Mid-depth Circulation of the World Ocean:
A First Look at the Argo Array

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As of February 2006, the Argo array of profiling floats has reached just over 80% of its target density of 3000 profiling floats in the global oceans. The floats now provide temperature and salinity profiles with nearly global coverage. In addition, as they drift at depth the floats provide information about the mid-depth circulation of the World Ocean. In the present study, we consider the sub-surface velocity information that is now being produced by the Argo floats. We find that float displacement data from the Argo array is now sufficient to produce global estimates of the general ocean circulation at 1000 m depth. Furthermore, we find that velocity information contained in the Argo float displacements is complementary to sea surface height measurements made by satellite altimeters and that in many regions altimeter data may be used to improve estimates of time averaged, mid-depth velocity by reducing the eddy-variability that is inherent and ubiquitous in the Argo displacement data.

Figure 1 shows a diagram of all available Argo float displacements as of March 10, 2006. About 166,000 displacements are shown representing 4300 float years of data. Each arrow represents a measurement of subsurface float displacement measured over a single float cycle. Argo float cycles begin at the ocean surface, where the float changes its buoyancy and sinks to its target depth, usually 1000 m. The float then drifts with the current, usually for a period of 10 days, before again changing its buoyancy and surfacing. While at the surface, the float send back via satellite data collected along the way, such as temperature, salinity and its position at the surface. The float's positions at the beginning and end of its subsurface drift are estimated from the trajectory of its drift at the surface using the techniques described by *Davis et al.* (1992). Conservative estimates of the uncertainty in time-averaged subsurface velocity measured during a single float cycle are found to be on the order of 1 cm/s.

The vast majority of floats in the Argo array drift at a depth of 1000 m, however, a significant number drift at depths of 1500 and 500 m. For the present study, the analysis depth of 1000 m was chosen for estimating subsurface velocity. Displacements from floats drifting at other depths had a correction applied based on geostrophic shear computed from the temperature and salinity fields of the 2001 World Ocean Atlas (WOA01) climatology (*Conkright et al.*, 2001) as described in *Lavender et al.* (2005). In this way, displacements from nearly all floats could be combined into a single estimate of the general circulation of the World Ocean.

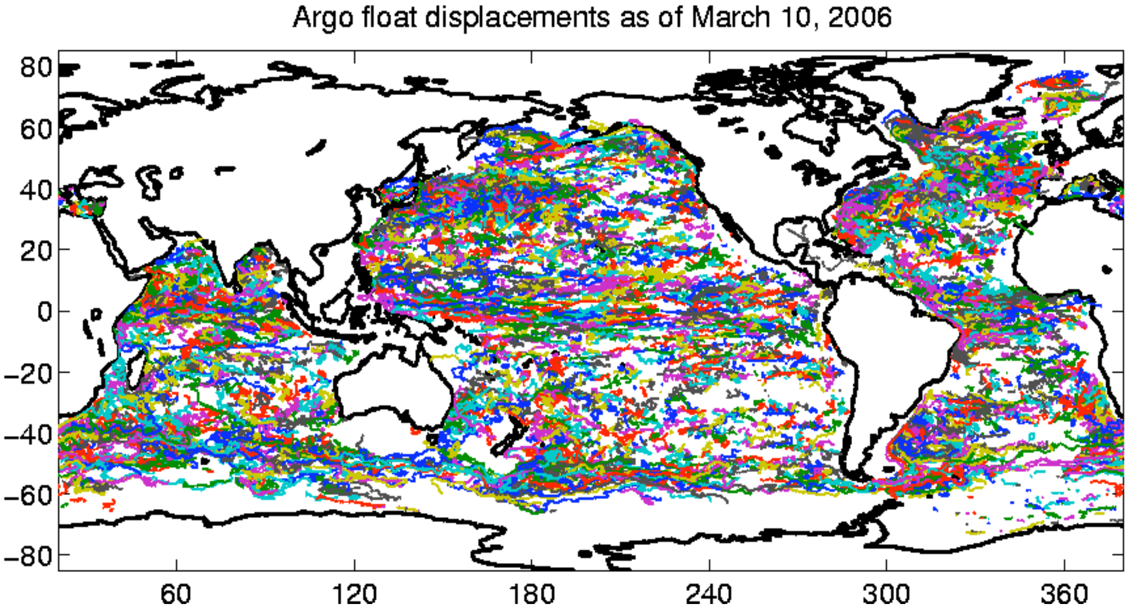

Figure 1. Argo float displacements as of March 10, 2006. Each displacement is represented as a single arrow and all displacements for a given float have the same color.

In addition to estimating the general circulation at 1000 m, we explored the complementarity between the float displacements and measurements of sea surface height anomaly (SSHA) from satellite altimeters. The altimeter data used for this purpose was the gridded sea-surface height field from the merged TOPEX/Poseidon, ERS 1 and 2 product produced by AVISO (*Ducet et al.*, 2000). The "delayed-mode" product was used where available and the "real-time" product was used otherwise. A spatially varying temporal mean was removed from the altimeter data for the period from the beginning of 2000 through the end of 2005. This corresponds to the period over which the Argo data were averaged in order to produce a time-averaged estimate of the general circulation at 1000 m.

Altimeters measure the height of the sea surface and to the extent that oceanic circulation is geostrophic, the spatial derivatives of sea surface height provide estimates of velocity at the surface. At present, however, altimeters only provide highly accurate information about the time variability of the sea surface height field, and hence the surface geostrophic velocity field. Nevertheless, as observed by *Roemmich and Gilson* (2001) in the North Pacific, the time-varying mesoscale field contains features that are highly coherent in the vertical. This suggests that we may be able to project time-varying surface velocities estimated using altimeter data down to the depths of the float displacements.

To determine if such a relationship exists between surface and mid-depth geostrophic velocity variability, we first considered a small region in the North Pacific between 15° to 25°N and 165°E to 175°W. Figure 2 shows a scatter plot of the zonal component of float displacements for all available float data in this region. Plotted against the observed float displacements are 'pseudo-displacements' computed by simply advecting an imaginary float, beginning at the same time and location as each observed float, through the anomalous geostrophic velocity field implied by SSHA from the altimeter data.

Figure 2 shows a clear relationship between geostrophic velocity at the surface and at 1000 m depth. The correlation coefficient between these two is 0.44 and is highly significant. It is important to note, however, that the slope of any best-fit line through these data would be much less than one. It is clear that the amplitude of the mid-depth float displacements is much smaller than the pseudo-displacements predicted from the anomalous velocity at the surface. This is in agreement with the results of *Roemmich and Gilson* (2001) who showed that the geostrophic velocity associated with mesoscale eddies was vertically coherent, but decreased rapidly with depth.

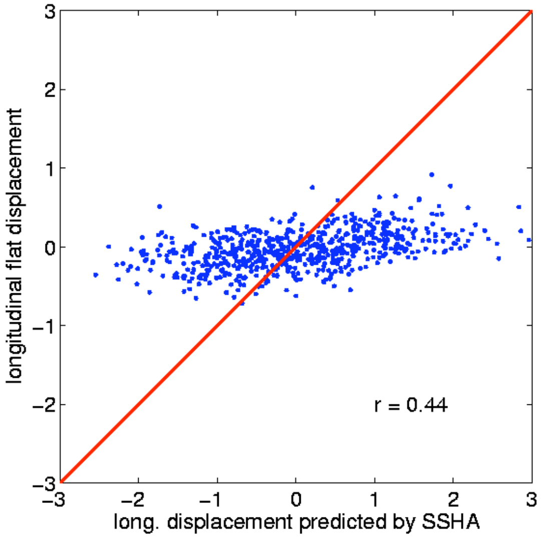

Figure 2. Observed longitudinal float displacements from the region 15° - 25°N, 165°E - 175°W vs. those predicted from advection by anomalous surface geostrophic velocity calculated using altimeter data.

By binning the displacement data into 10° x 10° regions, it was possible to compute a unique multiplier, α, for each region that would minimize the difference between the observed displacements and the pseudo-displacements computed using the surface geostrophic field determined by (α * SSHA). The value of α ranges from about 0.5 at high latitudes in the Southern Hemisphere to near zero close to the equator. At high latitudes in the Northern Hemisphere, the value again approaches 0.3. This strong latitudinal dependence of α likely reflects the mean stratification, which is shallow and sharp at low latitudes, but weaker high latitudes. The weaker stratification at high latitudes allows anomalous signals expressed in sea surface height to more effectively penetrate to the 1000 m drift depth of the floats.

Using α, pseudo-displacements can be computed from the SSHA data that correspond to each observed float displacement. Since the altimeter data has had a temporal mean removed, the pseudo-displacements represent an altimeter-based estimate of the temporally varying geostrophic velocity at depth. It is therefore possible to remove some of the temporal variability in the subsurface float data by subtracting the pseudo-displacements. By removing some of the eddy-variability, it will be possible to produce subsurface estimates of the time mean circulation with greater accuracy and less noise. This is illustrated in Figure 3, which shows the effect of the pseudo-displacements on a single float trajectory in the Southern Ocean. In the Figure, the green contours show 1000/2000 m dynamic height computed from WOA01. This represents an *a priori* estimate of the time-averaged circulation. In this figure, the tightly spaced contours represent the Antarctic Circumpolar Current, which advects the float westward. The blue vectors represent the observed float displacements. Note the large meanders as the float is advected by the powerful mesoscale eddy field. The red vectors show the float displacements after they have been 'corrected' by subtracting the pseudo-displacements from them. Note that after removing some of the time variability using the altimeter data, the red vectors align more closely with the contours that represent the mean flow.

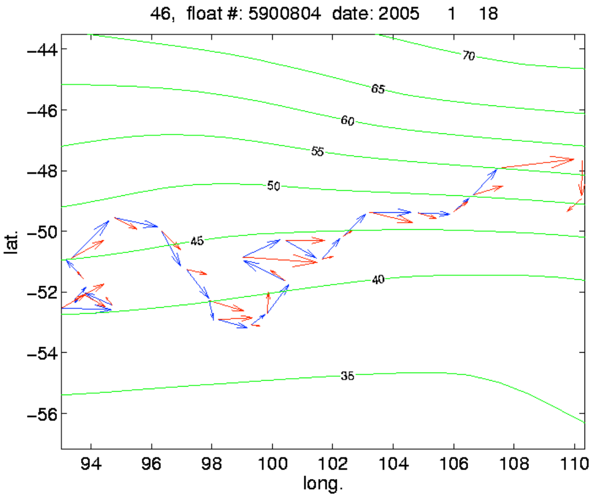

Figure 3. Float displacements from a float in the ACC. The blue vectors represent raw float displacements and the red vectors have been 'corrected' using (α * SSHA). The green contours are 1000/2000m dymanic height from WOA01.

Although not all regions show as clear an improvements as the one illustrated in Figure 3, this example, where both currents and eddies are strong serves to illustrate the utility of this technique and underscores the complementarity of the two datasets. Many regions do show a significant reduction in variance after the altimeter correction has been applied. In general, the variance of the float displacement data can be reduced by a factor of 1.5 to 2 at latitudes higher than 10 to 15 degrees. At lower latitudes, the stratification is sharper and shallower and the connection between the altimeter data and subsurface floats is weaker.

In addition to demonstrating the connection between the altimeter and float displacement data, we have also computed preliminary estimates of the mid-depth circulation based on the altimeter-corrected float displacement data. The technique used to estimate the circulation was that developed by *Davis* (1998). Float displacement data were first bin averaged on a 1° x 1° grid. For each grid box, the time-averaged velocity was calculated from all of the float displacements that fell into that grid. The averages were then re-centered to the geographically weighted mean over the data within each box. These bin-averaged velocities were then used as input data for an objective map of the time-averaged circulation at 1000 m. Objective maps of dynamic height, as well as the meridional and zonal components of velocity were computed using the technique discussed by *Davis* (1998). A covariance function was used that contained a term to model topographic steering by including a dependence on barotropic potential vorticity. The form of the covariance function, however, was that suggested by *Rio and Hernandez* (2004) with a meridional length scale of 300 km, a zonal length scale of 500 km and a signal-to-noise ratio of one. Finally, to avoid excessive computational expense, objective maps were computed in 5° latitude by 7.5° longitude tiles using data from a 30° latitude by 40° longitude region that encompassed the mapping area. The inclusion of such a large region helped to ensure agreement between maps computed in adjacent tiles. Finally, the maps were made using the 1000/2000 m dynamic height from the WOA01 climatology fields as an initial guess.

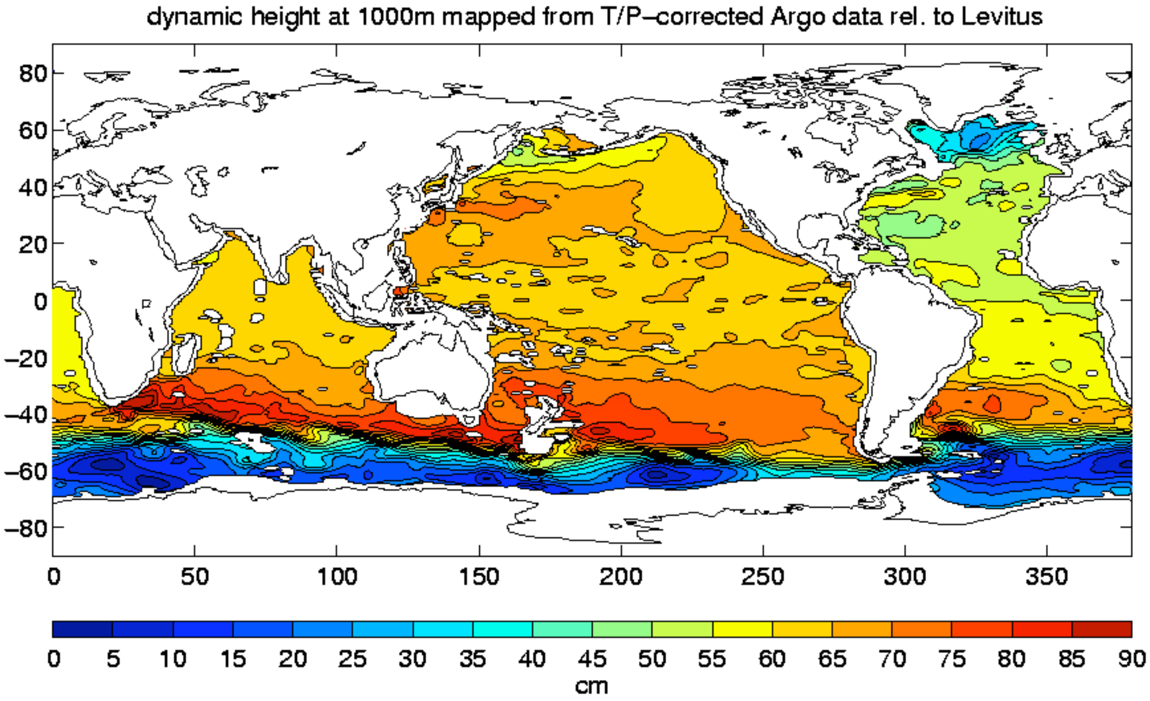

Figure 4. Dynamic height at 1000 m depth in cm objectively mapped from altimeter-corrected Argo float displacement data.

Figure 4 shows the objectively mapped dynamic height at 1000 m computed using the altimeter-corrected float displacements. The most striking feature is of course the tightly spaced contours that traverse the entire globe in the Southern Ocean. These represent the Atlantic Circumpolar Current (ACC). In addition, however, expressions of the deep subtropical gyres are visible in all major ocean basins.

Figure 5 shows the corresponding geostrophic velocities as a vector plot. Red arrows denote velocities greater than 10 cm/s. Note that the majority of the large-scale, time-averaged circulation at this depth exhibits speeds of 5 cm/s or less. Only in the ACC and a few basins where the western boundary currents extend to this depth do the velocities exceed 10 cm/s.

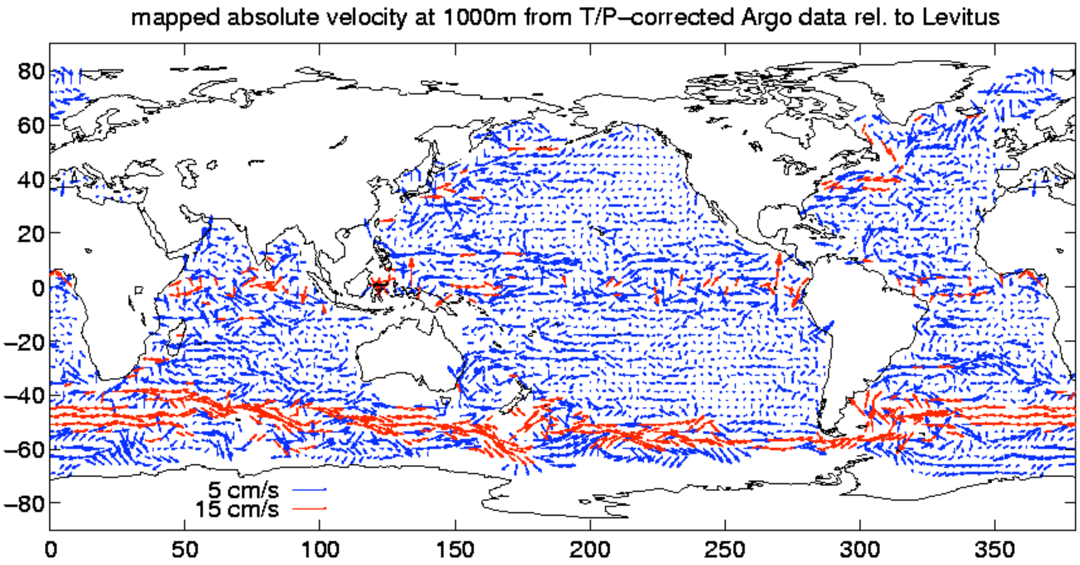

Figure 5. Vector plot of velocities at 1000 m based on objective maps of altimeter-corrected Argo float displacement data.

Finally, it is reasonable to ask what affect the use of the altimeter data in this analysis might be. In order to determine this, maps of the 1000 m dynamic height were also produced using only Argo float displacement data, without application of the altimeter correction. These maps were qualitatively very similar to the one shown in Figure 4. Nevertheless, subtraction of the corrected and uncorrected estimates revealed some regions where the impact of the altimeter data resulted in changes of 5 to 10 cm in the 1000 m dynamic height. These occur in the ACC where eddy variability is high, and correspond to corrections of a few cm/s in velocity.

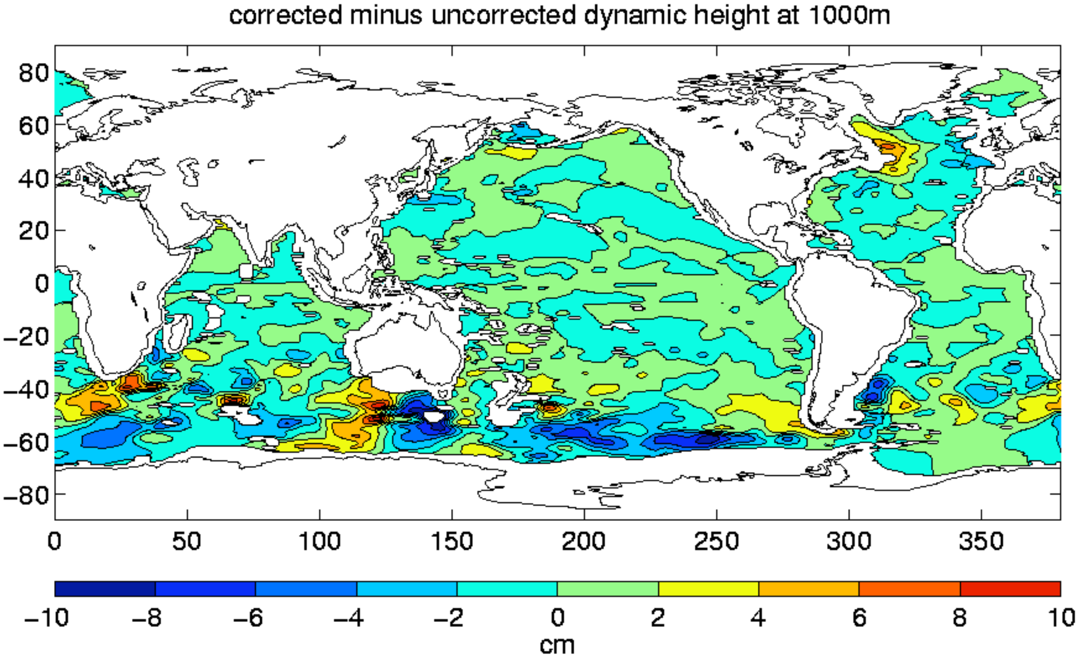

Figure 6. Effect of altimeter correction on 1000 m dynamic height.

In summary, satellite-based measurements of sea-surface height provide data that is highly complimentary to float displacement data from the Argo array of profiling floats. With roughly 4300 float-years of data now available, a preliminary estimate of the mid-depth circulation can be produced for the global oceans using Argo data. Furthermore, altimeter-based estimates of sea-surface height anomaly were found to be complementary to subsurface float displacements over most of the ocean outside of the tropics. A technique was developed for combining these two datasets and shown to reduce noise in time-averaged estimates of the mid-depth circulation due to the presence of eddy variability.

References

Conkright, M. E., R. A. Locarnini, H. E. Garcia, T. D. O'Brien, T. P. Boyer, C. Stephens, and J. I. Antonov, W*orld Ocean Atlas 2001: Objective Analyses, Data Statistics, and Figures, CD-ROM Documentation.* National Oceanographic Data Center, Silver Springs, MD, 2002.

Davis, R.E., Preliminary results from directly measuring middepth circulation in the tropical and South Pacific. *Journal of Geophysical Research – Oceans*, **103**, 24,619-24,634, 1998.

Davis, R.E., D.C. Webb, L.A. Regier, J. Dufour, The autonomous lagrangian circulation explorer (ALACE), *Journal of Atmospheric and Oceanic Technology*, **9**, 264-285, 1992.

Ducet, N., P.-Y. Le Traon, and G. Reverdin, Global high resolution mapping of ocean circulation from TOPEX/Poseidon and ERS-1 and -2. *J. Geophys. Res.*, **105**, 19 477-19 498, 2000.

Lavender, K. L., W. B. Owens, and R. E. Davis, The mid-depth circluation of the subpolar North Atlantic Ocean as measured by subsurface floats, *Deep-Sea Research I*, **52**, 2005.

Rio, M.-H. and F. Hernandez, A mean dynamic topography computed over the world ocean from altimetry, in situ measurements and a geoid model. *Journal of Geophysical Research*, **109**, C12032, 2004.

Roemmich, D., J. Gilson, Eddy Transport of Heat and Thermocline Waters in the North Pacific: A key to understanding interannual/decadal climate variability? *Journal of Physical Oceanography*, **31**, 6757-687, 2001.