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Subcommittee on Ocean, Atmosphere, Fisheries, and U.S. Coast Guard
Deep Sea Challenge: Innovative Partnerships in Ocean Observing

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Good afternoon Chairman Begich and Members of the Committee. My name is Dr. Susan K. Avery, and I am President and Director of the Woods Hole Oceanographic Institution in Woods Hole, Massachusetts. Thank you for the opportunity to testify today in support of our nation's community of ocean scientists and research institutions. I'd like to recognize Jim Cameron for his commitment to helping advance ocean science, exploration, and education, and his willingness to sharing his team's work on the DEEPSEA CHALLENGER with the science community, which Woods Hole Oceanographic Institution will facilitate.

IMPORTANCE OF THE OCEAN

The ocean is the dominant feature on Earth. Removing all that water reveals some surprising things about our planet: There are mountain ranges longer than anything on land, mountains higher than Everest, and canyons deeper and grander than the Grand Canyon. And it's all covered by a relatively thin skin of water. Despite this, the ocean most people see is the surface. A sunset over a healthy ocean looks just like one over a sick ocean. It is what happens underneath the surface that is critical to humanity.

The importance of the ocean in daily life, whether you live on the East Coast, the Great Plains, or the Mountain West, cannot be oversimplified or understated. In short, it is one of the most fundamental reasons why our planet is capable of supporting life and why we are able to sustain the economy and way of life that are among our national hallmarks. Our fate has always rested in one way or another with the ocean and its interaction with the atmosphere, land, and humanity. The ocean plays a critical role in governing Earth's climate system helping to regulate global cycles of heat, water, and carbon. The rates and regional patterns of land temperature and precipitation depend on the ocean's physical and chemical balances. It touches us every day, wherever we live through our climate and weather; rainfall, floods, droughts, hurricanes, and devastating storm surges such as what we witnessed with Hurricane Sandy.

The services the ocean provides—and that we often take for granted—range from endless inspiration and deep-seated cultural heritage to the very air we breathe and the rain that waters our crops. Roughly half of the oxygen we breathe and about 80 percent of the water vapor in our atmosphere comes from ocean processes. The ocean feeds us, processes waste, holds vast stores of mineral and petroleum reserves, and provides inexpensive transportation of goods and people. Its rich biodiversity is a potential source for new medicines and an insurance policy for our future. Many of these things it provides the planet without our intervention; other things we actively seek and extract—and we will continue to do so.

In 2010, maritime economic activities contributed an estimated $258 billion and 2.8 million jobs to the national economy.[1] In addition, roughly 41 percent of the nation's GDP, or $6 trillion, including 44 million jobs and $2.4 trillion in wages, was generated in the marine and Great Lake shoreline counties of the U.S. and territories.[2] The key for the future of the ocean and for humanity will be to learn how to balance these economic activities with the natural functioning of the ocean.

We know that the ocean is taking up more than 80 percent of the heat that is generated by rising levels of greenhouse gases in our atmosphere.[3] Excess carbon dioxide mixed into the upper ocean is lowering the pH of seawater, making it more acidic and raising the potential for large-scale change at the base of the marine food chain and in the coral reef ecosystems that are considered the breadbasket of the tropical oceans and an important source of biodiversity and income for many regions. Excess heat is causing Arctic sea ice to retreat to levels never before seen, setting up the likelihood of still further melting driven by positive feedback loops, as well as disruptions to the Arctic ecosystems that have evolved in an environment partly reliant on ice cover for millions of years. Sea level is also rising, both as a result of increased melting of terrestrial ice caps and of thermal expansion of the seawater, resulting in higher probabilities of more frequent and more severe storm surges such as those associated with Hurricane Sandy. Our ability to build properly designed and appropriately scaled adaptations into cities and societies around the world is predicated on our ability to accurately predict how, when, and how much the ocean will change in the future.

For these reasons and many others, our nation must recognize that the ocean is changing almost before our eyes. Perhaps the question is, not how much can we afford to invest in research on the ocean, but rather how can we afford not to?

Despite its importance, there remain many unanswered questions about the ocean. It is far more difficult to observe than the atmosphere. Because the ocean is opaque to most forms of electromagnetic radiation, satellite observations are limited in the type and resolution of information they can gather. We are capable of monitoring many surface features, including waves, winds, temperatures, salinity, carbon, color (a measure of biological productivity), as well as some large-scale sub-surface features. But satellites cannot tell us much about the diversity of life in the ocean or the many fine-scale dynamic processes at work beneath the surface, nor can they tell us much about the internal complex biogeochemistry that supports life. Satellites can’t show us the bottom of the ocean,

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[1] NOAA Coastal Services Center, *NOAA Report on the Ocean and Great Lakes Economy of the*
[1]*United States*, 2012, http://www.csc.noaa.gov/digitalcoast/_/pdf/econreport.pdf (accessed February 2013).
[2] NOAA National Ocean Service, Special Projects Division, *Spatial Trends in Coastal Socioeconomics*
[2](STICS), 2013 http://coastalsocioeconomics.noaa.gov/ (accessed February 2013); and NOAA Office of
[2]Program Planning and Integration The Ocean and Coastal Economy: A Summary of Statistics, 2013
[2]http://tinyurl.com/p55na2q (accessed June 2013).
[3] Levitus, S., J. Antonov, and T. Boyer, "Warming of the world ocean, 1955–2003," Geophys. Res. Lett. 32(2005), L02604, doi:10.1029/2004GL021592.

where volcanic hydrothermal vents sustain rich communities of exotic organisms—which might answer questions about the early evolution of life. To learn more about these important parts of the ocean system, we must have more and better eyes *in* the ocean and, at the same time, work to surmount the huge challenges of working in a cold, corrosive, and physically punishing environment.

FRONTIERS IN THE OCEAN

Jim Cameron is a visionary who is capable of looking beyond what we are currently able to see. Let me tell you about another visionary. In the mid-1930s, a physicist from Lehigh University named Maurice Ewing sent letters to several oil companies. He asked them to support a modest research program to see whether acoustic methods used to probe buried geological structures on land could be adapted to investigate the completely unknown geology of the seafloor. Ewing later wrote: "This proposal received no support whatever. I was told that work out in the ocean could not possibly be of interest to the shareholder and could not rightfully receive one nickel of the shareholder's money."[4]

Ewing did get a $2,000 grant from the Geological Society of America, however, and he and his students came to Woods Hole Oceanographic Institution to use its new ocean-going research ship, *Atlantis.* The ship and the institution were launched by a $3 million grant from the Rockefeller Foundation. The scientists launched novel experiments using sound waves to probe the seafloor. To Ewing, the ocean was annoyingly in the way. To study the seafloor, he and his colleagues had to learn how to negotiate the intervening water medium. In the process, they unexpectedly made profound and fundamental discoveries about ocean properties and how sound propagates through seawater.

In 1940, on the eve of war, Woods Hole's director, Columbus O'Donnell Iselin, wrote a letter to government officials, suggesting the ways the institution's personnel and equipment could be better utilized for the national defense. Soon after, one of Ewing's students, Allyn Vine, began incorporating their newly gained knowledge to build instruments called bathythermographs, which measured ocean properties. Vine trained naval personnel to use them to escape detection by sonar. It was the first among many subsequent applications of this research that revolutionized submarine warfare.

Many scientists pursued the marine geophysics research initiated by Ewing. Their work culminated in the late 1960s in the unifying theory of plate tectonics. It transformed our understanding of continents, ocean basins, earthquakes, volcanoes, tsunamis, and a host of other geological phenomena—including significant oil reservoirs beneath the seafloor—where oil companies now routinely drill and make money for their shareholders.

Al Vine remained in Woods Hole and spearheaded deep-submergence technology, including the research sub *Alvin*, which was named after him. Two years after it was

[4] Lippsett, L., "At Deepwater Horizon, basic research was applied," *Oceanus* 48(2011) http://www.whoi.edu/oceanus/viewArticle.do?id=116709 (Accessed June 2013).

completed, *Alvin* was applied to a national emergency, locating a hydrogen bomb that accidentally dropped into the Mediterranean Sea. A decade later, *Alvin* found seafloor hydrothermal vents. To humanity's utter astonishment, the vents were surrounded by previously unknown organisms sustained not by photosynthesis but chemosynthesis. This discovery completely changed our conceptions of where and how life can exist on this planet and elsewhere in the universe.

Thirty-five years later, Alvin was again called into action to help assess and monitor the Deepwater Horizon oil spill and its impacts in the Gulf of Mexico, but at the same time, the ocean science community was able to bring much more to bear in a time of national crisis. The community's unparalleled response in the Gulf was enabled by more than three decades of technological advancements related to development of remotely operated and autonomous underwater vehicles and new sensors and data assimilation techniques, and integrated networks of sensors, vehicles, and platforms that have opened the ocean to the light of new study, many of which were developed through novel partnerships with private funders.

Society has benefitted in the past from public-funded/private-funded partnerships that advance research and development, probably even before Queen Isabella financed Columbus's voyage of discovery in 1492. But I emphasize: It's a partnership. One doesn't replace the other. Each augments the other. In an unexpected bit of poetry, the NSF annual report from 1952 says: "That which has never been known cannot be foretold, and herein lies the great promise of basic research. … [It] enlarges the realm of the possible." The bottom line question is: How much are we willing to invest in enlarging the realm of the possible?

Jim Cameron did that with DEEPSEA CHALLENGER. He enlarged the realm of the possible by demonstrating that even the deepest part of the ocean is not beyond our physical presence. Still other advances are expanding the possible in many ways through the development and deployment of novel sensors, autonomous vehicles, and new ways for humans and machines to interact. There is a revolution in marine technology underway that is positioning us to reach many unexplored frontiers in the ocean—and the ocean has many. The deep ocean is only one.

We have barely gained access to explore the ocean beneath our polar ice caps—at a time when rapidly disappearing sea ice has profound implications for Earth's climate, for ocean ecosystems, expanded shipping, oil and mineral resource development, and national security. There is the microbial frontier, where 90 percent of the ocean biomass resides and which is invisible to the human eye. There are about 300,000 times more microbes in the ocean than there are observable stars in the universe.[5] Ocean scientists have just begun to explore this universe of marine microbes, which holds the key to healthy biological functioning of the ocean ecosystem, much as the microbiome in the human body is critical to our health. They are also searching for unknown biochemical pathways and compounds, for new antibiotics, and for novel treatments for diseases such as Alzheimer's and cystic fibrosis.

[5] Mincer, T., personal communication, June 6, 2013.

Then there is the frontier of temporal and spatial scales that must be overcome to monitor and forecast changes to the deep and open ocean. The ocean exhibits large, basin-wide patterns of variability that change over periods ranging from days and weeks to years, decades, and longer. Understanding and observing these patterns, including El Niño-Southern Oscillation (ENSO), offer potential for improved prediction of climate variability in the future. For most of my career, I have been an atmospheric scientist. The atmosphere and ocean are both fluids (one that is compressible, the other incompressible). These two systems are interwoven and inseparable.

But while we have long-established, extensive networks of meteorological instruments continually monitoring our atmosphere, we have just begun to establish a relative toehold of long-term observatories to understand, and monitor how the ocean operates. To truly comprehend Earth's dynamic behavior and to monitor how it affects us back on land, scientists must establish a long-term presence in the ocean, including platforms and suites of physical, chemical, and biological sensors from which to view how the ocean and seafloor change in fine resolution over seasons, years, and decades. This same observing capability will provide the basis for improved forecasts from models that incorporate data and observations from the ocean, atmosphere, and land and that provide the basis for decision making by national, state, and local agencies.

Variability such as weather events associated with ENSO has significant societal and economic impacts in the U.S., and a combination of a dedicated ocean-observing system in the tropical Pacific plus models that forecast ENSO impacts is now in place to help society adapt in times of increased variability. The promise of additional benefits from observing, understanding, and predicting the ocean and its impacts is real. Modeled reconstructions by Hoerling and Kumar of the 1930's drought in the Central U.S. recently linked that event to patterns of anomalies in sea-surface temperature far from the U.S.[6] The global scale of the circulation of the ocean and basin-scale patterns of ocean variability on decadal and longer time scales may present sources of improved predictive skill in future weather and climate models.

Moving forward, we need to be even more adaptive and agile, applying new technologies in ways that both make crucial observations more effectively and make coincident observations of the biology, chemistry, and physics of the ocean. At the same time we need at our modeling and prediction centers to establish the resources and mindset that will support testing and adoption of research results that lead to improved predictions.

We are on the edge of exploration of many ocean frontiers that will be using new eyes in the ocean. Public-funded/private-funded investment in those eyes is required, but will not be successful without adequate and continuing federal commitment to ocean science. Support such as Jim's and the Schmidt Ocean Institute, which was founded by Eric Schmidt and operates the research vessel *Falkor*, help fill gaps in support for research and development or for access to the ocean. However, the fact remains that federal

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[6] Hoerling, M and A. Kumar, "The perfect ocean for drought," *Science* 299(2013):691-694 doi:10.1126/science.1079053.

funding is by far the leading driver of exploration, observation, and technical research and development that has a direct impact on the lives of people around the world and on U.S. economic growth and leadership. It also remains the bellwether by which philanthropic entrepreneurs judge the long-term viability of the impact their investment will have on the success that U.S. ocean science research will have around the globe.

RECENT MODEL ADVANCES

Most advancements in global oceanographic and climate modeling in the recent past have been incremental, but have proved crucial to our greater understanding of Earth's ocean and climate as internally complex and interlocking systems. Further work needs to be done to provide greater insight into the workings of the ocean, atmosphere, land, and human systems individually and as an integrated whole. At its core, this requires enhanced observational infrastructure, as well as better data assimilation and more robust statistical and dynamic models.

Over the past 30 years, one of the most visible examples of breakthrough understanding of ocean processes related to climate and weather has been the link between the El Nino-Southern Oscillation (ENSO) and extreme weather events around the world, including patterns of drought and hurricane frequency in the tropical Atlantic. Understanding phenomena such as ENSO helps forecasters better predict how Earth’s climate will respond to changing conditions in the ocean over seasonal to annual time scales. But such oscillatory behavior is difficult to forecast under the changing conditions driven by increased atmospheric greenhouse gases.

There are, however, several noteworthy advancements in the recent past.

New sea ice projections[7]

Loss of nearly all Arctic sea ice in the summer is now projected to occur as early as 2050. An ice-free Arctic will have benefits for transportation and natural resource extraction, but these, in turn, will likely come at a cost. Territorial claims in the Arctic Ocean could lead to tension among regional partners, but also present opportunities for new avenues of international cooperation; and extractive activities pose risk for accidental oil spills in remote and hazardous locations. In addition, the loss of sea ice is a significant disruption to the fragile and unique ecosystem of the Arctic Ocean for which the implications, in the Arctic or beyond, are difficult to predict.

Expanded Sea-surface Temperature Forecasts[8]

It now appears possible to extend our ability to forecast some variations in sea-surface temperature which could prove to be an important tool for improving climate models. Research is focusing on patterns of decadal variability in sea surface temperatures. However, initialization data is very important to such a model, which means that a

[7] Overland, J.E. and M. Wang, "When will the summer Arctic be ice-free?" *Geophysical Research Letters* 40(2013), doi:10.1002/grl.50316.
[8] DelSole, T., J. Liwei, and M.K. Tippett, "Decadal prediction of observed and simulated sea surface temperatures" *Geophysical Research Letters* 40(2013), doi:10.1002/grl.50185.

comprehensive ocean observing system remains essential to incorporating this potential advancement into future predictive capability.

Improved horizontal resolution and improved model physics[9]

Higher resolution models are better able to incorporate the physical, chemical, and biological processes. A new suite of climate models known as CMIP5 is being used to prepare the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5) and, along with other developments, is helping provide better estimates of precipitation over the continental U.S. under an evolving climate. This comes at a time when evidence points to the fact that the water cycle is intensifying under global warming[10] and it is becoming increasingly important to understand and predict the accompanying intensification of droughts in dry regions and the incidence of floods in wet regions. The ocean is the major source of most rainwater and must be part of any effort to predict the future water supplies for metropolitan, agricultural, and industrial regions of the U.S.

Predicting long-term cycles[11]

Regular changes in sea-surface temperature in the tropical Pacific Ocean, such as the El Niño-La Niña cycle, influence precipitation and extreme events over a wide swath of the globe. However, many other, longer-term modes of ocean-temperature variability such as the Pacific Decadal Oscillation (PDO) exist that can impact regional climate and weather patterns far afield. Much of our understanding on these climate modes is based on the instrumental record of temperature, but this only extends back only a couple of centuries. Important new insights on past climate variability and extremes is being discovered by analyzing tree rings and other paleo-climate proxy records. Recent work also suggests the presence of centennial-scale cycles in the Pacific, and researchers are currently analyzing coral samples from remote islands of the western Pacific for signs long-term variability in ocean temperature that might confirm the presence of this and its current phase.[12]

Incorporation of biological processes into modeling and operational forecasts[13]

Advancements in predictions of harmful algal blooms (HABs) in the Gulf of Maine have reached a point where the research program will soon transfer to operational forecasting. Forecasts of HABs are already operational in the Gulf of Mexico and Lake Erie. The economic cost of HABs to recreation, fishing, public health, and coastal monitoring in the U.S. is estimated to be nearly $100 million annually. Forecasts of the severity of HABs in recent years have allowed fisheries managers and public health officials to take preemptive action that minimizes costs associated with beach and shellfish bed closures or the treatment of drinking water systems to remove cells and toxins. Recent research

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[9] Polade, S.J., " Natural climate variability and teleconnections to precipitation over the Pacific-North American region in CMIP3 and CMIP5 models" *Geophysical Research Letters* 40(2013), doi:10.1002/grl.50491.
[10] Durack, P.J., “Ocean salinities reveal strong global water cycle intensification during 1950 to 2000,” *Science* 336(2012):455-458 doi:10.1126/science.1212222.
[11] MacDonald, G.M. and R.A. Case, "Variations in the Pacific Decadal Oscillation over the past millennium," *Geophysical Research Letters* 32(2005) doi:10.1029/2005GL022478.
[12] Karnauskas, K.B., "A Pacific Centennial Oscillation predicted by coupled GSMs" *Journal of Climate* 25(2012), doi:10.1175/JCLI-D-11-00421.1
[13] Stumpf, R.P., et al. “Skill assessment for an operational algal bloom forecast system,” Journal of Marine Systems 76(2009):151-61, doiI: 10.1016/j.jmarsys.2008.05.016

and modeling also provided evidence that allowed for the 2013 opening of clam harvesting on Georges Bank after being closed for 22 years.[14]

Efforts to improve hurricane intensity prediction[15]

Accurate predictions of hurricane intensity prior to landfall are significantly hampered by high-resolution observations of upper-ocean heat content and mixing immediately upstream of a storm. Data collected from NOAA "Hurricane Hunter" aircraft using airborne expendable bathythermographs (AXBTs), which cost nearly $1,000 per instrument (not including aircraft costs), are limited by the one-time nature of the probes. Funding obtained through the Hurricane Sandy Relief Bill (HR-41) will enable advancements in the technology behind the Argo profiling floats that resulted in an air-deployable version of the autonomous floats. When deployed from the same aircraft, a single float should be able to make as many as 150 vertical profiles before, during, and after the storm to provide a more complete picture of heat transfer from the ocean that fuels a tropical storm like Sandy, at a cost of roughly $40 per profile.

OBSERVATIONAL CAPABILITY TO SUPPORT MODELING

The process of expanding our understanding of the ocean system, both alone and as it relates to other planetary cycles, is driven by our ability observe marine processes near and far from shore, deep beneath the surface, over large spatial expanses, and over long periods of time. This, in turn, provides much needed data that enables comprehensive modeling efforts to forecast natural and human-driven changes far into the future and over time frames that support a wide range of decision-making at the national, regional, and local levels.

Growth of our national modeling capability is inherently dependent upon continued research and development of new observational technologies, including autonomous tools and methods, and enhanced by new data-handling and assimilation systems, as well as development of new statistical and dynamical modeling capabilities. Four areas of increased observational capability are needed:

1. Observations that support detailed studies that help capture processes needed to improve models. To incorporate these observations, models will need spatial resolution sufficient to resolve these processes or, alternatively, the observations will help develop parameterizations of these processes to incorporate in models.

2. Ongoing broad-scale observations for initialization of models.

3. Long-term, sustained observations that serve as reference stations for model verification and validation, as well as motivation for model improvement.

4. International collaboration on sustained observations and access to the sea that capitalize on international assets in order to enhance the collective global

[14] NOAA Fisheries Northeast Regional Office, "New England offshore areas will reopen for Atlantic surfclam and ocean quahog fishing," December 18, 2012 http://tinyurl.com/nc2og8b (accessed June 2013).
[15] Owens, B. and S. Jayne, personal communication, June 6, 2013.

> observation of the ocean. For example, the access to the polar ocean regions would be better achieved through operational collaboration between the U.S., Australia, Japan, and Norway—all of which are pushing observing capabilities into high latitudes. This requires member states of the Intergovernmental Ocean Commission, to continue to take on responsibilities similar to what is done in the World Meteorological Organization.

IOOS AND THE ICOOS ACT

The networks and partnerships developed through the Integrated Ocean Observing System (IOOS) have connected academics with managers and other users of their work allowing co-development of projects and products to provide user-driven, science-based solutions to real-world problems. The reauthorization of the Integrated Coastal Ocean Observing (ICOOS) Act of 2009 is critical to ensuring this continued success.

IOOS provides core infrastructure for coastal, ocean, and Great Lakes research and discovery. Long-term, sustained observing systems are critical to understanding natural variability in U.S. waters and for rapidly detecting change that can have an impact on terrestrial and marine activities. These same observing systems can also be leveraged to allow more detailed studies, and novel sensors added to established systems, when combined with IOOS observations, are providing critical background and new insights on marine processes. Two examples in the northeast include the Pioneer Array, which is a part of the NSF-funded Ocean Observatories Initiative (OOI), and the NOAA-, NIEHS-, and NSF-funded Harmful Algal Bloom (HAB) work.

The location of the Pioneer Array is particularly important in understanding the important transports (nutrients, heat, etc.) associated with the abundant fisheries over the continental shelf and slope regions south of Georges Bank. Although a primary focus is on research, the sustained observations over five years together with partnerships with the fisheries industry will be mutually beneficial and may lead to a much wider investment in operational monitoring in this important economic area.

Coastal IOOS networks deliver key regional-scale information, both observations and models that help place local process studies at the Pioneer Array site into a regional context. Changes in regional-scale circulation and water properties detected by IOOS observing systems have proven an essential element to understanding and predicting HAB severity each year. In 2014, WHOI scientists will deploy four environmental sample processors, novel sensors capable of detecting HAB species autonomously at the molecular scale. Never before have four sensors been deployed at one time. This effort is part of an IOOS goal to accelerate the deployment and integration of new technologies.

Coastal IOOS also operate regional modeling systems that act as incubators for rapid advances in technology and methods. Through IOOS, state-of-the-art forecast systems are being developed by researchers in partnership with decision makers. Regional- and local-scale models are run every day at academic institutions and delivered to a range of agency and commercial users, including local Weather Forecast Offices of the National

Weather Service (NWS). Through IOOS partnerships, near-street-level inundation forecast systems have been developed with and for NWS forecasters and town emergency managers that often push the envelope of what is capable of being modeled. At a larger scale, similar rapid progress has been made with researchers and managers through the IOOS Coastal Ocean Modeling Testbed, which has also focused on research into how to disseminate and make accessible model output. This efficient management and communication of data is another core component of IOOS and OOI that is essential for its effective use by researchers.

For the most part, the ICOOS Act establishes an adequate structure for IOOS, but inadequate funding and other issues remain that, if solved, will help make the program more effective over the long-term. The primary issue of concern with IOOS is the continued low, flat funding of the program. The House version of the re-authorization limits the funding to appropriated amounts, or $29.6 million. At this level, the program will be forced to remove assets from the water and will not be able to address the gaps in the coastal observing network. In addition, the funding does not address the need to transition programs from research to operations, as in the case of the impending operationalization of HAB monitoring and forecasting in the Gulf of Maine. This decade-long research program made heavy use of the IOOS network. In addition, IOOS is an interagency program and many federal agencies benefit from IOOS data and products, but these same agencies do not support the infrastructure; currently, NOAA is the only program that supports the infrastructure.

IMPROVING RESEARCH TO OPERATIONS (R2O)

In 2010, the National Research Council's Committee on Assessment of Intraseasonal to Interannual (ISI) Climate Prediction and Predictability released a final report that addressed specific ways to improve the operations and integration of the U.S. research and forecasting communities. The committee identified three general areas of improvement to advance ISI predictive capability: **best practices**, **building blocks of ISI forecast systems**, and **research for sources of predictability**.

The Committee's 11 recommendations are outlined below. More detail of each can be found in the Committee's final report.[16]

Suggested improvements to best practices are focused on the activities of the operational forecast centers and aim to improve the delivery and dissemination of forecast information for both decision-makers and researchers. Specifically, it is recommended that the synergy between operational ISI forecasting centers and the research community be enhanced and the public archives of data used by operational ISI forecasting centers in forecasts be established. Data includes observations, model code, hindcasts, analyses, forecasts, re-analyses, re-forecasts, verifications, and official forecast outlooks.

[16] National Research Council of the National Academies, *Assessment of intraseasonal to Interannual Climate Prediction and Predictability*, Washington, D.C: National Academies Press, 2010.

Improvements to the building blocks of ISI forecast systems apply to both the operational and research communities and focus on the continued development of observations, statistical and dynamical models, and data assimilation systems. Recommendations are targeted at various improvements in models and model techniques, analysis and interpretation of errors, and improved incorporation of physical processes.

Improvements to research for sources of predictability are aimed primarily toward the research community and provides a set of longer-term research priorities based on a set of criteria indicating each has an impact on ISI variability and predictability, contains gaps in knowledge that prevents them from being exploited by ISI forecast systems, and there is potential social value for gaining knowledge of each as a source of variability. Examples of key processes that are likely to contribute to improved ISI predictions include the Madden-Julian Oscillation, ocean-atmosphere coupling, stratosphere-troposphere interactions, land-atmosphere feedback, and high impact events affecting atmospheric composition.

Underlying all of these recommendations is the challenge that the basic state of the ocean is changing on scales that are faster than our development of the understanding of those changes and how they might impact the processes that are needed to incorporate in models to advance our predictive capabilities and decision-support information.

CONCLUSIONS AND RECOMMENDATIONS

I conclude my remarks by highlighting the value of public-funded/private-funded partnerships to the future of R&D in this country. In addition to the above, I believe my recommendations will help U.S. ocean science community be more competitive in the international research arena for decades; will help advance national priorities in the economic, security, and research arenas; and ensure future success by bolstering STEM initiatives that keep students involved, interested and inspired to push the frontiers of knowledge and exploration beyond what we can imagine today.

Jim Cameron’s partnerships with Woods Hole Oceanographic Institution and also with Scripps Institution of Oceanography are welcome examples of how public and private funding can leverage each other. But I must emphasize that this partnership and others like it are only one type that helps us all meet these important national objectives. At the core must be a significant public commitment by the federal government supporting exploration, research, and observing infrastructure about our planet and the ocean processes that have a very real and significant impact on all of us every day.

Toward that end, I urge this committee to support the following:

1. **Fully fund NSF budget requests and support ocean science research by Navy/ONR, NOAA, NASA, DOE, and NIST**
   The leadership these agencies provide through their science and technology programs is essential to pursuing new lines of inquiry that can lead to new technologies, industries, and jobs, as well as novel ways to solve societal problems. Given the

current 15-to-20-year timeframe for doubling the NSFs budget, and taking into account inflation, support for the premier U.S. science agency is actually in danger of significantly declining in constant dollars over that same period. Even in the face of very difficult budget constraints and sequestration, continued investment in NSF will provide the unanticipated dividends that have helped our nation maintain its global economic competitiveness and leadership. Support for the NSF also enhances STEM initiatives, from K-12 through post-graduate, which further ensure U.S. leadership and competitiveness for decades.

2. **Reauthorize the Integrated Coastal and Ocean Observation Act**.
   This legislation provides the foundation for a national ocean observing system—one that enhances those provided by states and other non-governmental, academic, and private entities—to shed light on the oceans and provide knowledge and forecasts for fisheries, coastal residents, and shipping. Even with the existing and potential advances by IOOS assets, there is currently very limited capacity to understand what is happening below the surface of the ocean temporally or spatially. Broad spatial and temporal observation of the ocean will complement existing Earth-observing capacity that is currently dominated by satellite observation of terrestrial and atmospheric processes. Moreover, we are still learning about physical processes within the ocean that have a direct impact on humanity. This will require additional support for operational ocean observing systems and, support for mission-driven agencies such as NOAA, ONR, NASA, and other federal agencies.

3. **Reauthorize America COMPETES legislation to bolster innovation, research and development, and STEM initiatives**.
   Support science (R&D) and education (STEM) funding in general and, increasing understanding of the importance influence of ocean processes on humanity, in particular, will ensure our country has a ready supply of technological capacity and of young people with the drive and inspiration to push the boundaries of knowledge and gain the skills that will benefit the U.S. economy, environment, and national security well into the future.

4. **Continue to support and sponsor the lead role of the U.S. and its ocean agencies on the critical international stage.**
   The U.S. has provided international leadership and funding in sustained ocean observations, especially for the development and operations of key networks including the tsunami observing system, the TOGA array, the Argo float network, and OceanSites array. Our declining leadership puts much of the existing ocean observation networks at risk.

Thank you again for this opportunity to address the Committee.