THE DEVELOPMENT AND USE OF
AN
OPEN OCEAN OBSERVING SYSTEM

Statement of

Robert A. Weller, Ph. D.

Senior Scientist
and
Director, Cooperative Institute for Climate and Ocean Research
Woods Hole Oceanographic Institution
Woods Hole, Massachusetts

before the

Resources Subcommittee on Fisheries Conservation, Wildlife and Oceans

July 13, 2001

Good afternoon Mr. Chairman and members of the Subcommittee. Thank you for the opportunity to testify. I am Robert Weller, an oceanographer at the Woods Hole Oceanographic Institution and, recently, a member of the National Research Council's *Committee on a Seafloor Observatory Network for Oceanographic Research.* I am not formally reporting on the work of that committee on behalf on the National Research Council. I am today providing my own synthesis of the development of the open ocean observing system. I do field research that involves deploying moorings to study the interaction of the atmosphere and ocean and better understand the role of the ocean in weather and climate. I am at present co-chair of the Science Steering Committee of the U.S. CLIVAR (Climate Variability) Program, and participate in national and international groups working to design and implement ocean observing systems. In my testimony, I will discus the development of open ocean observing systems, the synergy between open ocean and coastal ocean observing systems, and how terrestrial, coastal, and open ocean observations are combined to document variability and change in the ocean as well as to develop products for diverse users.

To lay a foundation for discussion of ocean observing systems and to illustrate how the development of an integrated ocean observing system would serve the nation's needs, I will start by several examples of the influence of the ocean on our lives in the United States. The ocean, the atmosphere, and the land interact, exchanging heat, moisture, and other constituents. The ocean and the atmosphere are mobile and can transport energy, heat, and moisture from one location to another so that local and regional variability and change in one of the three components can be communicated through the ocean and through the atmosphere to cause variability and change at other locations. The variability and change we experience at any one place is as a result driven by a combination of local and regional processes and large-scale processes that can bring to our location the influence of regions of the global ocean far from where we live or work. For example, in May 1960 an earthquake in Chile triggered a tsunami that traveled across the Pacific and hit Hilo, Hawaii killing 61 people, destroying 537 buildings, and causing over $23 million dollars of damage.

The impact of remote ocean regions is evident in weather and climate variability and change as well. The ocean and the atmosphere have large-scale patterns or modes of variability on different time scales, including the El Niño-Southern Oscillation or ENSO mode (Figure 1) and the North Atlantic Oscillation (NAO) (Figure 2). In these modes

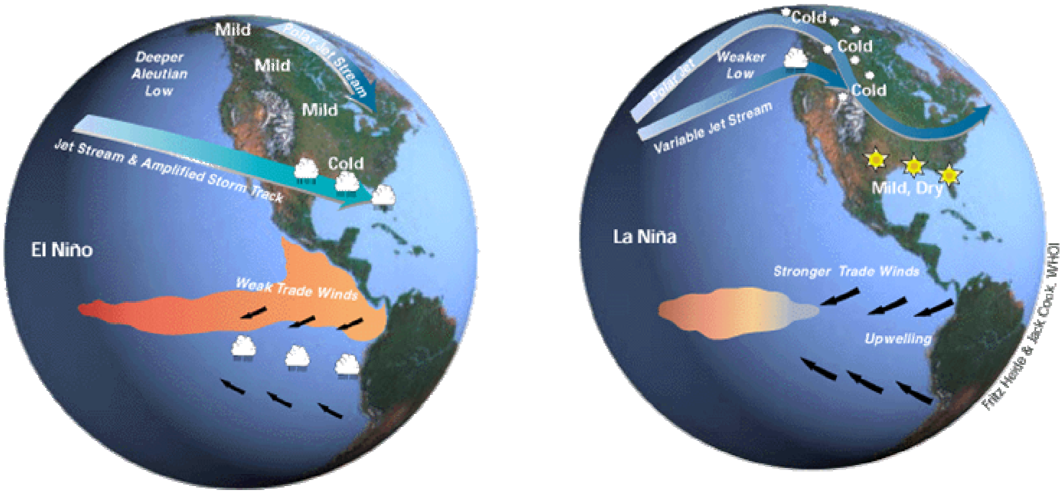


Figure 1. Large-scale patterns of coupled ocean-atmosphere variability during the El Niño (left) and La Niño (right) phases of ENSO. (Courtesy of F. Heide, J. Cook, Woods Hole Oceanographic Institution.)

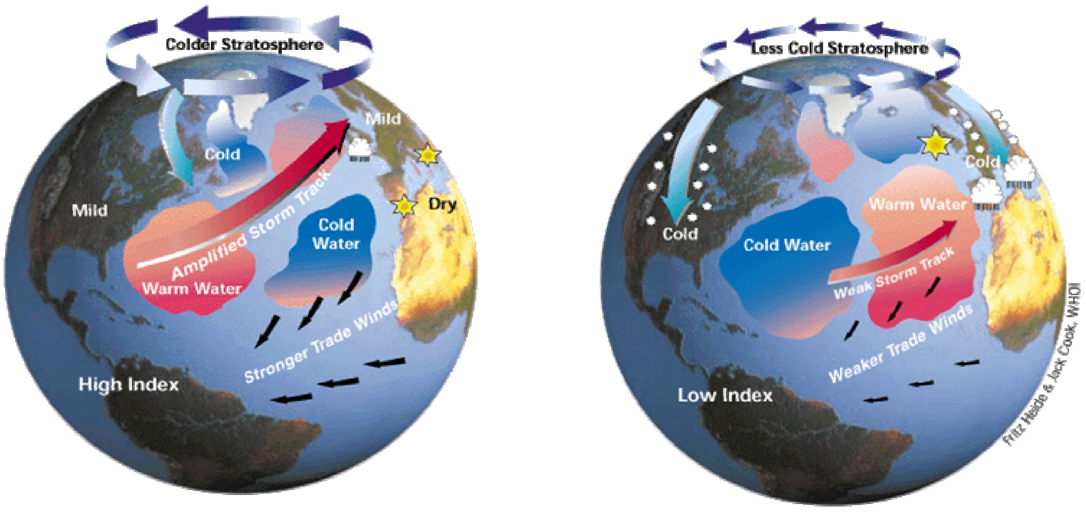


Figure 2. Large-scale patterns of coupled ocean-atmosphere variability during the High or positive (left) and Low or negative (right) phases of the North Atlantic Oscillation. (Courtesy of F. Heide, J. Cook, Woods Hole Oceanographic Institution.)

departures from normal sea surface temperatures play a key role in driving anomalous weather and climate.

Work by Siegfried Schubert at NASA Goddard Space Flight Center and colleagues (*Science*, vol. 303, 19 March 2004, pp. 1855-1859) points to the role of such large-scale patterns and their related sea surface temperature anomalies in the climate of the United States. Taking the historical observations of sea surface temperature they found that the great drought in the central United States in the 1930's was linked with anomalously cold sea surface temperatures just east of Japan and anomalously warm sea surface temperatures between eastern Canada and Europe (Figure 3).

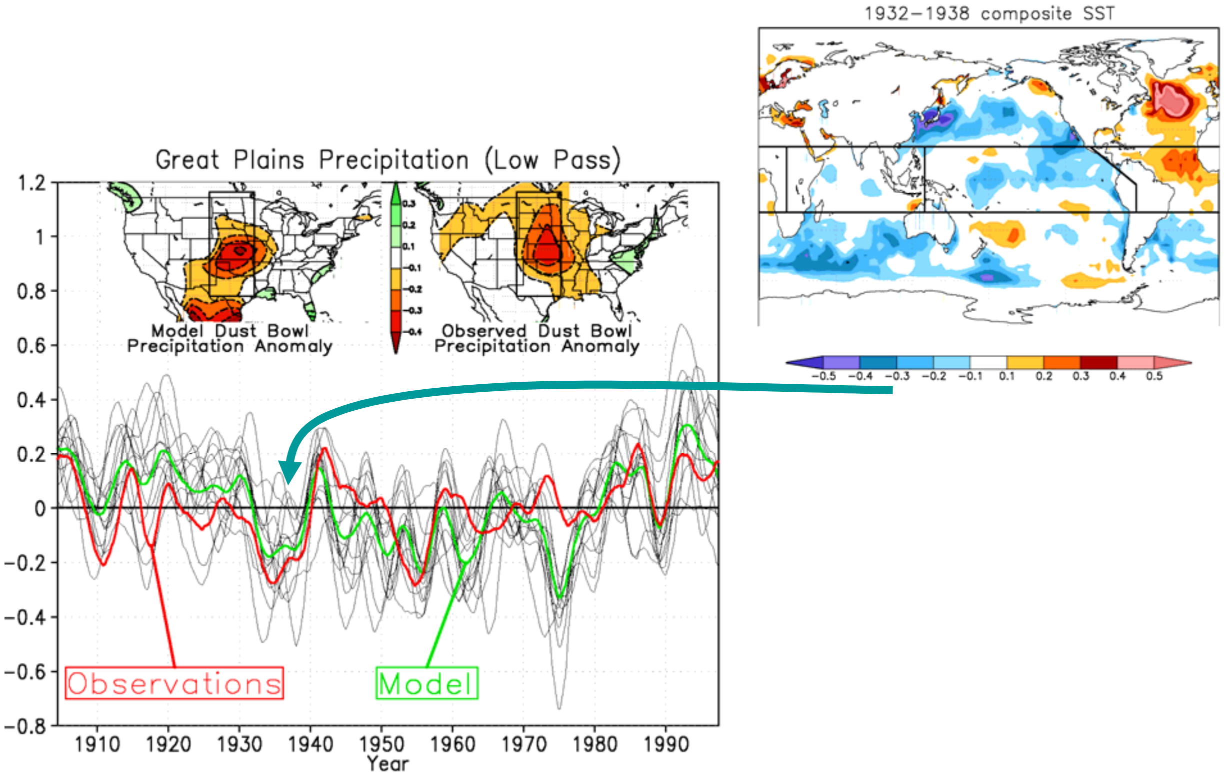


Figure 3. Adapted from the work of Schubert et al. (2004) in which atmospheric models recreated the drought of the 1930s (time series of precipitation in mm day^{-1} to the left showing that the average of the model runs in green replicated the observed rain in red) when forced with observed sea surface temperatures. During this period (upper right) the Pacific off Japan was anomalously cold and the North Atlantic between Canada and Europe was anomalously warm.

Other recent results, these from a team of scientists at the National Center for Atmospheric Research, Marty Hoerling, Jim Hurrell, and colleagues (Hoerling *et al.*, 2004, in press in *Climate Dynamics*) point to warming in the tropical Indian Ocean in the last half of the 20th century as a cause for change in the polarity of the North Atlantic Oscillation and thus in wintertime climate in the North Atlantic region.

Thus, though the earthquake in Chile, the anomalously cold ocean off Japan, and the warm water between Newfoundland and Europe are not close at hand, they impacted the United States. We have gathered much similar evidence of the role of the global ocean; the need now is to move forward to get the research and ongoing ocean data required to build understanding into new predictive capabilities and to provide the data required to initialize predictive models. We know from such evidence and present understanding the types of data that we should be observing. We are as a nation and in partnership with other nations at work on the task of developing ocean observing systems. This progress and the need for continuing work on ocean observations are being factored into the plans being developed by the intergovernmental Group on Earth Observations (GEO) that met first in July 2003.

Figure 4 is a summary presentation of the elements of the NOAA Climate Observing Program which has gone far to start the U.S. investment in the open

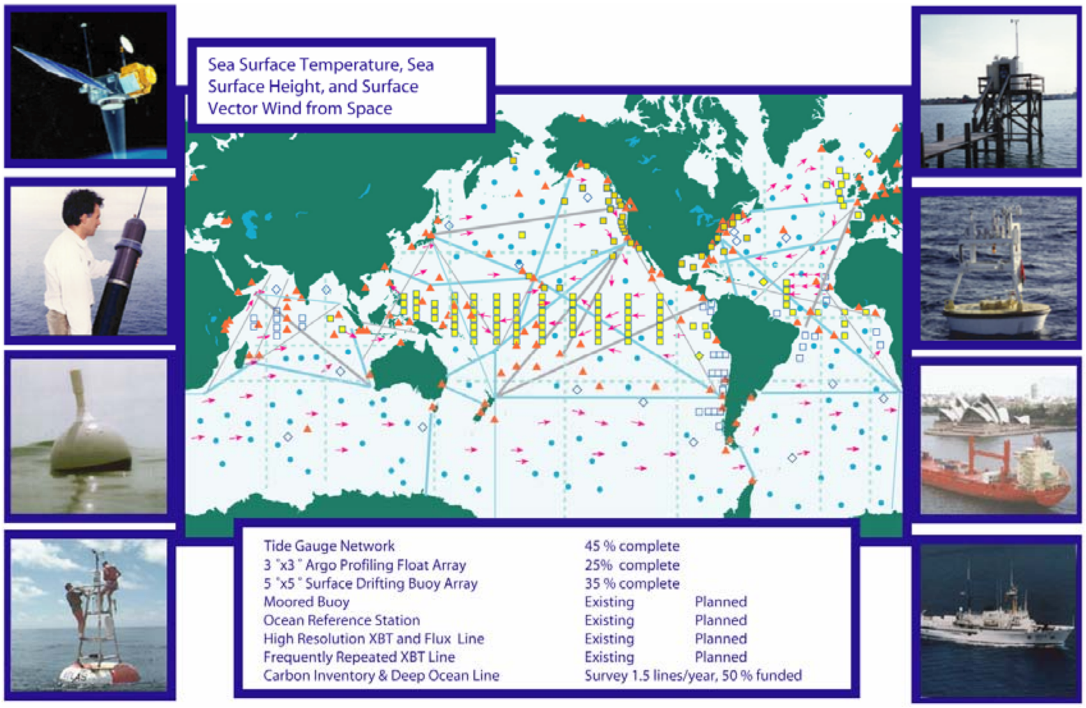


Figure 4. The elements of the NOAA Climate Observation Program and status of their implementation (from http://www.ogp.noaa.gov/mpe/co/ocean.htm). Clockwise from the upper right: tide gauge sea level station, surface buoy of an open ocean reference station mooring, commercial ship used for dropping expendable temperature probes and measuring surface meteorology and other parameters, research ship used to make full ocean depth observations of temperature, salinity, carbon and other constituents along section occupied every five to ten years, surface buoy of the equatorial Pacific Tropical Atmosphere Ocean (TAO) array, drifting surface buoy, ARGO profiling float, and satellite used for surface wind, sea surface elevation, and sea surface temperature observations.

Most of the key elements of the open ocean observing system are illustrated.

The ocean is a large source of energy, in the form of heat and water vapor; and anomalous patterns of sea surface temperature drive anomalous weather and climate via the atmosphere. To track the ocean anomalies, we need good global sea surface temperature measurements. This is done with surface drifters, which can also collect barometric pressure in support of weather prediction, and by satellite. To assess and to better model and thus predict the impact of sea surface temperature anomalies on the atmosphere, we need observations of the exchanges of heat and freshwater between the ocean and the atmosphere. These exchanges or fluxes are measured by surface buoys moored to the sea floor (Figures 5, 6) and by ships. To understand the potential for the surface anomalies to last and thus have long-lived impacts, we need to measure how deep the anomalies are by getting temperature profiles in the upper ocean. A variety of techniques are used to obtain temperature profiles, including expendable probes dropped from commercial ships, instruments on ocean moorings, and the recently developed drifting profiling floats called ARGO floats (Figure 7). We need the observations required to understand why and how the sea surface temperature anomalies form; these observations are of the surface winds, the air-sea exchanges or fluxes of heat and freshwater, the depth of the ocean surface mixed layer, and the ocean currents. Surface winds are measured by moored buoys, by ships, and by satellites. Heat and freshwater fluxes are measured by buoys and ships, and work is underway to improve estimates of these quantities using satellite observations. ARGO floats, moorings, and expendable probes give us mixed layer depth. Drifting buoys and current meters attached to

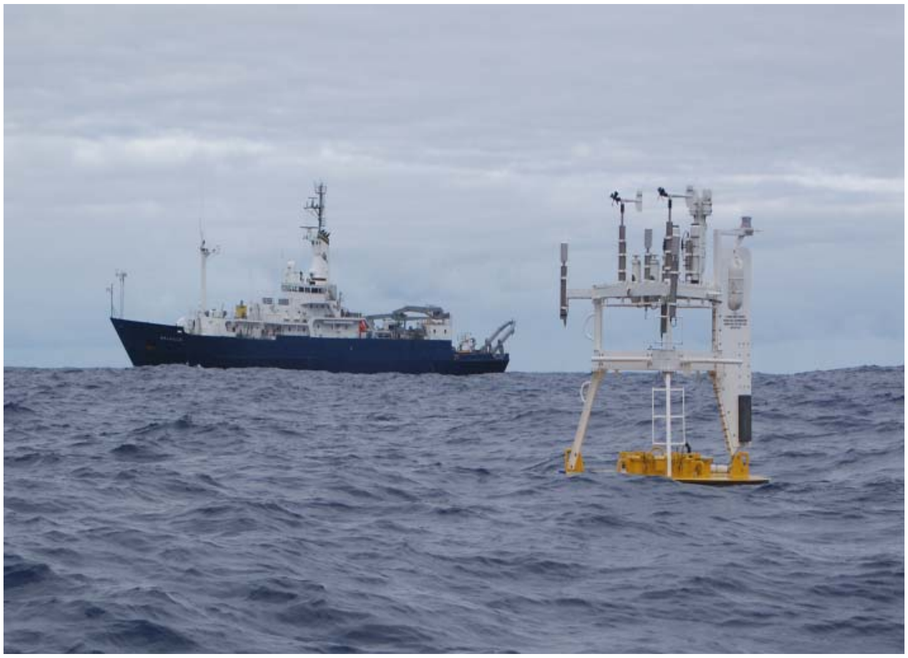


Figure 5. A surface buoy instrumented for surface meteorology, moored off northern Chile since October 2000. Research ships service the mooring once a year; the Scripps Institution of Oceanography's *RV Roger Revelle* is shown here.

moorings give us direct observations of ocean currents. We also estimate currents from satellite observations of the surface winds and the elevation of the ocean surface together with information about the temperature and salinity of the ocean from ARGO floats, moorings, expendable probes, and drifters.

Figure 6. Schematic diagram of the surface mooring deployed by the Woods Hole Oceanographic Institution off northern Chile since October 2000 with support from the NOAA Office of Global Programs and Climate Observation Program. The surface buoy is instrumented to measure surface meteorology. Along the mooring line, SEACAT's measure salinity and temperature; VMCM's measure temperature and velocity of the water, the rain gauge from Dr. Jeff Nystuen of the Applied Physics Laboratory of the University of Washington measures the noise created by raindrops, Tpod's and SBE-39's measure temperature, MicroCat's measure salinity and temperature, and the ADCP or Acoustic Doppler Current Profiler measures ocean velocity as does the FSI 3D-ACM.

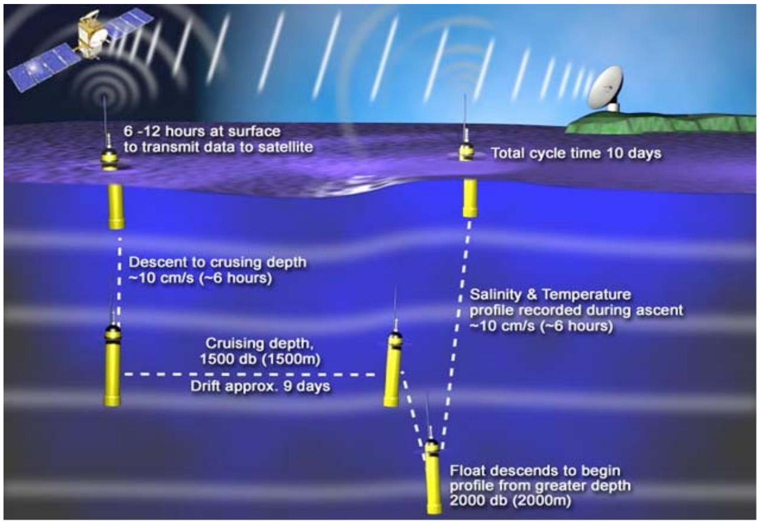
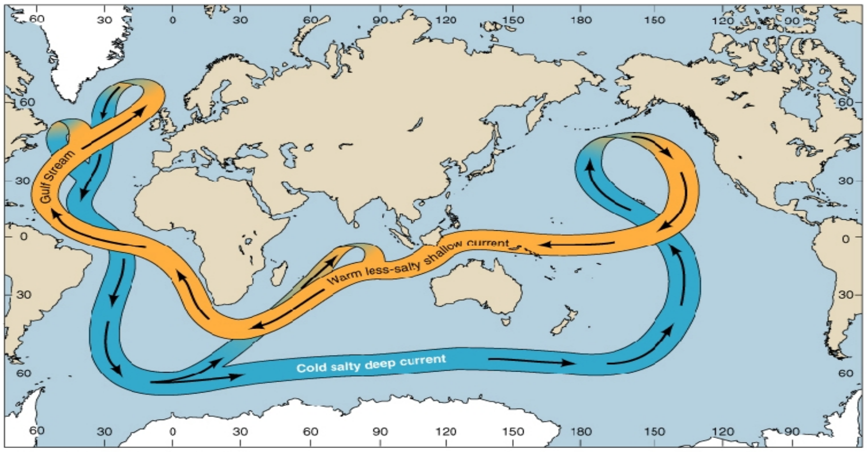


Figure 7. Schematic of the mission of an ARGO profiling float, which drifts freely but can change its buoyancy to dive, drift at a fixed depth, and surface to measure salinity and temperature as a function of depth.

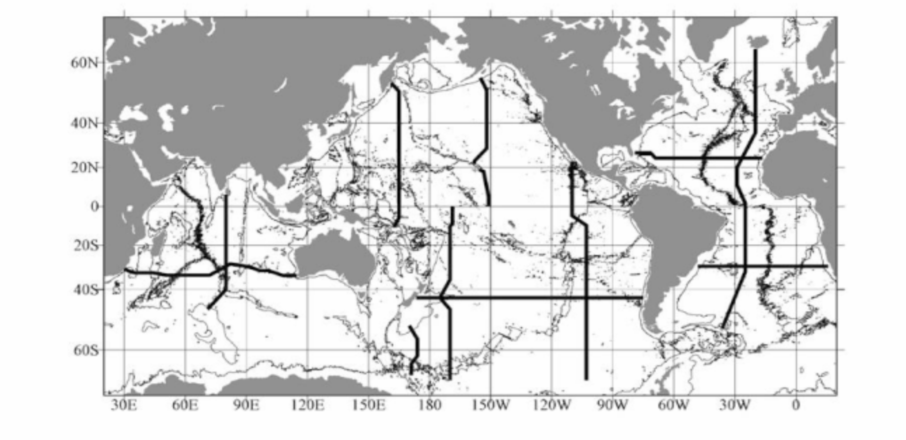
Ocean water exposed to the atmosphere in high latitudes loses heat and unless freshwater is added, it becomes denser and sinks as part of the large-scale three-dimensional circulation of the global ocean (Figure 8). Because the sinking depends on both the temperature and density of the water, it is called the thermohaline circulation. The thermohaline circulation plays a major role in carrying heat poleward from the tropics and in other countries, such as the United Kingdom, has become a major focus for ocean observations. Such observations seek to monitor the temperature and salinity of the water as well as the volumes of water of different temperature and salinity properties that move north and south through the ocean basins and circulate around the Antarctic in



Copyright 1999 John Wiley and Sons, Inc. All rghts reserved.

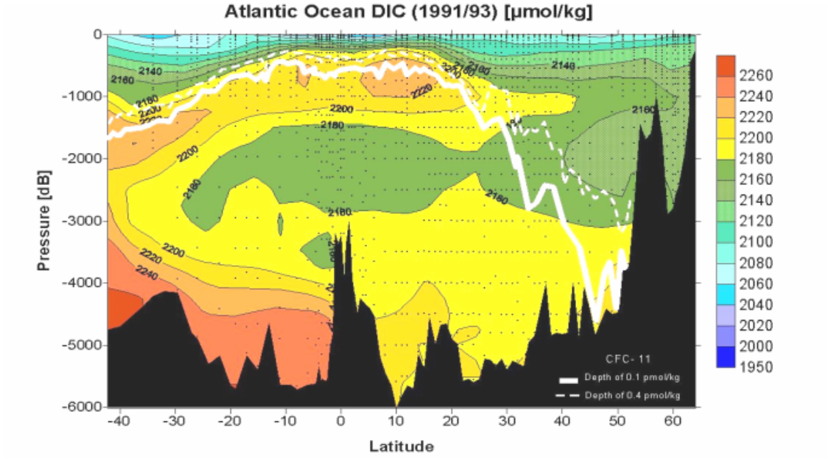
Figure 8. A greatly simplified diagram showing how the water that sinks at high latitudes flow at depth throughout the global ocean, rising to the surface to be warmed and return to the high latitude source region.

the Southern Ocean. At the same time, the process of exposure to the atmosphere and subsequent sinking into the interior of the ocean results in the ocean playing a major role in how carbon, as carbon dioxide and also in other forms of organic and inorganic carbon, and other compounds cycle through the atmosphere-ocean-land system. As a consequence, our observations should measure carbon dioxide, dissolved oxygen, and biogeochemical constituents and their exchange at the sea surface. Measurements of the penetration into the ocean of chemicals introduced by man into the atmosphere, such as chlorofluorocarbons (CFCs), provide a powerful means to assess change in the deep ocean and our ability to realistically simulate that change and the processes, including mixing that cause it. Passage of water through the deepest parts of the ocean on its way back to the surface is slow and a challenge to model; we need to at intervals of five to ten years make observations of temperature, salinity, and chemical constituents over the full depths of the oceans (Figures 9, 10).



Repeated sections to full depth along select lines, every 5 to 10 years

Figure 9. Track line (dark) showing where ships would occupy stations, lowering profilers to record temperature, salinity, and oxygen while at the same time collecting water samples. To be done as a multidisciplinary, multinational partnership.



Total CO_2 section (color) with CFC overlaid (white lines), Atlantic Ocean

Figure 10. An illustrative north-south section from the Atlantic showing total carbon dioxide and chlorofluorocarbon; this sections shows water in the high Atlantic sinking into the interior.

At the same time, for safety and for efficient use of the ocean, tsunamis, surface waves, and ocean currents should be measured. For tracking the tides and storm surges and for identifying long-term change in sea level, a global network of sea level gauges is needed. The U.S. partners in the global sea level network and the global surface drifter network, is building a tsunami warning network of moored buoys, and is working toward a global network of surface meteorological buoys. Because the ocean is a critical ecosystem for us as a food resource, as an element of global biogeochemical cycles, and as a resource for plants and animals that yield beneficial products other than food, we need to progress toward more comprehensive observations of nutrients, of populations of organisms, and of the biogeochemical properties of the open ocean.

We have as a community established these priorities for what to observe, identified key locations where to observe, and in some cases established multinational partnerships to scope what the contribution would be from the United States. However, we do not yet have the capability to implement all aspects of the global ocean observing system. Some locations, where there are high winds and high waves and where there are strong currents, are too challenging for present technology. Some locations require instrumentation that draws more power than we can provide with batteries alone. In some cases, the observations would be best done by laying cable that would both provide power and data communications. Further, we have not in these challenging locations yet done the detailed research-oriented observations required to develop the understanding and parameterizations of the processes that drive change and variability there and would be incorporated in predictive models that would be one user of long-term data coming from these challenging regions.

The ocean, though it is close at hand and has such impact on our lives, in many ways has proved a more formidable challenge to observe than space or the land surface. Seawater is corrosive. Marine life grows on sensors and causes them to degrade or fail. At the sea surface, the waves and currents can flex, fatigue, and break materials.

We are ready meet these challenges and soon push forward the state of the art of ocean observations and make a major step forward toward completion of an integrated ocean observing system. This will be done by building on the strong foundation of technology, capability, and research created over the past by the Office of Naval Research (ONR), the National Science Foundation (NSF), the National Oceanic and Atmospheric Administration (NOAA), and the National Aeronautics and Space Administration (NASA) and by the partnering of the new Ocean Observatories Initiative (OOI) of the National Science Foundation together with NOAA's commitment to lead a multi-agency partnership to implement the integrated ocean observing system.

The proposed NSF OOI aims to provide critical needed infrastructure and capability in three areas: the open ocean, on a regional scale, and along the coasts. Let me start with the open ocean and move through regional to coastal and end this talk by briefly pointing to the integrated system that we anticipate. To meet the challenge of severe environments and to provide power to instrumentation from the surface to the sea floor, the OOI is planning for a large, very capable surface buoy with a fiber optic and power cable to the seafloor (Figure 11). In locations with less severe sea states, a smaller buoy that provides a step forward in communications technology is planned (Figure 12). In both cases the emphasis is on bringing the observations of diverse ocean disciplines (physics, biology, geology, seismology, chemistry, optics) together for coincident collection of data, some or all of which would be available in real time, and thus enabling an unprecedented interactive, collaboratory open ocean observing capability.

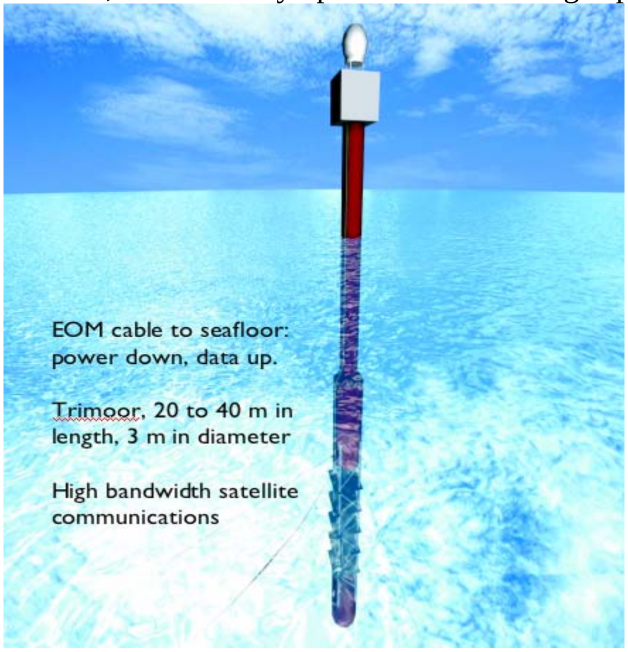


Figure 11. Drawing of a spar buoy proposed to provide a stable platform for use in regions of high waves and winds that would also provide electric power from generators on board and a high speed communication link via an electro-optical-mechanical (EOM) cable to the sea floor.

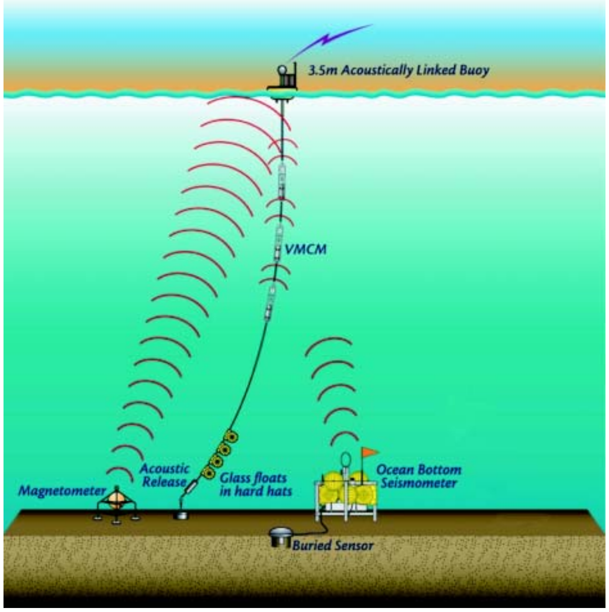


Figure 12. Medium bandwidth surface mooring, where acoustic telemetry provide the data link from the seafloor and the water column to the surface platform.

This intent to push the state of the art is also applied in the OOI to the notion of comprehensively instrumenting one of the plates that form the earth's crust beneath the sea. The goal is to make a step forward in capability to observe the interactions between the seafloor seismic activity, seafloor biology (for example, the rich ecosystems around hydrothermal vents) and seafloor geochemistry (for example, the release of methane during seismic activity) and the water column above. Because of the episodic nature of seismic activity, high sampling rates and a capable, flexible observing network are needed. This led to the development of the concept of the regional cabled observatory (Figure 13).

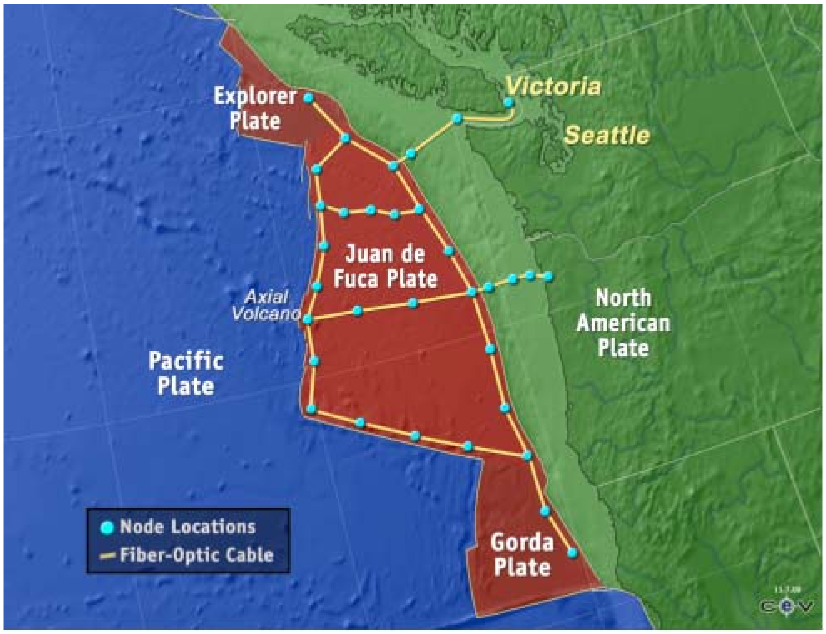


Figure 13. Location and basic structure of the regional cabled observatory proposed for the Juan de Fuca Plate. Canada has become implementation of its contribution, and the U.S. component is proposed as an element of the NSF OOI.

The third element of the NSF OOI addresses the aim of advancing the capabilities of coastal ocean observatories. At the coasts, additional processes contribute to variability and change (including nutrient and sediment runoff in rivers, mixing of bottom sediments, wind-driven coastal upwelling, breaking waves, and rip currents) and bottom topography and coastal orography combine to produce rich spatial variability on regional and local scales. To observe and understand variability and change in the coast, the OOI proposes a combination of long-term, fixed, well-instrumented arrays known as "endurance arrays" and more dense but shorter-lived "pioneer arrays". The endurance arrays would be permanent observing facilities at key locations. To achieve sufficient spatial sampling, the pioneer arrays would be installed in conjunction with an endurance array for several years at a time (Figure 14). The endurance and pioneer arrays would be instrumented to measure the surface forcing and air-sea exchanges (surface meteorology and heat and freshwater fluxes), the temperature, salinity, and velocity in the water column, and diverse biogeochemical parameters including dissolved oxygen, fluoresence, nutrients, and carbon dioxide. New sensor technologies would be tested for making observations of the populations of different species.

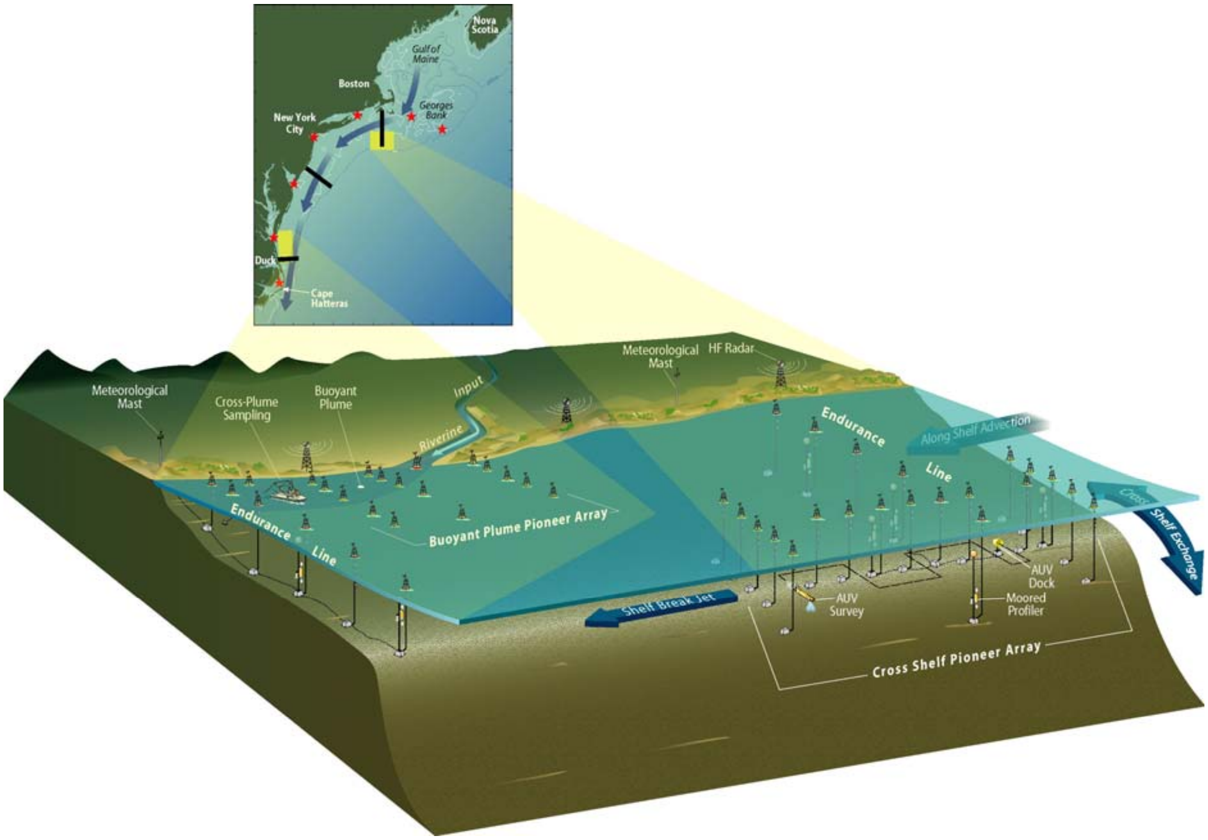


Figure 14. Schematic of the combined deployment of long-term 'endurance lines' or endurance arrays of cabled or individual moorings and of additional 'pioneer arrays' of moorings installed to provide higher spatial resolution for a limited duration. The inset (above) illustrates how a line of coastal arrays could be used to observe the flow southward along the coast of water from higher latitude and, for example, to investigate how variability and change in the transport of this water leads to variability and change in local ecosystems.

The NSF OOI will, in summary, greatly advance capability for global, regional, and coastal ocean observations. High spatial and temporal sampling and real time data links will advance our understanding of processes that cause variability and change and of the relationship, for example, between physical change and change in the ecosystem. At the same time, the OOI will result in a step forward in observing system capability, providing programs such as the NOAA Climate Observing Program with the technology and infrastructure experience required to successfully occupy the more challenging environments of the global ocean. Many of these locations, such as those in the Southern Ocean, are beyond present capability and yet are where the thermohaline circulation of the ocean is driven and where atmosphere-ocean exchange of heat and carbon dioxide is believed to be large. As a consequence, these sites are of very high priority in observing system plans.

I believe that we have in hand the all the elements to occupy such sites and thus make a leap forward in the development of ocean observation systems. We have the strong foundation built by the different ocean agencies. The Ocean Commission report and the international GEO process provide guidance at national and international levels for NOAA as the ocean mission agency to go forward. We have key remote sensing methods for sampling the ocean developed by NASA that should be recognized as of high national priority and sustained. We have the remarkable technological step forward proposed by the NSF to advance ocean sciences capabilities and the ongoing efforts of the Office of Naval Research to observe, understand, and predict ocean variability in support of Navy needs. There is a dialog between agencies that recognizes and builds on the synergy between ocean research, long-term ocean observations, assimilation of data, and improved predictive models and products.

Let me close be showing a satellite image of the Atlantic Ocean off the northeastern United States (Figure 15). This is an with productive fisheries, where many

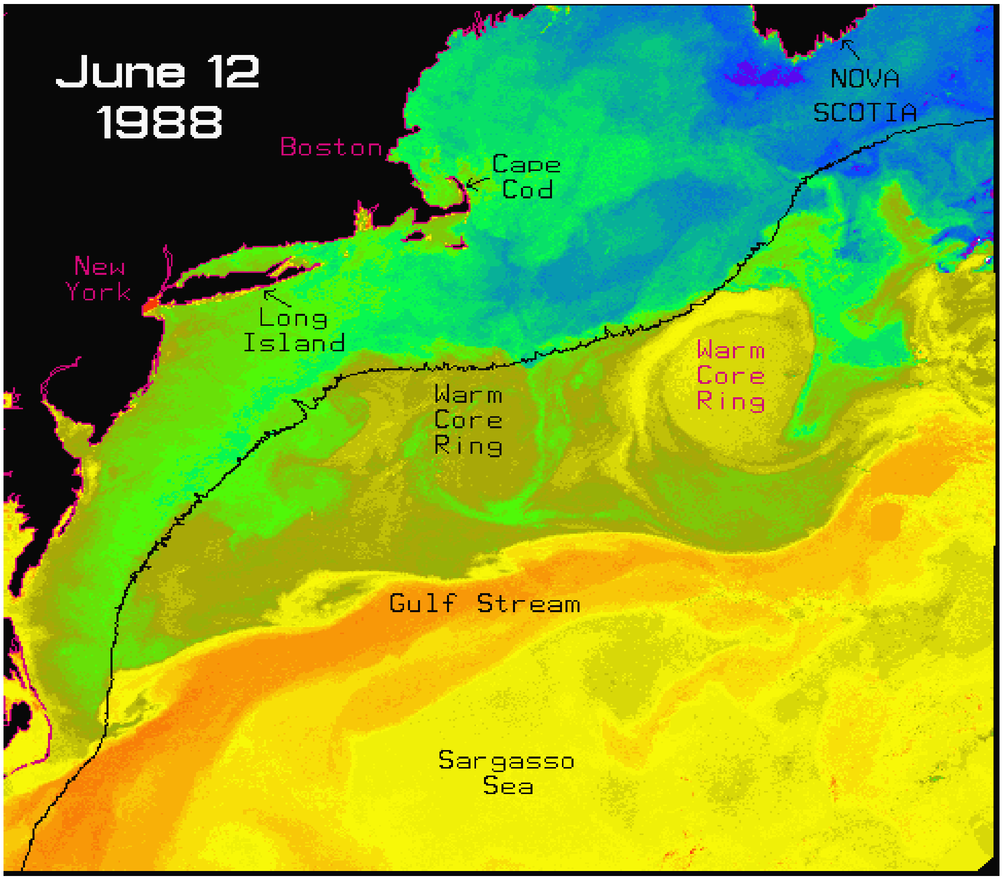


Figure 15. Satellite image of sea surface temperature, showing warm water flowing northeast in the Gulf Stream, the prominent western boundary current of the North Atlantic, and cool water closer to the shore, with indications of penetration southward of cool water from the east coast of Canada.

citizens live, work, and play, and a region where the ocean transports warm water from the south and cool water from the north. In the years after World War II, oceanographers at the Woods Hole Oceanographic Institution worked to develop techniques to predict the winter climate in New England based on knowledge of the weather systems in eastern North America and in the North Atlantic and on the sea temperature of the ocean off New England. They failed to develop reliable prediction methods.

We now know why. Variability in change in New England climate or in the ocean off New England is not solely driven by local processes. It results from a concatenation of remote, regional, and local processes. The global ocean, as I discussed in the beginning of this testimony, is a driver of change in the NAO. Model studies point to the need to consider the influence of the tropical Indian Ocean and the western Pacific Ocean off Japan as well as of the northern North Atlantic Ocean. If the oceanographers at Woods Hole had known this in the 1950s, they would have admitted to little chance of success. It is a much different perspective 50 years later. The efforts to develop ocean observing systems will come together. Regions like the waters of the Mid-Atlantic Bight and New England will be instrumented by the NOAA National Ocean Service, National Data Buoy Center, and by the regional associations Dr. Spinrad described as part of the coastal observing system. The global ocean observing system will be implemented, building on the NSF OOI and on the ocean research carried out by ONR and NSF, and under the oversight of NOAA and programs such as the Climate Observation Program.

The coastal and open ocean systems will be meshed. In this case, the global system in the Atlantic Ocean will provide the large-scale patterns of variability and change in which the coastal waters are embedded. At the same time the global array will provide the information of the variability of the ocean in remote locations such as the equatorial Pacific that also drive variability and change in New England. The coastal arrays will provide the offshore transports of freshwater, sediments, nutrients, and other properties into the open ocean, information about the regional processes, and record the variability and change along the coast. These ocean observing systems will be complementary to terrestrial and atmospheric observing systems. The land, the ocean, and the atmosphere are linked. Research programs such as the Global Energy and Water Cycle Experiment (GEWEX) and CLIVAR work together and, for example, show that terrestrial observations, such as of soil moisture, are needed to further develop the ability to predict drought conditions.

In closing, thank you for allowing me to submit this testimony. The United States is at the forefront of developing and implementing ocean observing systems, supported in the past mainly by the National Oceanic and Atmospheric Administration (NOAA), the National Science Foundation (NSF), the Office of Naval Research (ONR), and the National Aeronautics and Space Administration (NASA). The past diversity of the funding and the engagement of both government and academic oceanographers in the endeavor has been a great strength. We now have a convergence of planning, synergy between research and mission oriented goals, the development of new capability, and the recognition of the value of ocean observations. It is an exciting time, and I would be glad to answer your questions.