Argo
THE CHALLENGE OF CONTINUING 10 YEARS OF PROGRESS

BY DEAN ROEMMICH AND THE ARGO STEERING TEAM

A PROVOR float shortly before recovery by Japan Coast Guard Vessel *Takuyo*. *Courtesy of K. Suehiro, Japan Coast Guard*

ABSTRACT. In only 10 years, the Argo Program has grown from an idea into a functioning global observing system for the subsurface ocean. More than 3000 Argo floats now cover the world ocean. With these instruments operating on 10-day cycles, the array provides 9000 temperature/salinity/depth profiles every month that are quickly available via the Global Telecommunications System and the Internet. Argo is recognized as a major advance for oceanography, and a success for Argo's parent programs, the Global Ocean Data Assimilation Experiment and Climate Variability and Predictability, and for the Global Earth Observation System of Systems. The value of Argo data in ocean data assimilation (ODA) and other applications is being demonstrated, and will grow as the data set is extended in time and as experience in using the data set leads to new applications. The spatial coverage and quality of the Argo data set are improving, with consideration being given to sampling under seasonal ice at higher latitudes, in additional marginal seas, and to greater depths. Argo data products of value in ODA modeling are under development, and Argo data are being tested to confirm their consistency with related satellite and in situ data. Maintenance of the Argo Program for the next decade and longer is needed for a broad range of climate and oceanographic research and for many operational applications in ocean state estimation and prediction.

INTRODUCTION

Data assimilating models of the historical ocean for the period 1950–2000 are limited to using subsurface data sets that were "opportunistic" in nature rather than purposefully designed for regular global coverage, and are consequently deficient in some respects. The historical data were collected mostly for regional objectives and were restricted to the tracks of research vessels and commercial ships. These limitations ensured sparseness and inhomogeneity in spatial and temporal data distribution, even in the relatively well-sampled Northern Hemisphere oceans. Few measurements were collected south of 30°S. In addition to sparseness, the historical data are of uneven quality, with a mixture of instrument types and problems due to systematic errors (e.g., Wijffels et al., 2008).

The Argo Program presents a unique opportunity to correct many of these shortcomings in order to obtain more continuous, consistent, and accurate sampling of the present-day and future states of the ocean. Profiling float technology removes the constraint of needing to have a ship present at the time of measurement, making it possible to obtain high-quality data anywhere at any time. Argo is designed to observe large-scale (seasonal and longer, thousand kilometer and larger) subsurface ocean variability globally (Roemmich et al., 1999). The combination of the array's high-quality temperature and salinity sensors and its comprehensive data management system produces climate-quality data, with new techniques being developed to identify and minimize systematic errors. With the global array providing 9000 temperature/salinity profiles per month (Figure 1), Argo has far surpassed its historical precursors in data coverage and accuracy.

Here, we summarize plans for enhancing Argo's value in the coming years, with attention to ocean data assimilation (ODA) applications. The next section describes plans that include improvements to data coverage and to data quality, followed by a section describing gridded Argo data products, how they differ from historical counterparts, and their effectiveness in resolving large-scale variability for comparison and evaluation of ODA models. The final section addresses the need to examine the consistency of Argo and in situ and satellite-derived surface data sets. Consistency is a key issue for integrating global observations through ODA models.

THE EVOLUTION OF ARGO

New Argo Domains, Sensors, and Sampling Enhancements

Argo is a broad-scale array designed to accumulate about 100 profiles per season in every 10° square of ocean. The array is not eddy-resolving, but eddy noise is reduced by averaging over many profiles in a region to estimate large-scale variability. The design was based on statistics from satellite altimetric height and from earlier subsurface ocean data sets (Roemmich et al., 1999). The prescribed 3° x 3° x 10-day spacing of the array between 60°S and 60°N decreases the distance between instruments with increasing latitude, but not as steeply as the statistics of variability indicate to be appropriate (e.g., Stammer, 1997). The present design is a compromise made for accurate mapping of tropical climate variability (see section below on "The Argo-Era Global Ocean") while taking a more exploratory approach to the high-latitude ocean. Using five years of global Argo data accumulated from 2004–2008, and simultaneous altimetric height data, the Argo design is being revisited. An important question is whether interannual variability at middle and high latitudes is being resolved adequately. Argo should be sustained in order to increase the value of its present five-year global time series, but it can evolve for greater efficiency and effectiveness.

Beyond the design of the Argo array, recent developments in profiling float technology create opportunities for extending Argo's core objectives (Roemmich et al., 2009). Some floats are now active in the seasonally ice-covered zones poleward of 60°. What should be Argo's sampling plan for the high-latitude ocean, and how many additional floats are needed there? Glider technology (Davis et al., 2002) makes systematic sampling of ocean boundary currents a possibility. What are the global requirements for high-resolution sampling in the boundary currents and marginal seas, to complement the broad-scale Argo array? New sensors for biological and geochemical parameters, for wind and rainfall, and for better sampling of temperature and salinity structure in the ocean's surface layer could all increase Argo's value, but also its cost. The addition of oxygen sensors to Argo floats holds high promise for addressing global carbon cycle issues (Riser and Johnson, 2008), and over 100 Argo floats are presently equipped with oxygen sensors. Prototype floats carrying many other new sensors have been deployed. Present float designs are not capable of operating below 2000 m, but such measurements may be required because decadal climate signals are known to extend into the deepest layers. Deep sampling will require developmental work on both floats and sensors. Careful planning is needed to determine effective strategies for deployment of any extensions to the Argo array.

Improving Argo Implementation

Evolving the Argo Program not only means reviewing its design and objectives, but also improving its implementation with respect to the original

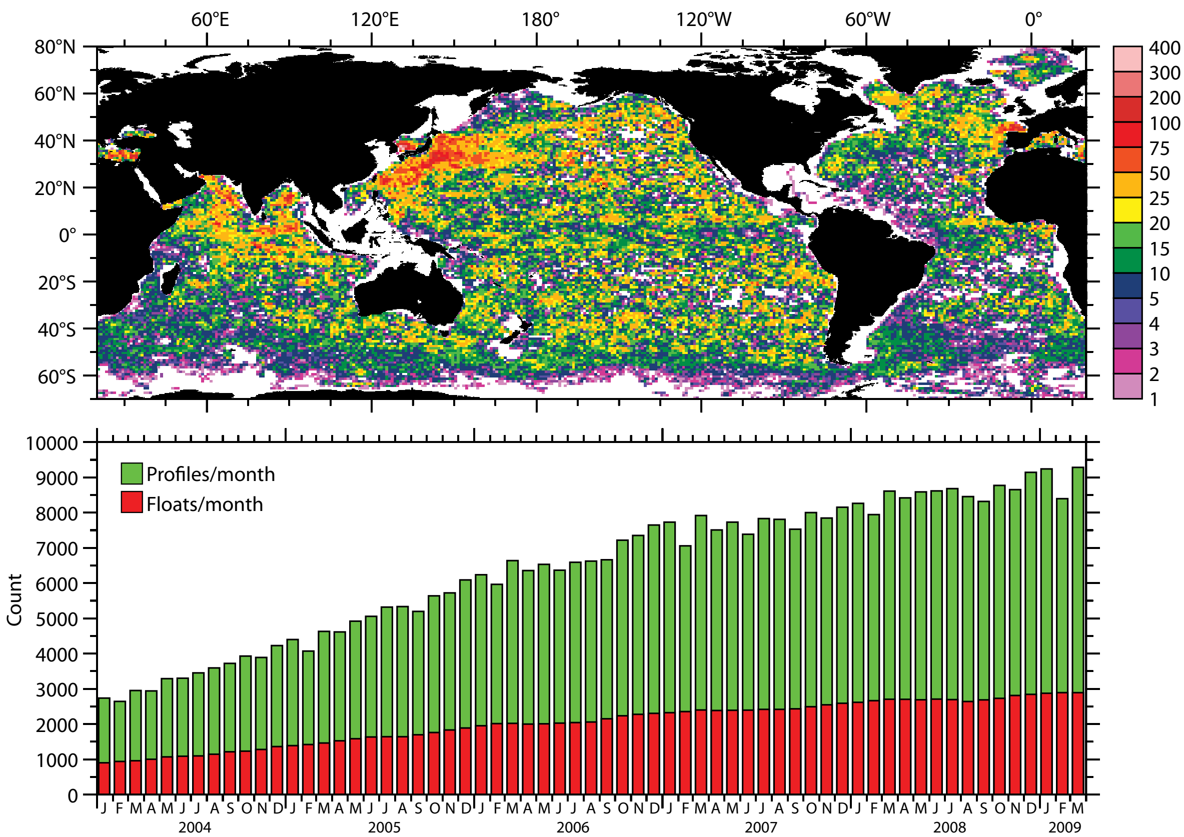

Figure 1. (Top) Map of the number of good Argo profiles obtained in each 1° x 1° box during the period January 2004 to March 2009. (Bottom) Number of floats per month (red) providing good data and number of good profiles per month (green).

objectives. Although more than half of active Argo floats are presently south of the equator, the Southern Hemisphere is under-sampled relative to the original program design (Figure 2). Indeed, over the Southern Hemisphere, the present Argo array is more than 500 floats short of its designed number. This shortfall in the number of floats, in spite of Argo having achieved 3000 active instruments, is due to a combination of factors. Many floats are deployed in marginal seas or poleward of 60°, and although these are of value, they were not considered in Argo's original design. Other instruments are not producing good profile data due to technical failures, which is being corrected through deployment of improved instruments. The coverage shortfall requires increased attention to Southern Hemisphere deployments by Argo national programs. Occasional ship visits to the remote regions of the ocean are essential for maintaining Argo. Although Argo is producing more profile data south of 30°S during a single austral winter than were produced in the entire pre-Argo history of oceanography (Figure 3), the program is not yet achieving its ambitious sampling objective there (Figure 2).

Another key objective in Argo implementation is to minimize systematic errors in the data stream (see also Le Traon et al., 2009). Two such systematic errors in Argo data have been identified and to a large extent corrected. First, over a period of years, slow drift in conductivity measurements occurs in some floats, due to biofouling or other causes. This drift can be corrected through careful statistical comparison of sequences of float salinity values to nearby high-quality profiles (Wong et al., 2003), which might consist of either shipboard conductivity-temperature-depth (CTD) data or nearby float data. Second, pressure offsets have been identified in some floats (e.g., Willis et al., 2007; Uchida and Imawaki, 2008),

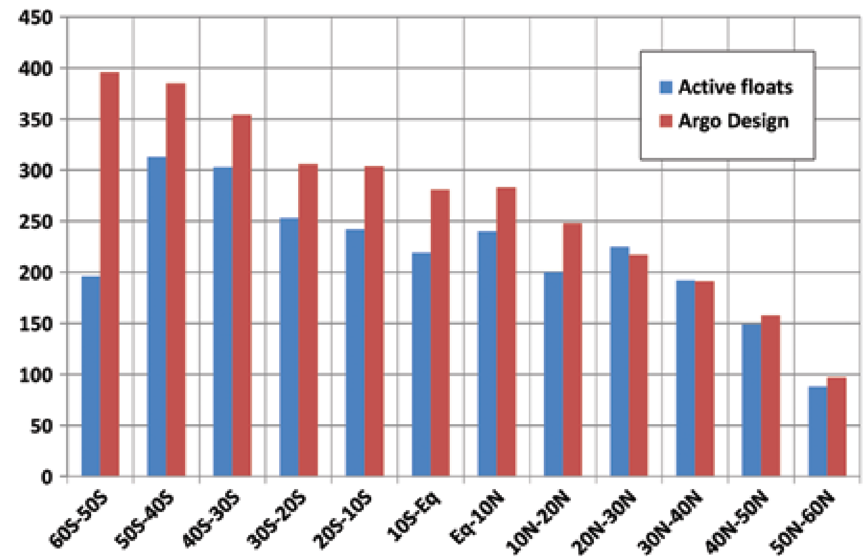

Figure 2. Blue bars show the number of Argo floats per 10° of latitude providing good profile data as of March 2009, excluding those in marginal seas. Red bars show Argo's design requirement for 3° x 3° open ocean sampling.

Dean Roemmich *(droemmich@ucsd.edu) is Professor, Scripps Institution of Oceanography, University of California, San Diego (UCSD), La Jolla, CA, USA. Members of the Argo Steering Team are (alphabetically):* **Mathieu Belbéoch** *(Argo Information Centre, France),* **Howard Freeland** *(Fisheries and Oceans, Canada),* **Sylvia L. Garzoli** *(National Oceanic and Atmospheric Administration, Atlantic Oceanographic and Meteorological Laboratory, USA),* **W. John Gould** *(National Oceanography Centre, Southampton [NOCS], UK),* **Fiona Grant** *(Irish Marine Institute, Ireland),* **Mark Ignaszewski** *(Fleet Numerical Meteorology and Oceanography Center, USA),* **Brian King** *(NOCS, UK),* **Birgit Klein** *(Bundesamt für Seeschifffahrt und Hydrographie, Germany),* **Pierre-Yves Le Traon** *(Institut français de recherche pour l'exploitation de la mer [Ifremer], France),* **Kjell Arne Mork** *(Institute of Marine Research, Norway),* **W. Brechner Owens** *(Woods Hole Oceanographic Institution, USA),* **Sylvie Pouliquen** *(Ifremer, France),* **Muthalagu Ravichandran** *(Indian National Centre for Ocean Information Services, India),* **Stephen Riser** *(University of Washington, USA),* **Andreas Sterl** *(Royal Netherlands Meteorological Institute, Netherlands),* **Toshio Suga** *(Japan Agency for Marine-Earth Science and Technology, Japan),* **Moon-Sik Suk** *(Korea Ocean Research & Development Institute, Korea),* **Philip Sutton** *(National Institute of Water & Atmospheric Research, New Zealand),* **Virginie Thierry** *(Ifremer, France),* **Pedro J. Vélez-Belchí** *(Instituto Español de Oceanografía, Spain),* **Susan Wijffels** *(Commonwealth Scientific and Industrial Research Organisation, Marine and Atmospheric Research, Australia), and* **Jianping Xu** *(Second Institute of Oceanography/ State Oceanic Administration, China).*

resulting from pressure sensor drift and from errors in float software. Such systematic errors, some of which were not anticipated, highlight the need for rapid identification and prompt correction of hardware errors or software flaws. A promising technique for detecting systematic errors is comparison of satellite altimetric height with Argo steric height from sequences of profiles and flagging large differences for more careful examination (Guinehut et al., 2009). Another technique is the use of climatological data for flagging statistical outlier profiles and instruments, a capability that is being improved (Gaillard et al., 2009) as Argo-era data supplement earlier data sets with more appropriate mean and variability statistics.

Because few Argo floats can be recovered for sensor recalibration, the final quality of Argo data will depend on the existence and availability of high-quality shipboard CTD data. Shipboard CTD transects are useful not only to detect systematic errors in Argo float data but also in joint analyses with Argo data for better description of interannual to multidecadal signals in the ocean. For example, recent work of Argo Steering Team member Pedro Vélez-Belchí and colleagues compares Argo data in the North Atlantic with nearby CTD data collected by the UK's 2001–2007 Rapid Climate Change program, showing similar multidecadal changes in these data sets relative to earlier transects along 24.5°N.

The Argo array is not yet "complete" with respect to its original design and objectives. The highest priority for Argo's international partnership is to implement further improvements in data coverage and quality to meet these requirements. At the same time as the Argo Program is being improved and maintained for its original goals, extensions to the array should be introduced carefully to increase Argo's long-term value.

THE ARGO-ERA GLOBAL OCEAN

Argo and Historical Data Sets

A key step in demonstrating the value of Argo is to show how well it represents the present-day ocean, including mean, annual-cycle, and large-scale variability. In modeling applications, data climatologies are used as initial states for predictive models, or as mean states with known variance, to limit unrealistic model variability and trends. Climatologies based on Argo data are more realistic representations of the modern ocean than historical data climatologies for several reasons. First, the ocean has changed substantially in the past several decades, becoming warmer overall (e.g., Domingues et al., 2008; Levitus et al., 2005, 2009), and exhibiting significant regional changes in temperature/salinity characteristics (Wong et al., 1999; Curry et al., 2003; Boyer et al., 2005). Second, the Argo-era ocean is better sampled than the historical ocean, especially in the Southern Hemisphere (Figure 3), leading to lower estimation errors. For the first time, it is possible to construct mean temperature and salinity fields for the ocean over a specific time period. Historical data climatologies are created by blending regional data collections from different eras and, as a consequence, the end

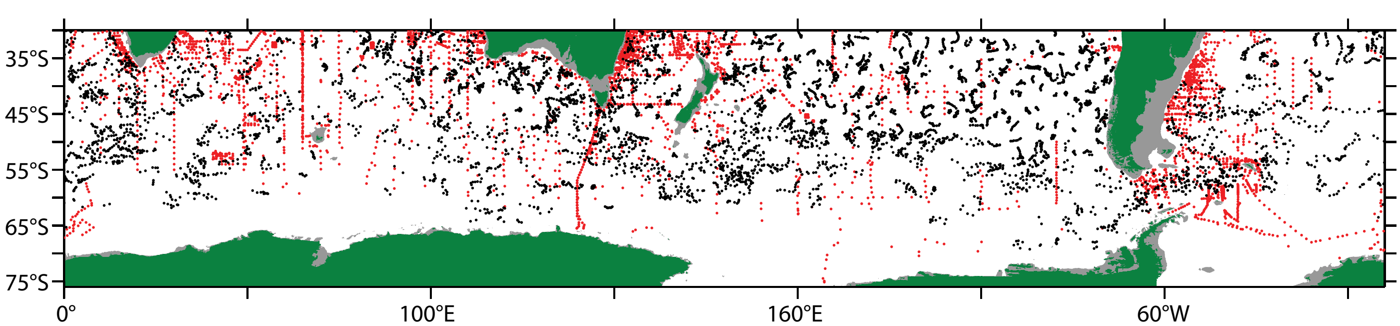

Figure 3. Location of all 4,093 temperature/salinity stations to depths of at least 1000 m during austral winter (July/August/September), south of 30°S from 1950–2000 (red dots; source: World Ocean Database), compared to 6,291 Argo station locations (black dots) from July/August/September 2008.

products are weighted toward different years in different regions. The sparseness of historical data and their spatial and temporal inhomogeneity make it difficult to assign error bounds to these climatologies (e.g., Roemmich and Sutton, 1998). Finally, care taken to minimize systematic errors in the Argo data set leads to Argo-only climatologies that are not contaminated by mixing of different instrument types.

Figure 4 shows an example of the differences between Argo (Roemmich and Gilson, 2009) and the *World Ocean Atlas 2001* (WOA01) historical data climatology (Conkright et al., 2002). The figure shows mean steric height from Argo, 0/2000 dbar, averaged over the period 2004–2008, during which the Argo array had global coverage. The difference between this Argo-era mean and WOA01, which is based on data collected over more than 50 years, is especially notable south of 30°S. There, the zonal mean difference is 5 dyn cm between 40° and 50°S, and differences are 10 dyn cm or more in some areas. Main causes of the Argo-minus-WOA01 differences are decadal change and mapping errors due to sparseness in the historical data set. For modeling the present-day ocean, Argo climatologies will replace the historical data products to provide initialization and background states that are consistent with the era that is represented.

Effectiveness of Argo Sampling

The effectiveness of Argo in resolving large-scale ocean variability can be tested in a variety of ways (Roemmich and Gilson, 2009), including statistical measures that complement model-based Observing System Evaluation activities (Oke et al., 2009). One estimate uses satellite altimetric height as a proxy for steric height. On large spatial scales, steric height and total sea surface height are very similar. By subsampling altimetric height fields at the locations of Argo profiles, interpolating the subsampled data, and then comparing to the full altimetric height data set, both the large-scale signal and noise of Argo steric height fields can be estimated. Sampling experiments have been carried out to test the impact of Argo's increasing coverage between 2004 and 2007, and to test its ability to resolve signals of varying spatial and temporal scales.

One such experiment is illustrated in Figure 5. Here, the goal is to estimate Argo's ability to detect large-scale variability over 15 years of sustained sampling by assuming that Argo's spatial coverage in the year 2007 is maintained. The 15-year gridded altimetric height record (Ducet et al., 2000) from 1993–2007 is subsampled each year at the location and year-day of the 2007 Argo data set. The subsampled anomalies from the 15-year mean and annual cycle are objectively interpolated, and then both full and subsampled anomaly grids are smoothed with a 10° x 10° x 3-month running mean. After smoothing, the temporal RMS signal is estimated from the full data set, and the RMS noise is estimated from the full-minus-subsampled differences. Figure 5 shows the zonal means of the RMS signal and the RMS noise. As expected, the signal-to-noise ratio is highest in the tropics due to enhanced signal and

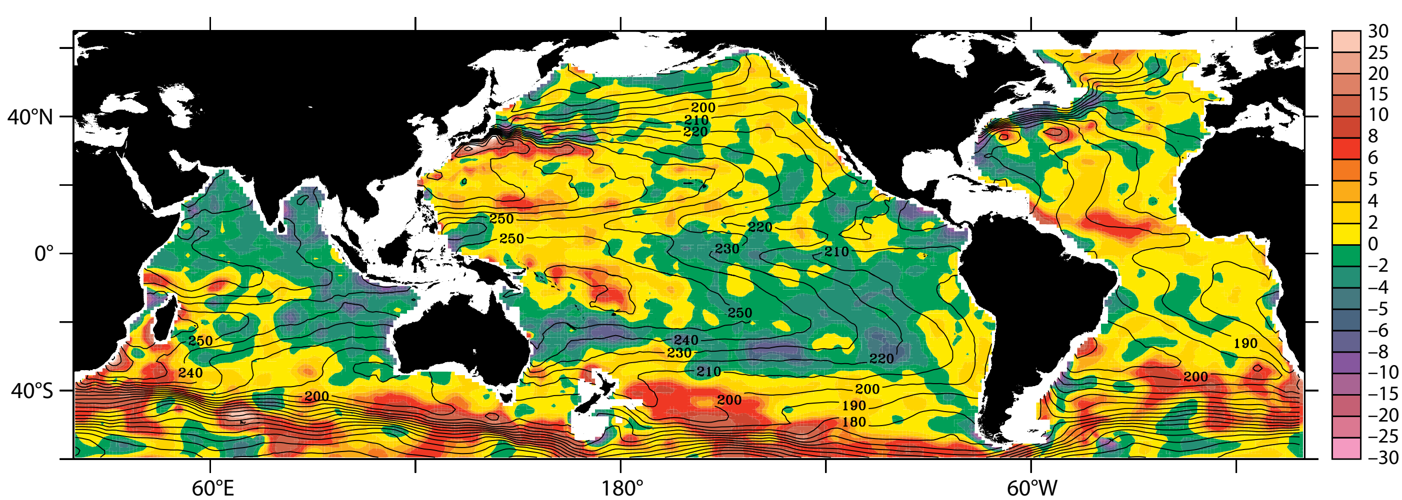

Figure 4. Contours indicate the steric height of the sea surface from Argo data, 0/2000 dbar (dyn cm), 2004–2008 mean. Color shading indicates the difference in steric height, Argo-minus-WOA01 (*World Ocean Atlas 2001*).

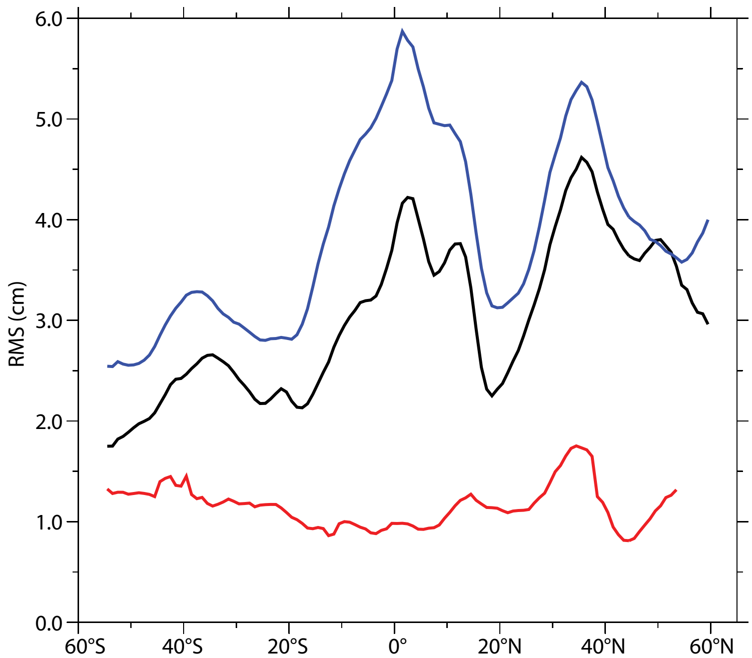

Figure 5. Zonally averaged large-scale (10° x 10° x 3-month) nonseasonal sea surface height signal (blue) and Argo sampling noise (red) for 15 years of sustained Argo sampling at the 2007 level, estimated from satellite altimetry (see text). The black line shows how the apparent signal is reduced in a shorter (four-year) record. *Results adapted from Roemmich and Gilson (2009)*

reduced noise. Figure 5 also illustrates how large-scale variability grows with the duration of the data set as a longer-term mean is estimated and removed and decadal variability starts to be observed. This method is one of several being used to assess Argo's errors and its effectiveness (Roemmich and Gilson, 2009), including mapping and comparison of Argo subsets, comparison to other observing system elements, and formal optimal interpolation error estimates.

In addition to the interpolated Argo-only data set (Roemmich and Gilson, 2009) used in Figure 4 for purposes of illustration, groups around the world are developing similar products. To promote their dissemination and usefulness, the Argo Steering Team is identifying global Argo analyses that are available for distribution (http://www.argo.ucsd.edu/AcGridded_data.html). There is much to be gained from comparing techniques and results of different analyses as well as from developing products for different applications. It is essential to provide ODA applications not only with accurate data sets and best estimates of the error. While ODA models continue to develop, it is also critical to provide individual data sets that are extensive enough for statistical interpolation, to compare with multi-data-set model results and with data-withholding model experiments.

ARGO AND OCEAN SURFACE DATA SETS

Argo is the dominant subsurface data set for the present-day ocean, but ODA models assimilate sea surface data sets as well, including sea surface height, sea surface temperature, and air-sea fluxes of heat, water, and momentum. It is important to examine the consistency of these data sets with Argo and with one another where they have complementary or overlapping information content. The ODA models allow for random data errors, but problems may arise when systematic errors create inconsistencies between data types.

Sea Surface Temperature

Sea surface temperature (SST) is estimated from satellite measurements, using sparse ocean surface drifters (at ~ 1-m depth) and other in situ SST measurements for bias correction (e.g., Reynolds et al., 2002). Argo profiles, which collect their shallowest data at around 5 m, are not used in most SST products at present. Questions include the magnitude of stratification between the depth of drifter SST measurements and the shallowest Argo data and whether Argo floats, which are more plentiful than surface drifters, are useful for SST estimation. Similarly, Argo's potential usefulness in combination with a scheduled sea surface salinity satellite mission is of interest. To investigate the issue, the surface drifter and Argo data sets were searched to identify nearby pairs of measurements. There were 21,100 Argo profile/drifter data pairs located within 60-km "scaled-distance" of one another during the period 2004–2008. Here, "scaled-distance" includes a time difference term, with 1 day equivalent to 10 km. Figure 6 shows the means and standard deviations of Argo-minus-drifter temperature as a function of distance, sorted into 5-km bins. The number of nearby pairs increases from 214 in the 0–5 km bin to 2,987 pairs in the 55–60 km bin. The mean differences are small, 0.02°C and less, and not statistically significant. Significant stratification was found between the 1-m and 5-m measurements only in a small subset of low-wind daytime conditions, so Argo data are a good approximation of bulk SST at most times. The comparison (Figure 6) suggests that Argo data may be valuable for SST estimation on a global basis.

Sea Surface Height

The relationship of satellite-derived sea surface height (SSH) and steric height variability is central to Argo. A global study of SSH and steric height variations during 1993–2003 (Guinehut et al., 2006) revealed high correlation between the two with some systematic differences due to barotropic ocean forcing. The consistency of global SSH variability in 2003–2007 with the component changes in Argo steric height and ocean mass (from the Gravity Recovery And Climate Experiment [GRACE] satellite mission) has been examined by Willis et al. (2008), Cazenave et al. (2009), and Leuliette and Miller (2009). Although the annual cycle in globally averaged SSH was consistent with the sum of steric and mass-related components, differing conclusions were reached regarding the four-year increase in SSH (by about 12 mm) in relation to its components. A longer time series is needed to be more definitive. These and other examples illustrate the strong need to close the ocean's mass and heat budgets with careful measurements of all components over an extended period of time.

As an example of the close relationship between SSH and steric height, Figure 7 shows the zonally averaged annual cycle of both quantities, using Archiving, Validation, and Interpretation of Satellite Oceanographic data (Aviso) SSH (Ducet et al., 2000) and steric height from Roemmich and Gilson (2009). In spite of the high similarity in the annual variations of SSH and steric height, there are also significant differences between them, for example, in the amplitudes at about 10°N and 35°S. A good test for ODA models is to see whether they reproduce the annual cycles in data sets with overlapping information content and can successfully rationalize differences such as those seen in Figure 7.

Air-Sea Fluxes

Air-sea exchanges of heat and freshwater on seasonal time scales are nearly balanced by oceanic storage (Gill and Niiler, 1973), with seasonal advection being a small residual term in ocean interiors. Roemmich and Gilson (2009) found good agreement seasonally, on hemispheric and global scales, between the Southampton Oceanography Centre/National Oceanography Centre historical data climatology of air-sea fluxes (Josey et al., 1998) and Argo-derived ocean heat storage. Regionally, maximum seasonal amplitudes in heat storage at 40°N and 35°S exceeded the amplitudes of air-sea flux by about 25 W m^{-2}, possibly due to seasonal displacement of the zonal oceanic boundary current fronts at those latitudes. Comparison of air-sea fluxes of freshwater with oceanic freshwater storage is more problematic. Patterns of freshwater storage are spatially more complex than heat storage, and estimates of evaporation and precipitation are subject to large errors. A challenge for ODA models is to exploit Argo's

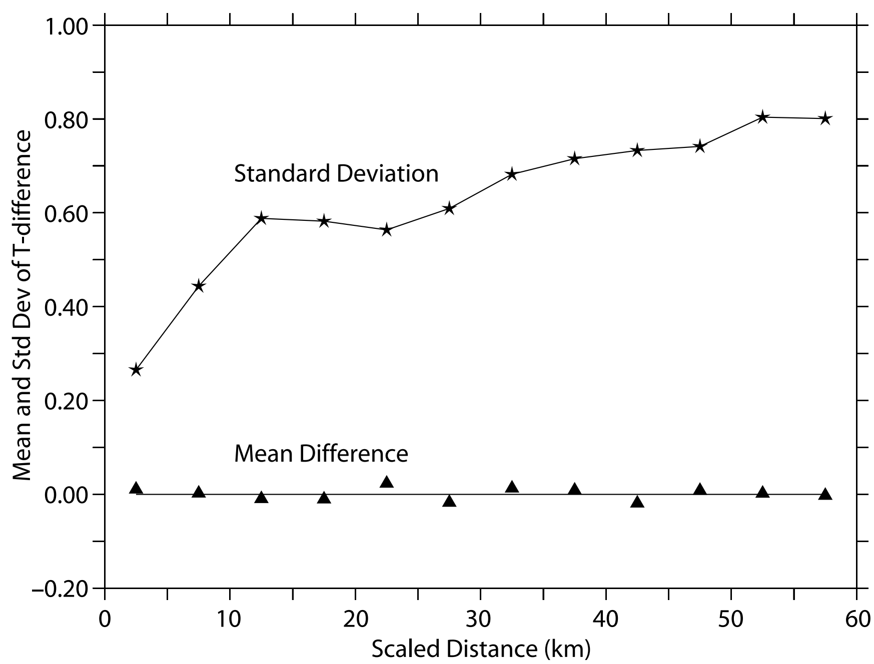

Figure 6. Argo-minus-surface-drifter mean and standard deviation of temperature difference (°C) as a function of "scaled distance" (see text), in 5-km bins, for 21,100 nearby pairs of observations.

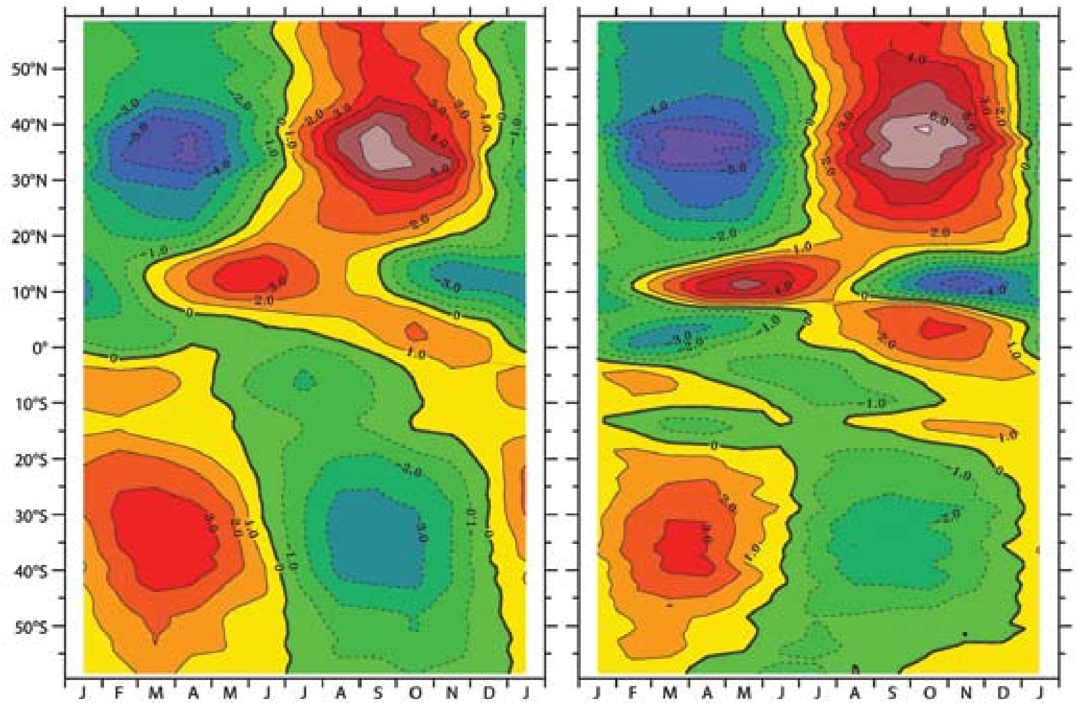

Figure 7. The annual cycle of zonally averaged steric height (0/2000 dbar) from Argo data (left panel), 2004–2007, is compared to that from altimetric height (right panel, Aviso product) from the same period.

global measurements of salinity for improved estimation of variability in the hydrological cycle.

DISCUSSION

A key goal of the Argo Program is to provide a global data set of value for assimilation by ODA models that is also extensive enough to enable evaluation of the results of those models. The Argo array now includes about 3000 instruments providing 9000 globally distributed temperature and salinity profiles monthly from the sea surface to mid-ocean depth. Five years of Argo data, including 400,000 profiles, have been collected since sparse global coverage was achieved in early 2004, comprising stable estimates of the mean and annual cycle for this period. All data are freely available, with about 90% of profiles accessible at two Global Data Assembly Centers within 24 hours of float surfacing. Argo's ground-breaking open access data policy is central to the value of the program and to building its international partnership. The Argo data set has been used to tackle a wide variety of basic research problems, and data quality exceeds original expectations. The Argo Program has made rapid progress in the decade since its planning began. Further increases in float numbers and improved coverage in the Southern Hemisphere, better ability to identify and correct systematic errors, and greater uniformity in production and release of delayed-mode data are all required to achieve the core objectives of the program. The broad Argo user community is needed to demonstrate the high value of the array, and the international Argo partnership must prove its ability to maintain the array for a decade and beyond. A caution is that the provision of highest-quality Argo data is a continuing process, and users should ensure the data set is appropriate for their applications.

As the Argo era of quasi-uniform, high-quality global sampling lengthens, it is important to review and improve Argo's design and objectives. Low-latitude interannual variability is well resolved in the present data set, while additional floats are needed at southern latitudes. Continuing advances in profiling float, ocean glider, and sensor capabilities raise new challenges for expansion of Argo's activities. Deeper profiling and sampling of seasonal ice zones, marginal seas, and boundary currents could all extend Argo's limits. Inclusion of new sensors could add important geochemical and biological dimensions. Operational control of the Argo array using two-way communication systems to change profile depth, cycle rate, and other mission parameters could increase Argo's value in many applications (Gary Brassington, Australian Bureau of Meteorology Research Centre, *pers. comm.*, 2009). In each case, for new objectives, energy and other added costs need to be weighed against the benefits, and new resources are needed to cover any new costs. An important challenge for Argo is to expand its constituency by demonstrating the value of the data set in a growing number of applications while maintaining the high data quality and spatial coverage needed for Argo's core objectives.

ACKNOWLEDGEMENTS

The Argo data used here were collected and are made freely available by the International Argo Program and by the national programs that contribute to it. The efforts of many international partners in planning and implementing the Argo array are gratefully acknowledged. Preparation of this manuscript was supported by US Argo and US GODAE through NOAA Grant NA17RJ1231 (SIO–JIMO). Graphics were produced using Ferret software, a product of NOAA's Pacific Marine Environmental Laboratory. The Aviso altimeter products were produced by the CLS Space Oceanography Division as part of the Environment and Climate EU ENACT project (EVK2-CT2001-00117) and with support from the Centre Nationales d'Études Spatiale (CNES). Argo/drifter comparisons (Figure 6) were provided by M. Scanderberg.

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