The Argo Project: Global ocean observations for understanding and prediction of climate variability

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Global ocean observations for climate

Oceanography is now engaged in the ambitious enterprise of designing and installing a global ocean observing system to provide unprecedented observation of seasonal to decadal variability (OCEANOBS99, 1999). This will enable major advances in understanding and prediction of climate along with other practical applications. The *in situ* backbone of the global system, indeed the only element that will produce a global subsurface dataset, is the Argo array of profiling floats (Argo Science Team, 1998, 1999a, 1999b).

Argo will consist of 3000 autonomous instruments (Figure 1), each returning a profile of temperature and salinity from 2000 m depth to the sea surface every 10 days (Figures 2, 3). The floats will be distributed over the global ocean with a spacing of about 3° in latitude and longitude. Data return is via satellite, and profiles will be rapidly transmitted to forecast centers for operational use, typically in less than 12 hours. Scientifically quality controlled data will be accessible via the internet within three months. All Argo data will be openly available with no proprietary restrictions. At any given time, the physical state of the global ocean will be observed and reported by this array.

The Argo project has drawn broad international interest and support. It is a pilot project of the Global Ocean Observing System (GOOS). It is strongly endorsed by the Climate Variability and Predictability (CLIVAR) experiment of the World Climate Research Program (WCRP) and the Global Ocean Data Assimilation Experiment (GODAE). Argo was recognized as an important contribution by the Fourth Conference of the Parties to the Framework Convention on Climate Change, by the Twentieth Assembly of the Intergovernmental Oceanographic Commission, and the Thirteenth World Meteorological Congress.

Within the U.S., the scientific and operational objectives of Argo together with its global scope and interdisciplinary potential have resulted in its implementation under NOPP. Argo stands at an important intersection of agency and disciplinary interests, making it a strong candidate for NOPP sponsorship.

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Why is Argo needed?

The major climate initiatives of the past 20 years, and especially the Tropical Ocean Global Atmosphere (TOGA) experiment and World Ocean Circulation Experiment (WOCE), revealed critical roles played by the ocean in the coupled climate system. Not only is the ocean the dominant reservoir for water and heat in air/sea/land variability, but ocean dynamics and thermodynamics participate through redistribution of heat and sequestration of climatically active gases. The active role of equatorial ocean dynamics in the evolution of El Niño was a breakthrough finding during TOGA. TOGA's installation of an *in situ* observing system in the tropical Pacific made possible the first successful El Niño forecasts.

WOCE analyses showed that ocean currents carry enormous quantities of excess heat from the tropics to mid-latitudes, about 2×10^{15} W in the northern hemisphere alone (Bryden et al., 1991), comparable in magnitude to heat transport by the atmosphere. WOCE data have also revealed large interannual variability in the ocean's heat engine. For example the tropical/extratropical heat transport in the North Pacific varies by at least 30% interannually (Roemmich et al., 2000). Many

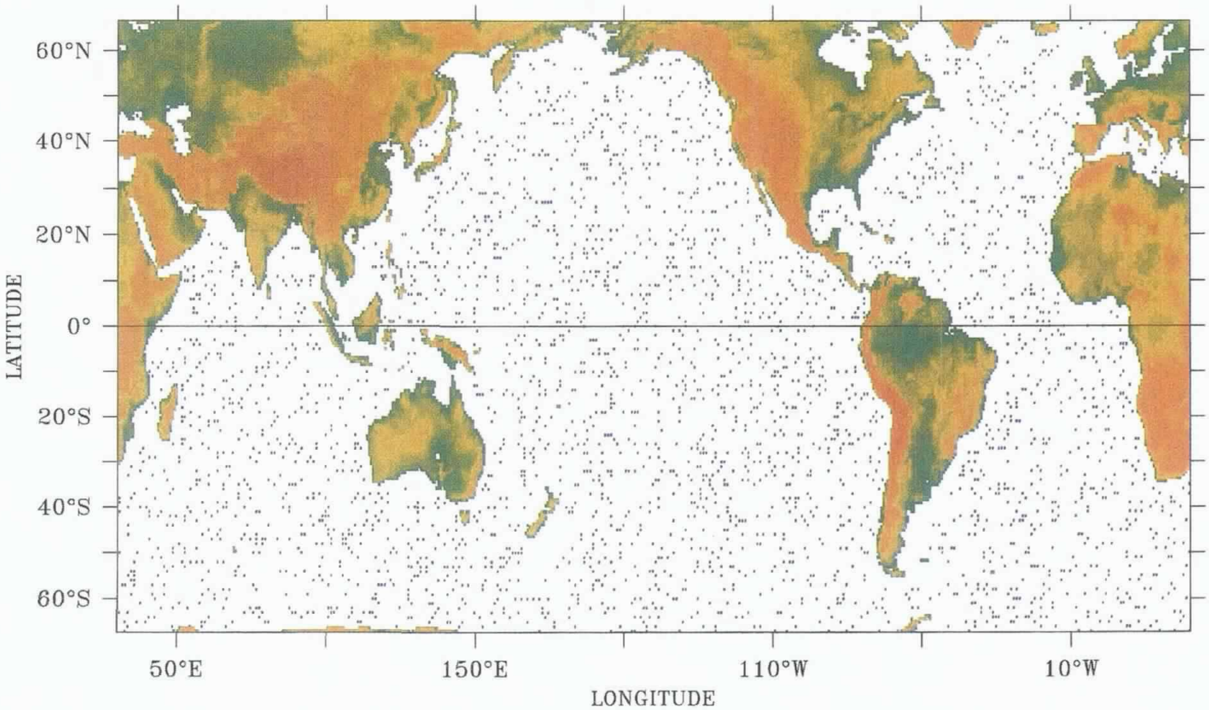

Figure 1. Schematic of the Argo array: a random array of 3000 locations spread over the globe in waters deeper than 2000 m.

unanswered questions remain about the processes that initiate and sustain interannual and decadal variability. It is widely agreed that further progress in understanding and predicting climate variability requires that the present, largely tropical Pacific, observing system be expanded to encompass the global ocean. Global measurements of oceanic storage and transport are necessary elements in a climate observing system.

While the scientific rationale for global ocean measurements has been built over decades, three recent developments make deployment of the Argo array a compelling step now.

- First, the development of the profiling float (Figure 2) during the 1990s makes it feasible for the first time to observe the physical state of the ocean (temperature and salinity profiles, and a reference velocity at depth) on a regular and routine basis anywhere in the world.
- Second, the availability of precision satellite altimeters, measuring sea surface height globally every 10 days, creates a strong need for *in situ* datasets to interpret and complement the surface topography (Figure 4).
- Finally, the ongoing maturation of data assimilation capabilities is a crucial development. Ocean state estimation (Stammer and Chassignet, 2000) provides a framework for integrating subsurface and remotely sensed surface datasets of wind forcing and oceanic response in a dynamically consistent fashion.

With a satellite observing system now in place, and the powerful machinery for data assimilation soon to be available, the deployment of a global subsurface array becomes a top priority for improved understanding of the climate system and exploration of predictability. Argo is one element of a global ocean observing system (e.g. OCEANOBS99, 1999). Its deployment in the next few years will greatly add to the feasibility and value of the many needed regional enhancements.

Argo and Jason

There is an especially close relationship between the profiling float array and satellite altimetry. The name Argo was chosen to stress this connection to the next generation Jason satellite altimeters to be launched by NASA and CNES. Just as Jason in Greek mythology required his ship, the Argo, for epic ocean voyages, so the altimeter Jason will need the modern Argo to complete its mission successfully.

The combination of profiling floats and altimetry provides a dynamically complete description of sea surface height and its subsurface causes (Figure 4). Fluctuations in sea surface height may be written as:

$$h' = \frac{1}{g}\int_{p_{ref}}^{0} (\rho')^{-1}\, dp + \frac{1}{\rho g} p'(z_{ref}) \qquad (1)$$

where h is sea surface height, ρ is water density (a function of temperature, salinity and pressure), p is pressure, g is gravitational acceleration and primes denote anomalies from the time mean. The left-hand side of this equation is measured by the altimeter. The first term on the right (known as dynamic height) is calculated directly from float profile data. This term measures the expansion or contraction of the water column due to changes in water properties (e.g. a heated water column expands). The second term on the right is obtained from the float's velocity during the time that it drifts at the reference depth between profiles (e.g. Davis, 1998).

Figure 2. A profiling float is held ready for launch.

The large-scale drift is in geostrophic balance:

$$\nabla p = \rho f u$$

where f is the Coriolis parameter and u is the drift velocity. The drift can therefore be used to calculate horizontal pressure gradients at the reference depth (corresponding to the reference pressure P_{ref}). This pressure term in equation (1) measures changes in the mass of water above the reference depth, such as those associated with the wind-driven component of ocean circulation. Hence, on the large spatial scales common to the float and altimetric data, the combined measurements account for both the density-related and mass-related contributions that make up the total of sea level variability.

Models that assimilate altimetric height alone cannot yet accurately describe this decomposition of sea level into density and reference pressure variability, nor can they accurately estimate the depth-distribution of the density signal. The ocean's dynamics and its evolution depend critically on this subsurface structure, so the subsurface array is a necessary part of the total observing system. Modern data assimilation is a powerful tool, but it is crucial that the models be strongly constrained by data for accurate simulation and forecast initialization.

What will Argo accomplish?

Argo will provide global, subsurface coverage of temperature and salinity to a depth of about 2000 m. WOCE also carried out global measurements but required 7 years and many ships to complete the global survey. In effect, Argo will be a real-time, upper-ocean WOCE, producing a snapshot of the global ocean every 10 days.

The anticipated accomplishments of Argo fall into three broad categories. The first of these includes stand-alone achievements in improving our basic knowledge and understanding of the sea, including its structure, circulation, and mass, heat and salt budgets. Accurate global climatologies of subsurface temperature and salinity will have known errors and statistics of variability. Time-series of heat and freshwater storage, as well as of the structure and volume of the world's thermocline and intermediate water masses will be available on a global basis. Argo will complete the global description of the mean and variability of large-scale ocean circulation, including interior ocean mass, heat and freshwater transport. The dominant patterns of interannual to decadal variability in the sea—the oceanic expressions of ENSO, the Pacific Decadal Oscillation, the North Atlantic Oscillation, etc.—will be observed.

A second group includes goals related to modeling and assimilation. Argo will provide an unprecedented dataset for data assimilation (Stammer and Chassignet, 2000)—to reveal the present physical state of the ocean and for initialization of predictive models. Operational real-time global ocean forecasts will become possible. The dataset will also allow dynamical consistency testing of the next generation of global ocean and coupled models, without which further improvement of models is not possible. With the observation of the oceanic component of coupled modes of variability, prediction of the corresponding atmospheric variability can improve. The predictive successes of the tropical Pacific ENSO observing system will be expanded with global ocean observations.

A final group of goals involves Argo's synergy with the Jason altimetric mission, as described above. The complementary nature of the measurement systems will allow altimeter/float combinations to examine a broad range of space- and time-scales. Combination of altimetry and profiling floats will provide more powerful constraints for ocean state estimation than either measurement system alone.

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The design of Argo

The design of Argo is an ongoing exercise in balancing the requirements of a global array against practical limitations. Moreover, since the statistics of ocean variability are poorly known in many regions, array design is an iterative process. The design of an interior ocean array has been considered from a variety of perspectives (Argo Science Team, 1998, 1999a), leading to the 3° latitude and longitude spacing proposed for Argo. These perspectives are:

- *Previous and ongoing float studies.* An array of 300 floats was deployed in the tropical and South

Pacific during WOCE. This vast region includes nearly half the global ocean. Davis (1998) found that the sparse dataset was sufficient to map the mean mid-depth circulation over a period of 5 years, but not its time variability. The Argo array will provide a 5-fold increase in the number of floats in this region—sufficient for accurate maps of seasonal to interannual variability in temperature, salinity and circulation. Recent experience with a dense array of profiling floats in the North Atlantic further emphasizes the need for substantial numbers of instruments to average over the noisy mesoscale eddy field and observe large-scale change.

- *The existing upper ocean thermal network.* Numerous network design studies have been carried out, using expendable bathythermograph (XBT) data sets to estimate necessary statistics (White, 1995). In approximate terms, an array with spacing of a few hundred kilometers is sufficient to determine heat storage in the surface layer with an accuracy of 10 W/m^2 on seasonal time-scales and over areas 1000 km on a side. This improves to about 3 W/m^2 for interannual fluctuations, and even better if temperature profiles and altimetric data are combined. These error bounds yield high signal-to-noise ratio in observing seasonal to interannual patterns of variability in the sea. Aside from their intrinsic interest, the heat storage measurements can provide powerful constraints on air-sea heat exchange in atmospheric and coupled models.
- *The altimetric data set.* Spectral analysis of altimetric data shows that, on a global basis, half of the variance in sea level is at wavelengths shorter than 1000 km (Wunsch and Stammer, 1995). If the climate signal of interest includes all wavelengths longer than 1000 km, then a float array with 3° spacing would resolve these signals with a signal-to-noise ratio of nearly 3:1. The unresolved variability—fronts, mesoscale eddies, etc.—has short time-scales, typically 10-20 days, compared with the seasonal and longer climate signals. Therefore, temporal averaging can further increase the signal-to-noise ratio. As a function of latitude, the half-power point in the altimetric spectrum varies from 1300-km wavelength in the tropics to 700 km at 50° N (Stammer, 1997). This shortening of the spatial scales with increasing latitude is the reason why Argo requires a higher density of floats at high latitude. A 3° array has twice the density of instruments at 60° latitude as at the equator.
- *Climate signals in WOCE hydrographic data.* A broad mid-depth warming on decadal time scales in the subtropical North Atlantic was seen in WOCE hydrographic transects compared with earlier data (Parilla et al., 1994). Subsampling experiments show that these basin-scale signals can be recovered from profiles at 3° spacing.

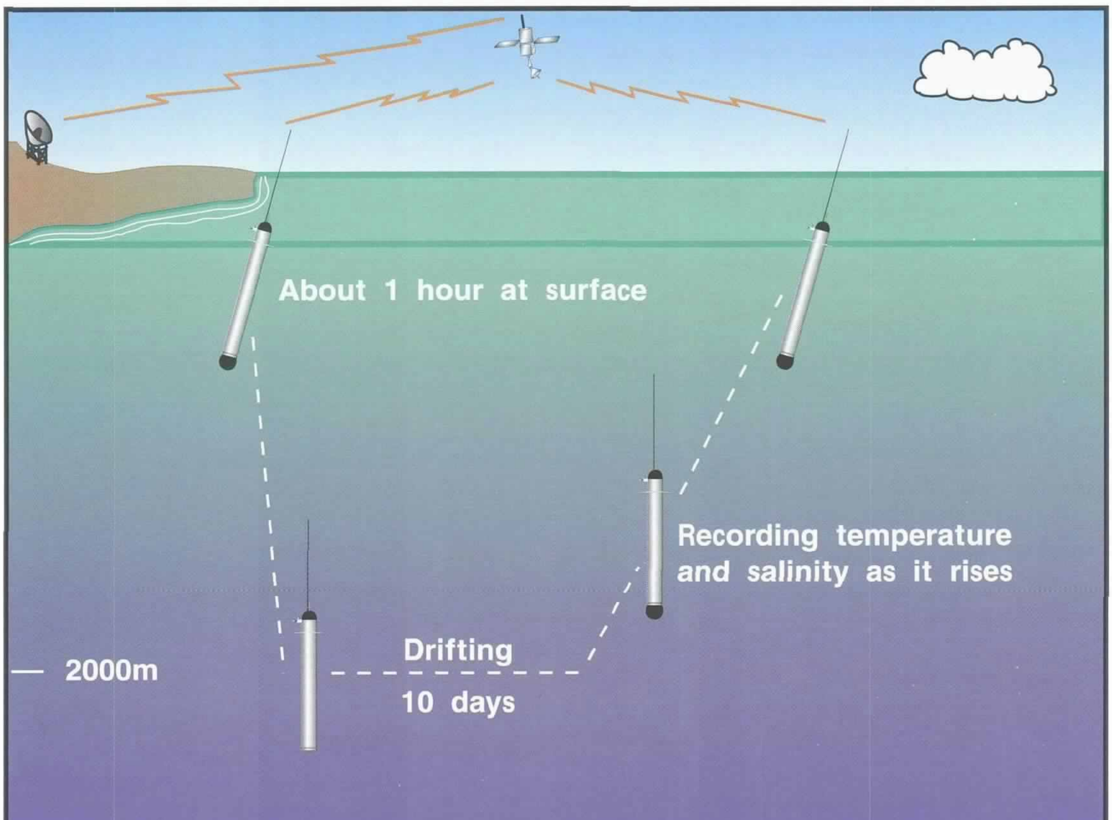

Figure 3. A single cycle in the mission of a profiling float, whose lifetime is about 4 years of 10-day cycles.

- *Requirements for assimilating models.* Initially, the modeling requirements are not distinctly different from the requirements for pure data analysis. The models require comparison fields based on data alone to allow rigorous model testing. Moreover, assimilating models require substantial data to determine the statistics linking point measurements to the smoothed fields of the models.

The U.S. contribution to Argo—a consortium under NOPP

In the U.S., the vision of a global array of autonomous profiling floats is shared by several government agencies having interest in the physical state of the ocean and in the coupled climate problem. Development of the profiling float has been the result of more than a decade of support from the National Science Foundation and the Office of Naval Research. These agencies recognized the instrument's potential in basic research into large-scale ocean circulation, water mass formation, and other climate-relevant processes. NSF's commitment to fundamental climate research continues, for example with the CLIVAR Basin Extended Climate Studies initiatives in the Pacific and Atlantic, in which Argo plays a major role. ONR views Argo as a crucial dataset for initializing global and regional ocean models in real-time. The National Oceanic and Atmospheric Administration became strongly involved in the float program through its mandate to observe and predict seasonal to interannual climate variability. NOAA participation, following a commitment by President Clinton at the National Ocean Conference in June 1998, is bringing a large expansion to the U.S. Argo program. NASA also has a clear interest—in the scientific integration of the float program with ongoing altimetric missions.

As an alternative to separate or loosely coordinated agency participation in Argo, an integrated implementation under NOPP is being pursued. A U.S. Float Consortium was formed including academic and government scientists with expertise in float technology, plus U.S. float manufacturers. The Consortium successfully proposed an Argo Pilot deployment of 50 floats per year beginning in FY99 in the tropical Atlantic and southeastern Pacific Ocean.

NOPP is helping facilitate the planning and implementation of the U.S. component of the global Argo array. It does so by bringing together the diverse, yet complementary, interests of the federal agencies. At the same time, it has enabled Float Consortium investigators at four different academic institutions, two government laboratories, and two private companies to pool their talents in a collaborative manner. The duplications of effort and gaps inherent in previous multi-agency programs are eliminated. With a single focus, U.S. Argo is simpler to integrate internationally with efforts in our partner countries. The NOPP mechanism formalizes the practical reality of Argo—a single project with a broad base of interest and support.

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The implementation of Argo—an international enterprise

The scope of Argo is too great for any nation to undertake individually. An International Argo Science Team (web address: www.argo.ucsd.edu) was formed by CLIVAR and GODAE with instructions to design Argo and coordinate its implementation. Countries with plans to purchase or build profiling floats for Argo include Australia, Canada, China, France, Germany,

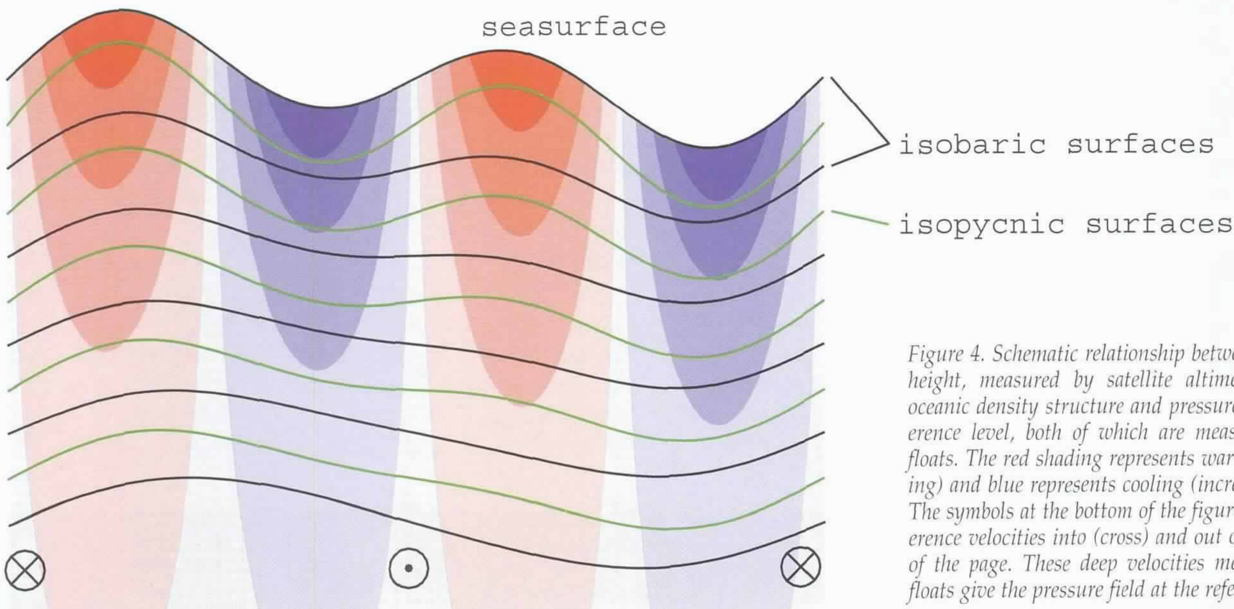

Figure 4. Schematic relationship between sea-surface height, measured by satellite altimeters, and the oceanic density structure and pressure at a deep reference level, both of which are measured by Argo floats. The red shading represents warming (freshening) and blue represents cooling (increased salinity). The symbols at the bottom of the figure represent reference velocities into (cross) and out of (arrow head) of the page. These deep velocities measured by the floats give the pressure field at the reference depth.

India, Japan, the Republic of Korea, the U.K. and the U.S., plus a proposal from the European Union. Additional participation is expected from other float-providing nations or from countries that may provide logistical support for float deployment or assistance in utilizing Argo data. A unique aspect of Argo has been the building of an international consensus that includes not only scientists but operational and agency participants in many countries.

All of the float-providing participants in Argo have agreed that global implementation is essential (Argo Science Team, 1999a). Argo is intrinsically a global array. Obvious priority regions for the float-providing nations include the global tropics, North Atlantic, and North Pacific Oceans. In order to accomplish global coverage, including the subtropical to polar southern latitudes, most participants have agreed to devote a substantial fraction of floats to the other regions. Key elements for achieving global coverage are: (i) Raise the level of national programs until the combined target of 750 floats per year is attained. With a mean lifetime of about 4 years, 750 floats annually are sufficient to sustain the 3000-float global array; (ii) Improve awareness of the importance of Southern Ocean and Indian Ocean sampling.

Coordination of the Argo Data System is another high international priority. Argo Data Centers will provide both a real-time dataset (via GTS) and the higher quality delayed-mode dataset. The Data Centers are developing a common format for the profile data to facilitate tracking and exchange. Up-to-date global Argo datasets will be available through any of the data centers, and data information will be maintained by an international Coordinator located in Toulouse, France. The Coordinator will carry out WMO-IOC instructions relating to Argo (i.e. informing coastal states of Argo floats that may drift through their EEZ), as well as fulfilling roles in merging the national efforts, such as facilitating the deployment of floats in given ocean basins.

Argo pilot deployments, design studies, and technology development programs are underway in several countries. The first Argo floats are being launched. There are strong national efforts to achieve the support required for the global array. International consensus places Argo as an immediate and highest priority contribution to the global observing system for climate. Many challenges remain. However, deployments are expected to attain the target rate of 750 floats per year by 2002. This will provide a sparse global array for the start of GODAE in 2003 and a complete 3000-float array by 2005.

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