PAPER

The *In situ* Global Ocean Observing System for Climate (and Other Needs)

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ABSTRACT

The Global Ocean Observing System (GOOS) is the international observation system that ensures long-term sustained ocean observations. The ocean equivalent of the atmospheric observing system supporting weather forecasting, GOOS, was originally developed to provide data for weather and climate applications. Today, GOOS data are used for all aspects of ocean management as well as weather and climate research and forecasting. National Oceanic and Atmospheric Administration (NOAA), through the Climate Observation Division of the Office of Oceanic and Atmospheric Research/Climate Program Office, is a major supporter of the climate component of GOOS. This paper describes the eight elements of GOOS, and the Arctic Observing Network, to which the Climate Observation Division is a major contributor. In addition, the paper addresses the evolution of the observing system as rapidly evolving new capabilities in sensors, platforms, and telecommunications allow observations at unprecedented temporal and spatial scales with the accuracy and precision required to address questions of climate variability and change.
Keywords: ocean observing system, ocean climate observing system, Global Ocean Observing System

Introduction

The mission of the Observations and Monitoring Program of the Climate Observation Division (COD) of National Oceanic and Atmospheric Administration's (NOAA) Office Oceanic and Atmospheric Administration/Climate Program Office is to develop and sustain, with national and international partners, an *in situ* Global Ocean Observing System to monitor, understand, and support prediction of the coupled ocean, Arctic, and atmosphere systems. This requires providing long-term, high-quality, global observational data in a timely manner, in support of researchers, forecasters, other service providers, and users that provide information and products for the benefit of society. The major components of this system that are within the COD are (1) the global network of profiling floats known as Argo; (2) the Global Drifter Program (GDP); (3) the Global Tropical Moored Buoy Array (GTMBA); (4) OceanSITES Deep Ocean Observing Strategy; (5) a component of the global network of Tide Gauges; (6) the Global Ship-Based Hydrographic Investigators Program (GO-SHIP); (7) surface measurements from Voluntary Observing Ship (VOS); (8) XBT (eXpendable BathyThermograph) Subsurface Temperature Network; and (9) Arctic Observing Network.

Argo

The primary goal of Argo was to create a global network of instruments integrated with other elements of the climate observing system to detect climate variability on seasonal to decadal time scales through observations of changes in the large-scale distribution of temperature and salinity and in the transport of these properties by ocean circulation. These are used for the initialization and constraint of climate models. Argo also provides the *in situ* data needed, in conjunction with satellite altimetric and gravity measurements, for understanding sea level changes and variability.

The original design of the array was to deploy a network of profiling floats measuring temperature and salinity to 2,000 m once every 10 days and acquiring observations at discrete levels and/or averaged over depth intervals and reporting data in near real time via satellite telecommunications. The instrument spacing was 3° × 3° (based on existing data from other networks and spatial statistics from satellite altimetry) from 60°N to 60°S and outside of marginal seas. These boundaries avoid operations in ice-covered regions and loss of instruments by grounding due to transport by winds and surface currents during the time an instrument was on the surface to transmit data. This required an array of ~3,300 floats. Between the sampling/surfacing cycles, the instruments remain ("park") at 1,000 m providing information on currents at that depth. Implementation of the global array is considered to have begun in January 2000. A relatively homogenously distributed global array of 1,521 floats was attained in November 2004. The full, homogeneously distributed array of 3,004 floats was attained in October of 2007.

The development of ice-sensing capability in floats using mathematical algorithms to predict whether ice is on the surface has allowed expansion of the array to ice-covered regions. In cases where a float may encounter ice at the surface, floats automatically terminate their cycle and return to parking depth until the next programmed cycle. Profiles are stored for transmission when the float is able to communicate. The development of real-time, two-way telecommunications has allowed the transmission of large volumes of data such as multiple profiles from floats under ice and much higher vertical resolution (2 decibar vs. 100 or so pressure levels). Higher transmission rates have dramatically reduced the time a float remains at the surface to transmit data to a few minutes, thereby minimizing the effects of surface currents and winds on movement such that floats are now being deployed in marginal seas. Figure 1 presents the number of active (having transmitted data within one month) floats in the Argo array.

Argo is presently delivering over 120,000 such profiles a year, many of them now high-vertical resolution. The data are made available in near real time via World Meteorological Organization's (WMO) Global Telecommunication System (GTS) and two Argo GDACs. In addition to providing highly quality-controlled (QC) data in real time, the data undergo extensive QC over time (e.g., to assess and possibly correct for instrument drift) referred to as Delayed-Mode QC for research applications. Profiling floats operate in any sea state and are not restricted in spatial (i.e., collecting observations only where ships go, which excludes most of the Southern Hemisphere) or temporal coverage (i.e., mid to high latitudes in the wintertime hemisphere). With an average lifetime approaching 4 years for the global array and an expected lifetime of 4–5 years for recently deployed instruments, the array can be maintained with only periodic (2–4 years) reseeding.

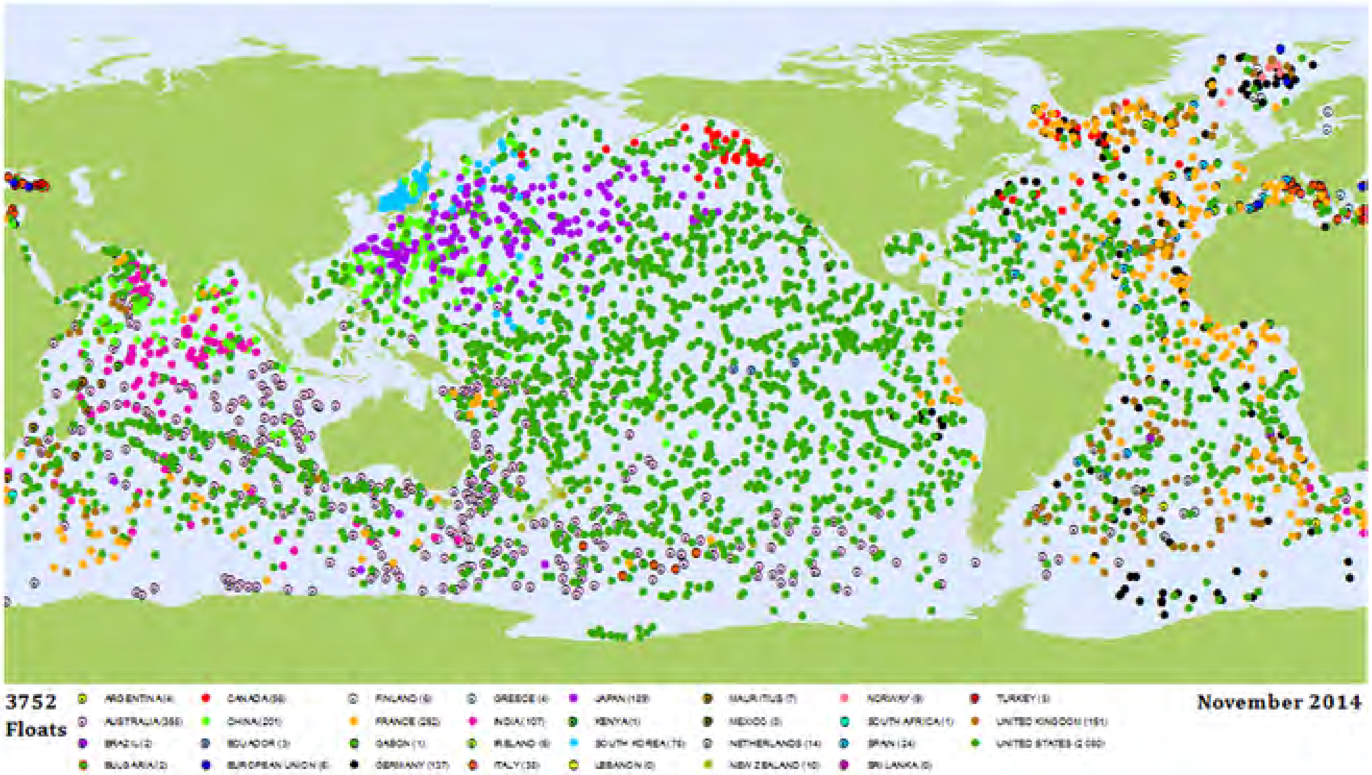
Sampling to 2,000 m provides information from about one half of the ocean volume. It is believed that a significant amount of heat is being absorbed into the deep ocean. Figure 2 plots the density of temperature and salinity profiles below 1,000 m per 1° square in the Argo database (top) and in the World Ocean Database (bottom). While the Argo average density (2000–2014) is relatively uniform throughout the ice-free oceans at over 20 profiles per 1° square, the entire World Ocean Database (1773–2009), excluding profilers, has a density of fewer than five profiles per 1° square with large areas having none.

In order to balance the earth's heat budget, the remaining one half of the ocean volume needs to be observed. Autonomous instruments capable of providing observations to 6,000 m (encompassing approximately 98% of the ocean volume) that will operate for 4 years without replacement requires the application of more advanced technologies in terms of pressure vessel form and materials, buoyancy engine, hull penetrations, and bottom avoidance measures than existing floats. Such sampling also requires the development of an entirely new generation of sensors capable of the accuracy and precision necessary to detect the extremely small changes in ocean properties at abyssal depths and be stable for four years. In June 2014, two prototype Deep Argo floats equipped with the new sensors were deployed in 5,600+ m of water east of New Zealand (Figure 3). These floats cycle at 3-day intervals and will be recovered after 1 year to examine the performance of the pressure vessel and the penetrations. An array of 10 floats cycling at 10-day intervals is planned to be deployed in the same area. In conjunction with the deployments, an extensive program of calibrations of the new sensors involving reference standards, shipboard CTD casts, and water sampling for laboratory analyses of salinity was conducted.

Coincident with the development of profiling floats and other autonomous instruments, sensors for applications other than ocean dynamics and capable of operating from profiling floats have been developed. Oxygen sensors began being routinely deployed on profiling floats in the global Argo array in 2004. The introduction of new sensors has also been severely limited by the amount of data that could be telemetered from the instrument, both in the amount of data and the power consumed to transmit data. Advanced telecommunications, almost exclusively via the Iridium Communications System, have provided the bandwidth and have dramatically reduced the power consumed in data transmission. Along with Iridium Telecommunications, the implementation of lithium batteries into floats has permitted the deploying floats equipped with a suite of sensors to understand BioGeoChemical (BGC) processes, including ocean acidification

FIGURE 1

Active profiling floats in the Global Argo Array, November 2014.



and sequestration of carbon dioxide by the ocean. Figure 4 presents the status of floats equipped with BGC sensors (termed Bio-Argo floats) along with the basic T, S, and P Argo sensor.

A program has recently been announced by the U.S. National Science Foundation to implement a global array of multi-BGC sensor equipped floats throughout the Southern Ocean deploying ~40 floats a year over 6 years. The Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM) program is being implemented in collaboration with NOAA. The basic SOCCOM float is shown in Figure 5.

Global Drifter Program

The primary goal of the GDP is to maintain a global 5° × 5° array of ~1,250 (Figure 6) satellite-tracked surface drifting buoys to meet the need for an accurate and globally dense set of *in situ* observations of mixed layer currents, sea surface temperature, atmospheric pressure, winds and salinity, providing QC data in support of short-term (seasonal to interannual) climate predictions as well as climate research and monitoring. The GDP makes its data available in real time via the WMO's GTS under WMO's Data Buoy Cooperation Panel (http://www.jcommops.org/dbcp/overview/about.html) in support of numerical weather prediction and ocean forecast activities worldwide.

The use of surface drifting buoys for meteorological purposes dates back to the 1970s. Lagrangian surface drifting buoys were standardized during the World Ocean Circulation Experiment (WOCE) and Tropical Ocean Global Atmosphere (TOGA) programs under the title of the Surface Velocity Program (SVP). The surface buoy is attached to a 15-m drogue with current directions and velocities derived from satellite positioning. In the early 1990s, barometers were added providing sea level pressure observations from vast areas where none were available, particularly in the southern hemisphere. As with profiling floats, additional sensors have been added, particularly sea surface temperature and (recently) sea surface salinity. Wind speed and direction have also been added to drifters deployed in specific areas like hurricane development regions. Unlike profiling floats, sensors on surface drifters are very subject to biofouling, even with anti-fouling agents. Drifters are

FIGURE 2

Temperature/salinity profiles at and below 1,000 m: (top) Argo Array as of April 2014; (bottom) all sources, excluding Argo, World Ocean Database 2009 (Boyer et al., 2009).

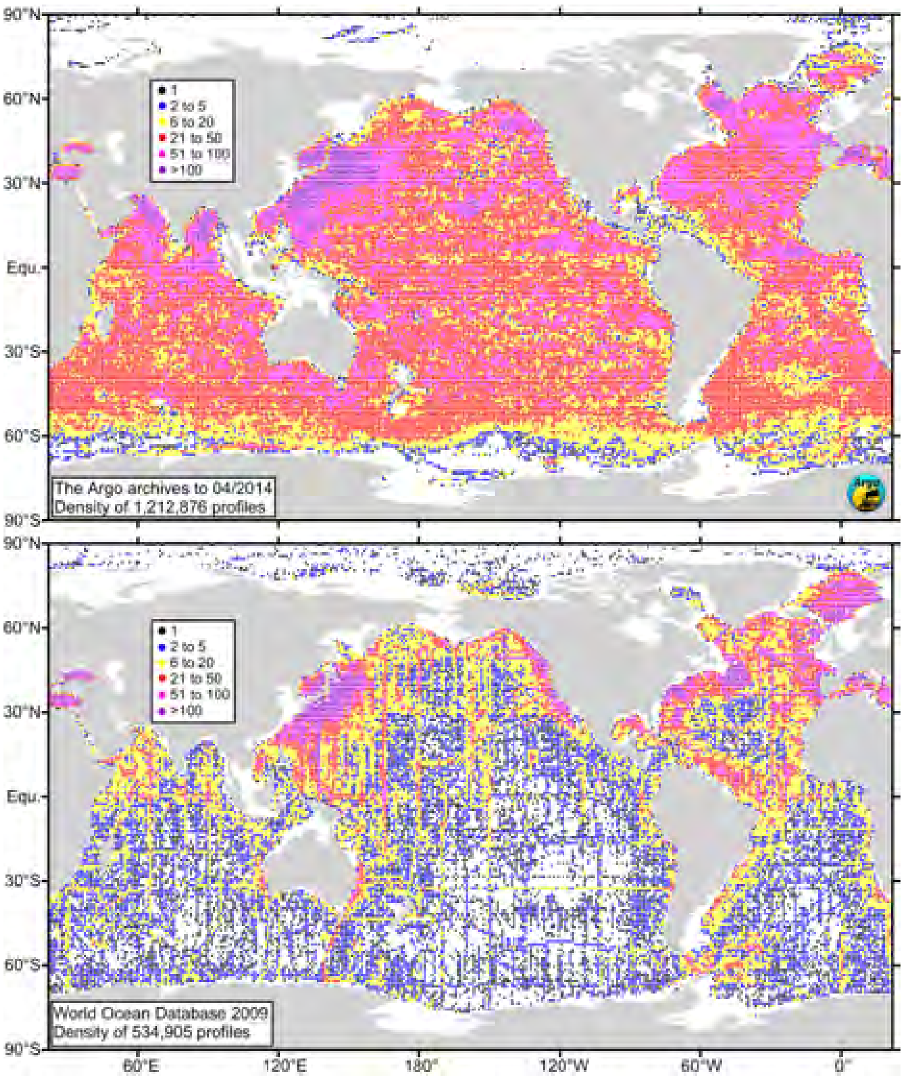


FIGURE 3

Deploying a Deep Argo profiling float.

also subject to issues of power consumption. The lifetimes of drifters are approximately 12–18 months depending on power consumption and drogue failure. Unlike profiling floats, drifters tend to become more heterogeneously distributed as they follow strong surface currents. This makes maintaining a global 5° × 5° grid difficult with limited deployment opportunities as the program relies on volunteer, commercial ships, and research vessels for deployments.

The greatest immediate benefit of Iridium Telecommunications has been in providing timely data to operational marine forecasting programs for marine transportation and search and rescue. As is the case for profiling floats, having high-resolution spatial (vertical and horizontal) and temporal observations can enable new areas of research. Surface drifters are now being used in studies of submesoscale processes and tidal motion.

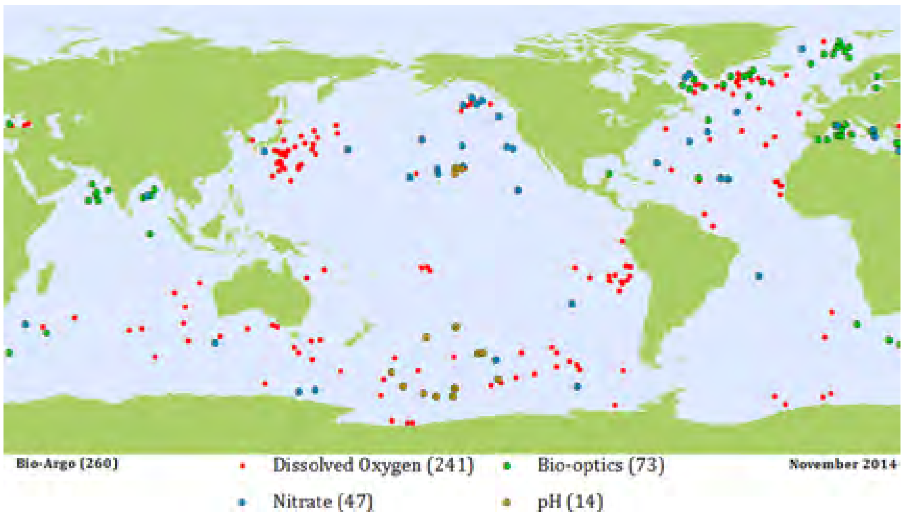
Global Tropical Moored Buoy Array

The GTMBA is a multinational effort to provide data in real time for climate research and forecasting. The major components include the TAO/TRITON (Tropical Atmosphere Ocean/Triangle Trans-ocean Buoy Network Array in the Pacific), PIRATA (Prediction and Research Moored Array in the tropical Atlantic), and RAMA (Research Moored Array for African-Asian-Australian Analysis and prediction) in the Indian Ocean (Figure 7).

The GTMBA provides high-quality moored time series and related data throughout the global tropics for improved description, understanding, and prediction of seasonal to decadal time scale climate variability. The

FIGURE 4

Active Argo profiling floats equipped with BioGeoChemical (BGC) sensors.



major foci of the array are basically the physical climate system: El Niño/Southern Oscillation (ENSO) in the Pacific; the interhemispheric dipole mode, equatorial warm events, and hurricane activity in the Atlantic; and the monsoons, the Indian Ocean Dipole, and intraseasonal variability in the Indian Ocean. As is occurring for profiling floats, BioGeoChemical sensors are being introduced into the array.

The majority of PIRATA and RAMA sites consist of a mooring system that was designed in the 1990s and is encountering issues of component obsolescence and limitations to expand capabilities. A new system is under development, which draws upon technologies developed at NOAA's Pacific Marine Environmental Laboratory and is designed to be functionally equivalent to the existing system but using commercially available components as much as possible. Iridium telemetry of all hourly data (compared to mainly daily mean data for ATLAS) will reduce high temporal resolution data loss if moorings are lost.

One of the continuing issues with respect to moorings is the need to revisit them on a fairly regular basis. Revisits are necessitated for a number of operational purposes including servicing sensors, changing sensors for calibration of the deployed sensors, and downloading of high-resolution data stored on the mooring. Moorings also may need to be replaced due to vandalism and damage due to (for example) commercial fishing operations. Servicing moorings requires large amounts of ship time, generally on large ships that are relatively expensive to operate. A next generation mooring under development is designed to be more robust, with more stable sensors, than the present moorings and is planned to last 18 months between servicings versus the present one year. Other moorings are under development that will be more resistant to vandalism and damage by commercial fishing operations. The introduction of Iridium Telecommunications on next generation moorings (already deployed on TAO in the Pacific) will facilitate the transfer of much more data in real time, thereby reducing or eliminating any data loss due to a lost mooring. The Tropical Pacific Observing System-2020 Project (http://tpos2020.org/)

FIGURE 5

Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM) Program float.

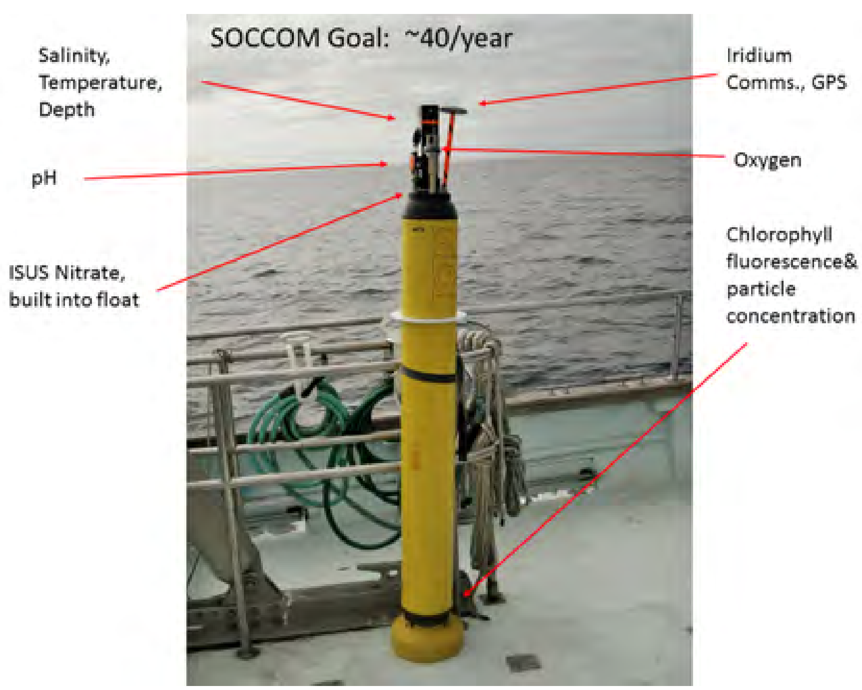
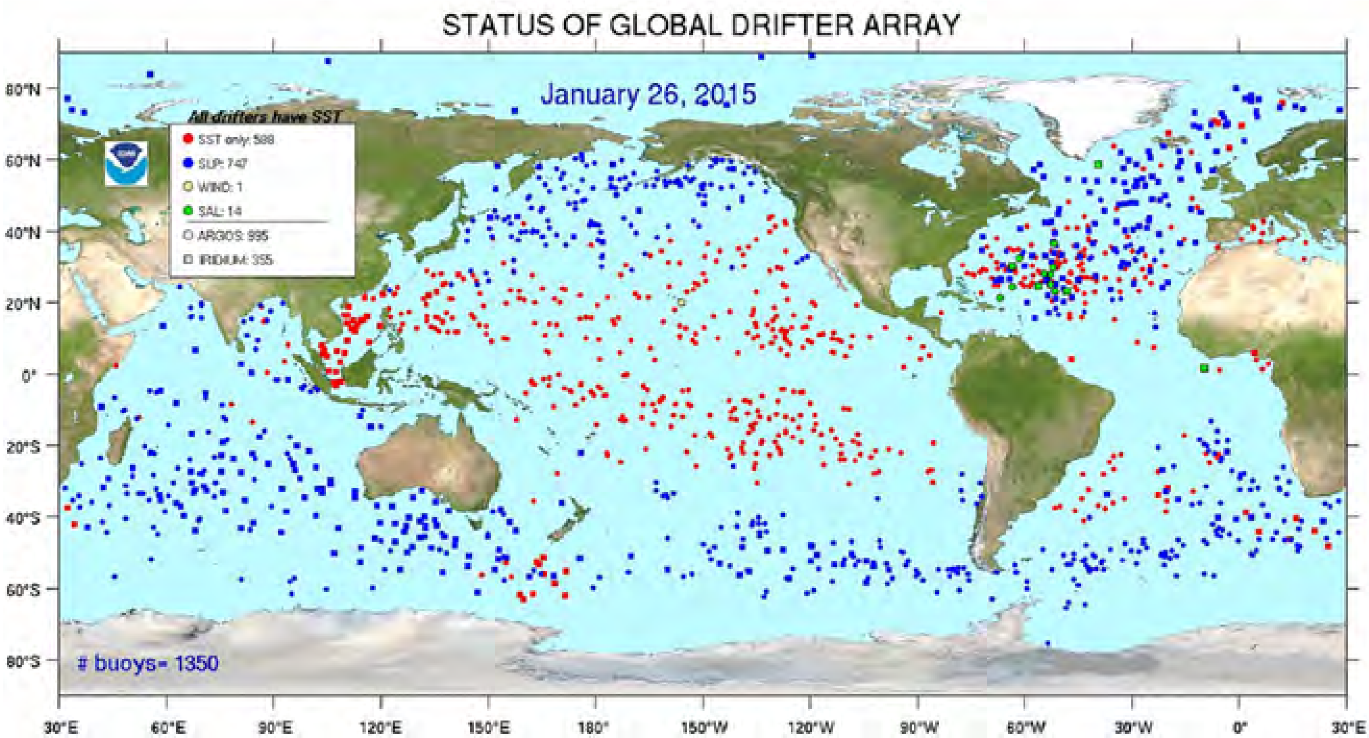


FIGURE 6

Status and composition of the Global Drifter Array. This represents approximately 75% of the International Drifting Buoy Program (http://osmc.noaa.gov/OSMC/reports.html).



will address the need for new observing strategies and capabilities in the decades to come and will encourage testing and use of new/different observing technologies.

OceanSITES

OceanSITES is a global network of long-term, open-ocean reference stations measuring large numbers of variables and monitoring the full depth of the ocean from air-sea interactions down to the seafloor (Figure 8). The stations measure many aspects of the ocean's surface, including meteorology, and water column using, where possible, automated systems with advanced sensors and telecommunications systems high time resolution, often in real time, while building a long record. Observations cover meteorology, physical oceanography, biogeochemistry, and parameters relevant to the carbon cycle, ocean acidification, ecosystem processes, and geophysics.

OceanSITES moorings provide (1) high temporal resolution, sampling down to minutes to record high amplitude, short-lived events in the surface meteorology, air-sea fluxes, and upper ocean structure; (2) high vertical resolution observations in the stratified upper ocean that is in close contact to the atmosphere and links the upper ocean to the interior of the ocean; and (3) continuous time series at a point for validation of other components of the ocean observing system, including remote sensing. The locations of the sites have been selected to sample more dynamic, changing environments of the ocean in a sustained way.

FIGURE 7

Global Tropical Moored Buoy Array.

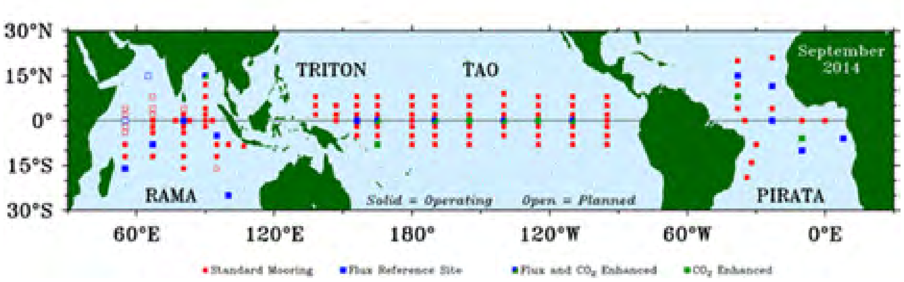
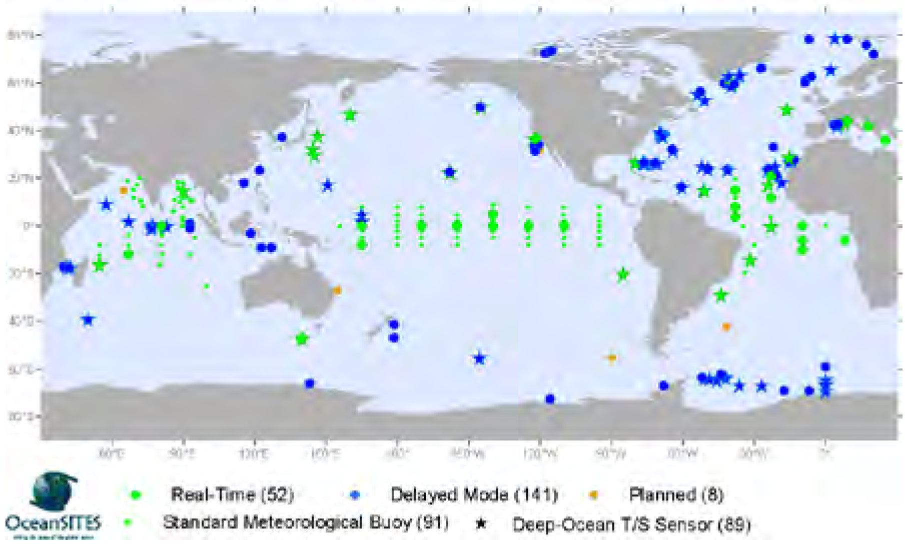


FIGURE 8

OceanSITES network.



Data from instruments on "Delayed Mode" sites are stored internally, retrieved when the moorings are recovered and submitted to the Data Assembly Centers. There is some telemetry of data from "Real-Time" sites, primarily near-surface and surface meteorological observations.

Tide Gauges

The purpose of the tide gauge program is to ensure that tide gauge data from around the world are collected, quality assessed, distributed, and archived for use in climate, oceanographic, ocean engineering, and geophysical research. The primary focus is the set of stations that constitute the Global Sea Level Observing System (GLOSS) and the Global Climate Observing System (GCOS). The GLOSS (Figure 9) and GCOS networks cover most major oceanic islands and island chains, with a subset of available continental coastal stations distributed evenly around the margins of ocean basins. Because of their importance for global and regional sea level reconstructions, vertical land motion monitoring is recommended at all GLOSS and GCOS stations and 11 continuous GPS receivers are included in this network.

The Fast Delivery data set provides preliminary, quality-assured, hourly tide gauge data within 4–6 weeks of collection. A Research Quality data set, which is an archive of hourly tide gauge data that have undergone a complete quality assessment, is available generally within 1 year of collection.

Global Ship-Based Hydrographic Investigators Program

Shipboard hydrography remains the only method of obtaining high-quality, globally distributed, vertical resolution measurements of many chemical, physical, and biological parameters over the entire water column. Global hydrographic surveys were conducted in the 1970s (Geochemical Ocean Sections Studies, GEOSECS), 1980s (Joint Global Ocean Flux Study, JGOFS), and 1990s (WOCE). GO-SHIP is a systematic and global reoccupation of select hydrographic sections to quantify changes in storage and transport of heat, fresh water, carbon dioxide (CO_2), chlorofluorocarbon (CFC) tracers and related parameters. GO-SHIP is designed to assess changes in the ocean's biogeochemical cycle in response to natural and/or anthropogenic activity and global warming-induced changes in the ocean's transport

FIGURE 9

The Global Sea Level Observing System (GLOSS).

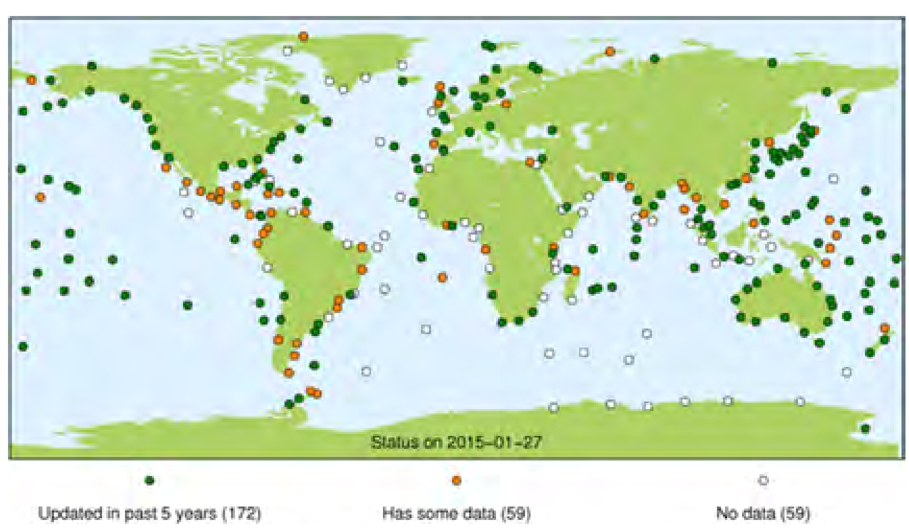
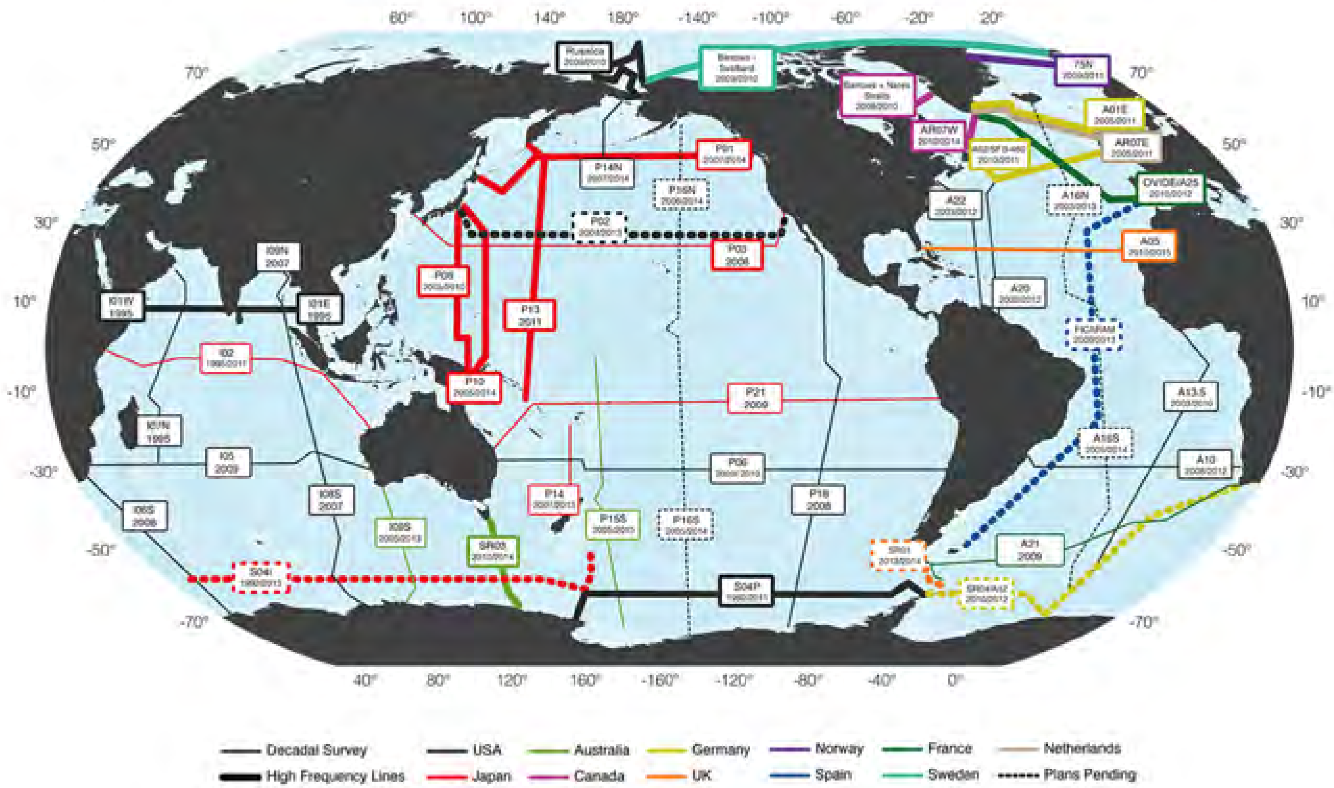


FIGURE 10

Repeat Hydrography sections-1995 (2) Northwest Indian Ocean; 2000–2015 completed or scheduled.

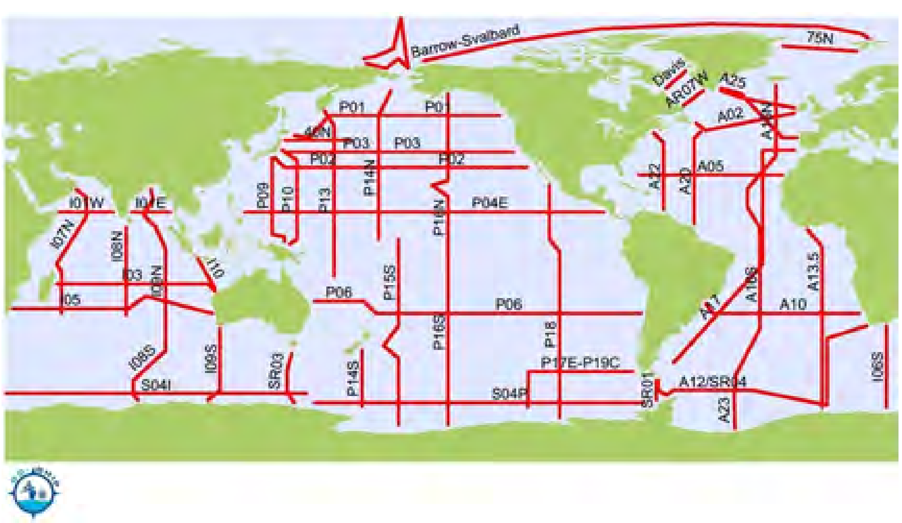


of heat and freshwater. Figure 10 presents hydrographic sections conducted since 1995 and planned through 2015.

The U.S. contribution to GO-SHIP is cosponsored by NOAA and the National Science Foundation and is being implemented to maintain decadal time-scale sampling of ocean transports and inventories of climatically significant parameters in order to (1) understand and document large-scale ocean water property distributions, their changes, and drivers of those changes and (2) address questions of a future ocean that will increase in dissolved inorganic carbon (Intergovernmental Oceanographic Commission of UNESCO and the International CLIVAR Project Office, 2009). Figure 11 presents the surveys planned by the International GO-SHIP Committee through 2023.

FIGURE 11

GO-SHIP survey through 2023.



VOS and the XBT Subsurface Temperature Network

The VOS program is an international program comprising member countries of the WMO that recruit ships to take, record, and transmit weather observations while at sea. Today approximately 6,000 ships from approximately 50 nations participate in the VOS program. A program within the VOS program is the Ship of Opportunity Program (SOOP), which is an international effort that supports the implementation of a network of cargo vessels, cruise ships, and research vessels to deploy scientific instruments that collect oceanographic observations. The most important of these instruments is the XBT. XBTs are deployed along fixed, pre-established transects at approximately 150- to 200-km intervals (Figure 12), which are repeated at least four times per year, to measure the water temperature from the sea surface to a maximum depth of 850 m.

The SOOP is also responsible for the installation and operation of ThermoSalinoGraphs (TSGs) on some ships. TSGs are instruments that continuously measure the values of sea surface temperature and salinity along the ship path. TSG observations are used in conjunction with carbon dioxide measurements to provide critical information on frontal regions and mixed layer depths for ocean acidification assessments.

Figure 12 presents the SOOP transects in 2013. Presently approximately 30 lines are occupied annually. Transects are sampled in three modes: high resolution (HR), high density (HD), and frequently repeated (FR). Some transects include time series with more than 30 years of data. The high-resolution (HR-XBT) mode conducts boundary-to-boundary repeating transects that resolve both the oceanic boundary currents and the corresponding interior circulations of the global oceans. Each transect is repeated nominally on a quarterly basis. A technician is on board to carry out sampling, with XBT probe spacing at 50 km or less in the ocean interior and as fine as 10 km in boundary currents. The HD (HD-XBT) mode samples are at approximately 25-km intervals quarterly while the FR (FR-XBT) mode samples are at 100- to 150-km intervals up to 18 times a year. The major technological developments underway for the XBT are the development of a more accurate temperature sensor and more precisely determined probe mass for better determination of the fall rate of probes, thereby reducing the uncertainty in depth of observations and providing better climate-relevant data.

FIGURE 12

Ship of Opportunity Program.

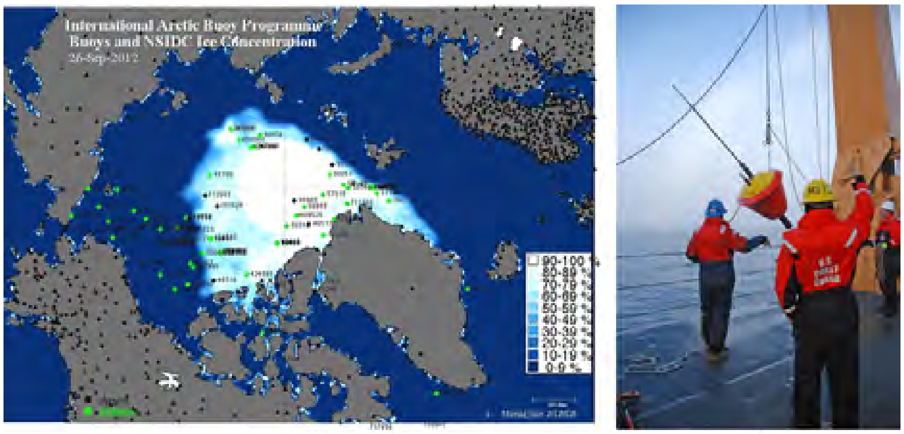
Arctic Observing Network

Participants from 10 nations work together under the International Arctic Buoy Program (IABP) to maintain a network of drifting buoys in the Arctic Ocean to provide meteorological and oceanographic data for real-time operational requirements and research purposes. Following recommendations by the U.S. National Academy of Sciences, the Arctic Ocean Buoy Program began operations in 1979 with the establishment of a network of automatic data buoys to monitor synoptic-scale fields of sea level pressure, surface air temperature, and ice motion throughout the Arctic Ocean. In 1991, the IABP succeeded the Arctic Ocean Buoy Program (Figure 13a).

Sea ice extent has receded to about half its normal area during summer, and thickness has decreased by over 40%. In addition to implications for the Arctic and global system, these changes challenge our ability to monitor Arctic weather and climate. Older, thicker sea ice, which is now rare across the Arctic Ocean, used to provide a robust stable platform on which drifting buoys could be deployed. Presently the Arctic Ocean is covered primarily by younger, thinner sea ice, which is more responsive to changes in wind, less stable, and more likely to melt out each summer. In order to address these challenges, the U.S. Interagency Arctic Buoy Program (USIABP) has

FIGURE 13

International Arctic Buoy Program and Ice Mass Balance Studies. (a) Ice concentration. (b) Deployment of an AXIB buoy from the CCG Healy in the Beaufort Sea.



(a) (b)

been developing the Airborne Expendable Ice Beacon (AXIB). These buoys are designed to measure the fundamental meteorological parameters, as well as other physical variables, but most importantly the AXIB is designed to survive in the harsher environment of the seasonal ice zone and weather the annual cycles of thawing and freezing of the Arctic Ocean. The first AXIB prototype was deployed in 2008 and continued to report for 5 years. Since then the USIABP has partnered with the Coast Guard to deploy AXIBs from C-130s from Air Station Kodiak and the ice breaker CCG Healy (Figure 13b).

The Near Future

NOAA's Science and Technology Enterprise vision centers on an understanding of the interdependencies between human health and prosperity and the intricacies of the Earth system. NOAA's ocean observing system portfolio needs to meet increasing demands (e.g., deep ocean observations, under-ice observations, observations of biogeochemical processes) while sustaining existing long-term data sets. This will require the development and transitioning of new observing technologies such as autonomous vehicles to maintain existing data sets along with the incorporation of new sensors into existing platforms. Along with new sensors, increasing demands include higher temporal and spatial resolution, more accurate and precise observations, observations at higher vertical resolution, and real-time command and control of platforms to, for example, change sampling protocols and/or mission programs. Advanced telecommunication capabilities and data management processes will be required to implement the enhanced capabilities and provide the data to users. While ships will still be required for complex, multimission operations and moorings for long time series, the vastness of the oceans compared with the number of ships available, the cost of ship operations and moorings, and the limitations of ships by weather have resulted in biased data sets, in the case of ships biased to the Northern Hemisphere and to summertime observations, particularly in high latitudes. Autonomous platforms reduce or eliminate the biases of ship operations in terms of both spatial and temporal distributions of data but also provide high-frequency observations. The reduced cost per observation from autonomous instruments will enable the deployment of more platforms with additional sensors into more regions with data gaps, thereby improving model performance. Models themselves will be modified to accept data of various sensors at various locations in both space and time, vice gridded data assimilation routines.

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