The 2004 – 2007 mean and annual cycle of temperature, salinity and steric height in the global ocean from the Argo Program

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Keywords: Temperature, salinity, steric sea level, ocean circulation, climatology, air-sea interaction

Submitted to: Progress in Oceanography
June 3, 2008

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## Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract</td>
<td>3</td>
</tr>
<tr>
<td>1. Introduction</td>
<td>4</td>
</tr>
<tr>
<td>2. Data and methods</td>
<td>7</td>
</tr>
<tr>
<td>3. The 2004 – 2007 mean</td>
<td>16</td>
</tr>
<tr>
<td>3.1 Temperature, salinity, and density</td>
<td>16</td>
</tr>
<tr>
<td>3.2 Steric height and ocean circulation</td>
<td>20</td>
</tr>
<tr>
<td>3.3 Sampling errors</td>
<td>22</td>
</tr>
<tr>
<td>4. The 2004 – 2007 annual cycle</td>
<td>25</td>
</tr>
<tr>
<td>4.1 Temperature</td>
<td>25</td>
</tr>
<tr>
<td>4.2 Sea-surface temperature</td>
<td>26</td>
</tr>
<tr>
<td>4.3 Heat gain</td>
<td>27</td>
</tr>
<tr>
<td>4.4 Salinity, freshwater content, and sea-surface salinity</td>
<td>29</td>
</tr>
<tr>
<td>4.5 Steric height and ocean circulation</td>
<td>31</td>
</tr>
<tr>
<td>5. Discussion and conclusions</td>
<td>33</td>
</tr>
<tr>
<td>6. Acknowledgements</td>
<td>37</td>
</tr>
<tr>
<td>7. References</td>
<td>38</td>
</tr>
</tbody>
</table>
Abstract

The Argo Program has achieved four years of global coverage, growing from a very sparse global array of 1,000 profiling floats in early 2004 to 3,000 instruments in late 2007. Using more than 250,000 temperature and salinity profiles, we constructed an upper-ocean climatology and monthly anomaly fields for the 4-year era of global coverage, 2004 – 2007. A basic description of the modern upper ocean based entirely on Argo data is presented here, to provide a baseline for comparison with past datasets and with ongoing Argo data, to test the adequacy of Argo sampling of large-scale variability, and to examine the consistency of the Argo dataset with related ocean observations from other programs. The Argo four-year mean is compared to the World Ocean Atlas, highlighting the middle and high latitudes of the southern hemisphere as a region of strong multi-decadal warming and freshening. Moreover the region is one where Argo data have contributed an enormous increment to historical sampling, and where more Argo floats are needed for documenting large-scale variability. Globally, the Argo-era ocean is warmer than the historical climatology at nearly all depths, by an amount that increases toward the sea surface; it is saltier in the surface layer and fresher at intermediate levels. Annual cycles in temperature and salinity are compared, again to WOA01, and to the NOC air-sea flux climatology, the Reynolds SST product, and AVISO satellite altimetric height. These products are consistent with Argo data on hemispheric and global scales, but show regional differences that may either point to systematic errors or to physical processes that need further investigation. The present work is viewed as an initial step toward integrating Argo and other climate-relevant global ocean datasets.
1. Introduction

Descriptions of the global ocean’s large-scale temperature and salinity distributions and circulation have always been severely limited by the sparseness of the underlying datasets. Until recently, subsurface data could not be collected over whole ocean basins simultaneously, resulting in historical data with strong regional and seasonal biases. The best available syntheses of the subsurface ocean, such as the World Ocean Atlas series (e.g. WOA01, Conkright et al., 2002) have necessarily been compiled using regional datasets from different eras. These “mixed-era” climatological fields have many important applications, but they do not represent the time mean ocean over a given period, and thus are problematic for assigning error bounds (e.g. Roemmich and Sutton, 1998). Even the ambitious World Ocean Circulation Experiment’s (WOCE) global hydrographic survey sampled different oceans in different years and left vast gaps of thousands of kilometers between widely-spaced ship tracks.

The interpretation problems posed by historical subsurface ocean datasets go far beyond simple sparseness. The data are very inhomogeneous in space and time. They have strong biases toward the northern hemisphere oceans and toward developed nations’ coastlines. There are far more summer data than winter data in the archives. Data collected south of 30°S in winter are especially rare. To illustrate the extent of these sampling issues, consider the 339,218 temperature-salinity-depth ocean stations containing data deeper than 1000 m in the U.S. National Oceanographic Data Center’s archive. Of that total, only 30,531 (9%) are south of 30°S, and only 4237 (1.2%) are from the winter months of July to September. About 1/3 of the area of the world’s
oceans deeper than 1000 m is south of 30°S, so the Southern Ocean and especially southern winter is seriously under-represented in the historical archive.

The implications of such inhomogeneous sampling, in turn, go beyond the difficulty of defining climatological fields. Since the mean for any given decade is poorly sampled, so the estimation of decadal and multi-decadal variability is subject to large errors, particularly in the southern hemisphere. For example, estimates of the 50-year increase in steric sea level and ocean heat content (Levitus et al., 2005, Ishii et al., 2006) may be biased low by up to 100% (Gregory et al., 2004, Gille, 2008) because the objective analysis technique used in these studies estimates zero anomaly in unsampled regions. Climatologies are widely used for initialization and to limit unrealistic variability in prognostic and data assimilation models. Their deficiencies as representations of the mean state can affect those models significantly, for example by creating spurious signals where new observations are inconsistent with the previous estimate of the mean. A further complication with some climatologies based on historical datasets is their reliance on multiple instrument types. Recent work has highlighted significant biases that result from mixing XBT and hydrographic data (Gouretski and Koltermann, 2007, Willis et al., 2007, Wijffels et al., 2008).

The technology of autonomous profiling floats has made it possible to sample the subsurface oceans globally, and the Argo Program was initiated (Roemmich et al., 1998) to exploit float technology for that objective. This work presents a “fixed-era” single-instrument climatology for the global upper ocean, in contrast to the previous “mixed-era”, and often multi-instrument, climatologies. The fixed-era climatology is the temporal mean over the period 2004 – 2007, based on the Argo dataset. Beyond
simply describing the time mean fields and the annual variability, the value of the fixed-era ocean climatology is illustrated with a few comparative examples. A primary objective is to provide a baseline against which both ongoing Argo data and past datasets can be compared for estimates of interannual to decadal variability. Another objective is to begin integrating the global ocean observing system by comparing Argo to related global datasets such as air-sea fluxes, sea surface temperature, and satellite altimetric height. The present work is a first effort, and the accuracy of Argo-based multi-year mean fields will continue to progress with time and with improvements in the number, distribution, and data quality of Argo floats.

The Argo dataset greatly reduces the sampling biases noted above in historical hydrographic data. In the present work, 251,842 Argo temperature-salinity-pressure profiles are used from the period January 2004 to December 2007. The 2004 starting point was chosen as the first year that Argo achieved sparse global coverage. Of the total stations, 27% are south of 30°S, and 7% are from the winter months July through September. Thus the 4-year Argo dataset has many times the number of Southern Ocean winter stations obtained in the entire pre-Argo history of oceanography, and the regional and seasonal biases are greatly reduced.

Some sampling problems remain, presenting challenges to the Argo Program for future improvements. Over, the 4-year period, the number of Argo floats tripled to more than 3000, with greatly increased coverage in some regions. Because the coverage was changing during the 4-year averaging period, there is a degree of ambiguity in separating seasonal and longer-term variability. There are few Argo floats in most marginal seas and few (but increasing) floats in seasonally ice-covered regions. The
latter limits the effective coverage of the array to about 60°S to 65°N. Due to present limitations on buoyancy adjustment, many floats in the tropics do not sample below about 1000 dbar. Finally, a northern hemisphere bias still exists. In the 4-year dataset, the average number of profiles per unit area of ocean deeper than 2000 m is about 40% greater in the northern hemisphere than the southern hemisphere. Another objective of the present work is to illustrate the need for continuing expansion of the well-sampled Argo domain, in profile depth and in spatial distribution of floats.

In the next section, the dataset and interpolation methods are described. Section 3 shows 4-year time means of temperature, salinity and steric height from Argo, and compares them with WOA01. In Section 4, the annual cycle calculated from Argo is examined and compared for consistency with annual cycles in air-sea exchanges of heat and freshwater from the National Oceanography Center (NOC) Air-Sea Flux Climatology (Josey et al., 1998), sea surface temperature (Reynolds et al., 2002), and sea surface height from satellite altimetry (Ducet et al., 2000). These data products are independent of Argo, but describe closely related quantities. Discussion and conclusions are presented in the final section.

2. Data and methods

The Argo profiles used in this study were those available from the Argo Global Data Assembly Center (GDAC) in early 2008. The dataset included 317,521 candidate profiles gathered during 2004-2007, with differing levels of quality control (QC) applied. New Argo data are available in a real-time quality controlled state (RTQC) having only automated QC procedures applied. Older data have delayed-mode quality control (DMQC) including a more rigorous examination by the scientist responsible for the Argo
float. Data of both QC levels were used here, but with additional testing of the RTQC files. The Argo QC flags attached to the temperature and salinity profile values were used as a first pass quality assessment. The Argo climatology in the present work is based on a reduced subset of 251,842 profiles (Fig. 2.1a), a 20.7% reduction of the total available dataset. Some exclusions were for reasons of data quality (temporary or otherwise), while others were specific to the choice of spatial domain for the present work. Specifically:

1) 4.9% of profiles were removed due to systematic pressure errors detected (e.g. Willis et al., 2007) in a subset of profiles from Woods Hole Oceanographic Institution (WHOI) SOLO floats equipped with Falmouth Scientific Instruments (FSI) Conductivity-Temperature-Depth (CTD) sensors. The majority of data from these floats can be corrected. Those that are correctable through automated methods have been corrected and were used here. Most of the data from the remaining floats require individual inspection of a sequence of profiles for correction, and are not yet available. Regionally the reduction is more severe in the Atlantic Ocean, where most of the problematic floats are located, resulting in gyre-scale low coverage gaps in the Argo array (Fig 2.1a), most notably between 10-30°N and in the South Atlantic.

2) 5.6% of the eligible profiles were excluded either because they fell outside the mapping domain or did not report a position. The present mapping domain (see Fig 2.1a) excludes marginal seas, of which only a few have good Argo sampling. The data domain is limited to 63°S to 65°N, excluding high latitudes where coverage is too sparse for our purposes and is not year-around because of
seasonal ice. Although data were included to $63^\circ$S, the gridded region ended at $60^\circ$S.

3) 3.2% of eligible profiles were rejected by comparing against the Argo ‘greylist’ of problematic instruments. This is in addition to greylisted WHOI FSI profiles discussed above.

4) 3.2% of profiles were rejected for not returning viable temperature and salinity values over a significant pressure range. This includes early-Argo-era floats not equipped with CTD’s and entire profiles marked bad during QC.

5) Adjustment for conductivity sensor drift, by comparing salinity values to a historical estimate (e.g. Wong et al., 2006, Owens and Wong, 2008), is a critical task of DMQC. RTQC profiles without the benefit of DMQC, were adjusted by an offset to agree with WOCE Global Hydrographic Climatology (WGHC, Gouretski and Koltermann, 2004) salinity over the deepest portion of the profile. This procedure was judged to be insufficient, and the profile rejected, if the difference between the profile and WGHC was more than 0.1 psu (1% of profiles) or if the profile only extended to a pressure shallower than 600 dbar (1.6% of profiles).

Salinity adjustments were applied to about 105,000 RTQC profiles, with a mean shift of .0005 psu and RMS of 0.023. In DMQC profiles, the deviations from historical salinity over most of the oceans decrease with depth, and are considerably smaller at 2000 dbar than in intermediate pressure layers. For this reason, we conclude that the T-S adjustments applied to RTQC profiles are mainly correcting for sensor drift, rather than cancelling climatic T-S changes. The global
T-S differences in Argo data relative to WOA01 at intermediate and upper levels, described in Section 3, are not very sensitive to the salinity adjustment.

6) Additional quality checks resulted in less than 1% of profiles being rejected.

Reasons for rejecting whole profiles included low vertical pressure resolution, lack of QC flags applied within the Argo file, and density inversions of greater than 0.01 kg/m$^3$ (0.05 kg/m$^3$) deeper (shallower) than 400 dbar. Smaller density inversions shallower than 400 dbar were common and not usually indicative of a bad profile, so only the inverted levels were removed. For pressure inversions or "stalls", often indicative of grounded instruments, only levels at or below the stall or inversion were removed.

The remaining Argo profile data were linearly interpolated onto 56 pressure levels spanning 0 to 2000 dbar, with separate levels spaced from 10 to 100 dbar apart. The shallowest sampled value, if above 15 dbar, was assumed to represent the near-surface value. In a few early-era Argo models, the shallowest values were at 10 dbar, while newer floats tend to sample closer to the sea surface. Finally, on each pressure level the Argo profiles were compared to a local mean and variability in $10^\circ\times10^\circ$ spatial boxes. If the value at any level differed from the mean by more than 6 standard deviations, the whole profile was excluded, resulting in an additional 0.1% of rejections.

Data coverage for shallow pressure levels is shown in Fig 2.1. Coverage decreases substantially between 1000 and 2000 dbar in tropical oceans as some Argo float models cannot yet produce the buoyancy required to reach the sea surface from 2000 dbar in the highly-stratified tropical oceans.
The monthly number of Argo profiles and floats included in the Argo climatology has grown more than three-fold from approximately 2300 monthly profiles (800 floats) in early 2004 to 7100 profiles (2300 floats) in late 2007 (Fig 2.1b). As the Argo array has now reached its target of 3000 active floats, future growth in the number of profiles included in the climatology will occur due to inclusion of marginal seas and high latitudes in the study domain, increased float and CTD reliability, and continuing DMQC of the dataset.

In the present dataset, monthly southern hemisphere profiles have outnumbered those in the northern hemisphere since December 2004. However the monthly density of profiles is lower in the southern hemisphere even today. In 2004-2005, large but diminishing coverage gaps existed in the southeast Pacific, South Atlantic, and Southern Oceans. Including all data from the 4-year span (Fig 2.1a), there are still some smaller, unsampled areas of the open ocean. In addition to the gaps in the Atlantic and Southern Ocean, smaller gaps can be found in the eastern central ocean basins where floats tend not to move far from their deployment locations. Best coverage is found where float numbers and dispersion are high, such as the Kuroshio Extension region and the northern Indian Ocean. Coverage in later months of the year (e.g. November, December) is slightly denser than early months (e.g. January, February) due to the 4-year continuous growth in the number of floats.

For interpolation of the Argo temperature and salinity data, a 4-year mean field for each month was first estimated using a weighted least-squares fit to nearby data. Then, anomalies from this first estimate, for each of the 48 months of the time-series, were calculated by objective analysis. The weighted least-squares procedure was adopted
after some experimentation, to arrive at a stable “first guess” of the mean field. The fact that results have some sensitivity to the procedure indicates that 4 years of Argo data still leaves significant uncertainty in the mean field (see section 3.3 on errors).

The weighted least-squares fit was carried out similarly to Ridgway et al. (2002), but differing in several details. As in that work, the fit included linear and quadratic terms in latitude, longitude, and pressure, and was carried out separately at each pressure level. Here we included six temporal harmonics (i.e. periods of 2 to 12 months), rather than just two, to permit a more irregular annual cycle. A total of 3600 “nearest” points were used for each fit, 100 from the present pressure level plus 100 from each adjacent pressure level above and below, for each of the 12 months. Data were weighted in inverse proportion to their horizontal distance from the grid point, with the nearest data point receiving a weight of 1 and the most distant a weight of 0.02.

For both the least-squares fit and the objective analysis of anomalies, the horizontal distance between data and grid points was increased by an amount proportional to the difference in barotropic potential vorticity ($f/H$, where $f$ is the Coriolis parameter and $H$ the ocean depth), similarly to that used by Lavender and Davis (2005). This term improved the representation of narrow topography-following features such as western boundary currents, which may have relatively few data on their inshore sides. Hence:

$$\text{distance} = \sqrt{\text{dist}_y^2 + \text{dist}_x^2 + \text{dist}_{pv}^2}$$

where $\text{dist}_x$ ($\text{dist}_y$) is the horizontal distance in km in the zonal (meridional) direction, and $\text{dist}_{pv}$ is the added distance penalty (km) for crossing $f/H$ contours, calculated as

$$\text{dist}_{pv} = 200 \text{ km} \cdot S^{1/2} \cdot \left[ \frac{(f/H)_d -(f/H)_g}{((f/H)_d)^2+(f/H)_g^2} \right]^{1/2}$$
with the subscripts \(d\) and \(g\) referring to \(f/H\) evaluated at data and grid points respectively. This scaling equates a doubling of \(f/H\) with a distance of 200 km. While the \(f/H\) term was helpful with the representation of boundary currents, it was less so with the Antarctic Circumpolar Current, which also has sparse sampling, decreasing toward the south. Therefore, south of 35°S and away from land, the \(f/H\) term was replaced by a distance penalty for crossing steric height contours (0/2000 dbar, from WOA01), equating 100 km distance with a 15 dyn cm change in steric height:

\[
\text{dist}_{DH} = 100 \text{ km} \cdot \text{abs} \left( \text{SH}_d - \text{SH}_g \right) / 15 \text{ cm}
\]

Finally, distance was considered to be infinite between ocean locations separated by continental land, such as southern India, or by substantial islands including New Zealand, Madagascar, and Tasmania.

The first estimate by least-squares fit worked well for grid points surrounded by nearby data, and less well in regions where data were predominantly on one side of the grid point and far away, causing unstable extrapolations. We discarded the fit in cases where the estimated value of temperature or salinity was outside the data envelope, replacing it with the corresponding data extremum. These extrapolation problems occurred mostly in the data-sparse Southern Ocean. Finally, after fitting all pressure levels, density inversions occurred occasionally in near-surface waters. These were eliminated by adjusting temperature and salinity of shallower layers to remove unstable density differences relative to deeper values. The quality of the first-estimate mean field is a strong concern, and errors in the mean field are estimated in section 3.3.

After making this initial estimate of the 4-year mean for each month, the 48 monthly anomaly fields were then calculated using objective analysis (Bretherton et al.,
1976; see also Roemmich, 1983, for an example using hydrographic data). For the objective analysis, spatial correlations of the monthly data anomalies were represented as functions that approximate the sample correlations (Fig 2.2). Sample correlations were formed by subtracting the first-estimate monthly mean field, linearly interpolated to Argo profile locations in space and time, and then averaging the correlation estimates as a function of distance separation (as defined above) globally and over the 48-month record.

Fig 2.2 shows the sample correlation estimates for temperature anomaly at 2.5, 50, and 200 dbar. This is based on pairs of profiles that are separated in time by less than 5 days. The correlation decays rapidly out to horizontal separations of about 200 km, with diminishing values from the sea surface to 200 dbar at longer separations. Values deeper than 200 dbar were similar to the 200 dbar level.

Fig 2.2 also shows, for comparison, the modeled spatial correlation of altimetric height anomaly relative to a 7-year mean (Willis et al., 2004), corresponding to the universal spectrum proposed by Zang and Wunsch (2001). The altimetric height correlation in Fig 2.2 is similar, though elevated, in comparison to that of vertically-averaged temperature. An important point is that as the record length increases with time, interannual and decadal variability raises the large-spatial-scale portion of the sample correlation (see also Fig 3.9). Previous studies of spatial correlation of temperature anomalies from XBT datasets (e.g. White, 1995) indicate higher correlation at large spatial lags than seen in Fig 2.2, and this is partly attributable to the longer-term mean used in those studies. Evaluation of the effectiveness of Argo for sampling large-scale variability will need to take this into account.
For the objective analysis, which was done separately for each month and pressure level, the spatial correlation of temperature was represented as the sum of two Gaussian functions (Fig 2.2). The small-scale Gaussian had an e-folding scale of 111 km and amplitude increasing from 0.76 at the sea surface to 0.99 at pressures greater than 350 dbar. The large-scale Gaussian had an e-folding scale of 1555 km. Its amplitude was reduced from 0.24 at the sea surface to 0.01 at 350 dbar and greater.

For salinity, sample correlations were somewhat lower than for temperature, but we used the same functional representation in order to avoid spurious features such as density inversions in the objective interpolations. Finally, the noise-to-signal variance ratio (added to the main diagonal of the data correlation matrix) was taken to be 0.35 at the sea surface, decreasing to 0.15 at 220 dbar and below. Each $1^\circ \times 1^\circ \times 1$ month anomaly was estimated using the nearest 100 data points from that month, and the anomaly fields were added to the first-estimate means to form the final 48 monthly estimates.

This interpolation procedures described above include elements that appear both complicated, such as the distance definition or the least-squares fitting parameters, and simplistic, such as the lack of a temporal correlation term. While the objective was to produce an Argo-era climatology, the relatively small volume of data to date, and uncertainties in the statistics of the fields, make an \textit{ad hoc} mapping procedure necessary in regions where the data deficiencies are still significant. For the anomaly mapping, we sought consistency with the statistics indicated by the data, while making simplifications for more efficient computing. The sensitivity of final maps to details of the mapping procedures and statistical assumptions was tested, and is not great.
Nevertheless, the maps will clearly improve with time as the growing Argo dataset contributes to the background mean field and to more accurate statistics of variability.

3. The 2004 - 2007 mean

The 4-year Argo time-averaged fields of temperature and salinity versus pressure were obtained by averaging the monthly fields, including the first-estimate and the monthly anomalies, over the 48-month period. Additionally, the monthly temperature and salinity fields were used to calculate potential density, steric height, and geostrophic velocity. These derived quantities in turn were also averaged over the 48-month period. In calculations of zonally or globally averaged quantities, pressure levels deeper than the mean depth of a 1° x 1° grid box were masked out. In addition, grid points near continental coastlines and large islands were masked out at all depths if the average depth in the 1° x 1° grid box was less than 1000 m, because these inshore extrapolated values tended to have large estimation errors (Section 2).

3.1 Temperature, salinity, and density

In order to compare temperature, salinity, and density from the Argo climatology to that of WOA01 (Conkright et al., 2002), the latter product was masked to the same grid point locations as Argo by eliminating marginal seas and shallow regions. The depth coordinate in WOA01 was converted to pressure, and linearly interpolated onto the same pressure surfaces used for Argo. Fig 3.1 shows contours of zonally-averaged temperature, salinity, and density from Argo, as a function of pressure. Color shading is used to show the differences, Argo-minus-WOA01. Fig 3.2 shows maps of temperature, salinity, and density, vertically averaged over the top 100 dbar, again with contour lines.
for Argo and color shading for Argo-minus-WOA01 differences. The differences include sampling and interpolation errors as well as decadal changes.

The zonally-averaged temperature (Fig 3.1a) shows bands of warming extending deep into the ocean in Argo-minus-WOA01 differences in both hemispheres at middle and high latitude. The area of the northern hemisphere oceans north of 40°N is much smaller than that of southern hemisphere oceans south of 40°S. Thus, although the zonally-averaged temperature increase is greater in the north, it represents a much smaller difference in total heat content than the southern hemisphere signal. In addition to these signals which extend to depth, the surface layer is warmer in Argo than in WOA01 at nearly all latitudes. Surface layer warming is greatest in the Atlantic (Fig. 3.2a). When volume-averaged globally from 0 to 2000 dbar, the Argo climatology is 0.036°C warmer than WOA01, with maxima in area-averaged temperature difference at the sea surface and about 1000 dbar (Fig. 3.3).

In zonally-averaged salinity (Fig. 3.1b), the northern hemisphere ocean is generally saltier in Argo than in WOA01, while the southern hemisphere ocean is mostly fresher. The southern freshening signal is seen as a tongue of negative salinity difference extending from the sea surface at high southern latitudes into the ocean interior and northward at intermediate depth. This freshening is consistent with previous comparisons of modern and historical data by Wong et al. (1999) in the Pacific and Indian Ocean and by Curry et al. (2003) in the Atlantic. In Argo compared to WOA01, the southern freshening is seen in all three oceans. The salinity increase in the north is dominated by the Atlantic Ocean, and occurs mainly north of 40°N. This has been previously noted by Hatun et al. (2005), with the increase occurring during the past
decade. In addition to these deeper salinity signals, there are surface layer changes (Fig. 3.1b, 3.2b) including salinity increases in the evaporative regions of 20° – 40° N and S in all oceans. The Argo-era surface layer of the Atlantic is saltier in both hemispheres (Fig. 3.2b colors), suggesting decreased precipitation-minus-evaporation (P-E) in that ocean, and balanced largely by freshening in the Pacific. A strong surface freshening signal is seen, centered at 9°N (Fig. 3.1b), near the salinity minimum that lies beneath the Inter-Tropical Convergence Zone (ITCZ). Fig. 3.2b shows pronounced freshening in the west under both the Pacific ITCZ and the South Pacific Convergence Zone. These signals may in part be due to a preponderance of La Niña conditions in the Pacific during the Argo era.

The volume-averaged 0 to 2000 dbar Argo climatology is .002 fresher than WOA01, with area averages showing a shallow salinity increase with maximum at about 100 dbar (Fig 3.3) and deeper salinity decrease with maxima at 500 and 1000 dbar. The mean salinity decrease above the density surface $\sigma_9$ equals 27.6 is also .002 psu, equivalent to dilution of the water column by 8 cm of fresh water. Averaging above a density surface is done to exclude the vertical displacement of density and salinity from the estimate. This net freshening would include contributions from the melting of both continental ice and floating ice over the period of a few decades between the WOA01 and Argo eras, and it lies within the large uncertainty in the estimated rates of melting (e.g. Munk, 2003).

The zonally-averaged density differences, Fig 3.1c, reflect the north/south asymmetry in salinity difference. That is, in the Southern Ocean the freshening signal reinforces the warming, with both causing density to decrease. But in the 40° – 50° N
band, the salinity increase tends to cancel the warming signal, and a small density increase is seen at all depths below the surface layer. Hence, while substantial deep temperature increases are seen at high latitude in both hemispheres (Fig 3.1a), the corresponding density decrease is greater in the southern hemisphere. This point is reinforced in the next section below on steric height.

To investigate the causality of temperature and salinity changes, it is useful to separate changes due to vertical displacement of isopleths from those due to changes in the T/S relation. Fig. 3.4 shows zonal averages of Argo salinity and Argo-minus-WOA01 salinity differences on potential density surfaces. The upper 200 dbar is excluded to focus on the subsurface variability. The north/south asymmetry is seen clearly, with the southern freshening being pronounced in the density range from $\sigma_\theta$ equals 26.7 to 27.3 including Sub-Polar Mode Water and Antarctic Intermediate Water. Shallower densities around $\sigma_\theta$ equals 25.8 show the salinity increase in the evaporative regions. As noted by Bindoff and McDougall (1994), changes in temperature or salinity on density surfaces can be due either to changes in air-sea heat flux or freshwater flux, and additional analysis is needed to separate these causes.

Finally, we provide temporal context for the Argo-minus-WOA01 differences using the pentadal temperature and salinity anomalies for the World Ocean provided by Levitus et al. (2005) together with mean fields. Again we have converted the Levitus et al. (2005) depth coordinate to pressure and subsampled in latitude and longitude to match the area included in the Argo climatology. The area-averaged and pressure-averaged (0 – 2000 dbar) temperature time-series from Levitus et al. (2005) and from Argo are shown in Fig 3.5 (upper panel), with the area-averaged anomaly as a function
of pressure shown in the lower panel. For both Argo and WOA, anomalies are relative to the WOA mean field. The Levitus et al. (2005) pentadal time-series ends in 1996, so there is a gap between it and the beginning of global Argo coverage. Much of the decadal variability in the Levitus et al. (2005) time-series in the upper 700 dbar has been attributed by Wijffels et al. (2008) to time-variations in the fall-rate of XBT probes. After correction for fall-rate variations, Wijffels et al. (2008) found a slightly greater long-term trend and reduced decadal variability. The global mean temperature, 0 – 2000 m from Argo is about 0.07°C warmer than the WOA estimate 50 years earlier, equivalent to a warming rate of about 0.3 W/m². Domingues et al. (2008) applied fall-rate corrections to the historical XBT dataset and estimated the 0-700 m warming rate to be 0.35 ± 0.08 W/m² for the period 1961 – 2003.

3.2 Steric height and ocean circulation

Fig 3.6a shows the mean steric height of the sea surface relative to 2000 dbar (0/2000) from the Argo climatology. Three subsurface levels, 200, 500, and 1000/2000 dbar are shown in Fig. 3.6c,d, and f. The steric height difference, Argo-minus-WOA01, for the sea surface and the 500 dbar level, is also shown (Figs. 3.6b,e).

The varying depth penetration of the five subtropical gyre interiors is evident in these figures, with the North Pacific interior gyre circulation being the strongest at the sea surface and 200 dbar, while the South Pacific and South Indian gyres have the strongest interior circulations at 1000 dbar. At the 500 and 1000 dbar levels the “Tasman leakage” connection south of Australia between the subtropical South Pacific and Indian gyres (Speich et al., 2002, Ridgway and Dunn, 2007) is seen clearly.
Roemmich et al. (2007) noted that the strength of all of the southern gyres was increased in Argo compared to hydrographic and altimetric data from the early 1990’s. A similar increase can be seen in Fig 3.6 in the coincidence of the maximum steric height gain at 500 dbar (Fig 3.6e) with the latitude of the gyre center at that depth (Fig 3.6d). Indeed, that increase is a noticeable circulation difference between Argo steric heights (Fig. 3.6) and previous basin-scale analyses such as Reid (1986) for the South Pacific and Reid (2003) for the Indian Ocean.

Gille (2008) interprets the multi-decadal change as a southward shift of the Antarctic Circumpolar Current. The location of maxima in sea surface steric height increase (Fig 3.6b, 3.7), coinciding with maxima in the meridional gradients of steric height (Figs. 3.6a) is consistent with that interpretation. However, Fig 3.1c suggests that there is downward as well as southward displacement of isopycnals. At the latitude where $\sigma_\theta$ isopleths from 27.0 to 27.6 are deepest, around 40\textdegree S, the density decreases can only be interpreted as deepening of the isopycnals, not as meridional displacements. This can be seen in a vertically-integrated sense in Fig 3.7. At the latitude near 40\textdegree S of the steric height maximum marking the deep gyre center, the Argo-minus-WOCE steric height increase can only be interpreted as deepening of isopycnals.

The zonal averages of the steric height of the sea surface, 200, 500, and 1000 dbar, relative to 2000 dbar, are shown in Fig 3.7. The tendency of the southern subtropical gyres to extend deeper in the water column is seen at the 1000 dbar, and even the 500 dbar level, where the southern high is more prominent than the northern one. The zonal averages of steric height difference, Argo-minus-WOA, show the
southern height increase extending deep into the water column over latitudes from 30°S to 60°S.

As noted earlier, the warming in the northern North Atlantic is partly density-compensated due to a salinity increase. Therefore the steric height changes seen there are more limited in north-south extent. There are also steric height increases in Argo relative to WOA01 in the tropical Atlantic and the western Pacific (Fig 3.6b), particularly the Kuroshio region. The dominance of the Southern Ocean signal in steric height difference is seen in large-area averages. South of 30°S, the steric height of the sea surface (0/2000 dbar) is higher in the Argo climatology by an average of 3.5 dyn cm while over the rest of the ocean north of 30°S the average is only 0.7 dyn cm.

3.3 Sampling errors

Argo is a sparse array, and its capability to estimate mean fields and low frequency variability depends on averages over energetic noise due to eddies, fronts, and other unresolved variability. Systematic errors in the mean field, as well as in the variability, can be introduced by irregularities in float deployment patterns, such as the tendency for fewer floats to be deployed south of 50°S in the Southern Ocean, by convergences of floats caused by drift on the sea surface or at depth, or by analysis methods.

On large spatial and long temporal scales, variations in the height of the sea surface measured by satellite altimetry are dominated by density fluctuations (e.g. White and Tai, 1995, Gilson et al., 1998). Altimetric height, and especially the multi-altimeter product used here (Ducet et al., 2000), has higher intrinsic resolution than Argo and
serves as a useful proxy for steric height in estimating Argo sampling error. Because sea surface height also contains variability due to mass and to abyssal-ocean density changes that are not in Argo data, the differences between fully-sampled altimetric height fields and ones that are subsampled at Argo profile locations will form an upper bound on Argo sampling error.

First, the impact of Argo sampling errors on the mean sea surface steric height field (Fig 3.6a) is estimated. Suppose, for the sake of argument, that the WOA01 steric height was the correct mean for the 2004-2007 period. How much of the Argo-minus-WOA01 differences shown in Fig. 3.6b could be attributed to Argo sampling and interpolation errors? For this experiment, the 2004-2007 altimetric height mean was subtracted from the gridded AVISO altimetric height field (Ducet et al., 2000) and replaced by the annual mean steric height (0/2000 dbar) from WOA01. This combination of the WOA01 mean plus the altimetric height anomaly was then subsampled at the space and time location of each Argo profile. The subsampled field was subjected to the same two-step fitting and objective mapping as was described for Argo data in Section 2. Finally, this subsampled and mapped 48-month average was compared to WOA01 (Fig. 3.8) and the difference is interpreted as the impact of Argo sampling and interpolation errors on the mean steric height field.

The panel on the left-hand side of Fig 3.8 shows the zonal average of the Argo-minus-WOA01 steric height difference (0/2000 dbar, dotted line, from Fig. 3.7) together with the zonal average of the estimated Argo sampling and interpolation error (red). While the sampling error is substantial in the Southern Ocean, it is less than the signal in steric height difference by a factor of 1/6 overall between 30°S and 60°S. Of course,
this estimate of sampling error applies only to the Argo mean, and the corresponding
sampling error in WOA01 may be larger. In addition to the Antarctic Circumpolar
Current region, other steep gradients in the mean steric height field, such as the ridge
and trough of the North Equatorial Countercurrent, are seen to be systematically
underestimated in Fig 3.8.

A primary objective of Argo is estimation of seasonal-to-interannual variability on
large-spatial scales. Again, altimetric height can be used as a proxy, but this time to
estimate errors in large-scale steric height variability. First the $1/3^\circ \times 1/3^\circ \times$ weekly
gridded AVISO altimetric height anomalies, with the 2004 – 2007 altimetric height mean
removed, were smoothed with a running mean over $10^\circ \times 10^\circ \times$ 3 month scales. For the
smoothed data, the temporal RMS anomalies were then zonally-averaged (Fig. 3.9,
solid line) to show the latitude dependence of the large-scale signal. Next, the
unsmoothed AVISO data, with the 2004 – 2007 mean removed, were subsampled at
the location and time of each Argo profile. The subsampled dataset was then fitted and
mapped using the same procedures as the Argo data, and the mapped fields were
smoothed over the $10^\circ \times 10^\circ \times$ 3 month scales. At full Argo resolution, a $10^\circ \times 10^\circ \times$ 3
month region contains about 100 profiles. The large-scale Argo sampling error was then
estimated as the difference between the full and subsampled, smoothed altimetric
height (Fig 3.9., dashed line). The large-scale signal varies with latitude from 2 to 4.5
cm, while the sampling error varies between about 1 and 1.6 cm. The ratio of RMS
signal to RMS error is about 1.5 in the Southern Ocean but up to about 3 in the
equatorial zone.
Several conditions apply to the estimates in Fig. 3.9. First, the AVISO altimetric height fields do not contain all of the small-scale variability of the point-wise Argo profile data. Hence, the noise estimate in Fig. 3.9 is low to the extent that the small-scale variability not resolved in the multiple altimeter dataset would be aliased into the large scale. Second, the present 4-year Argo time-series is short in the sense that the interannual variability will increase as the series lengthens and as the mean is calculated over a longer period. This was noted in Section 2, in discussing the spatial correlation of temperature anomalies, Fig 2.2. By repeating the calculation of RMS signal using the full 1993 – 2007 altimetric height time-series, the estimated large-scale signal increases as shown in Fig. 3.9 (dotted line), with a corresponding increase in the signal-to-noise ratio. Finally, since Argo coverage was sparse during the early part of the 2004-2007 record, the error level will be lower for a sustained period of sampling at full Argo coverage.

4. The 2004 – 2007 annual cycle

For estimation of the annual cycle, the 4-year Argo record was averaged for each month, i.e. four Januarys, etc. The smoothed fields and analyzed quantities such as surface layer heat gain were calculated from the monthly time-series prior to the 4-year averaging.

4.1 Temperature

The difference between zonally averaged March and September temperature (Fig. 4.1) reveals interesting hemispheric asymmetries. Most strikingly, the northern
oceans show a maximum seasonal temperature change at the sea surface of 9.4°C at 42°N, while the corresponding southern maximum is only 5.3°C at 35°S. In both hemispheres at middle latitudes this seasonal contrast drops to about 3°C at 50 m; hence the northern oceans have a substantially more stratified surface layer in summer (Fig. 4.2) than the southern ones. These findings are similar to historical datasets (e.g. WOA01), but with improved accuracy in the southern hemisphere due to the higher volume of Argo data there, and the greater homogeneity of the Argo-only dataset. The pronounced asymmetry in seasonal temperature change is largely due to asymmetry in the latent heat component of air-sea heat flux. Examination of the NOC air-sea flux climatology (Version 1.1, Josey et al., 1998) shows that the zonal average of latent heat flux at 42°N has annual amplitude of 40 W/m², versus 15 W/m² at 35°S. The subsurface maxima in temperature variability in the tropics seen in Fig. 4.1 are dynamical signals, discussed below.

4.2 Sea-surface temperature

Fig 4.3 compares the annual cycle in zonally-averaged Argo near-sea surface temperature (SST) with that of the Reynolds et al., (2002) monthly-averaged SST product. The latter dataset was subsampled to the same spatial grid as Argo, and averaged over the same 4-year period from 2004 – 2007. The two panels of Fig. 4.3 are very similar in pattern and magnitude. Compared to the values noted above for the March-minus-September SST changes for Argo, the Reynolds product shows similar seasonal differences, 9.5°C at 42°N and 5.4°C at 35°S.
It’s also of interest to compare individual Argo profile data with the Reynolds SST product (which does not incorporate Argo data) in order to identify systematic differences. Random differences are due mainly to the fact that the individual Argo profiles contain small-scale variability not represented in the smoothed monthly SST grids. Most Argo floats collect their shallowest temperature measurement at about 5 m depth. The Reynolds product uses satellite data adjusted for consistency with drifter measurements of temperature at about .5 m depth, so temperature stratification could lead to systematic anomalies in Argo-minus-Reynolds differences. Other possible causes of systematic differences include clouds, sea ice, and diurnal variability, all of which pose potential problems in the gridded SST product.

The comparison of individual Argo near-surface values to the weekly Reynolds product is shown in Fig 4.4. Results were binned by 1°C intervals of Argo near-surface temperature, with a mean and standard deviation of temperature difference calculated for each bin. Standard error bars shown in Fig 4.4 assume that one-third of the temperature comparisons in each bin are independent, since successive float profiles at 10-day intervals may sample the same mesoscale feature. At mid-range temperatures of 10 to 20°C the standard deviation of temperature differences is 0.9 °C. Mean differences are near zero for a broad range of temperatures from about 8 to 28°C, though with most values slightly negative (consistent with stratification) between 10 and 15°C. Below 8°C the mean differences are increasingly negative, to about -0.5°C for Argo temperatures between 0 and -1°C. This could be due either to stratification or problems in the SST product near sea ice. At the other end of the temperature scale, Argo is warmer than the Reynolds product by 0.5°C at Argo temperatures between 30
and 31°C (mainly in the western Pacific warm pool). The cause of this difference is not known, but could be a combination of diurnal variability and cloud effects.

4.3 Heat gain

The monthly heat gain by the ocean’s surface layer was calculated from the Argo climatology by averaging temperature over a depth range that includes all locally-outcropping waters. The calculation was similar to that described by Moisan and Niiler (1998), but here using density instead of temperature to locate the base of the surface layer:

\[
\text{heat gain} = \rho c_p \left( \langle h \rangle \frac{\partial <T_a>}{\partial z} \right)
\]

where \( \langle h \rangle \) is the monthly mean depth of a “nearly outcropping” density surface, defined by the densest isopycnal seen at the sea surface at a given location over the 4-year period, plus 0.04 (\( \sigma_\theta \)). \(<T_a>\) is the monthly and vertically averaged temperature above that “nearly outcropping” isopycnal. The choice of the base of the surface layer is an imperfect tradeoff, intended to minimize both adiabatic changes in heat content due to vertical advection of deep isotherms and downward heat loss from the surface layer due to vertical mixing.

The surface layer heat gain defined as above was compared to air-sea heat flux from the National Oceanography Centre (NOC) 1.1 climatology (Josey et al., 1998). The hemispheric and global averages of the annual cycle of surface layer heat gain are shown in Fig 4.5 together with the NOC 1.1 product. The annual mean was removed from the air-sea flux, and that dataset was masked so that its spatial grid matched that of the Argo grid (60°S to 65°N, with marginal seas omitted). The two datasets are in
reasonable agreement on these planetary scales, with amplitude greater in the Argo
dataset by about 5 W/m². This difference, and the small phase difference, could be
attributed to systematic errors in either estimate or to interannual variability, with the
Argo data representing the mean for 2004-2007, and the NOC dataset being compiled
from marine meteorological reports during 1980-1993. Aside from systematic errors,
another possible contributor to the hemispheric differences is annual variability in cross-
equatorial ocean heat transport.

In Fig 4.6, zonally-averaged monthly heat gain from Argo is compared to zonally-
averaged air-sea heat flux from the NOC climatology, with the annual mean removed
from the latter. The annual patterns of ocean heat gain and air-sea flux are very similar,
consistent with the interior ocean scaling argument presented by Gill and Niiler (1973).
However, at middle latitudes in both hemispheres the amplitude of ocean heat gain
exceeds that of air-sea flux – by about 50 W/m² at 40°N and 25 W/m² at 40°S. At these
latitudes the zonally averaged temperature fields (Fig 3.1) have strong meridional
gradients due to zonal flow in the separated western boundary currents. The Gill and
Niiler (1973) interior ocean scaling does not hold in the presence of small seasonal
meridional displacements of these currents. Clear evidence that these discrepancies
occur in the western boundary currents was seen in monthly anomaly maps of ocean
heat gain minus air-sea heat flux (not shown). Further support for this explanation was
found in the salinity field discussed below. Of course, the discrepancy could also be due
to systematic errors in ocean storage gain or air-sea flux in the western boundary
current regions.
4.4 Salinity, freshwater content, and sea-surface salinity

The difference between zonally averaged March and September upper-ocean salinity is shown in Fig 4.7. This is analogous to the seasonal temperature difference of Fig 4.1, but with salinity contours from the Argo 4-year mean overlain. Several things are evident in this figure. First, the low latitude northern and southern atmospheric convergence zones are seen as out-of-phase maxima in the seasonal salinity signals at the sea surface. The maximum in salinity difference at about 8°N corresponds well with the minimum in sea surface salinity (contours). While the seasonality is equivalent in the two hemispheres, the mean salinity is much lower below the northern Inter-Tropical Convergence Zone (ITCZ) due to the stronger zonally-averaged annual mean precipitation there than in the south, where the South Pacific Convergence Zone dominates the zonal average.

Second, the net evaporative regions with high mean salinity at about 25°N and 25°S have minima in seasonality. The seasonal contrasts increase again at high latitudes where mean rainfall is high and mean salinity is low. Of interest are the seasonal signals at about 100 dbar at 40°N and to a lesser extent 40°S. The subsurface phase reversal at 40°N relative to the surface layer at that location suggests an explanation other than P-E. Instead, these signals are consistent with small meridional displacements of the mean salinity field, as are the seasonal temperature changes at these locations (Fig 4.1) and with the discrepancy between seasonal ocean heat gain and air-sea heat flux noted above. Future improvement in the comparison between heat and freshwater air-sea exchanges and oceanic storage will require that the ocean’s advective component be included, even for seasonal variations.
Finally, just as the annual mean salinity has more meridional structure than the temperature field (Fig. 3.1a and b), so the seasonally varying salinity (Fig. 4.7) is more structured than seasonally varying temperature (Fig. 4.1). This and the likelihood of greater sampling errors in seasonal salinity and precipitation estimates than in temperature and air-sea heat fluxes makes it more problematic to compare freshwater storage with P-E. In doing so (not shown), we still found reasonable agreement between seasonal freshwater gain in the surface layer and P-E from the NOC climatology in the latitude band of the ITCZ, but less so at other latitudes.

A comparison of the annual cycle in sea surface salinity (SSS) between Argo and WOA01 is shown in Fig 4.8. Argo and WOA01 show a similar pattern of annual variability in SSS, but with lower amplitude in Argo, particularly in the northern tropics. This could be due to interannual variability, or it may be that with sparser data in WOA01 the annual cycle is noisier. The historical dataset has far fewer salinity data than temperature data, with even the surface layers poorly sampled in remote southern hemisphere regions.

4.5 Steric height and ocean circulation

The annual cycle of steric height is dominated in most regions by changes in the heat content of the surface layer, with smaller contributions from salinity and from subsurface temperature changes due to ocean dynamics. Fig 4.9 shows the annual cycle of steric height (0/2000 dbar) for northern and southern hemisphere averages and for the global average (solid lines). Annual means have been removed from each. The southern hemisphere maximum in March at 2.2 cm is lower than the corresponding
northern hemisphere value of 2.7 cm in September. However, since the southern hemisphere oceans have much greater area, the phase of the global average follows that of the southern hemisphere, though the amplitude is greatly reduced by the hemispheric cancellation.

Annual sea surface height variability includes the upper ocean steric height contribution plus any annual variability in deep ocean steric height and variability in mass (bottom pressure). Fig 4.9 shows the annual sea surface height variability from satellite altimetry (Ducet et al., 2000, dashed lines), masked to represent the same northern hemisphere, southern hemisphere, and global regions as the Argo steric height. The averages were calculated for the same 2004 – 2007 period as for steric height. If we compare the Argo steric height with historical data (WOA01) or compare the 2004-2007 altimetric height with the full 1993 – 2007 altimetric record, the resulting differences due to interannual-to-decadal variability are smaller than the differences between steric height and altimetric height seen in Fig 4.9. The fact that the southern hemisphere steric annual cycle has greater amplitude than its altimetric height counterpart is interesting, and suggests a reduction in the latter due to inter-hemispheric and sea-land exchanges of mass. The out-of-phase relationship between the global averages of steric height and altimetric height has been noted previously, e.g. by Chen et al. (1998), and attributed to seasonal continental storage of water. The global average of altimetric height minus steric height, also shown in Fig 4.9 (dotted line), is similar to that of Chambers et al. (2004), who analyzed historical steric height data for this purpose, and reported the difference to be similar to mass variability measured by the GRACE satellite mission.
Geostrophic velocity and transport in the tropics has long been known to have substantial seasonal variability (e.g. Wyrtki, 1974). The subsurface maxima in September minus March temperature differences, Fig 4.1, are an expression of this dynamical signal during those months. In Fig 4.10, the annual cycle in sea surface steric height (0/2000 dbar), zonally-averaged in the central Pacific Ocean from 160°E to 140°W is shown for Argo and WOA01. A similar figure is shown by Wyrtki (1974, his Fig. 3). Fig 4.10 also shows the speed of the geostrophic flow on the sea surface, averaged over the same longitude range. The Argo and WOA01 patterns of annual variability in tropical Pacific steric height are quite similar. Argo shows less annual variation in the steric trough that marks the northern edge of the North Equatorial Counter Current (NECC) near 10°N and hence less annual variation in the strength of the NECC. It’s interesting that both the steric height and SSS have less annual variability in Argo than in WOA01 at 9°N, suggesting that interannual variability in the atmospheric annual cycle forcing may be responsible. In Fig 4.19 the Argo annual cycle in steric height also appears more regular (less noisy) on the equator and farther south.

5. Discussion and Conclusion

The temporal mean ocean and the annual cycle for the period 2004 – 2007 have been estimated from Argo data in order to compare the Argo era with historical data and to examine Argo’s annual cycle for consistency with related global ocean surface measurements. Argo data alone were used to construct the gridded dataset analyzed in this study, in order to test the array’s stand-alone capabilities, to ensure that the present estimates are not biased toward earlier data, and to ensure that they are not
contaminated by mixing of instrument types. Stable estimates of the mean and annual cycle were obtained from a first estimate based on a weighted least-squares fit to the temperature and salinity data, followed by objective analysis of monthly anomalies using statistics derived from sample correlation estimates.

It is important to recognize that a longer averaging period with the full Argo array is desirable, even though the errors in the mean are already smaller than the differences between it and historical climatologies. There remain some regions with insufficient Argo sampling, potentially leading to biases in the mean field, especially near ocean boundaries and south of 50°S (Fig 2.1). In these regions the mean remains sensitive to the details of the estimation technique until more data are available. More uniform coverage in the array will improve estimation of both the mean and the time-variability. Systematic errors in estimates of low frequency variability result from biases in the mean field in the presence of evolving data coverage. For example, if the Southern Ocean estimated mean has a warm bias, then increasing numbers of Argo floats in that region would produce a spurious appearance of cooling. Such systematic errors are seldom considered even though they may be large.

Comparison of the Argo era to the WOA01 historical hydrographic climatology (Conkright et al., 2002) emphasized that multi-decadal warming extending into the deep ocean is seen in both hemispheres at middle and high latitudes. The Southern Ocean warming is distributed across all three oceans and may include both a downward and a southward displacement of isotherms. It is accompanied by a freshening signal along pressure and density surfaces that correspond to Sub-Polar Mode Water and Antarctic Intermediate Water. The northern warming is mainly in the North Atlantic, and is
accompanied by a salinity increase of fairly recent origin. The near-surface ocean is warmer at all latitudes than the historical climatology. Its salinity is increased at middle (evaporative) latitudes and mostly decreased in regions of excess P-E.

Argo’s annual cycle appears largely consistent with the Reynolds et al. (2002) SST product for the same 2004-2007 period, with the NOC air-sea heat flux climatology (Josey et al., 1998), and with gridded satellite altimetric height (Ducet et al., 2000). Some interesting differences were identified in all of these comparisons, and may be due to systematic errors or attributable to ocean processes. The differences indicate a need for more detailed comparative studies that are beyond the scope of this work.

Error estimates were made for both the mean and variability in steric height, based on subsampling experiments that use satellite altimetry. These indicated that the Argo-minus-WOA differences are greater than Argo sampling errors. With respect to large-scale (seasonal, thousand kilometer) variability, Argo sampling was found to have reasonable signal-to-noise characteristics, better at low than high latitudes as expected, and suggesting a need for improved sampling in the Southern Ocean. It was noted that increased interannual variability will emerge when the Argo mean is extended over a longer period of time.

In any time-series study, it is tempting to wait for a longer dataset. Despite the limitations of the present Argo time-series, it is essential to begin Argo analysis now for several important reasons.

1) The Argo array continues to evolve, and should do so effectively. Questions of how well the array is performing in relation to its initial design studies (Roemmich...
et al., 1998) are central to continuing and improving the array for its goal of sampling large-scale ocean variability.

2) The present Argo dataset is a better representation of the modern upper ocean than is any historical climatology, especially in the southern hemisphere. The improvement in the mean fields resulting from a few incremental years of sampling will be smaller than the contrasts to historical data. Argo is already demonstrating its value in studies of climate variability and change.

3) The systematic pressure error in a subset of Argo floats discussed in Section 2 was discovered through scientific analysis of the data (Willis et al., 2007) rather than by the formal quality control process. Careful data analyses are needed to identify any remaining problems too subtle for the QC system, and to develop improved QC tools. Climatologies are powerful tools for QC.

4) A key activity for global ocean observations is their use in ocean data assimilating models for ocean state estimation and prediction. While these models include errors, their characterization typically does not allow inconsistencies between the data types that are assimilated. It is important to investigate the consistency of the ocean observing system through conventional statistical comparisons.

We plan to continue developing estimation techniques for interpolating the global Argo dataset, to update the mean and monthly gridded product, and to compare it with other Argo-based estimates and related datasets. The present 48-month global time-series is included with this work as supplementary material. Updates of this gridded dataset and comparable products from other authors using different dataset selection, QC procedures and estimation techniques, will be noted on Argo web sites (see
http://www.argo.net) . We believe that comparative effort by interested investigators around the world is the best pathway toward improvement of the Argo dataset, its products, and its scientific utilization. Argo’s open data policy is an invitation for everyone to join the Argo analysis initiative.

6. 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. Analysis was supported in part by the NASA JASON-1 project through JPL Contract 961424 to SIO. The authors and their part of the Argo project were supported by U.S. Argo through NOAA Grant NA17RJ1231 (SIO–JIMO). The statements, findings, conclusions, and recommendations herein are those of the authors and do not necessarily reflect the views of the National Oceanic and Atmospheric Administration or the Department of Commerce. The efforts of many international partners in planning and implementing the Argo array are gratefully acknowledged. 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 CNES. Valuable comments on the manuscript were provided by P. Sutton.
7. References


Figure Captions:

Figure 2.1.a. 1°x1° binned count of Argo temperature and salinity profiles used in this analysis, January 2004 – December 2007. b. Monthly census of profiles (green) and floats (red) used in this analysis.

Figure 2.2 The spatial correlation of Argo temperature anomaly at 2.5 (solid line), 50 (dashed), and 200 (dotted) dbar. Modeled correlations used in the objective mapping for the same pressure levels are overlain as thin lines of the same line types. The modeled spatial correlation of altimetric height anomaly relative to a 7-year mean (Willis et al., 2004) is shown as the dot-dash line.

Figure 3.1.a. Zonally-averaged temperature (°C) versus pressure for the Argo 4-year mean (contours) and Argo-minus-WOA01 difference (color shading). b. Same as (a) except for salinity. c. Same as (a) except for density (σθ).

Figure 3.2.a Map of 0 – 100 dbar vertically averaged temperature (°C) from the Argo 4-year mean (contours) and Argo-minus-WOA01 difference (color shading). b. Same as (a) except for salinity. c. Same as (a) except for density (σθ).

Figure 3.3 Global average of temperature (solid line) and salinity (dashed) difference versus depth, Argo 4-year mean minus WOA01.

Figure 3.4 Zonal average of salinity on density (σθ) surfaces from the Argo 4-year mean (contours) and salinity difference, Argo-minus-WOA01.

Figure 3.5 Time series of temperature averaged globally and over 0 – 2000 dbar (top) and globally versus pressure (bottom) from Levitus et al. (2005) for the period 1957 – 1996 and from Argo for the period 2004 - 2007. The Levitus et al. (2005) data are a 5-year running mean; the Argo data are a 1-year running mean.
Figure 3.6.a Steric height (dyn cm) of the sea surface relative to 2000 dbar from the 4-year Argo mean. b. Steric height (0/2000 dbar) difference Argo-minus-WOA01. c. Same as (a) except for 200/2000 dbar. d. Same as (a) except for 500/2000 dbar. e. Same as (b) except for 500/2000 dbar. f. Same as (a) except for 1000/2000 dbar.

Figure 3.7. Zonal average of steric height of the sea surface, 200, 500, and 1000 dbar surfaces relative to 2000 dbar for Argo (solid lines), WOA01 (dashed), and for the Argo-minus-WOA01 difference (thin dotted lines, with origins offset).

Figure 3.8 Map of the Argo sampling error’s impact on mean sea surface height (right, cm), based on adding altimetric height variations (subsampled at Argo profile locations versus not subsampled) to the WOA01 mean steric height (0/2000 dbar). See text. The left-hand panel shows the zonally averaged sampling error (red) compared to the zonally averaged difference of Argo-minus-WOA01 steric height (0/2000 dbar).

Figure 3.9. Zonally-averaged RMS (cm) of large-scale (10° x 10° x 3 month) altimetric height variability for 2004 – 2007 (solid line) and 1993 – 2007 (dotted). Argo sampling error, 2004 – 2007 (dashed), is estimated from the difference between the complete altimetric height dataset and that subsampled at Argo profile locations.

Figure 4.1 Zonally-averaged September-minus-March temperature difference (°C) versus pressure for the Argo 4-year mean.

Figure 4.2 Annual cycle of zonally-averaged temperature stratification in the upper 100 dbar (T_{100} – T_0, °C) at 42°N (solid line) and 35°S (dashed).
Figure 4.3 Annual cycle of zonally-averaged near-sea surface temperature (°C) anomaly, 2004 – 2007, from Argo (left) and Reynolds et al. (2002) SST (right).

Figure 4.4 Near-sea surface temperature from individual Argo profiles compared to the difference from monthly-averaged Reynolds et al. (2002) SST at the same locations and times (+ symbols). Averaged differences (Argo-Reynolds) in 1°C Argo temperature bins are overlain (centers of circles) as well as the standard error of the averages (error bars, assuming N/3 independent estimates).

Figure 4.5 Annual cycle in area-averaged ocean heat storage from Argo (W/m², solid lines, see text for details) compared to air-sea heat flux anomaly from the NOC 1.1 climatology (dashed, Josey et al., 1998), for the northern hemisphere, southern hemisphere, and global ocean.

Figure 4.6 Annual cycle in zonally-averaged ocean heat storage from Argo (W/m², left) compared to air-sea heat flux anomaly from the NOC 1.1 climatology.

Figure 4.7 Zonally-averaged September-minus-March salinity difference (color shading) versus pressure for the Argo climatology; zonally-averaged Argo annual mean salinity (contours).

Figure 4.8 Annual cycle in near-sea surface salinity anomaly (from the annual mean) from Argo (left) and WOA01 (right).

Figure 4.9 Annual cycle in area-averaged Argo steric height of the sea surface (solid lines, 0/2000 dbar, annual mean removed) compared to altimetric height (dashed, AVISO product) for the northern hemisphere, southern hemisphere and global ocean. The dotted line is the global average of altimetric height minus steric height.
Figure 4.10 Annual cycle in zonally-averaged Central Pacific (160°E – 140°W) steric height (0/2000 dbar) from Argo (left, contours) and from WOA01 (right, contours). The color shading indicates the corresponding speed of the surface geostrophic flow, \((u^2 + v^2)^{1/2}\), omitting values within 3° of the equator.
Figure 2.1.a. $1^\circ \times 1^\circ$ binned count of Argo temperature and salinity profiles used in this analysis, January 2004 – December 2007. b. Monthly census of profiles (green) and floats (red) used in this analysis.
Figure 2.2  The spatial correlation of Argo temperature anomaly at 2.5 (solid line), 50 (dashed), and 200 (dotted) dbar. Modeled correlations used in the objective mapping for the same pressure levels are overlain as thin lines of the same line types. The modeled spatial correlation of altimetric height anomaly relative to a 7-year mean (Willis et al., 2004) is shown as the dot-dash line.
Figure 3.1.a. Zonally-averaged temperature (°C) versus pressure for the Argo 4-year mean (contours) and Argo-minus-WOA01 difference (color shading).  b. Same as (a) except for salinity.  c. Same as (a) except for density ($\sigma_\theta$)
Figure 3.2.a Map of 0 – 100 dbar vertically averaged temperature (°C) from the Argo 4-year mean (contours) and Argo-minus-WOA01 difference (color shading). b.

Same as (a) except for salinity. c. Same as (a) except for density ($\sigma_\theta$).
Figure 3.3 Global average of temperature (solid line) and salinity (dashed) difference versus depth, Argo 4-year mean minus WOA01.
Figure 3.4 Zonal average of salinity on density ($\sigma_\theta$) surfaces from the Argo 4-year mean (contours) and salinity difference, Argo-minus-WOA01.
Figure 3.5 Time series of temperature averaged globally and over 0 – 2000 dbar (top) and globally versus pressure (bottom) from Levitus et al. (2005) for the period 1957 – 1996 and from Argo for the period 2004 - 2007. The Levitus et al. (2005) data are a 5-year running mean; the Argo data are a 1-year running mean.
Figure 3.6.a Steric height (dyn cm) of the sea surface relative to 2000 dbar from the 4-year Argo mean. b. Steric height (0/2000 dbar) difference Argo-minus-WOA01. c. Same as (a) except for 200/2000 dbar.
Figure 3.6. d. Same as (a) except for 500/2000 dbar. e. Same as (b) except for 500/2000 dbar. f. Same as (a) except for 1000/2000 dbar.
Figure 3.7. Zonal average of steric height of the sea surface, 200, 500, and 1000 dbar surfaces relative to 2000 dbar for Argo (solid lines), WOA01 (dashed), and for the Argo-minus-WOA01 difference (thin dotted lines, with origins offset).
Figure 3.8 Map of the Argo sampling error’s impact on mean sea surface height (right, cm), based on adding altimetric height variations (subsampled at Argo profile locations versus not subsampled) to the WOA01 mean steric height (0/2000 dbar). See text. The left-hand panel shows the zonally averaged sampling error (red) compared to the zonally averaged difference of Argo-minus-WOA01 steric height (0/2000 dbar).
Figure 3.9. Zonally-averaged RMS (cm) of large-scale (10° x 10° x 3 month) altimetric height variability for 2004 – 2007 (solid line) and 1993 – 2007 (dotted). Argo sampling error, 2004 – 2007 (dashed), is estimated from the difference between the complete altimetric height dataset and that subsampled at Argo profile locations.
Figure 4.1 Zonally-averaged September-minus-March temperature difference (°C) versus pressure for the Argo 4-year mean.

Figure 4.2 Annual cycle of zonally-averaged temperature stratification in the upper 100 dbar (T_{100} – T_0, °C) at 42°N (solid line) and 35°S (dashed).
Figure 4.3 Annual cycle of zonally-averaged near-sea surface temperature (°C) anomaly, 2004 – 2007, from Argo (left) and Reynolds et al. (2002) SST (right).
Figure 4.4 Near-sea surface temperature from individual Argo profiles compared to the difference from monthly-averaged Reynolds et al. (2002) SST at the same locations and times (+ symbols). Averaged differences (Argo-Reynolds) in 1°C Argo temperature bins are overlain (centers of circles) as well as the standard error of the averages (error bars, assuming N/3 independent estimates).
Figure 4.5 Annual cycle in area-averaged ocean heat storage from Argo (W/m², solid lines, see text for details) compared to air-sea heat flux anomaly from the NOC 1.1 climatology (dashed, Josey et al., 1998), for the northern hemisphere, southern hemisphere, and global ocean.
Figure 4.6 Annual cycle in zonally-averaged ocean heat storage from Argo (W/m², left) compared to air-sea heat flux anomaly from the NOC 1.1 climatology.
Figure 4.7 Zonally-averaged September-minus-March salinity difference (color shading) versus pressure for the Argo climatology; zonally-averaged Argo annual mean salinity (contours).
Figure 4.8 Annual cycle in near-sea surface salinity anomaly (from the annual mean) from Argo (left) and WOA01 (right).
Figure 4.9 Annual cycle in area-averaged Argo steric height of the sea surface (solid lines, 0/2000 dbar, annual mean removed) compared to altimetric height (dashed, AVISO product) for the northern hemisphere, southern hemisphere and global ocean. The dotted line is the global average of altimetric height minus steric height.
Figure 4.10 Annual cycle in zonally-averaged Central Pacific (160°E – 140°W) steric height (0/2000 dbar) from Argo (left, contours) and from WOA01 (right, contours). The color shading indicates the corresponding speed of the surface geostrophic flow, $(u^2 + v^2)^{1/2}$, omitting values within 3° of the equator.