonal-to-interannual climate variability. For example, El Niño events are known to have a substantial impact on many regions of the world, influencing agricultural yields and impacting hurricane frequency. Current evidence suggests that the tropical ocean also influences the occurrence of multi-year droughts. The global ocean is also an important component of the global water cycle; it receives and redistributes fresh water from rivers and ice discharge, and provides moisture (through evaporation) to the atmosphere that precipitates over the ocean and continents. Changes in large-scale ocean circulation may influence both long-term gradual and possible abrupt changes in climate.

Recently, changes in major ocean processes (regime shifts) have been demonstrated to affect marine ecosystems, causing, for example, large swings in the populations of commercial fisheries and coral-reef-bleaching events. The future amount of greenhouse gases in the atmosphere, such as CO_2 and methane, will depend, in part, on the exchange of these gases in both open ocean and coastal systems (e.g., wetlands). Substantial changes in ocean chemistry as a result of oceanic uptake of these gases will further influence ecosystems and their processes. For example, rising atmospheric CO_2 levels are lowering ocean-water pH. A more acidic ocean affects calcifying organisms, such as corals, with significant effects to reefs, the ecosystems they support, and their ability to protect vulnerable coastlines. The growing body of knowledge about the impact of climate on marine chemistry and ecosystems will also enhance ecosystem-based management of the ocean.

RESEARCH PRIORITIES

Consistent with the scientific challenges identified in the Strategic Plan for the U.S. Climate Change Science Program,[xxiv] it is essential to improve understanding of and education about the ocean's role in past, present, and future climate. A pressing barrier to improved understanding is the lack of sufficient observing capabilities. These capabilities will allow enhanced understanding of climate-related processes in several important regions, and on global, regional, and local scales. They will permit investigation of phenomena that contribute to climate change and variability, including large-scale, long-term coherent variability (e.g., Pacific Decadal Oscillation [PDO], North Atlantic Oscillation [NAO]); large-scale, non-linear behavior (e.g., abrupt changes in large-scale ocean circulation); and ocean-atmosphere fluxes (i.e., of carbon, momentum, heat). A greater understanding of the ocean's past and present role in climate change and variability will enable better predictions and projections of climate effects on ocean processes and components (e.g., ecosystems). This understanding will help inform current and future management efforts.

Understand ocean-climate interactions across regions. Regional ocean sectors, such as tropical, polar, and deep-sea, have the potential to influence, and in turn, be influenced by, climate change. Currently, our understanding of the type and extent of this influence is limited. Improved short-term climate predictions require a more complete understanding of the influence of the global tropical ocean phenomena (as demonstrated by El Niño, PDO, and NAO events and monsoons in the Indian and eastern Pacific ocean). Increasing global temperatures could lead to an ice-free Arctic Ocean in summer, with potentially widespread impacts, such as changes in polar albedo and ocean-atmosphere heat exchange, alterations in sensitive Arctic ecosystems, and development of new shipping routes, which may lead to economic development. A warmer Artic will contribute to coastal flooding due to melting ice sheets and may influence abrupt or longer-term climate change. At the opposite pole, the Southern Ocean is a region of significant biological productivity, CO_2 uptake, and large-scale ocean circulation forcing, with significant climate implications. Finally, the role of the deep ocean must be ascertained, particularly with regards to mitigating climate change (e.g., via carbon sequestration and heat storage).

Understand the impact of climate variability and change on the ocean, including its biogeochemistry and ecosystems. Changes in physical properties of the ocean (e.g., heat, fresh water and circulation), as well as biogeochemical properties (e.g., carbon, nitrogen, trace elements), can have a variety of implications, particularly on ecosystems, ranging from coastal watersheds, to shallow and deep-water coral reefs, to open-ocean systems. For example, increasing ocean acidity, altered biogeochemistry, changing current patterns, loss of sea ice, rising sea levels, and altered salinity and sea surface temperature (SST) may irreversibly alter ecosystems. Sustained observations (e.g., global and coastal observatories), process research (e.g., air-sea exchange, ecosystem interactions) and modeling (e.g., integrating global and regional data) will help determine and quantify impacts on ecosystems of the greatest importance. This effort will also help enable effective management of these ecosystems so that they remain healthy and viable.

Apply understanding of the ocean to help project future climate changes and their impacts. Climate is always changing. Currently, the ocean is getting warmer, more fresh water is being added by melting ice sheets, and more CO_2 is being absorbed from the atmosphere. The ability to predict the timing and magnitude of climate changes and how they will impact society will be enhanced by increased resolution and dynamical complexity of global ocean models. Integrating expanded global and regional ocean observations, paleoceanographic data and assessments, and enhanced process research into global coupled ocean-ice-atmosphere-land climate models will help determine the past and present influence of ocean processes on climate change, including the potential for abrupt change. Coupled climate models will also allow improved short-term predictions (e.g., hurricane intensity) and long-term projections (e.g., sea level rise) for use by policy- and decision-makers.

NECESSARY TOOLS

The continuing challenge for climate-related ocean research remains the establishment of a robust, integrated system of global ocean observatories (based on quantitative design studies) capable of sustained observations. Observations from the individual components of this system (including *in situ* and remote [e.g., satellite] sensors) must be integrated through data management and communication capabilities that provide open access, searchable content, and routine delivery to all users. In addition to collecting physical, biological and biogeochemical data, the observing system effort should include the capability to integrate with future observing systems, and incorporate data collected outside of this effort (e.g., paleoceanographic data) into a larger database. In addition to this global observing effort, coastal and coastal watershed observing systems should be developed. The databases from these systems should be integrated with the global system.

Ocean and coupled climate model improvements will be necessary to integrate large volumes of observational data and reconstruct past states of the ocean and predict future states. Increased computational capabilities, including versatile software, efficient algorithms, focused resolution, and capacity, are required to support these advances in data and modeling capabilities.

Improved satellite and *in situ* ocean sensors are necessary to collect information on a broader range of climate parameters, such as currents, salinity, and sea-ice thickness. Next-generation *in situ* chemical and biological sensors that collect a variety of information, including data on sentinel organisms and habitats, will also be important. This enhanced data collection must be accomplished while maintaining long-term climate records of key variables.

IMPROVING ECOSYSTEM HEALTH

Multi-faceted and complex, marine[xxv] ecosystems provide a wealth of benefits to humankind. They are also finite and vulnerable to overuse or misuse from human activity and impacts from natural events. Comprehensive, well-focused, interdisciplinary research can provide the information needed to balance competing uses of the marine environment, to better predict the impacts of such use, and to manage those impacts in a manner that ensures the long-term health[xxvi] and sustainability of marine ecosystems.

RATIONALE

Marine ecosystems range from the Great Lakes and ice-capped polar expanses to warm tropical seas, from deep ocean waters and productive continental shelves to coastal waters, including bays, estuaries, and wetlands. They interface with terrestrial ecosystems not only at shorelines, but also through riverine watersheds. Marine ecosystems provide abundant products and services that not only enhance, but also are essential for life on Earth, such as climate regulation, food and marine products, waste disposal and pollution control, energy sources, and recreation.[xxvii] Much remains to be learned about the structure, function, and vulnerability of these systems, including factors controlling ecosystem stability and productivity; processes across the land-water interface, including the effects of human activities; linkages between ecosystem types (e.g. riverine and coastal, continental shelf and deep pelagic); and the role of marine ecosystems in the ocean-Earth-atmosphere system that enables life in its myriad forms. Management and governance systems that are informed by scientific understanding will help ensure the sustained vitality and diversity of marine ecosystems, as well as the social, economic, ecological, and human-health benefits society derives from them.

RESEARCH PRIORITIES

Marine ecosystems are molded by their biological, physical, and chemical environments. They are linked in intricate and extensive food webs by ecological interactions such as predation, competition, and various forms of symbiosis. Effective and adaptive ecosystem-based management will require a more complete understanding of the mechanisms governing ecosystems and an ability to accurately predict society's effects on them. Expanding the understanding of ecosystem structure, function, complexity, and stability will require investments in exploration, inventory, and novel methods to investigate ecosystem mechanisms. Such investigations will be complemented by research on other societal themes, all of which are linked to marine ecosystem health.

Understand and predict the impact of natural and anthropogenic processes that govern the overall level of ecosystem productivity. The relationships that determine ecosystem structure and productivity are often complex and non-linear. They vary spatially (e.g., local, regional, basin-wide, global) and temporally (e.g., seasonal, annual, decadal, centennial), and incorporate various feedback effects. Understanding these relationships requires incorporating existing knowledge and information at appropriate scales to explore the full range of physical, chemical, biological, and ecological mechanisms that determine observed ecosystem changes. Such changes can result from large-scale shifts in oceanic and atmospheric properties (e.g., regime shifts, El Niño/La Niña events). Shifts in ecosystem structure can be induced by climate-ecosystem interactions (e.g., coral reef degradation via ocean acidification) or human activities (e.g., watershed activities, resource extraction), and shifts can be induced by productivity-driven or predation-driven trophic mechanisms (e.g., invasive species). Improved ecosystem forecasting requires: (1) more comprehensive analyses of changes in ocean physics and chemistry and their impacts on productivity; (2) better models of the dispersal mechanisms for marine organisms; and (3) development of next-generation trophic dynamics models. To run and validate such models requires sophisticated modeling techniques and observational and experimental data collection.

Apply understanding of ocean-related socioeconomic activities to assess the ability of marine ecosystems to provide essential goods and services. To determine and predict society's total impact on marine ecosystems, research efforts should focus on investigating and modeling social and economic factors (e.g., market and non-market resource valuation, energy uses, coastal and watershed development, land use, water use, resource use perception) that determine how society views and uses marine ecosystems.

New approaches are needed to evaluate consumptive and non-consumptive use of resources and characterize the value society places on competing uses. To ensure sustainability of ecosystem goods and services, those approaches must consider the rights of future generations and include discounting procedures for adjusting cost-benefit analyses over time. Thus, an effective and adaptive ecosystem-based management approach for the marine environment will require the integration of socioeconomic science with more traditional ocean science.

Apply understanding of marine ecosystems to develop appropriate indicators and metrics for their sustainable and effective management. A robust suite of indicators of ecosystem structure, function, products, and services must be developed, evaluated, and implemented at multiple scales (local, regional, basin-wide). These indicators will assess pressures on ecosystems (e.g., eutrophication and harmful algal blooms, loss of coastal wetlands, shoreline development, overuse of harvested species, invasive species, introduction and cycling of contaminants, and changes in biodiversity, ecosystem productivity or resilience). Identifying such indicators requires input from a range of scientific disciplines. Additionally, metrics need to be developed to help monitor the restoration and recovery of degraded ecosystems. Such metrics will provide feedback for assessing management efficacy and a basis for incorporating new information and understanding to adapt management practices.

NECESSARY TOOLS

These ambitious but essential research priorities depend on the continued development and implementation of an ocean observing system for assessing physical, chemical, and biological properties of marine ecosystems over time, as well as for assessing human impact on key ecosystem properties, such as productivity, diversity, and resilience. An effective observing system must provide essential data on ecosystem types, ranging from terrestrial watersheds, to productive coastal and continental shelf regions, to the deep, pelagic realms. The information gathered will be essential input into effective, reliable ecosystem models. Collection of such data will require extensive infrastructure, including research vessels, automated buoys, and autonomous vehicles for short- and long-term sampling of water-column properties; satellite-based assessment of surface characteristics (e.g., temperature, chemical properties, surface currents, wave heights); *in situ* observatories in the ocean, on the seafloor, and across the land-water interface; shore-based facilities for sample analysis and observing system maintenance; and a range of survey (e.g., mapping) capabilities. Improvements in information technology and infrastructure also will be essential to ensure that data assimilation, analysis, and modeling tools are available for ecosystem and socio-economic data.

Ensuring an effective and adaptive ecosystem-based research and management approach requires an investment not only in technology and infrastructure, but also in the education systems that produce the scientists and managers needed to implement this approach. Research efforts also require a diverse workforce knowledgeable in natural sciences (e.g., biogeochemistry, taxonomy, systematics[xxviii]) as well as social sciences (e.g., sociology, economics).

ENHANCING HUMAN HEALTH

The ocean holds untapped resources for enhancing human well being; however, the ocean can also be a source of health hazards. In the next decade, efforts to enhance human health will include understanding the causes, and enabling the prevention, of diseases, and identifying and developing new ocean products to effectively treat human disease. Understanding the causes of health hazards and how they can be mitigated or managed will lead to fewer illnesses from contaminated seafood, polluted waters, known and emerging disease-causing microbes, and harmful algal blooms (HABs). Exploration of new habitats, combined with emerging biochemical and biotechnical techniques, will promote the discovery and development of bioproducts that promote human health.

RATIONALE

Waters from the open ocean, coasts, coastal watersheds, and Great Lakes present health risks to people through a variety of mechanisms. These mechanisms include consumption of contaminated seafood (via pathogens, toxins, or chemical pollutants); direct contact with pathogens, toxins, and pollutants in drinking water, and through recreation, work, and weather events; and indirect contact such as breathing fresh salt air that may contain algal toxin aerosols.

It is estimated that tens of thousands of individuals per year, thousands of whom require hospitalization, become ill from eating contaminated shellfish and finfish. However, these figures may be inaccurate due to major gaps that exist in illness reporting and epidemiological knowledge of seafood-caused[xxix] human illnesses.[xxx] Given the huge scale and complexity of the ocean, and the incredible diversity and numbers of organisms and their associated pathogens, the ocean should not be overlooked as a potential reservoir of pathogenic threats to humans.[xxxi] Risks from anthropogenic contaminants, such as heavy metals, petrochemicals, and other current and emerging contaminants in water, sediment, and most notably, seafood, continue to be important health concerns as well. Isolating the causes and impacts of these hazards will help protect human health and safeguard the quality of the seafood supply.

In addition to providing a wealth of known resources, such as food, the ocean is full of potential human health assets. Scientists have recently discovered whole new ecological communities in the ocean with unique biochemical systems. These communities, along with ones yet to be discovered, hold huge possibilities for development of products to improve human health and well being. Prior discoveries that now have practical applications include pharmaceuticals (i.e., anti-cancer drugs), diagnostics (i.e., endotoxin detection), molecular probes (used in biochemical process/disease research) and nutrients (e.g., xanthophylls, feed additives derived from algae).[xxxii]

RESEARCH PRIORITIES

Many challenges face the ocean community in addressing the relationship between the ocean and human health. Adequate monitoring, data sharing, and data interpretation are needed to predict ocean risks to human health, to enhance current understanding of the potential benefits from the ocean, and to support the needs of a wide variety of end-users. Many of the research efforts require interaction between oceanography and other disciplines, such as biomedicine, to provide a broader understanding of the issues and to communicate the results of this research to support effective decision-making.

Understand, forecast and reduce ocean-related risks to human health from pathogens, biotoxins, and chemical contaminants. Basic and applied studies in ocean-related risks should target ocean ecosystems and processes that impact human health. These studies should also incorporate research being carried out on ecosystem health. Processes that need to be studied include the cycling and effect of current and emerging pathogens, contaminants and toxins within food webs (e.g., bioaccumulation, biotransformation, biomagnification) and ocean environments, the mechanisms that stimulate and sustain HABs, and the influence of climate variability on water-borne diseases. Identifying, developing, and implementing new and improved sensors, assays, models and methods will enable assessment, monitoring and prediction of a variety of human health risks, such as HAB onset, extent and duration, infectious disease potential (including microbes that can cross from animal to humans), and pollutant loading.

Understand human health risks associated with the ocean and the potential benefits of ocean resources to human health. While many ocean-based risks and benefits to human health are known, most are poorly understood and their direct health effects on humans (both positive and negative) are inadequately documented. Research should focus on characterizing benefits (e.g., to cardiovascular health) to humans associated with consumption of seafood, and quantifying risks and impacts of exposure to health hazards (e.g., pollutants, pathogens and toxins) via various pathways, including skin contact, respiration (e.g., inhalation of airborne materials), and consumption of food or water, on the incidence and severity of human illnesses. Initial epidemiological studies should focus on those human populations expected to be most at risk (e.g., children, pregnant women, individuals with compromised respiratory or immune systems, and people who spend a large amount of time on or in the ocean, coasts and Great Lakes –e.g., commercial, recreational, or subsistence fishers) and on diseases in ocean species that may serve as sentinels for new or ongoing threats. Ocean data and modeling should be integrated with epidemiologic studies to define exposures and refine risk assessments.

Understand how human use and valuation of ocean resources can be affected by ocean-borne human health threats and how human activities can influence these threats. Coastal and Great Lakes environments hold great attraction for people. They are places for recreation, and they play major roles in human culture and in this nation's economic vitality. However, the use and value of these environments and their resources may be significantly impacted by ocean-borne threats. These impacts include beach, fishery, and shellfish harvest area closures due to contamination by pathogens, toxins, or pollutants, and other human-health threats (real and perceived). Human activities, such as coastal development, can contribute to the onset and persistence of many of these human health threats. Understanding and predicting the relationship between social and economic drivers and human health threats will require integrating socio-economic investigations with ecosystem-based studies of health threats, which will, in turn, help support management and mitigation efforts.

Apply understanding of ocean ecosystems and biodiversity to develop products and biological models to enhance human well being. Ocean environments provide unparalleled opportunity for discovery and development of useful materials. Research should focus on the rapid discovery, testing, and development of ocean bioproducts (e.g., pharmaceuticals, nutrients, diagnostic tools, reagents, enzymes); the use of marine species as mechanistic models for the study of diseases, toxicology, and biochemical processes relevant to human health; and the identification and employment of appropriate sentinel species and habitats that may serve as early warning systems of potential ocean risks to humans.

NECESSARY TOOLS

A system capable of recording comprehensive illness data due to pathogens, biotoxins, and chemical pollutants will require expanded environmental monitoring and infrastructure. Such a system would require collection of human and animal health data, collection of relevant environmental data (via remote, moored, and mobile platforms and sensors as part of an integrated ocean observing system), data condensing and interpretation capabilities, and rapid data communication plans. Once in place, the system could serve to monitor and predict ocean conditions that place people and other animals at risk or that may be favorable to human health in some way.

Sensors capable of detecting biological and chemical parameters, such as microbial densities, species, and contaminant concentrations must be enhanced or developed. Remote sensing of ecological changes and real-time, high-frequency (temporal and spatial) *in situ* monitoring combined with modeling efforts (statistical-empirical and mechanistic) are necessary to inform our understanding of ecosystems and to track and predict outbreaks and other impacts. Developing, enhancing, and applying new methods and tools at shore-based facilities with specialized instrumentation (e.g., gene sequencing) in areas such as genomics, proteomics, and bioinformatics will expand surveying and screening capabilities. Improved coordination of federal and state data systems is needed for toxic algal bloom monitoring, pathogen source tracking, marine disease surveillance, and medical illness reporting, and in the design and development of a national database of monitoring and screening methodologies. Successful pursuit of the research priorities and use of the research results will depend on the integration and collaboration of researchers and managers from disciplines ranging from oceanography to biomedicine to public health.

OPPORTUNITIES FOR PROGRESS

DEVELOPING THE TOOLS

Society's ability to fully develop the understanding needed to address key ocean-related societal issues and to apply existing understanding to support meaningful decision-making depends on technological and intellectual innovation. The ocean components and processes that affect and influence society occur on a wide range of spatial and temporal scales, necessitating development and application of a broad infrastructure with which to investigate these phenomena. Each societal theme outlines the necessary tools to address the research priorities for that specific theme, such as fleet expansion and enhancements (Sustaining Our Natural and Cultural Ocean Resources), shore-based facilities with specialized instrumentation (Enhancing Human Health), and reactive deployment capabilities (Increasing Resilience to Natural Hazards); however, several key infrastructure needs were common across many themes. If addressed, these key infrastructure needs, described below, will support research efforts addressing a diverse set of interactions between society and the ocean.

Observing Systems—The need to acquire, manipulate, analyze, and deliver requisite information about the ocean calls for development of an integrated ocean observing system. An integrated system represents an ambitious effort of the national and global ocean community to establish and maintain a robust, adaptive, continuous presence in the ocean. This system will consist of existing capabilities (e.g., established *in situ* networks, current and planned satellite missions) that will be continually integrated with future systems (e.g., seafloor networks, regional observing systems). Covering a diverse suite of spatial and temporal regimes, an integrated ocean observing system will provide data to address a broad spectrum of societal issues, build the foundation for advancing basic understanding of ocean processes, and revolutionize scientific and public access to the ocean. Key steps to the full implementation of the system include:

- Fully integrating existing (e.g., buoy networks) and future (e.g., surface water quality monitoring networks) components of a national observing system ("national backbone"), which will provide nationwide coverage of the most commonly required ocean parameters in a structure that is closely coordinated with the Global Ocean Observing System;[xxxiii]

- Expanding regional and local coastal observing system capabilities (fixed and mobile), which will provide greater density and diversity of observations on a regional basis, and address region-specific observational needs, such as watershed-specific monitoring and land-water fluxes;
- Maintaining continuity of existing satellite missions and incorporating new remote-sensing capabilities. Integral to this effort is the need for continued sensor development, validation and calibration that will ensure delivery of functional data to users;
- Implementing data management and communications plans to promote interoperability between components of the system, to integrate new components, and to enable data discovery, access, use and archiving of the data streams collected by the observing system and other observing assets (e.g., vessels); and,
- Expanding sensor development for physical, biological, and chemical parameters.

Models—Questions about how the ocean will react to future conditions cannot be answered only by direct observation. Combining existing data sets with scientific and social theory and modeling will provide a window on conditions in the past and enable predictions of the future.

Computer simulation models, the type of models discussed in this document, incorporate one or more mathematical models, which define the relationships among system components, to provide outputs such as tables, charts, or other products. These models may be developed for several reasons, including *exploring* the relationships among physical, chemical, biological, and socioeconomic variables, *forecasting* the impacts of environmental change or management practices, and *hindcasting* previous conditions in an area. Depending on the specific questions of interest in a model and its preferred applications, the model may emphasize generality (ability to represent multiple systems or locations), precision (ability to reduce the uncertainty of a particular measurement), or realism (ability to replicate the system behavior qualitatively), but a single model cannot simultaneously maximize all three characteristics. An example of current and emerging capabilities is community models. These models reflect shared development, regular user interaction, and ready availability of software and documentation.[xxxiv] Also in use are high-resolution models of the global ocean. These models have wide-ranging forecasting capabilities (days to centuries), and can be integrated with even higher-resolution regional modeling efforts (called nesting).

Some existing capabilities are sufficient for the efforts described in the research priorities; other processes require advances in model capabilities. In addition to the development of new models in response to specific research priorities, it is also necessary to enhance existing models with observational data obtained through the ocean observing system and improve model analysis through model diagnostics and intercomparison activities. The amount of data provided by the observing system, along with model advancements due to increased understanding of processes and mechanisms, will require substantial increases in computational capacity over that currently available.

MAKING A DIFFERENCE

The ocean research priorities outlined in this document must be addressed to improve society's interaction with the ocean and improve the health of the ocean. For these research efforts to be effective, they must be accompanied by a strong investment in communicating the results so that society can understand and effectively use this information.

Information To Support Decision-Making

Scientific results must be actively translated into readily understandable information and made available to the public, and their trustees and elected representatives. Information from managers and decision-makers will, in turn, help develop and inform research efforts.

Develop mechanisms to further integrate research results into adaptive management efforts - Effective resource management must include mechanisms to design, evaluate and modify management approaches. Science-based management decisions require a close coupling of problem formulation and data collection. Communication between researchers and decision-makers will allow managers to acquire the information they need, and to adapt management efforts to incorporate new data and understanding of processes.

***Establish dedicated mechanisms to translate research results into readily utilized products* -** A wise use of the limited workforce is to hire professional communicators to assist researchers and end users in developing more accessible, derivative products. These professional communicators would be cognizant of both scientific objectives and management goals.

Foster mechanisms to transition developing technologies into operational capabilities. Many of the research priorities outlined in this document require new sensors, platforms, data management technologies, and models. However, there is often a gap between the development of these capabilities and their use as robust components of integrated systems. Fostering communication among researchers, engineers, and end users will support efforts to overcome technical barriers and promote effective development and use of these technologies.

Establishing An Ocean Literate Nation

Support of the ocean research priorities in the broadest sense requires a society that appreciates the importance of a healthy ocean to life on Earth. Our goal is a nation whose citizens are good stewards of the ocean, who possess the knowledge to make informed decisions about their interactions with it. This goal can only be attained through improved education efforts for the entire spectrum of ages ("K-gray")—encompassing ocean literacy for the general public, formal and informal education, proactive workforce development, and effective communication.

Ocean research provides the information needed to develop education and communication materials that are based on sound science. Ocean research activities also provide a training ground for a range of ocean professionals, an aspect of the research enterprise that is particularly important as ocean science incorporate other fields, such as medicine and social sciences. It is this application of research results that is one of the most potent tools in realizing the goal of sustainable use of the ocean and its resources. Coordinated and sustained education and training efforts among diverse groups, from government agencies and the academic community to school systems and scientific societies, will promote a knowledgeable, ocean-literate public and a larger and well-prepared workforce, and ultimately, help retain U.S leadership in science and technology.

***Expanding and sustaining formal and informal education efforts* -** Currently, ocean science is rarely included in formal education settings. A barrier to inclusion is that knowledge of ocean science is not a requirement of national science standards. Incorporating ocean science into K–undergraduate curricula first requires assessing any current ocean-based curricula and then developing new ocean-related and cross-curricular materials. Providing professional development opportunities for teachers ("educating the educators") and expanding and acknowledging the role of scientists in education and outreach efforts are additional key steps in expanding ocean science in formal education settings.

Incorporation of educational goals will add value to research efforts. For example, the integration of ocean-observing data into K–12 classrooms will help realize the full potential of the observing systems and provide real-world application to the learning environment. Strategies for using these data need to be coordinated at a national level.

Aquaria, museums, science centers, zoos, and other informal education centers welcome over 142 million visitors a year and play a major role in educating the public about the ocean.[xxxv] Media outlets, such as newscasts, television specials, and online portals, provide necessary information, such as hazard warnings, as well as provide a window into the world of ocean science exploration and discovery. Expanding and supporting these forums for lifelong learning will enable the transfer of understanding about the ocean from the research community to the general public.

Advancements in formal and informal education must be accompanied by efforts to address and capitalize on differences in culture, geography, language, and values to reach a diverse audience. These efforts should include strategies to recruit and retain students from all population segments.

***Maintaining intellectual capacity* -** The diversity of technical and research requirements presented in this document necessitates the further development and expansion of a workforce with interdisciplinary (e.g., biology, chemistry, geology, physics) and inter-community (e.g., oceanography, biomedicine, engineering, economics, information technology, public health science, community planning) knowledge bases, the ability to develop and use key research tools, such as models, and the capacity to translate research results into information for decision support. This need is particularly evident as ocean science expands from having single-discipline foci to addressing topics that transcend natural science and incorporate social and economic sciences. The workforce necessary to use the research results outlined in this document must include individuals who are well versed in scientific discovery and understanding, and who possess the means to effectively communicate research results to inform management decisions and policy development.

Efforts to develop and expand the ocean science workforce include assessing existing workforce capacity, expanding opportunities for obtaining graduate degrees and interdisciplinary training, including experience-based (“hands-on’) learning opportunities, developing professional certification programs, and creating competitive incentives to develop and establish training programs.

THE PATH FORWARD

When it comes to understanding the ocean, society is limited only by its ingenuity and determination to push the boundaries of science. What if we could know the impacts of a newly established invasive species on the native vegetation of an ecosystem *before* it happens? What if we understood enough about complex dynamics of physical and biological systems to predict next year's Walleye Pollock stock? What if we knew how much more untreated runoff would go into Puget Sound if 50,000 more people settle in Seattle? Just how much will sea level rise affect southern Florida, and by when?

OVERARCHING OPPORTUNITIES

The ocean research priorities outlined in this document provide an opportunity to redefine society's relationship with the ocean over the next decade. For that relationship to foster advances, like those noted above, and ultimately lead to a healthy ocean now and in the future, three key science and technology efforts must be pursued: (1) developing the understanding and capability to forecast ocean processes; (2) collecting the scientific information needed to support ecosystem-based management of resources, especially those found in coastal and near shore ecosystems; and (3) accelerating deployment of an ocean observing system that will, in turn, advance forecasting and management capabilities.

The understanding and capability to forecast certain ocean and ocean-influenced processes and phenomena will change how society takes action in the future, much like weather forecasts do today. The tremendous potential of this capability has been demonstrated in the forecasts of El Niño and La Niña phenomena that are now used routinely by governments and the private sector. For example, these forecasts currently influence the buying and selling of energy resources, and reduce agricultural loss by adapting agricultural practices using early estimates of the magnitude of El Niño related weather hazards. These forecasts have emerged from investments in the basic understanding of equatorial Pacific Ocean circulation and its relation to weather, in observing systems capable of providing key data, and in model and simulation capability.

Developing the capability to forecast key processes related to hurricane and severe storm formation, ocean currents, fish stocks, and human health hazards, to name a few, would expand not only the economic benefits of ocean forecasts, but their societal and environmental benefits as well.

Managing resources in ways that identify and account for the complex interactions between those resource and other parts of the marine environment -- including humans -- is a substantial challenge. Ecosystem-based management is now widely recognized as one of the most effective ways to cope with a variety of increasing natural and human-induced pressures. Implementing ecosystem-based management requires determining which interactions are most critical, as well as the physical, biological and human factors affecting those interactions, and the way those factors will change in the future.

A robust observing system that can describe the actual state of the ocean will fundamentally alter society's view of the ocean environment. As outlined in the societal themes, observations underpin fundamental knowledge of the open ocean, coasts, coastal watersheds, and Great Lakes. Although much work remains, mature plans for many components of an integrated, global ocean observing system have been developed by the communities interested in ocean research and ocean management. Deploying the priority elements of that observing system will allow researchers to enable the promise of ocean forecasting and ecosystem- based management during the next decade.

These three areas are critical and necessary steps on the path towards expanded awareness of the ocean and wise interaction with it. Society has the opportunity to expand its vision of the ocean and ensure its legacy for future generations.

NEAR-TERM PRIORITIES

Near-term (2-5 years) priorities were developed from the 21 research priorities identified in this document. The near-term priorities incorporate aspects of each of three overarching opportunities (understanding and capability for forecasting ocean processes, scientific support for ecosystem-based management, and targeted deployment of elements of an ocean observing system). The near-term priorities outlined below incorporate aspects of each of these three areas. Advancing the three overarching opportunities through these near-term priorities supports the efforts of all of the societal themes outlined in this document, ranging from stewardship of our natural and cultural resources to enabling marine operations to enhancing human health. These near-term priorities, each with equal priority, were developed using the criteria outlined for the general research priorities, with an added focus on impact (i.e., why the work would be of value), urgency (i.e., why a concentrated effort should be pursued over the next 2-5 years rather than a modest effort over 10 years), and partnerships (i.e., will the effort maximize collaborations among agencies and sectors).

***Forecasting the Response of Coastal Ecosystems to Persistent Forcing and Extreme Events* –** Understanding the response of natural and constructed landscapes and ecosystems to extreme weather events, natural disasters and changing ocean conditions, such as hypoxia, and forecasting the frequency, intensity, and impact of those events is integral to constructing more resilient structures and communities, and protecting the natural environment. This effort will integrate and enhance regional observing systems and models, yielding improved understanding and better forecasts of coastal system responses to extreme events, persistent natural processes, and human influences across the coastal zone. These data will be made widely available to diverse end-users through the national ocean observing system. Results from this effort will inform hazard mitigation and response plans, provide forecasting data to support navigation safety, and assist regional resource managers in sustaining ecosystem health and promoting hazard resilience.

Observations of physical characteristics and processes, including material inputs from adjacent watersheds, ocean influences on hurricane intensification, and characterization of submerged and coastal landscapes will be integrated to support data-assimilative modeling of, for example, water quality, nutrient, sediment, and contaminant transport, waves and water levels, and the coastal response to hurricane processes. Biological observations, including new DNA-based techniques, will enable development of coupled physical and biological models of ecosystem-level response to various stressors. Coupled observations and model development might focus on identification, quantification, and transport of pathogenic microbes and various species of harmful algae, and lead to robust, timely forecasts of human health threats. Additionally, linking environmental quality data with public health surveillance activities will support modeling and prediction of the geographic expansion of potential health risks from hurricanes and specific waterborne vectors and pathogens.

This effort will build upon extensive existing surveillance, observational, and modeling capabilities; promote the transition of models from research tools to operational applications; and support the establishment and linkage of regional and national ocean and water quality data networks. Decision-support models will inform prevention strategies, rescue and recovery operations, spill tracking, safe maritime navigation, water quality forecasting, and resource management, taking into account the vulnerability of ecosystems as well as their capacity for mitigating harmful impacts.

***Comparative Analysis of Marine Ecosystem Organization* –** Management of marine ecosystems can be improved by elucidating their underlying dynamics at a variety of scales. Forecasting marine ecosystem responses to management strategies requires an understanding of the complex dynamics that control and regulate ecosystem processes. This effort will provide a greater basic understanding of these processes, and practical tools for evaluating the effectiveness of local and regional ecosystem-based management efforts.

Ecosystem-based approaches emphasize interactions among components and the impacts that various human activities have on productivity and organization. Forecasting these impacts requires understanding complex dynamics controlling: (1) productivity of various trophic levels; (2) predator-prey interactions; (3) connectedness of sub-populations; (4) impacts of natural climate variation; and (5) various anthropogenic pressures. Since marine ecosystems cannot be understood through classical controlled experimentation, two types of analyses will be undertaken. First, constructing and applying various classes of energy budget and dynamic models to managed marine ecosystems will enable greater understanding of the impacts of human activities by contrasting biomass changes by trophic level. The second approach will compare systems where ecosystem management strategies have been enacted.[xxxvi] Such comparisons will include before and after closure contrasts, where sufficient data are available, as well as inside versus outside comparisons for established managed ecosystems. Mapping efforts will include ecosystem-scale characterization, design of interpretive products, and provision of tools to assimilate and disseminate geospatial information in support of research, observations, modeling, forecasting and management decision support.

Candidate ecosystem types for inclusion in this study may include the sub-Arctic, continental shelves, coral reefs, and estuaries. Analysis of these ecosystems will focus on how feedbacks influence ecosystem productivity, biodiversity and conservation of managed species, through comparisons using consistent modeling frameworks. Evaluation of the effects of management efforts will involve assimilation and synthesis of existing biological information by trophic level, linkages to higher levels and impacts on human use patterns (e.g., such as displacement of human activities from marine protected areas and their socioeconomic effects). Pursuing these efforts will help ensure that effective ecosystem-based management strategies are based on sound scientific understanding.

Sensors for Marine Ecosystems **–** New, improved sensor capabilities are necessary to realize the full potential of *in situ* ocean observing networks and satellite-based observations to enhance understanding of marine ecosystems. However, significant limitations exist in observational capabilities and associated methodologies with existing in-water sensor technologies. Immediate improvements can be made to *in situ* instrumentation in eco-genomics, interdisciplinary ocean observing, and sensors in support of satellite-derived “ocean color” (used to estimate the biological (phytoplankton) and biogeochemical (carbon) materials in surface waters) and new biological and biogeochemical observations. Such advancements can revolutionize understanding of the ocean environment by providing information at temporal and spatial scales not currently available.

Creation of a common library of genetic "barcodes" is a critical step in the development of fast, economical genetic screening procedures to identify marine organisms. Such procedures will help reveal basic ocean processes controlling biodiversity and productivity, including the distribution and abundance of harmful algae and pathogens. Advancing novel capabilities and moving high impact/high utility sensors from research to broad operational use will allow for physical sensors capable of providing a better understanding of ocean transport and fluid velocity, and chemical sensors that can reliably detect toxins and ecologically important nutrients. Enhancing in-water instrumentation used in ground-truth exercises will improve the quality and usefulness of remotely sensed "ocean color" data, and allow for the development of new space-based, ocean biological and biogeochemical measurements. Improving ground-truth and *in situ* observations will significantly advance understanding of — and ability to model — ocean systems (ecology, biology, carbon) and their role in the Earth System, as well as the potential impact of human activities. Parallel advances in power supply technologies and data transfer must also occur to ensure *in situ* sensor operation in a variety of environments and within a variety of networks. Advancing sensor capabilities will enable new, multi-scale observations that provide information needed to better define marine resource management options, help understand processes that influence ecosystem productivity, serve as the basis for forecasting ocean-related risks to human health and safety, and shed light on the impact of climate variability and change on the ocean, marine life and humans.

Assessing Meridional Overturning Circulation Variability: Implications for Rapid Climate Change –The ocean plays a central role in many of the mechanisms that impact global climate. Thus, incorporating ocean observations and understanding into an integrated Earth system analysis capability is needed to assess the current state of the climate system. Specifically, the meridional overturning circulation (MOC) of the Atlantic Ocean, an element of the global scale ocean circulation responsible for long-term climate variations, has been identified as a key process related to rapid or even abrupt climate change (i.e., changes over a few years to a few decades). Understanding how to monitor, detect, and analyze rapid changes in this key component of the ocean conveyer belt could have implications for many significant changes in climate.

Understanding how to implement an observing and now-casting capability for the Atlantic MOC will enable improved understanding of the physical mechanisms behind fluctuations in the MOC, the impacts of MOC fluctuations on regional and global climate and ecosystems, and the potential for prediction of these fluctuations. Assessing the potential for future abrupt changes and developing the capability to predict their occurrence will require a national program that includes: (1) observations; (2) now-casting; (3) model development for decadal forecasting; (4) past climate-change reconstructions; and (5) climate impact assessments. Incorporating existing and planned infrastructure, this capability will include *in situ* observations (e.g., currents, temperature, carbon), satellite observations (e.g., sea surface height, surface vector winds), and ocean data assimilation capabilities to provide routine basin-scale analyses. These analyses will provide now-casts of the status of the MOC, accelerate the development of improved models, and provide the initial conditions for experimental decadal forecasts and climate projections. Establishing the basis for a long-term monitoring system for the MOC over the next 2-5 years will provide the observational data needed to challenge and improve climate models, and to more accurately establish the true variability of the MOC and its effects.

THE NEXT STEPS

As called for in the OAP, the JSOST will develop an implementation strategy to address the national ocean research priorities articulated in this document. That implementation strategy will describe a set of operational principles and conceptual guidelines defining how to implement the research priorities. The implementation strategy will place particular emphasis on the following:

- Roles and responsibilities of each constituent sector (e.g. federal agencies, state agencies, private sector, academia and non-governmental organizations) in planning, programming, budgeting and execution of the priorities defined herein;
- Use of existing mechanisms for collaboration among the federal agencies and with international, state, local, and tribal entities, and the private sector (e.g. National Oceanographic Partnership Program);
- Concepts for new public/private mechanisms of coordination;
- Enhanced coordination between resource management communities (including states and regional bodies) and the ocean science community;
- Enhanced translation of ocean research to expand ocean literacy and promote public discourse;
- Articulation and implementation of meaningful performance measures and regular evaluation mechanisms for ensuring continued progress on the research priorities; and
- Need for an annual planning cycle that will allow the JSOST to coordinate planning for ocean research investments among the federal agencies in support of their budget requests.

The implementation strategy will take advantage of ongoing planning efforts in the governmental, academic, non-governmental, and industrial communities to integrate the ocean research priorities into current and future activities. Concurrently, the federal agencies will continue, as directed by the Office of Management and Budget and the Office of Science and Technology Policy, to implement actions outlined in the Administration's OAP, to begin to lay the ground work for aligning future budgets with the research priorities, and to integrate U.S. ocean observing efforts into the Global Earth Observation System of Systems. The implementation strategy will ensure the nation's ability to make progress toward achieving the vision articulated by the USCOP and the OAP.

ENDNOTES

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[i] http://www.uscg.mil/hq/g-o/g-opl/LMR/LMR.htm (accessed July 5, 2006)

[ii] U.S. Commission on Ocean Policy. *An Ocean Blueprint for the 21st Century, Final Report.* Washington, DC, 2004. p. 1 (http://www.oceancommission.gov/documents/full_color_rpt/welcome.html)

[iii] U.S. Commission on Ocean Policy. *An Ocean Blueprint for the 21st Century, Final Report.* Washington, DC, 2004. p. 327

[iv] E.g., National Research Council. Exploration of the Seas: Voyage into the Unknown. National Academy Press, Washington, DC. 2003; Brewer, P. and T. Moore. Ocean Sciences at the New Millenium. UCAR/JOSS. 2001.

[v] Approximately 3.4 million square miles (www.uscg.mil/hq/g-o/g-iol/LMR/LMR.htm - accessed July 5, 2006)

[vi] U.S. Commission on Ocean Policy. *An Ocean Blueprint for the 21st Century, Final Report.* Washington, DC, 2004. p. 275.

[vii]Report to Congress: Comprehensive Inventory of the U.S. Outer Continental Shelf Oil and Natural Gas Resources," Energy Policy Act of 2005 -- Section 357, U. S. Department of the Interior, Minerals Management Service, table 2, page 31, February 2006.

[viii] www.nrei.gov/docs/fy06osti.39479.pdf (accessed July 5, 2006)

[ix] Collett, T.S., 1995, Gas hydrate resources of the United States, in Gautier, D.L., Dolton, G.L., Takahashi, K.I., and Varnes, K.L., eds., 1995 National assessment of United States oil and gas resources on CD-ROM: U.S. Geological Survey Digital Data Series 30

[x] Collett, T.S., 1997, Resource potential of marine and permafrost associated gas hydrates, in Max, M.D., Pallenbarg, R.E., and Rath, B.B., eds., Oceanic gas hydrate: guidance for research and programmatic development at the Naval Research Laboratory (Proceedings of the workshop on Naval Research Laboratory gas hydrate research program, September 23-24, 1997, Washington, D.C.): NRL/MR/6100-97-8124, 51 p

[xi] http://www.glerl.noaa.gov/pr/ourlakes/ (access July 28, 2006)

[xii] U.S. Commission on Ocean Policy. *An Ocean Blueprint for the 21st Century, Final Report.* Washington, DC, 2004. p. 35.

[xiii] "Ecosystem-based management is an integrated approach to management that considers the entire ecosystem, including humans." Scientific Consensus Statement on Marine Ecosystem-Based Management. March 21, 2005. http://compassonline.dorg/?=EBM

[xiv]Office of Science and Technology Policy and National Marine Fisheries Service. *NOAA Fisheries Data Acquisition Plan.* 1998. (http://www.st.nmfs.gov/st2/DataPlan.pdf)

[xv] www.oceanservice.noaa.gov/programs/mb/supp_csh_population.html (accessed June 29, 2006)

[xvi] http://www.ncdc.noaa.gov/oa/reports/tech-report-200501z.pdf (accessed June 29, 2006)

[xvii] U.S. Commission on Ocean Policy. *An Ocean Blueprint for the 21st Century, Final Report.* Washington, DC, 2004. P. 192.

[xviii] Marine operations as discussed here are the broad set of commercial activities that occur in the ocean, coastal waterways, and Great Lakes; however, this discussion focuses on primarily on transportation issues and energy and resource production, not commercial fishing or recreational aspects of the marine environment.

[xix] Arctic Council and International Arctic Science Committee. *Impacts of a Warming Arctic: Arctic Climate Impact Assessment*. Cambridge University Press. 2004 (www.acia.uaf.edu)

[xx] Short sea shipping uses inland and coastal waterways to move commercial freight from major domestic ports to its destination. (http://www.marad.dot.gov/Programs/sssbroc.htm - accessed June 29, 2006)

[xxi] Research efforts for marine transportation will be coordinated with efforts of the cabinet-level committee on the Marine Transportation System (www.waterways-rd.gov/about/CMTS.htm)

[xxii] www.natice.noaa.gov/icefree/FinalArcticReport.pdf

[xxiii] For example, the Multipurpose Marine Cadastre Initiative (www.mms.gov/Id/PDFs/MappingInitiative.pdf - accessed July 6, 2006).

[xxiv] U.S. Climate Change Science Program and Subcommittee on Global Change Research. *Strategic Plan for the U.S. Climate Change Science Program.* Washington, DC. 2001. (http://www.climatescience.gov/Library/stratplan2003/final/default.htm)

[xxv] Inclusive of ecosystems in the open ocean, coasts, coastal watersheds, and Great Lakes.

[xxvi] Ecosystem health goals and objectives are management tools that guide an ecosystem-based approach to environmental planning and management. Ecosystem goals are statements that describe the desired state of an ecosystem. Ecosystem objectives are more specific. They describe desired conditions for a given ecosystem accounting ecological characteristics and uses.

[xxvii] Millenium Ecosystem Assessment. www.maweb.org//en/About.Overview.aspx

[xxviii] The study of the evolutionary relationships of species

[xxix] "Seafood" refers to all consumer seafood products as well as all forms of recreational and subsistence take such as marine mammal harvest by Native Americans.

[xxx] Excluding allergic reactions to seafood

[xxxi] Kuiken et al. (Science 309:1680-1681, 2005), Taylor et al. (Philos. Trans. R. Soc. London Ser. B 356: 983, 2001).

[xxxii] U.S. Commission on Ocean Policy. *An Ocean Blueprint for the 21st Century, Final Report.* Washington, DC, 2004. pp. 340–342.

[xxxiii] http://www.ioc-goos.org/content/view/12/26/ (accessed July 5, 2006)

[xxxiv] OITI Steering Committee. *An Information Technology Infrastructure Plan to Advance Ocean Sciences*, Washington, DC., 2002. (http://www.geo-prose.com/oiti/report.html)

[xxxv] www.aza.org/AboutAZA/CollectiveImpact1 (accessed June 26, 2006)

[xxxvi] The number of managed ecosystems continues to increase. For example, in the past two months the United States has designated the world's largest marine conservation area in the Northwest Hawaiian Islands (http://www.whitehouse.gov/news/releases/2006/06/print/20060615-18.html), and more recently, the world's largest MPA in the Aleutian Islands (http://www.noaanews.noaa.gov/stories2006/s2673.htm).