Argo Profiling Floats Bring New Era of In Situ Ocean Observations

PAGES 179, 190–191

The Argo profiling float project will enable, for the first time, continuous global observations of the temperature, salinity, and velocity of the upper ocean in near-real time. This new capability will improve our understanding of the ocean's role in climate, as well as spawn an enormous range of valuable ocean applications. Because over 90% of the observed increase in heat content of the air/land/sea climate system over the past 50 years occurred in the ocean [*Levitus et al.*, 2001], Argo will effectively monitor the pulse of the global heat balance. The end of 2003 was marked by two significant events for Argo. In mid-November 2003, over 200 scientists from 22 countries met at Argo's first science workshop to discuss early results from the floats. Two weeks later, Argo had 1000 profiling floats—one-third of the target total—delivering data. As of 7 May, that total was 1171.

The Argo Project

Argo is an international effort collecting high-quality temperature and salinity profiles from the upper 2000 m of the ice-free global ocean and currents from intermediate depths. The data come from battery-powered autonomous floats (Figure 1) that drift mostly at depth, where they are stabilized at a constant pressure level by being less compressible than sea water. At typically 10-day intervals, the floats pump fluid into an external bladder and rise to the surface over about 6 hours while measuring temperature and salinity. On surfacing, satellites position the floats, and receive the transmitted data. The bladder then deflates and the float returns to its original density and sinks to drift until the cycle is repeated. Floats are designed to make about 150 such cycles.

Profiling floats were developed during the 1990–1998 World Ocean Circulation Experiment, but despite their extensive earlier use, the technological challenges of building and maintaining the 3000-float Argo array should not be underestimated. Over 800 deployments will be required each year, and each float must deliver high-quality data while cycling over 200 atmospheres and through a temperature range that may approach 30°C. Argo continues to improve float performance and reliability through close collaboration between float operators and manufacturers.

Building the Array and Delivering Data

The array is made up of 18 different countries' contributions that range from a single float, to the U.S. contribution, which is 50% of the global array. Argo is quite new: the first floats were launched in 1999, and in most countries, funding is still identified as supporting the pilot phase of the program. That phase needs to cover the completion of the global array and its operation and evaluation over a multi-year period of the order of 10 years. Funding mechanisms differ widely between counties and involve over 50 research and operational agencies. Each national program has its own priorities, but all nations subscribe to the goal of building the global array, and to Argo's open data policy. Almost all Argo observations are available—with gross errors corrected or flagged—to anyone wanting to use them from Global Data Assembly Centers (GDACS) in Brest, France, and Monterey, California. The target is for data to be available within approximately 24 hours of its transmission from the float. The data reach

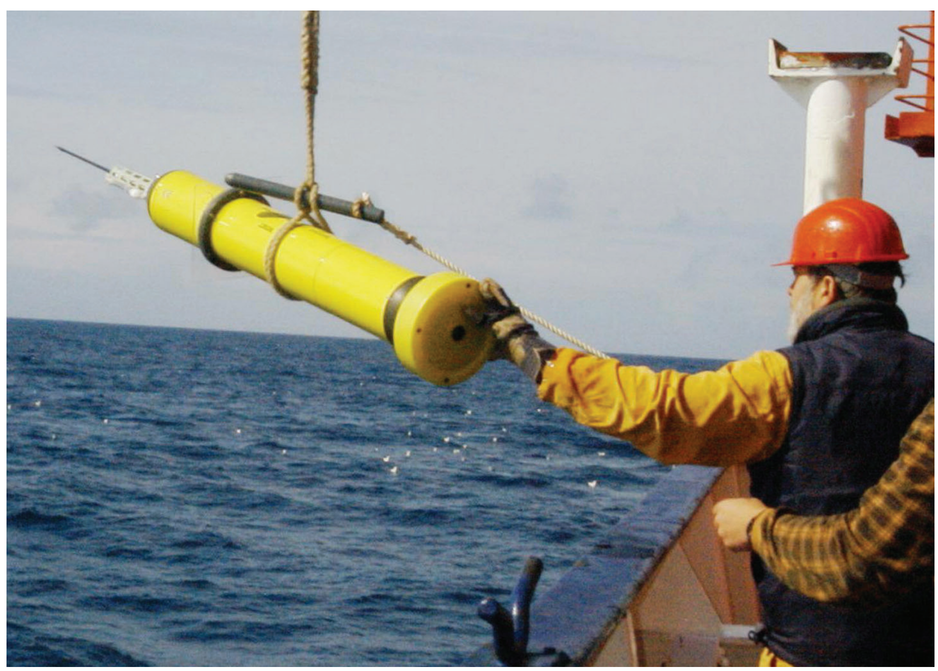

Fig. 1. An Argo float is launched from a research vessel. (Photo courtesy of Institut für Meereskunde/GEOMAR, Kiel, Germany.)

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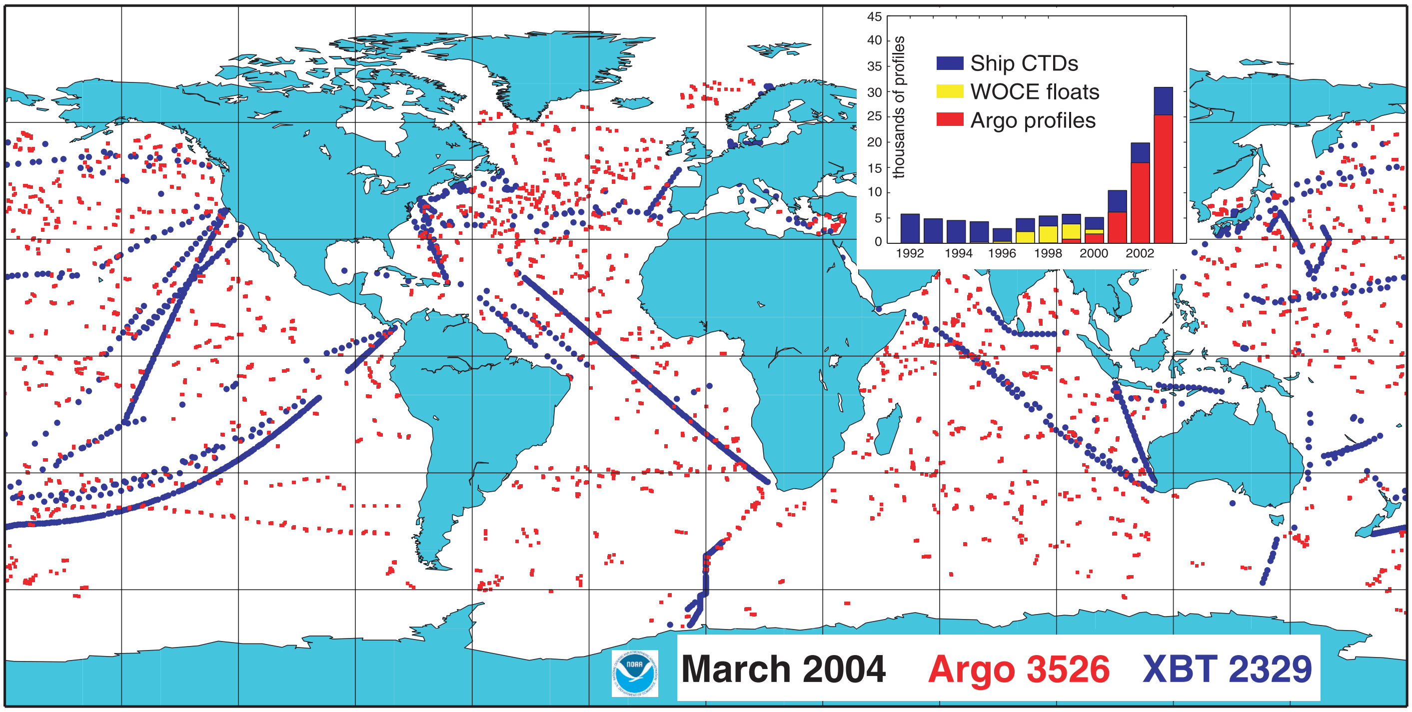

Fig. 2. The spatial distributions of profiles collected from Argo floats and from XBT measurements from volunteer and research ships are shown for March 2004. Argo data have salinity and temperature measurements to depths as great as 2000 m. XBTs measure temperature alone typically to 750 m. The data are from the real time data streams and most were available to users within 24 hours of collection. (Figure courtesy of the National Oceanic and Atmospheric Administration, Atlantic Oceanographic and Meteorological Laboratory, Miami, Florida.) The inset graph shows the growth of the contribution of Argo to the global inventory of CTD profiles. The full array will deliver 100,000 profiles per year. (Figure prepared by Josh Willis, Scripps Institution of Oceanography.)

operational centers via the Global Telecommunications System (GTS). The array's growth is monitored by the Argo Information Center.

Populating remote and previously data-sparse regions of the southern hemisphere poses particular challenges. Most floats are launched from research ships (including Antarctic supply vessels) on an opportunistic basis. A smaller number have been launched from merchant vessels on passage. However, many areas in the southern hemisphere are rarely visited by any ship. For these regions, dedicated ship charter or aircraft deployment must be used.

The thousandth float marks one-third of Argo's originally planned target that, given the expected levels of national Argo commitments, should be reached in 2006. That array will provide 100,000 temperature/salinity (T/S) profiles per annum. To put this in context, there are typically between 1500 and 2000 ship-based conductivity-temperature-depth (CTD) profiles each year to depths as great as 2000 m and about 5000 to 1000 m. Argo is already the largest source of profile data to these depths (Figure 2). To maximize battery life, most low-latitude floats restrict profiling to 1000 m, with profiling to 2000 m used at high latitudes, so as to reach stable deep-water masses.

The target array represents one float every 3° of latitude and longitude and, though it will not resolve the meso-scale variability, it will make an enormous increase in our knowledge of the sub-surface ocean. The data are of vital importance for two global projects that were Argo's originators. The Global Ocean Data Assimilation Experiment (GODAE), will combine Argo and other in situ data with satellite altimeter observations (Argo is teamed with Jason-1, the high-precision altimeter satellite launched in 2002). Argo's other sponsor is the World Climate Research Programme's CLIVAR study on climate variability and predictability on time scales from seasons to centuries, in which the oceans' role is crucial. Argo is a pilot project of the Global Ocean and Global Climate Observing Systems (GOOS and GCOS).

In addition to the real-time data stream, Argo has the potential after careful data assessment to provide salinity profiles that approach ship-based data accuracy. In general, there is no possibility of carrying out calibration checks on a float's sensors after it has left the laboratory, or has been launched by a research ship that might make a nearby CTD cast. One means of adjusting salinities is to look at deviations from a stable, deep temperature/salinity climatology [*Wong et al.*, 2003], or to compare profiles from floats that coincide in space and time. A challenge for the application of the *Wong et al.* approach is to detect real changes in the deep ocean T/S. The so-called delayed-mode data delivery system is not yet fully implemented.

First Argo Science Workshop

Despite its infancy, Argo, along with profiling float data collected during the World Ocean Circulation Experiment, represents a considerable and unique (in terms of its global distribution) body of information. With this in mind, Argo held its first science workshop in Tokyo, Japan, 12–14 November 2003. The 85 presentations provided ample evidence of the breadth of applications for which profiling float data can be used.

At short time scales, Argo data have been used to study the evolution of near-surface temperature and salinity beneath tropical cyclones. The data show clear temperature differences left and right of the cyclone track, but produce conflicting patterns of salinity change. Monsoons and ENSO events dominate the low-latitude seasonal/inter-annual ocean-atmosphere variability. Argo data, when combined with TAO/Triton tropical buoy array data, extend the mapping of tropical Pacific Ocean structures, and are also used in ENSO forecast systems. Argo profiles have also revealed the Arabian Sea space-time response during the summer monsoons of 2002 and 2003.

Many results focused on exploration of the circulation and the definition of the properties and abundance of winter-formed mode waters in mid-latitude ocean basins. This could even be done in areas such as the Okhotsk Sea, where there is extensive ice cover in some years. Twelve operational analysis/forecast centers routinely use Argo data, and through GODAE, are routinely producing ocean state products. Improvements in ocean predictions from assimilating Argo data were demonstrated at the workshop. These give an exciting foretaste of the likely impact of the full Argo array when combined with remote sensing data.

Although the Argo array is not yet complete, its impact on global-scale problems can already be seen from studies such as *Willis et al.* [2003], where Argo allows heat and fresh water storage in the ocean to be estimated. Its advantage over ship-based observations is the uniform geographical and seasonal distribution, depth penetration (deeper than the typical 750 m of XBTs), and data volume (Figure 3).

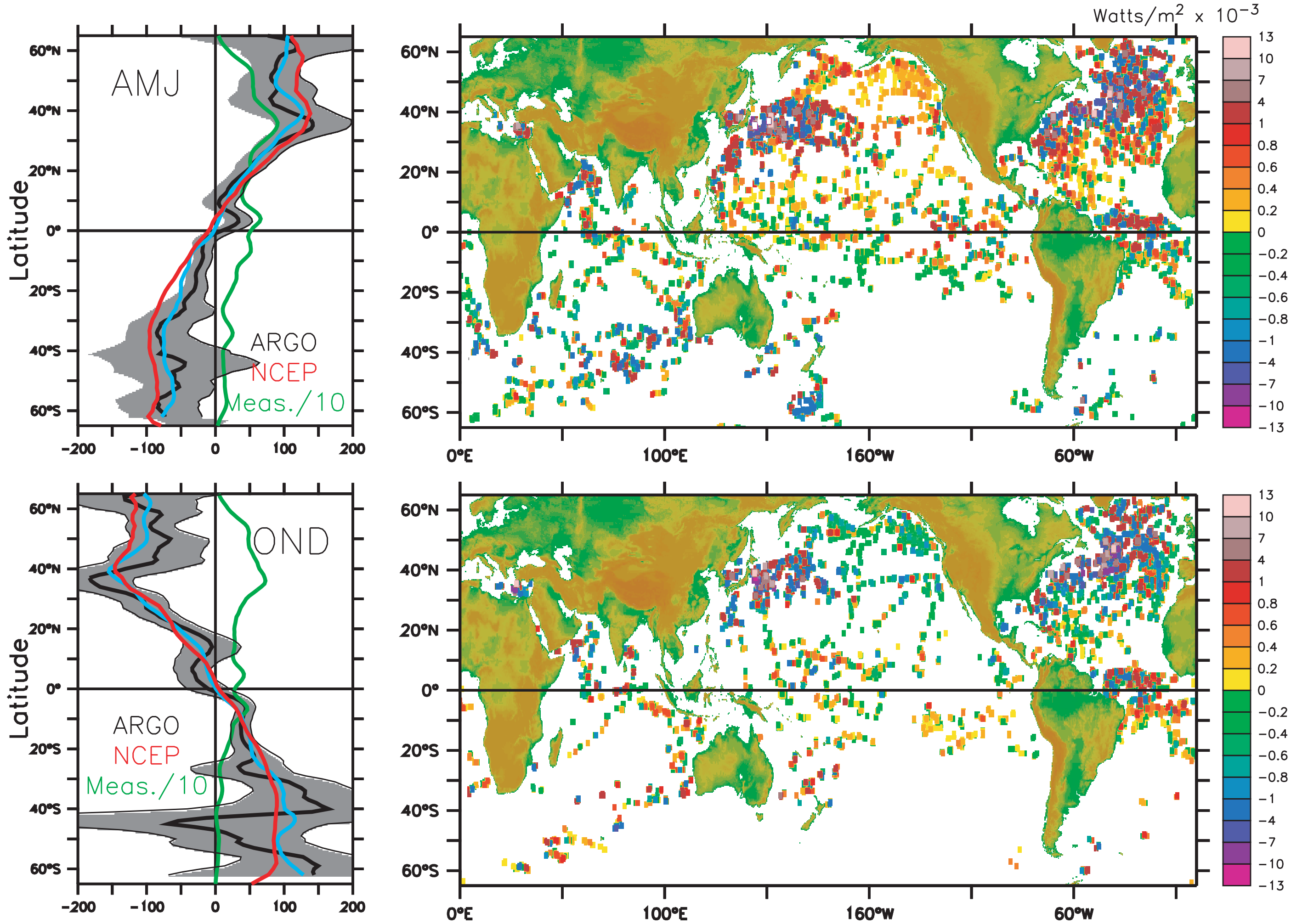

Fig. 3. Seasonal heating and cooling as revealed by Argo. Argo data were used to construct time series of heating/cooling by differencing successive (typically 10-day) profiles and averaging over seasons: boreal spring (AMJ) and fall (OND). The panel at left shows the latitude-averaged heating and cooling from Argo (black curve with error estimate), compared with NCEP estimates (red curves). Also shown are numbers of station pairs per 10° latitude band; 34,000 Argo profile pairs were available. (Courtesy of John Gilson, Scripps Institution of Oceanography, La Jolla, Calif.)

Argo data have been shown to be of high enough quality to document changes over almost 20 years in sub-surface salinity across the south Indian Ocean, an area where climate change models predict that anthropogenic change will be most easily detected [*Banks and Wood*, 2002]. However, applications of this type highlight the need for caution in adjusting float data to climatological values.

While much emphasis is placed on Argo profile data, velocity estimates both at depth and from the floats' time at the surface have been used for the global estimation of inertial oscillation statistics to reveal hitherto unsuspected sub-surface circulation patterns. When combined with surface drifter data and T/S profiles, they can be used to derive velocity field estimates on basin (and ultimately global) scales throughout much of the water column.

The workshop presentations and links to operational applications can be found at http://www.argo.ucsd.edu/.

Future Directions

Reaching one-third of the target array and holding the workshop were mere markers along the path that Argo is pursuing. Float reliability has improved, and there have been successful trials using low-Earth orbit, two-way satellite communication with GPS positioning, allowing transmission of more detailed profiles in less time at the surface. Two models of oxygen sensors have been deployed, acoustic sensors are being tested to estimate wind speed and rainfall, bio-optical sensors hold great promise [*Bishop et al.*, 2002; *Emerson et al.*, 2002], and floats have collected data under sea ice. However, Argo will, for the foreseeable future, give priority to its core of temperature, salinity, and circulation measurements. The data system is established, and delayed mode data (with drift-adjusted salinities) will soon be available from the GDACS later this year. Regional centers will assemble data and produce products based on Argo observations. A concerted effort in 2004 is underway to deploy floats in the empty areas of the southern hemisphere. Above all, there will be a rapid expansion of the use of Argo data by researchers, and by operational ocean and climate analysis and forecasting centers.

Argo poses challenges not previously faced by the oceanographic community. As mentioned earlier, each country has a different model for running its national contribution. In all countries, research scientists are playing a leading role, but there are varying degrees of involvement by operational agencies. The challenge is to sustain initial funding for 10 years, long enough to complete the array and demonstrate its value, but longer than the usual duration of research funding. Success in meeting that challenge will depend on demonstrating the value of the data in addressing a wide range of problems, and establishing in each country an effective partnership between operational agencies and researchers.

There is an increasing recognition, as shown by the Global Earth Observation (GEO) process and by the earlier Global Monitoring for Environment and Security (GMES) initiative in Europe, that sustained monitoring of our planet is essential if we wish to address a wide range of environmental and socioeconomic issues. Argo is positioned to be a central and essential element of these observing strategies.

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Table 1. Information Web Sites

Argo Information Centre	http://argo.jcommops.org/
Argo Project Page	http://www.argo.ucsd.edu/
Argo Data from Coriolis	http://www.coriolis.eu.org/cdc/argo.htm
Argo Data from U.S. GODAE	http://www.usgodae.org/argo/argo.html
GODAE project	http://www.bom.gov.au/GODAE/
CLIVAR project	http://www.CLIVAR.org/
Satellite altimetry	http://topex_www.jpl.nasa.gov/mission/jason_1.html
GCOS	http://www.wmo.ch/web/gcos/gcoshome.html
GEO	http://www.earthobservationsummit.gov/
GMES	http://www.gmes.info/

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