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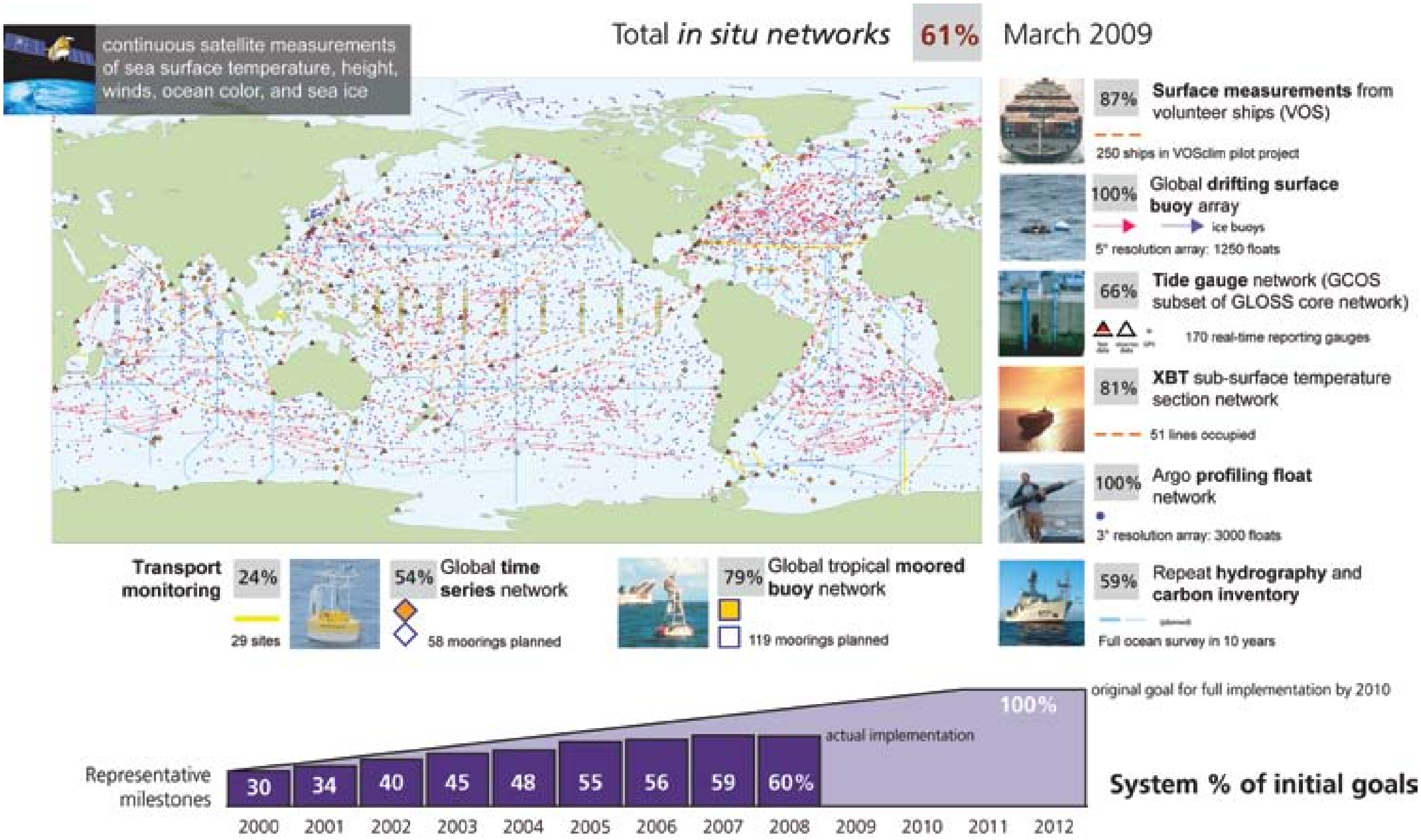
An Overview of Global Observing Systems Relevant to GODAE

BY CANDYCE CLARK AND THE IN SITU OBSERVING SYSTEM AUTHORS,
AND STAN WILSON AND THE SATELLITE OBSERVING SYSTEM AUTHORS

Figure 1. (facing page) Status of the in situ Global Ocean Observing System (GCOS) against targets defined by the GCOS Implementation Plan and accepted by the World Meteorological Organization-Intergovernmental Oceanographic Commission Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM).

ABSTRACT. A global ocean observing system for the physical climate system, comprising both in situ and satellite components, was conceived largely at the Ocean Observations conference in St. Raphael, France, in October 1999. It was recognized that adequate information was not available on the state of the world ocean or its regional variations to address a range of important societal needs. Subsequent work by the marine carbon community and others in the ocean science and operational communities led to an agreed international plan described in the Global Climate Observing System (GCOS) Implementation Plan (GCOS-92, 2004). This foundation observing system was designed to meet climate requirements, but also supports weather prediction, global and coastal ocean prediction, marine hazard warning systems, transportation, marine environment and ecosystem monitoring, and naval applications. Here, we describe efforts made to reach the goals set out in the international plan. Thanks to these efforts, most of the ice-free ocean above 2000 m is now being observed systematically for the first time, and a global repeat hydrographic survey and selected transport measurements supplement these networks.

The system is both integrated and composite. It depends upon in situ and satellite networks that measure the same variable using different sensors. In this way, optimum use is made of all available platforms and sensors to maximize coverage and attain maximum accuracy. Wherever feasible, observations are transmitted in real time or near-real time to maximize their utility, from short-term ocean forecasting to estimation of century-long trends. Because our historical knowledge of oceanic variability is limited, we are learning about the sampling requirements and needed accuracies as the system is implemented and exploited. The system will evolve as technology and knowledge improve. The biggest challenge for the greater oceanographic community—including both research and operational components—will be demonstrating impacts and benefits sufficient to justify the funds needed to complete the observing system, as well as to sustain its funding for the long term.



INTRODUCTION

The delivery of ocean services to society depends upon operation of an observing system adequate to support the services desired, analysis systems to integrate all available observations and permit the extraction of ocean information, and appropriate assimilation/analysis/forecast systems to deliver forecasts of the desired extent into the future. An effective observing system—in situ and/or satellite—depends upon many data system elements. In particular, measurements must be made with sensors whose characteristics are understood and acceptable; observations from the sensors must be transported to a facility where they can be assembled and given preliminary quality control; access by the wide range of potential users must be provided, including that for near-term operational purposes; and these observations must be integrated with others so that delayed-mode quality control can be done for more exacting research applications.

This paper discusses the current status of those global ocean observing systems that are relevant to, and whose data have been used by, the Global Ocean Data Assimilation Experiment (GODAE). It concludes with a discussion of some of the challenges facing these observing systems in our effort to establish sustained funding for them.

GLOBAL OBSERVING SYSTEMS

The Global Climate Observing System (GCOS) Implementation Plan (GCOS-92, 2004) serves as a useful starting point. It calls for the phased implementation of an integrated and composite satellite and in situ observing system, with related data management and analysis activities. Figure 1 shows the 10-year implementation ramps, the year-by-year progress in reaching the 10-year goals, and the status to date.

In Situ Observing Networks

Successful operation of a global in situ observing system requires coordination of activities on a number of levels. Sensors and best practices need to be agreed on. Deployment opportunities need to be identified and instruments delivered to take advantage of them; where no opportunistic deployment is feasible, timely provision of special deployment efforts needs to be made.

The system's data coverage needs to be monitored along with sensor lifetimes and provision made to anticipate where gaps will appear so that deployment can be arranged. Successful implementation depends fundamentally upon near-real-time transmission of both observations and relevant metadata. Given that a number of nations participate in each of the observing networks and both "operational" and "research" programs are involved, this monitoring/system management function is critical.

There are two different classes of observing activities underway in situ—those from fixed points and those whose locations vary with time. Fixed-point observations are made either from moorings or from repeated occupation of stations. Observations whose locations vary with time are made from platforms that move as a result of the ocean's motion or that of a moving vessel. Some moving platforms are thought to follow the motion of water parcels fairly well (i.e., "Lagrangian").

Fixed-Point Observing Networks

The networks of this type are the Global Tropical Moored Array, the OceanSITES program, the Global Sea Level Observing System (GLOSS), and some station-keeping repeat hydrographic surveys.

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Global Tropical Moored Array. Earth's tropics are where heat exchange between ocean and atmosphere is the greatest. The near-equatorial upper ocean, with its strong and quite variable currents, poses many observational challenges; however, arrays on fixed moorings are the fundamental ocean observing system building block. By 1999, the National Oceanic and Atmospheric Administration (NOAA) deployed the Tropical Atmosphere Ocean/Triangle Trans-Ocean Buoy Network (TAO/TRITON) in the tropical Pacific, while doubling its Prediction and Research Moored Array in the Atlantic (PIRATA) from 10 moorings in 1999 to the current 20. The Indian Ocean Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction (RAMA) was begun during the GODAE period and is about 50% complete (Figure 2). See http://www.pmel.noaa.gov/tao/global/global.html.

Ocean Sustained Interdisciplinary Timeseries Environment Observation System (OceanSITES). A global network of ocean reference station moored buoys is being implemented to provide the most accurate long-term climate data records of oceanic and near-surface atmospheric variables in key ocean regimes. OceanSITES is one of the most challenging because of the expense of maintaining highly accurate instruments in remote ocean regions, yet the network is essential for evaluation of climate model outputs. OceanSITES has plans to deploy and maintain 89 ocean reference stations (including transport, flex, and multisensor platforms) that will sample as comprehensively as is feasible. There are currently 43 reference stations. See http://www.oceansites.org/.

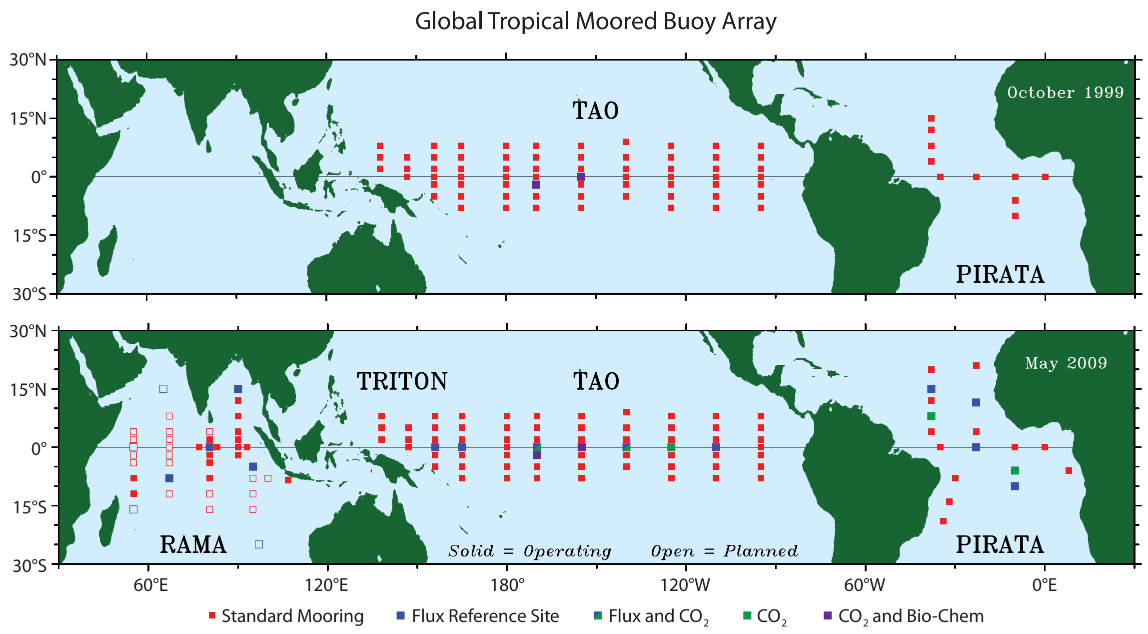

Figure 2. Global Tropical Moored Buoy Array in October 1999 (top) and May 2009 (bottom).

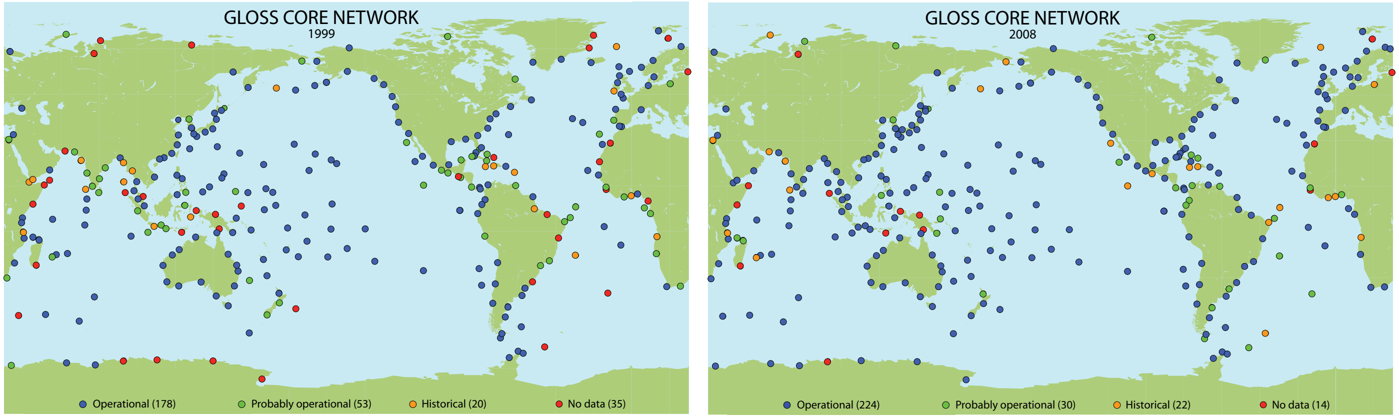

Figure 3. Configuration of the Global Sea Level Observing System/GCOS Core Network in 1999 (left) and 2008 (right). There have been important improvements in the number of tide gauges reporting high-frequency data in real time during the GODAE period. GLOSS = Global Sea Level Observing System.

Global Sea Level Observing System (GLOSS). GLOSS is one of the oldest networks of the global ocean observing system, with some tide gauges having been maintained since the nineteenth century. Tide gauges are necessary for accurately measuring long-term trends in sea level change and for calibrating and validating satellite altimeter measurements, which are assimilated into global climate models for predicting climate variability and change. Since 1999, there have been important improvements in the number of gauges reporting high-frequency data that are also in real time (Figure 3). In support of GODAE, fast-delivery-mode (available within one month of collection) and real-time (available in 15 minutes to three hours) GLOSS data are assembled and provided by the University of Hawaii Sea Level Center. The British Oceanographic Data Centre provides final delayed-mode data (see http://www.gloss-sealevel.org/). The status of real-time reporting stations and recently collected time series are available at the Sea Level Station Monitoring Facility maintained by the Flanders Marine Institute (VLIZ). See http://www.vliz.be/gauges/.

Repeat Hydrographic Surveys. The global repeat hydrographic survey is an essential observing system element for understanding the controls and distribution of natural and anthropogenic carbon, circulation tracers, and a large suite of biogeochemically and ecologically important chemicals in the ocean's interior, including nutrients and oxygen. The surveys also remain critical for understanding ocean changes below 2 km (52% of global ocean volume), and their contributions to global freshwater, heat, and sea-level budgets. See http://www.ioccp.org/.

Moving Observing Networks

Networks of this type are the Argo profiling float program, the surface drifting buoy network, the Arctic and Antarctic buoy programs, the Volunteer Observing Ship (VOS) scheme, and the Ship of Opportunity Programme (SOOP).

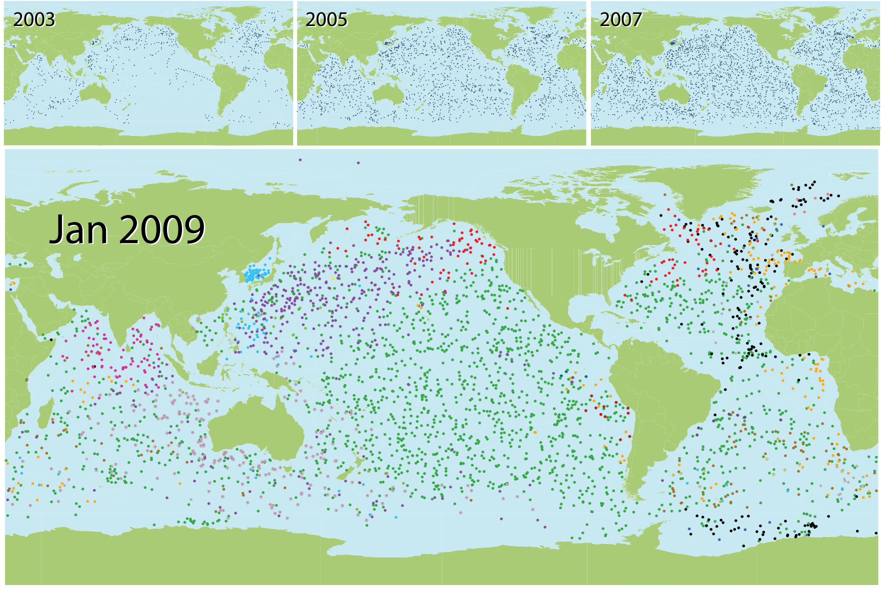

Figure 4. Global distribution of Argo profiling has grown to its initial implementation goal of 3000 floats during GODAE.

Argo Profiling Float Program. This array was developed as a GODAE observing system initiative to understand upper ocean temperature variability and heat content. It attained its initial implementation goal of 3000 operating floats, distributed relatively homogeneously throughout the world's ocean basins between 60°N and 60°S, in November 2007 (Figure 4). Although it has not yet reached its desired geographical coverage of a float per 3° x 3° region, the Argo array is providing a nearly global picture of the world ocean every 10 days, and the development of instruments capable of operating in ice-covered regions is extending this into higher latitudes in both hemispheres (see Roemmich et al., 2009; also http://www.argo.ucsd.edu/).

Surface Drifting Buoy Program. Planning for this array was begun in 1967 as part of the first Global Atmospheric Research Programme (GARP) experiment, designed to provide ocean surface information from regions not sampled by the volunteer observing ships. It plays a fundamental role in providing accurate "bulk" sea surface temperature (SST) observations and surface pressure observations to the integrated observing system. Standard global SST analyses are derived from satellite retrievals, but the satellite measurements must be continuously tuned using surface in situ measurements. The network, coordinated by the Data Buoy Cooperation Panel, reached its initial number goal of 1250 drifters in 2005, but has not yet achieved the desired geographical coverage of a drifter per 5° x 5° area of the ice-free ocean (see Figure 5; http://www.jcommops.org/dbcp/ and http://www.aoml.noaa.gov/phod/dac/gdp.html).

International Arctic Buoy Programme. This network of buoys is used to monitor synoptic-scale fields of sea level pressure, surface air temperature, and ice motion throughout the Arctic Ocean. The Arctic ocean observing buoys have more than doubled during GODAE (24 in 1999 and 54 in 2008). See http://iabp.apl.washington.edu/.

Voluntary Observing Ship Scheme. In this effort, research, private, and commercial crews report a variety of air-sea variables, either from automated sensors or by direct measurement. This network, which has its roots in the observations recorded routinely in ship logs, is perhaps the oldest in the global marine observing system. It is maintained primarily for weather observations at sea, but the observational data are used extensively for climate studies as well, particularly for assessing long-

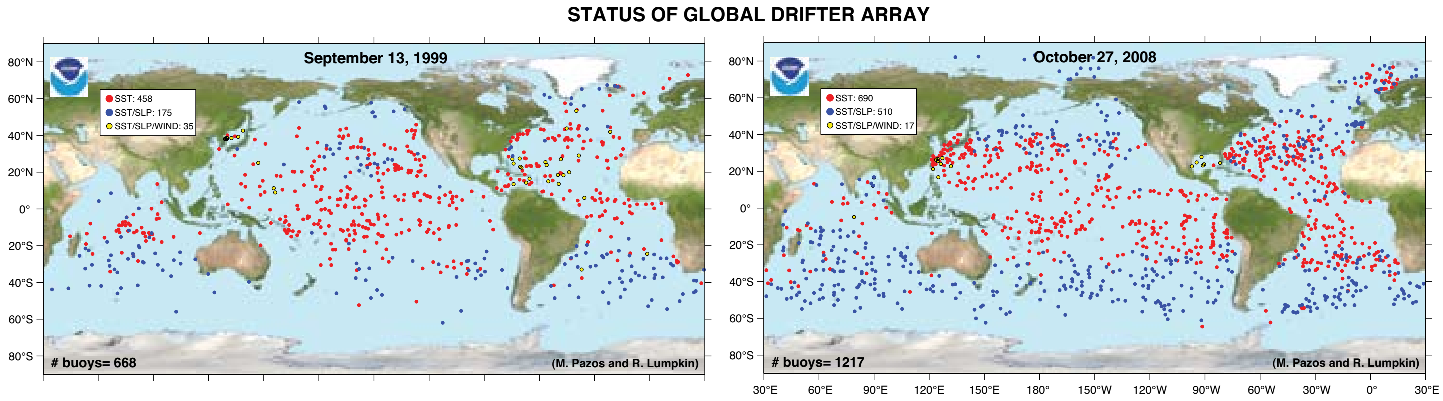

Figure 5. The configuration of the surface drifting buoy network on September 13, 1999 (left), and on October 27, 2008 (right). The network reached its initial implementation goal of 1250 in 2005.

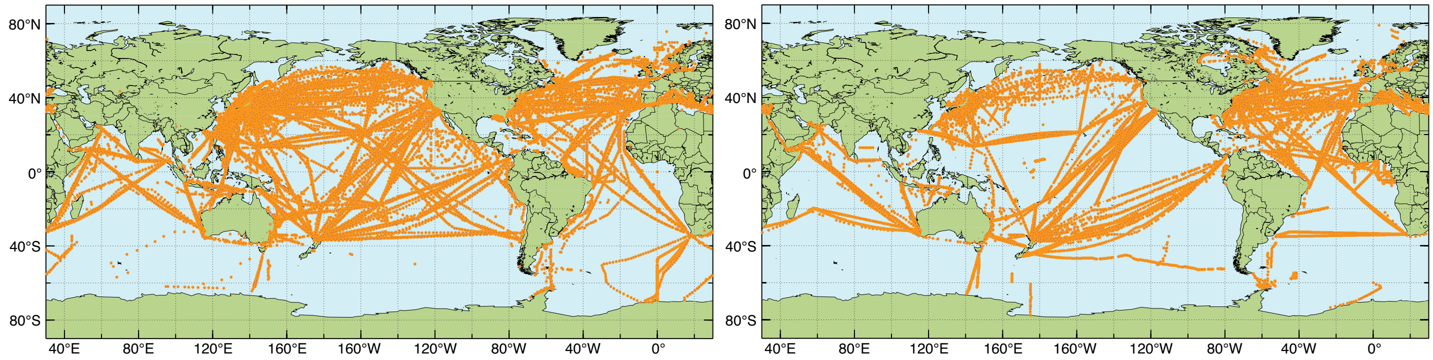

Figure 6. The global distribution of expendable bathythermograph (XBT) observations from ships of opportunity in 1999 (left) and 2005 (right). The total number of XBT profiles from the Ship of Opportunity Programme (SOOP) decreased during the GODAE period as the Argo array was implemented.

term trends. This network is uniquely capable of providing information about marine surface atmospheric pressure, air temperature and humidity, and clouds. See http://www.bom.gov.au/jcomm/vos/.

Ship of Opportunity Programme. SOOP is similar to the VOS scheme, but it is focused on oceanographic observations rather than on atmospheric measurements. The primary sensors employed by ships of opportunity are expendable bathythermographs (XBTs), thermosalinographs (TSGs), and sensors equipped to measure the partial pressure of carbon dioxide ($p\mathrm{CO}_2$). In this program, ships either deploy XBTs or expendable conductivity-temperature-depth (XCTD) sensors, or pump water to laboratory sensors. The global atmospheric and oceanic data from SOOP have provided the foundation for understanding long-term changes in marine climate, and they are essential input to climate and weather forecast models. Over the past decade, there has been an effort to focus on repeat sections in order to systematically explore spatial and temporal scales of oceanic variability (Figure 6). The total number of XBT profiles from SOOP decreased during the GODAE period as the Argo array was implemented. See http://www.jcommops.org/soopip/.

Satellite Observing Systems

The research space agencies have made great progress over the past three decades. Today, spaceborne sensors have a demonstrated capability to collect data for a variety of variables, including altimetry to observe ocean surface topography or sea level, scatterometry to observe ocean surface vector winds, infrared and microwave radiometry to observe sea surface temperature, microwave radiometry to observe sea ice cover, and visible and near-infrared radiometry to observe ocean color. Only several representative satellite systems will be discussed in this article, and only one of those at any length; for additional information, see Wilson et al. (2008). For a comprehensive overview of satellite capabilities prepared by the European Space Agency on behalf of the Committee on Earth Observations, see http://www.eohandbook.com/eohb2008/earthobservation.htm.

Ocean Surface Topography

Precision altimetry was initiated by the US National Aeronautics and Space Administration (NASA) and the French Centre National d'Études Spatiales with the launch of TOPEX/Poseidon (T/P) in 1992; it is being continued by Jason-1 and Jason-2 (launched in 2008) today. These satellites have provided a continuous record of global sea level. NOAA and the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT)—as counterpart operational agencies—are proposing[1] a Jason-3 for launch in 2013 as a follow on to provide continuity of these observations in the future. See http://sealevel.jpl.nasa.gov/ and http://ibis.grdl.noaa.gov/SAT/slr/.

Why maintain the sea level record? Global sea level rise (GSLR)—the most obvious manifestation of climate change in the ocean—directly threatens coastal infrastructure through increased erosion and more frequent storm-surge flooding.

Although its latest projections for GSLR over the coming century range from 28 to 79 cm, the Intergovernmental Panel for Climate Change (IPCC, 2007) states, "the upper values of the ranges given are not to be considered upper bounds" for GSLR because existing models are unable to account for uncertainties such as changes in ice sheet flow. And, regarding these changes, the US Climate Change Science Program has gone on to say that, "Sea level rise from glaciers and ice sheets has accelerated" (CCSP, 2008).

Given such uncertainties, it is critical that systematic observations of global sea level be maintained, and the only feasible way to resolve the spatial variability needed in an accurate determination of GSLR is by means of precision satellite altimetry—T/P and the ongoing Jason series of satellites (e.g., Figure 7). A complementary global network of GLOSS tide gauges, each with geodetic positioning to estimate vertical land motion, provides essential cross-validation for GSLR. Together, these observations suggest that GSLR is accelerating; in particular, the value of ~ 3.1 mm yr^{-1} from altimeters over the decade beginning in 1993 (IPCC, 2007) is almost twice the estimate of ~ 1.7 mm yr^{-1} from tide gauges over the past century.

To understand and improve the projections of GSLR, it is necessary to collect systematic observations of the two major contributors—thermal expansion due to the warming ocean and the addition of melt water due to the warming of terrestrial ice sheets and glaciers. Thermal expansion estimates—previously based on sparse coverage by ship observations, especially in the Southern Hemisphere—now principally come from the global Argo array of 3000 profiling floats (see article by Roemmich, 2009).

A number of research programs are directed at estimating the addition of melt water, for example, by measuring changes in gravity of both the ice sheets and oceanic water masses, as well as changes in the topography and flow rate of glaciers and ice sheets. Together with Jason and Argo observations, these estimates can be used to infer a contribution from melting glaciers and ice sheets as a consistency check for these research efforts, as well as to help assess the performance of climate models projecting sea level rise.

Oke et al. (2009) describe how GODAE systems have used observations from different observing systems to meet the needs of a variety of operational oceanographic applications. For example, the climate data record of sea level from Jason-class satellite altimetry—together with Argo float profiles and satellite observations of SST (Donlon et al., 2009)—is required to characterize decadal variability in the ocean and its relation to droughts, floods, and fishery regime shifts, as well as support seasonal forecasting (Balmaseda et al., 2009). These same data records, when combined with those from complementary altimeters (like that on the European Space Agency's Environmental Satellite [Envisat] and the US Navy's recent Geosat Follow-On [GFO]), enable an approximation of the oceanic mesoscale field—the ocean's weather—and contribute to many applications such as marine safety (Davidson et al., 2009), marine pollution monitoring (Hackett et al., 2009), hurricane

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[1] On May 7, 2009, when the President's budget proposal for fiscal year 2010 was submitted to the Congress for approval, funding for the US portion of Jason-3 was included as a new NOAA initiative. Although Jason-3 will serve a broad range of GODAE applications, as reflected in its justification by both EUMETSAT and NOAA, the most convincing rationale for its inclusion in NOAA's fiscal 2010 budget submission concerned the issue of global sea level rise. This budget submission is why several paragraphs here have been devoted to this issue, even though it is not a direct priority for GODAE. The target for approval of the Jason-3 budget for both NOAA and EUMETSAT is the end of calendar year 2009.

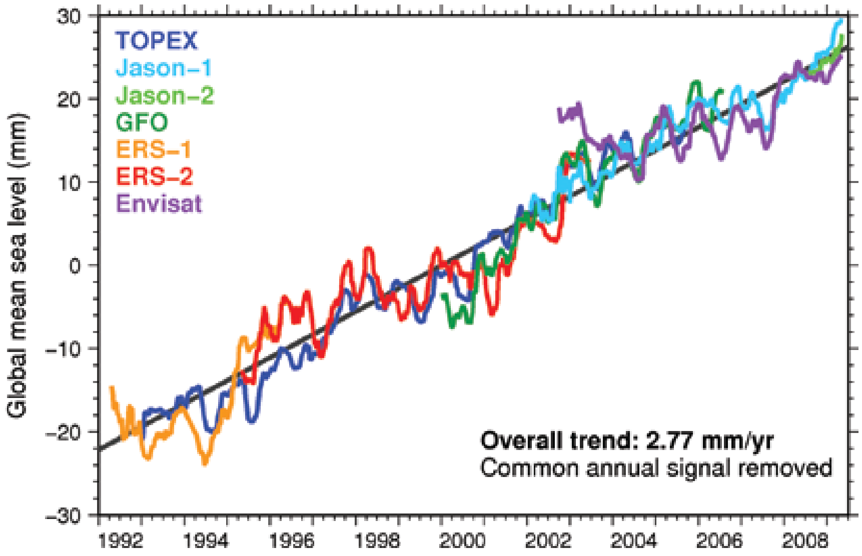

Figure 7. All satellite altimeters show global mean sea level to be rising. The current estimate of ~ 2.8 mm yr^{-1} is somewhat lower than the ~ 3.1 mm yr^{-1} cited by the Intergovernmental Panel on Climate Change, most likely due to recent cooling associated with a protracted La Niña. In this figure, the high-precision TOPEX/Poseidon and Jason altimeters provided the reference baseline, and results from each of the additional altimeters were adjusted for bias to minimize differences with the baseline. *Courtesy of the NOAA Laboratory for Satellite Altimetry and Altimetrics LLC*

intensity forecasting (Goni et al., 2009), and Naval applications (Jacobs et al., 2009). They also provide boundary conditions for nested coastal models (De Mey et al., 2009), support surface wave forecasting, and help characterize the physical context for marine ecosystems (Brasseur et al., 2009). See http://www.aviso.oceanobs.com/.

Ocean Surface Vector Winds

For more than a decade and a half, satellite scatterometry has provided observations—although with varying degrees of spatial coverage—of the surface vector wind field over the ocean. The longest-running with the broadest coverage, NASA's Quick Scatterometer (QuikSCAT), was launched in 1999 and is still operating today; the first fully operational scatterometer, the Advanced Scatterometer (ASCAT), on EUMETSAT's Metop-A satellite, was launched in 2006 with units on MetOp-B and -C to follow.

Observations of ocean surface vector wind fields are needed for operational forecasting as well as research. For the former, they are needed for early detection, tracking, and characterization of hurricanes and tropical systems; observing and forecasting surface waves and storm surge; detection and characterization of extra-tropical, hurricane-force winter storms; and observing and forecasting localized wind events and frontal passages (e.g., Figure 8). For research, scatterometer observations provide fundamental characteristics of the wind forcing that drives the oceanic circulation. Moreover, such observations will be key in documenting extreme weather events at sea—events that are thought to become more frequent and intense with our warming climate. See http://winds.jpl.nasa.gov/missions/quikscat/ and http://www.knmi.nl/scatterometer/.

Sea Surface Temperature

For a couple of decades, SST observations, to varying degrees of accuracy, have been provided by infrared radiometry (IR). In contrast to IR's relatively fine spatial resolution, which is blocked by the presence of clouds, microwave radiometry (MR) offers all-weather, but relatively coarse, resolution. The interested reader is directed to Donlon et al. (2009), who discuss how the Global High-Resolution SST Project combines the best attributes of IR and MR to develop improved SST products.

Sea Ice Cover

Continuing observations of sea-ice cover have been collected using MR techniques since 1978; these results have shown in easy-to-understand terms how the Arctic permanent ice cover has visibly declined over the 30-year record of satellite observations (e.g., Figure 9). Moreover, MR has been complemented more recently by scatterometry and synthetic aperture radar to provide information on ice concentration, ice age, and ice temperature. See http://nsidc.org/.

Additional Variables

There are several additional variables that—while important—have been of less direct relevance to GODAE, so they will only be mentioned in passing. A continuous ocean color climate record was initiated in 1997 and is being continued by several satellites (see http://oceancolor.gsfc.nasa.gov/). Observations of Earth's gravity field have been

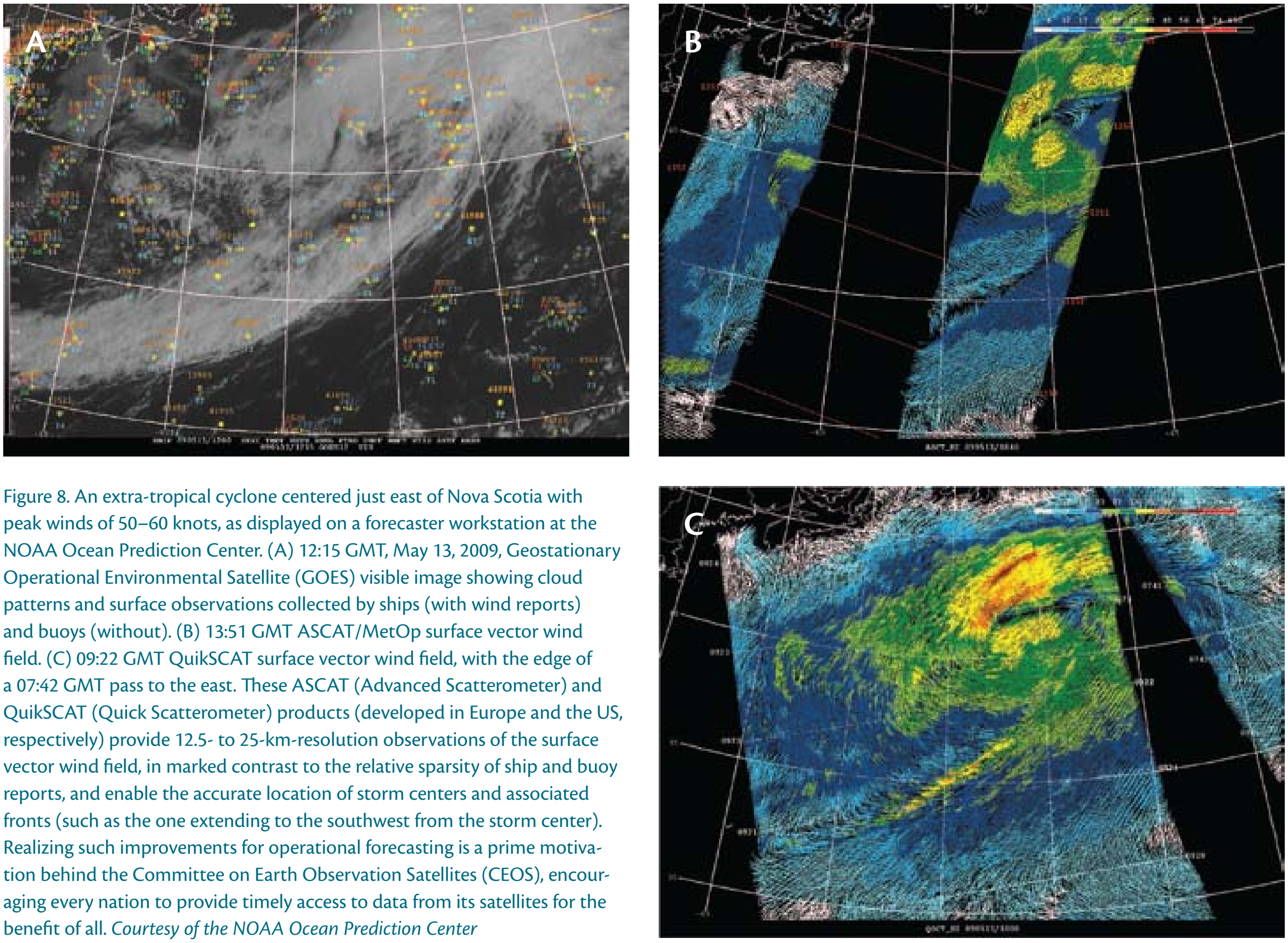

Figure 8. An extra-tropical cyclone centered just east of Nova Scotia with peak winds of 50–60 knots, as displayed on a forecaster workstation at the NOAA Ocean Prediction Center. (A) 12:15 GMT, May 13, 2009, Geostationary Operational Environmental Satellite (GOES) visible image showing cloud patterns and surface observations collected by ships (with wind reports) and buoys (without). (B) 13:51 GMT ASCAT/MetOp surface vector wind field. (C) 09:22 GMT QuikSCAT surface vector wind field, with the edge of a 07:42 GMT pass to the east. These ASCAT (Advanced Scatterometer) and QuikSCAT (Quick Scatterometer) products (developed in Europe and the US, respectively) provide 12.5- to 25-km-resolution observations of the surface vector wind field, in marked contrast to the relative sparsity of ship and buoy reports, and enable the accurate location of storm centers and associated fronts (such as the one extending to the southwest from the storm center). Realizing such improvements for operational forecasting is a prime motivation behind the Committee on Earth Observation Satellites (CEOS), encouraging every nation to provide timely access to data from its satellites for the benefit of all. *Courtesy of the NOAA Ocean Prediction Center*

provided since 2002 (see http://www.csr.utexas.edu/grace/). MR will be used to demonstrate the feasibility of observing sea surface salinity later in 2009 (see http://www.esa.int/esaLP/LPsmos.html).

SUSTAINING THE OBSERVING SYSTEMS

At present, the majority of the in situ ocean observations are funded by research agencies, and this mode of support is likely to continue for the foreseeable future. At some point, research agencies may look to the operational agencies to assume some responsibility for sustaining at least partial support for routine, systematic observations over the long term. GODAE recognized this need when it was organized a decade ago. One of its basic motivations was to demonstrate in an operational setting the impact of having timely access to data from global ocean observing systems funded by research agencies and, depending on that impact, to develop a rationale to justify the transition of funding for those systems from the research to the operational agencies. Ideally, once the utility of observations had been demonstrated, the operational agencies would incorporate support for at least some of those observing systems into their ongoing programs, thereby providing one avenue to sustain their support.

There are many challenges to be addressed in maintaining what has been achieved over the past decade. All programs face nontrivial increases in the cost of hardware and salaries. The VOS program is feeling the impact of cutbacks in national weather services support of the program, particularly reduction in the number of Port Meteorological Officers, and changes in the patterns, staffing, and security concerns of the global merchant shipping fleet. The XBT program also strains to achieve its coverage because of changes in the routing of outfitted ships. The Argo and surface drifting buoy programs require special deployment assistance in areas remote from commercial shipping. The global hydrographic survey is strongly affected by decreases in the availability and increases in the cost of operating blue-water research ships. Sustaining moored arrays requires dedicated ships and personnel able to go where and when replenishment is needed or data return suffers, and vandalism restricts effectiveness in some regions. Data sharing of tide gauge observations is problematic in some key regions.

For the satellite observing systems, the issue of transitioning support from research agencies to operational agencies is a critical one, and both the technical feasibility of observing a given variable and the scientific utility of the resulting observations needs to be demonstrated. In the transition process, the research and operational agencies share the next step, demonstration of the operational utility of an observation, that is, that availability of the observation will have a significant impact on an operational agency's ability to meet a mission need.

This justification entails convincing the government supporting that operational agency of the potential impact or value, in terms of societal relevance, of the data collected by a given observing system. Note that some impacts can be expressed in more immediate and quantifiable terms, for example, how much a weather forecast is improved where the impact is realized within hours to days of the time when a given set of observations has been collected. Other values may be expressed in terms of the variable's role in the climate system, for example, the specific impact of the collection of a given set of observations to assess or quantify that variable's role in climate may not be realized for years to decades.

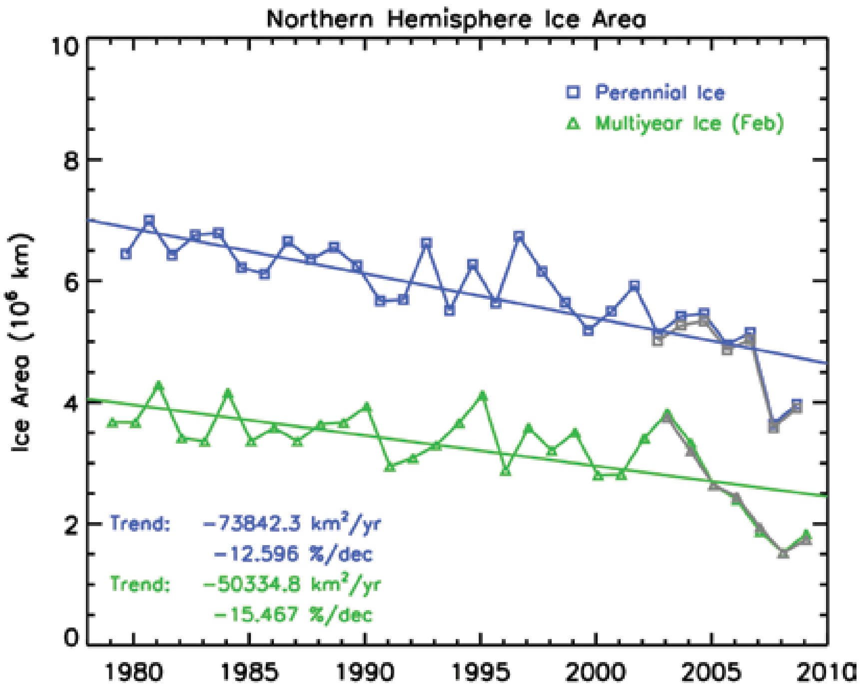

Figure 9. The Arctic ice cover has been in decline over the three decades of satellite observation. Perennial Ice (blue line), defined as the area of minimum ice cover, survives melting and occurs in late summer. Multiyear Ice (green), the area of ice at least three years old and generally the thickest, is observed in February; it typically takes several summers for brine to drain from sea ice, leaving it almost salt free and with a distinctive microwave signature. Because Multiyear Ice is declining faster than Perennial Ice, the thickness of the Arctic ice cover is, on average, declining as well. This time series demonstrates the value of being able to integrate observations from multiple sources into a single climate record. It is based on data collected by three US satellite-borne instruments: the Scanning Multi-frequency Microwave Radiometer (SMMR) on Nimbus-7, the Special Sensor Microwave Imager (SSMI) on the Defense Meteorological Satellite Program satellite (DMSP), and the Advanced Microwave Scanning Radiometer (AMSR-E) on the Aqua satellite (grey line since 2003). *Courtesy of Joey Comiso, NASA Goddard Space Flight Center*

Ensuring Sustained Operations

As the operational agencies collaborate with their research counterparts to ensure sustained operations of the global observing systems, there are particular challenges to be faced.

Societal Relevance

The operational agencies need to make the case that what is proposed to be implemented on a long-continuing basis is worth a corresponding continuing investment of tax dollars over the long term. This rationale is often different from making the case within a research agency.

Fiscal

Operational and research agencies operate, and will continue to operate, in a tight budget environment. For example, in the United States, NOAA is attempting to establish elements of a new (for NOAA) operational ocean capability in a level-funding environment on top of a well-established and growing operational weather forecasting program.

And in Europe, research and operational programs frequently compete within essentially the same overall envelope, so more support for operational programs can mean less for research.

Climate Change

To the extent that political leaders recognize and appreciate climate change as an issue that must be addressed, the operational agencies could provide a valuable service to the research agencies by assuming responsibility for maintaining transitioned observing systems and thereby providing the research agencies a valuable continuing stream of climate data. But in so doing, the operational agencies must maintain a close partnership with the research community to ensure that the integrity of the climate data record is maintained. Further, oceanographers need to recognize that they are competing within the overall earth science community for resources in the climate arena, and there is a need to clearly articulate and promote the critical role played by the global ocean.

Organizational Focus. Some countries have, at the national level, an organizational focus for the implementation of operational oceanography. An example is the group of French agencies involved in oceanography. Over almost two decades, this group has recognized the need for cross-agency coordination and the establishment, as needed, of organizations such as Mercator Océan and Coriolis Operational Oceanography to provide an integrated approach to ocean modeling and forecasting, and in situ ocean observations, respectively. This example of effective programmatic integration for other nations is useful, although it is recognized that in other countries support for the in situ system will continue to come from research agencies, or a combination of operational and research entities.

Observing System Support and Monitoring

Sustaining the required spatial and temporal coverage of observations requires substantial coordination and at many different levels, and the advantages of a systematic framework to support these observing systems' deployment and monitoring activities is clear. Much of this work is done by JCOMMOPS (the World Meteorological Organization-Intergovernmental Oceanographic Commission Technical Commission for Oceanography and Marine Meteorology in situ Observing Platform Support Centre; http://www.jcommops.org), and the Observing System Monitoring Center (http://www.osmc.noaa.gov/) is a useful tool for monitoring real-time status and performance of the global in situ ocean observing system.

Integrating In Situ and Satellite Observing Systems

It is essential for the in situ and satellite observing communities to work together on an integrated system. The two sets of systems are complementary; for example, satellite systems can resolve horizontal variability at the surface and in situ networks can resolve variability in the vertical. The ocean is relatively opaque to electromagnetic radiation, and there is only so much that may be inferred from surface observations. Subsurface structure can deviate immensely from that on the surface. Directed subsurface observations from in situ observing systems are a critical piece, but at the same time, those observations by themselves are incomplete without the satellite observations. Ocean models can play an important role here, integrating observations from both systems. No one working on either system should be unaware of the importance of the other.

Focus and Prioritize

Operational agencies typically have little budgetary flexibility, and therefore need to focus and prioritize when attempting to implement operational infrastructure. They need to concentrate on those variables for which there have been successful demonstrations of technical feasibility and scientific utility. If there were some degree of community consensus based, for example, on compelling issues of societal relevance, it could be used as the basis for prioritization.

Clear, Concise, and Consistent Message

Securing the resources to implement a sustained infrastructure for observing the global ocean will require a clear, concise, and consistent message coming from the community at large that reflects priorities in a progression of successive steps.

LOOKING TO THE FUTURE

Although moving an observational capability from the point of theoretical possibility to an ongoing, sustained reality is a decades-long process, it is important to note that significant progress has been made. For the first time, most of the ice-free ocean above 2000 m is now being observed systematically. We need to concentrate on the near-term opportunities, as well as engage in a number of international activities that could have significant benefit for promoting and integrating the in situ and satellite observing system, including:

1. The World Meteorological Organization-Intergovernmental Oceanographic Commission Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM) coordinates the implementation of the in situ observing system, and offers an opportunity to strengthen effective integration with space observation systems through its Observations Coordination Group.
2. The Global Earth Observing System of Systems (GEOSS) offers an avenue for ministerial-level political visibility; this visibility could be critical as the two communities help each other secure the resources needed to implement a shared international effort in operational oceanography.
3. The Committee on Earth Observation Satellites (CEOS) Constellations represents a potentially valuable international forum to help member space agencies seek development of common data products, formats, and protocols as well as consensus data policies for timely sharing of data, because no agency or nation can afford to collect all of the data it needs.

The ocean science community has demonstrated during the GODAE period that a global ocean observing system can be implemented, and can provide critical data to support global ocean forecasting and analysis. With the observations being used ever more effectively, it is hoped that the coming decade will see not only continuity but also increased coverage, including measuring more variables. From this foundation observing system, important progress will be made in ecosystem management, sustainable fisheries, weather and climate forecasting, marine operations, and the safety of life at sea. Impressive progress has been made in a relatively small number of years and, in many respects, much more has been achieved than was ever expected or even dreamed of; however, there is still much to be done.

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