In Situ Data Biases and Recent Ocean Heat Content Variability*

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ABSTRACT

Two significant instrument biases have been identified in the in situ profile data used to estimate globally integrated upper-ocean heat content. A large cold bias was discovered in a small fraction of Argo floats along with a smaller but more prevalent warm bias in expendable bathythermograph (XBT) data. These biases appear to have caused the bulk of the upper-ocean cooling signal reported by Lyman et al. between 2003 and 2005. These systematic data errors are significantly larger than sampling errors in recent years and are the dominant sources of error in recent estimates of globally integrated upper-ocean heat content variability. The bias in the XBT data is found to be consistent with errors in the fall-rate equations, suggesting a physical explanation for that bias. With biased profiles discarded, no significant warming or cooling is observed in upper-ocean heat content between 2003 and 2006.

1. Introduction

As the earth warms due to the buildup of greenhouse gasses in the atmosphere, the vast majority of the excess heat is expected to go toward warming the oceans (Levitus et al. 2005; Hansen et al. 2005). Changes in globally integrated upper-ocean heat content anomaly (OHCA) therefore have very important implications for understanding the earth's energy balance and the evolution of anthropogenic climate change.

A large and apparently significant cooling in OHCA between 2003 and 2005 was reported by Lyman et al. (2006). It has been suggested that this cooling could be attributed to transitioning from the warm-biased expendable bathythermograph (XBT) array and changes in sampling caused by the introduction of large amounts of data from the Argo array of profiling floats (more information available online at http://www.argo.net) in the Southern Ocean (AchutaRao et al. 2007). However, an additional source of systematic data errors has been discovered in a small number of Argo floats, which on balance, report temperature profiles that appear spuriously cold. In the present analysis, the cooling reported by Lyman et al. (2006) is shown to be an artifact caused by both the XBT warm bias and the cold bias in the Argo data. Estimates of the sampling error based on altimeter data suggest that changes in coverage did not contribute substantially to the spurious cooling despite the rapid introduction of new data in the Southern Ocean from the Argo array.

A description of the systematic errors in the Argo data as well as their cause and extent follows (section 2). The

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warm bias in the XBT data during the period of the cooling is discussed, and a possible explanation for its cause is presented (section 3). Finally, the effect of these biases on the OHCA estimate from 2003 through 2006 is discussed (section 4), followed by discussion and conclusions (section 5).

2. Argo data errors

In the OHCA estimate of Lyman et al. (2006), rapid cooling was exhibited in the tropical and subtropical Atlantic Ocean between 2003 and 2005. Comparison of individual temperature profiles with historical data in this region uncovered significant biases in profiles from a number of Argo floats (Fig. 1). All of the affected profiles were found in Argo real-time data, which had not undergone scientific quality control.

The data error occurs in Sounding Oceanographic Lagrangian Observer (SOLO) instruments fabricated at the Woods Hole Oceanographic Institution (WHOI) and equipped with either Falmouth Scientific, Inc. (FSI), or SeaBird Electronics, Inc. (SBE), conductivity–temperature–depth (CTD) sensors. Further investigation of the data returned by these instruments uncovered a flaw that caused temperature and salinity values to be associated with incorrect pressure values. The size of the pressure offset was dependent on float type, varied from profile to profile, and ranged from 2–5 db near the surface to 10–50 db at depths below about 400 db. Almost all of the WHOI FSI floats (287 instruments) and approximately half of the WHOI SBE floats (about 188 instruments) suffered from errors of this nature. The bulk of these floats were deployed in the Atlantic Ocean, where the spurious cooling was found.

From 1 January 2000 through 30 June 2007, the WHOI FSI floats produced approximately 20 000 profiles, almost all of which contain spurious pressure values. During the same period, WHOI SBE floats produced approximately 14 800 profiles, about 7000 of which had pressure errors. These 30 000 spurious profiles account for about 8% of the total number of Argo profiles during this period.

Although errors in the affected profiles varied depending on float configuration, their net effect was to produce a strong cold bias at depth. A regional mean of temperature differences between the affected profiles and climatological temperature from the World Ocean Circulation Experiment (WOCE) Global Hydrographic Climatology (WGHC, Gouretski and Koltermann 2004) illustrates this (Fig. 2). In contrast, the mean temperature anomaly based on non-WHOI float data from the same region and time is smaller and positive. Data used in Fig. 2 were restricted to the Atlantic Ocean between 50°S and 50°N and from 1 January 2003 to 30 June 2007.

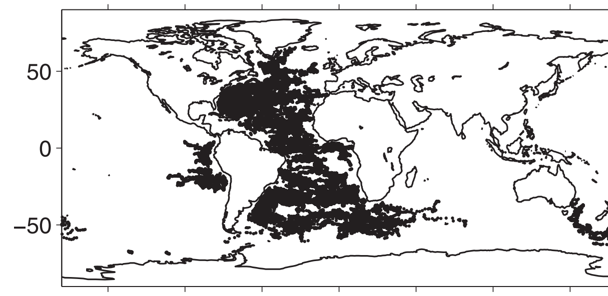

FIG. 1. Distribution of profiles from WHOI floats with spurious pressure values reported from 1 Jan 2003 through 30 Jun 2007.

This includes about 24 200 of the biased profiles and about 31 200 profiles from non-WHOI floats.

The cold bias is greater than −0.5°C between 400 and 700 m in the average over the affected data and has a vertical structure that is similar to the cooling discussed in Lyman et al. (2006). This structure is due primarily to the WHOI FSI floats, which assigned incorrect pressure values that were predominantly biased shallow. Pressure offsets in the affected WHOI SBE profiles were somewhat smaller and changed sign depending on depth and float configuration.

It is important to note that these systematic errors were caused by improper processing of data by a small subset of floats, and they do not reflect an inherent flaw in the observing system. About one-half of the affected profiles have been corrected exactly, and the remainder may eventually be corrected to a good approximation. Corrected profiles have been uploaded to the Global Data Archive Centers for a large number of the floats. Profiles that have not been corrected are now flagged as "3 – bad data that are potentially correctable," in the variable "PRES_QC." (Further details regarding the status of these data, as well as complete lists of the affected floats, may be found online at http://www-argo.ucsd.edu/Acpres_offset2.html.)

These data cannot be easily repaired by the end user because correction requires additional information reported by the floats and is not a uniform offset over entire profiles. Furthermore, the effect on an individual profile can be fairly small and difficult to detect (Fig. 2) without comparison to historical data and averaging over many profiles. Therefore, profiles that remain uncorrected should be excluded from scientific analyses that may be affected by pressure errors until corrected profiles become available.

3. XBT instrument bias

Although XBT profiles account for a large fraction of historical ocean temperature data since the late 1960s,

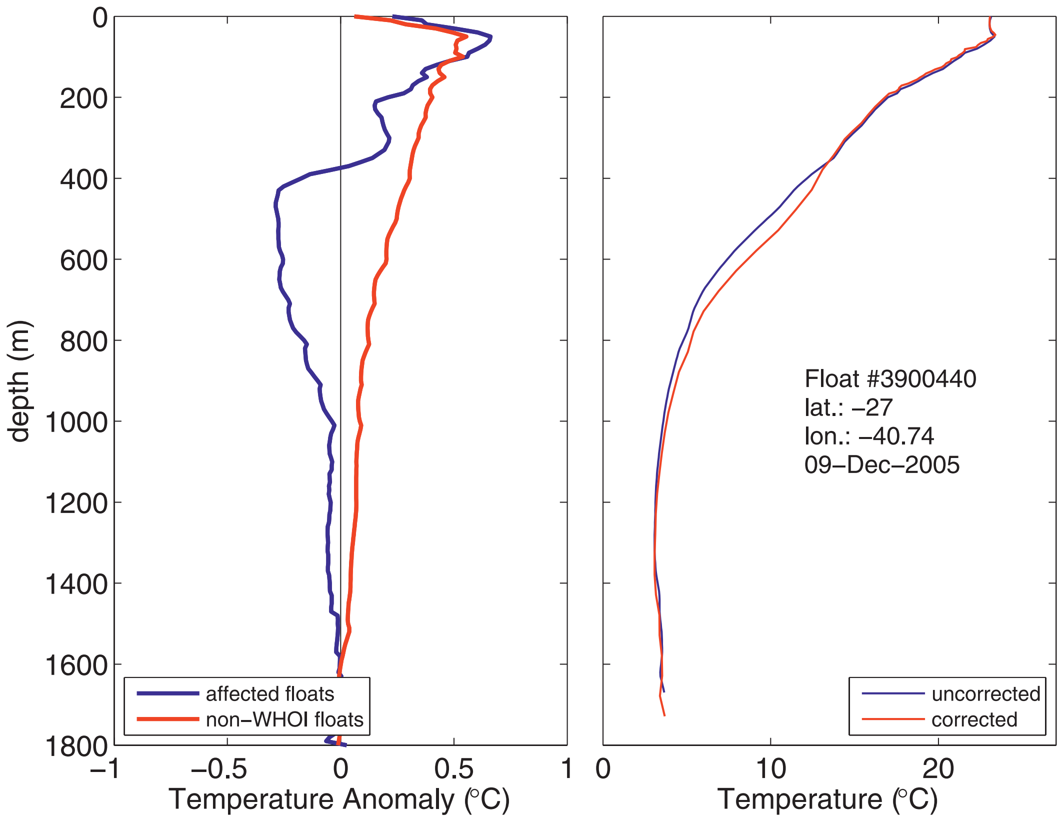

FIG. 2. (left) Temperature anomaly vs depth relative to the WGHC for WHOI floats with incorrect pressure values (blue line) and non-WHOI floats from the same region (red line). Data were restricted to the Atlantic and to latitudes between 50°S and 50°N from 1 Jan 2003 through 30 Jun 2007. (right) Effect of the correction for a single float WHOI FSI float in the south Atlantic.

these inexpensive instruments were not designed to provide climate-quality scientific data. These probes do not measure pressure or depth but instead record temperature as a function of time since the probe entered the water. They are designed to fall at a known rate, and fall-rate equations are used to convert elapsed time into depth. The existence of systematic errors in the fall-rate equations provided by the manufacturer have been known for some time, and new fall-rate equations as well as a correction factor for old XBT data have been estimated (Hanawa et al. 1995). Both here and in Lyman et al. (2006), the corrections recommended by Hanawa et al. (1995) were applied.

However, recent reports of time-dependent temperature biases in the XBT data (Gouretski and Koltermann 2007) suggest that systematic errors in the fall-rate equations may remain. Errors in the fall-rate equations result in temperatures that are assigned to the incorrect depth. If temperature biases are related to the fall-rate equations, then these biases will be better explained by considering isotherm displacements, as attempted here.

For the data used by Lyman et al. (2006), isotherm displacements were computed relative to the local temperature climatology as follows: $Z = (T - T_{\mathrm{clim}})/(\partial T_{\mathrm{clim}}/\partial z)$. Here T is observed temperature, T_{clim} is local climatological temperature from WGHC, and $\partial T_{\mathrm{clim}}/\partial z$ is the vertical temperature gradient, also computed from climatology. To test whether warm biases in recent XBT data are consistent with a fall-rate error, XBT profiles are compared with nearby Argo temperature profiles (excluding data from all affected WHOI floats).

XBT/Argo pairs are defined to be within 2° latitude, 4° longitude, and 90 days in time. This results in about 24 000 pairs from 2003 through the end of 2006. Regions with vertical temperature gradients smaller than 0.002°C m^{-1} were excluded. Median differences between isotherm displacements computed from nearby XBT and Argo profiles strongly suggest fall-rate errors (Fig. 3). The isotherm displacements derived from XBT probes are systematically deeper than Argo displacements by about 2% in the median. The fact that this discrepancy approaches zero near the surface (outside of the mixed

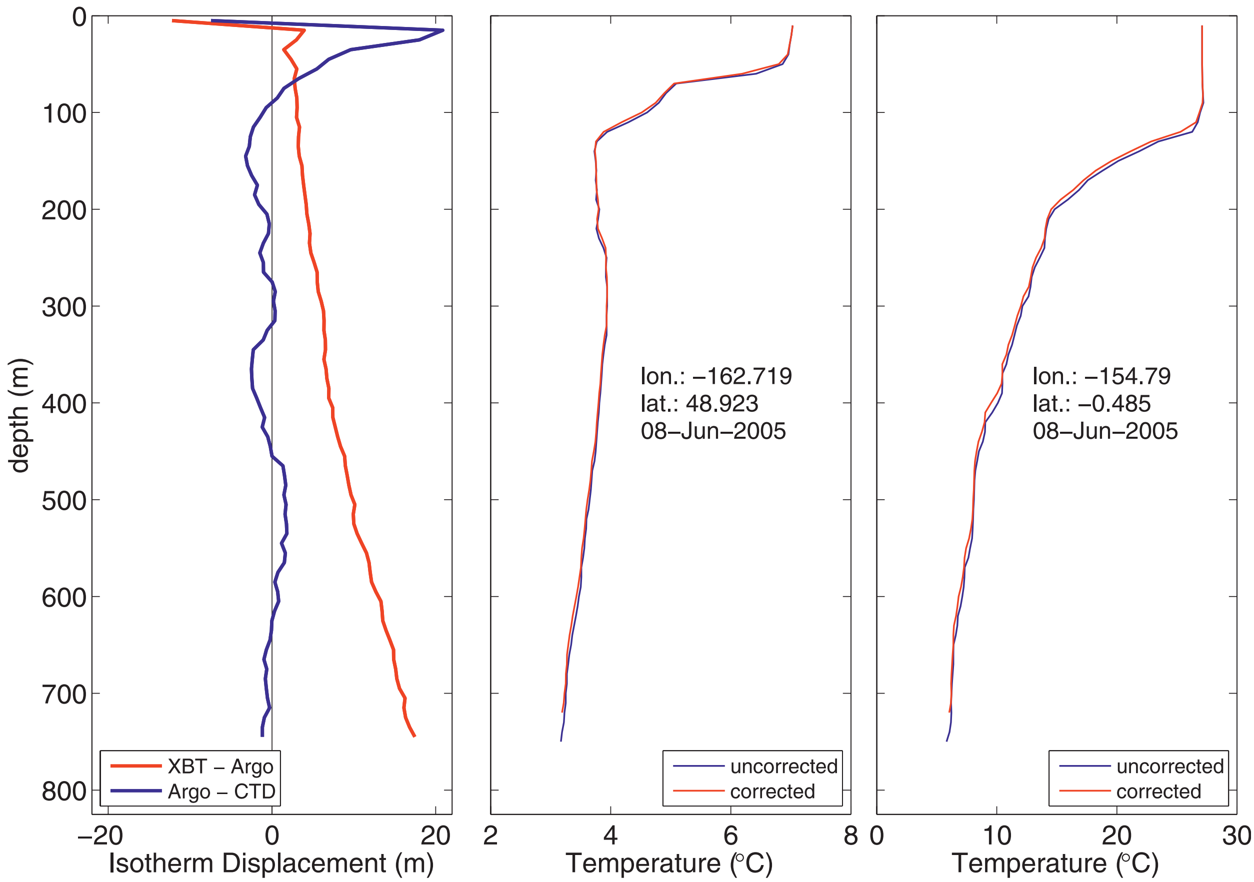

FIG. 3. (left) Median difference between isotherm displacements computed from 24 000 nearby XBT and Argo pairs collected between 1 Jan 2003 and 31 Dec 2006 (red line). Also shown is the median difference between isotherm displacements computed from 2300 nearby CTD and Argo pairs collected between 1 Jan 2000 and 31 Dec 2006 (blue line). All WHOI floats were excluded from this analysis. Positive displacements reflect deeper isotherms. Also shown is the effect of a 2% bias on two individual profiles in the (middle) North Pacific and (right) tropical Pacific.

layer) and increases linearly with depth suggests that the XBT bias is related to incorrect calibration of the fall-rate equations, rather than an actual bias in temperature.

A similar comparison between isotherm displacements from Argo (excluding WHOI float profiles) and CTD pairs from 1 January 2000 through 31 December 2006 (Fig. 3) shows no such pattern. Only about 2300 Argo/CTD pairs were available, resulting in a somewhat noisier estimate. However, the difference between displacements computed from nearby CTD and Argo profiles is close to zero over most of the depth range analyzed. The only range with large differences encompasses the surface mixed layer, where vertical temperature gradients can be small and temporal variations are large. These two factors make the near-surface results noisy. The Argo/CTD comparison suggests that once the WHOI float profiles have been removed, the remaining systematic errors in the Argo data are much smaller than systematic errors in the XBT data.

Thus, in the aggregate during the study period, XBT probes assign temperatures to depths that are about 2% too deep (Fig. 3). Despite the clear signal in the average, this bias is small and difficult to detect in individual profiles, at either high or low latitudes (Fig. 3). It is important to note, however, that the median values presented here represent an average over many different types of XBT instruments. Previous authors have shown that fall-rate errors may vary depending on probe type (Hanawa et al. 1995) and manufacturer (Kizu et al. 2005a,b). Furthermore, misapplication of corrections to fall-rate errors has compounded such problems in the past (Willis et al. 2004; Lombard et al. 2004). Therefore, we caution against application of any depth correction on the basis of the results presented here. However, a detailed analysis of XBT fall-rate errors and their dependence on time and probe type was recently completed (Wijffels et al. 2008). The 2% error in depth presented here is in good agreement with their findings for the period considered here.

4. Recent OHCA variability

The effects of these systematic data errors on OHCA estimates between 2003 and 2006 are demonstrated using subsets of the profile data. These subsets were used to compute yearly maps of OHCA in the manner of Willis et al. (2004), which were spatially integrated to produce OHCA time series (Fig. 4).

Error bars (Fig. 4) are computed as in Lyman et al. (2006) using the multisatellite estimate of sea surface height (SSH) anomaly from Archiving, Validation and Interpretation of Satellite Oceanographic (Aviso) data (Ducet et al. 2000). These error bars represent sampling error only and there may be additional uncertainties, most notably from instrument biases and inaccuracies in the climatology. Because the satellite altimeters provide near-global coverage during this period, and since numerous studies (White and Tai 1995; Gilson et al. 1998; Willis et al. 2003, 2004) have demonstrated the strong relationship between SSH anomaly and OHCA or thermosteric sea level anomaly (Zang and Wunsch 2001, their Fig. 6), altimeter data can be used as a proxy for testing the effects of in situ data sampling on estimates of globally averaged OHCA.

The OCHA estimate made using all data including spurious float profiles (Fig. 4, thick solid line) shows an apparent cooling of 77×10^{21} J from 2003 to 2006. Another estimate using all data except the spurious float profiles (Fig. 4, thick dashed line) suggests much less cooling, only about 41×10^{21} J. More than half of the erroneous cooling arises because of the increasing fraction of spurious profiles in the Argo data stream produced by the WHOI floats, primarily the floats with FSI instruments.

The effect of the XBT bias is demonstrated by making OHCA estimates from two more subsets of the data. The first is made using only Argo data but excluding the spurious WHOI profiles (Fig. 4, thin solid line). This "Argo only" estimate shows no significant warming or cooling between 2003 and 2006, with a decrease of only $-4\ (\pm 18) \times 10^{21}$ J during this period. This estimate of OHCA variability is the most robust during this short time interval.

The final OHCA estimate is made by excluding all Argo float data (Fig. 4, thin dashed line) and consists primarily of XBT profiles that are uncorrected for the fall-rate bias shown in Fig. 3. The amount of non-Argo data is small during these years, and large gaps exist in the data coverage for this estimate of OHCA. This is reflected by the 20–30 $\times 10^{21}$ J sampling error bars for this estimate (Fig. 4). Although it is not a robust estimate of OHCA, this "XBT only" estimate is 75×10^{21} J warmer than the Argo-only estimate and lies well outside the sampling error bars of either estimate. This large separation exists despite the paucity of data in the XBT-only estimate and the fact that the mapping procedure causes both estimates to relax to the same mean in regions with little data. We note that this positive offset was not visible in Lyman et al. (2006) because in that study, record-length means were subtracted from the two different OHCA estimates before plotting.

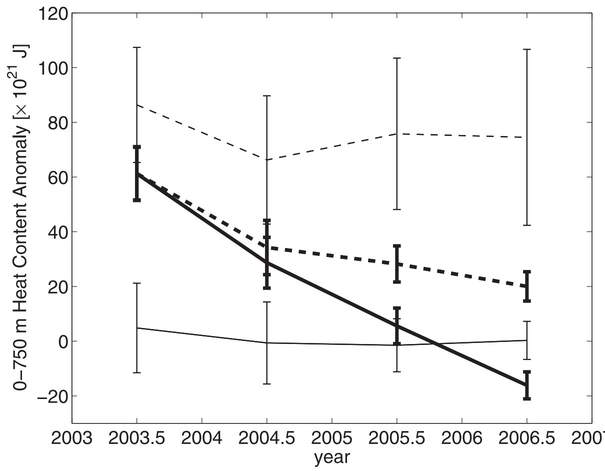

FIG. 4. Annual values of globally integrated OHCA in the upper 750 m using all available data (thick solid line), using all data except profiles from WHOI floats with spurious pressure values (thick dashed line), using only Argo data except profiles from affected WHOI floats (thin solid line), and using no Argo data (thin dashed line). As in Lyman et al. (2006), error bars reflect only sampling errors and not the complete error budget.

The reason for the apparent cooling in the estimate that combines both XBT and Argo data (Fig. 4, thick dashed line) is the increasing ratio of Argo observations to XBT observations between 2003 and 2006. This changing ratio causes the combined estimate to exhibit cooling as it moves away from the warm-biased XBT data and toward the more neutral Argo values.

To test the suggestion by AchutaRao et al. (2007) that increased sampling in the Southern Ocean from the Argo array was partly responsible for the spurious cooling, an experiment was conducted using the Aviso data as a proxy for OHCA. The technique was similar to the one used to determine the sampling error (Lyman et al. 2006). Altimetric height was first subsampled by interpolating to the time and location of each profile. The subsampled data were then mapped using the same mapping procedure as that of the OHCA estimates. The resulting maps of altimetric height were globally averaged and compared with the globally averaged Aviso maps (Fig. 5). This exercise illustrates the effect of the changing in situ data distribution on estimates of the global average. Although the subsampled estimate dips

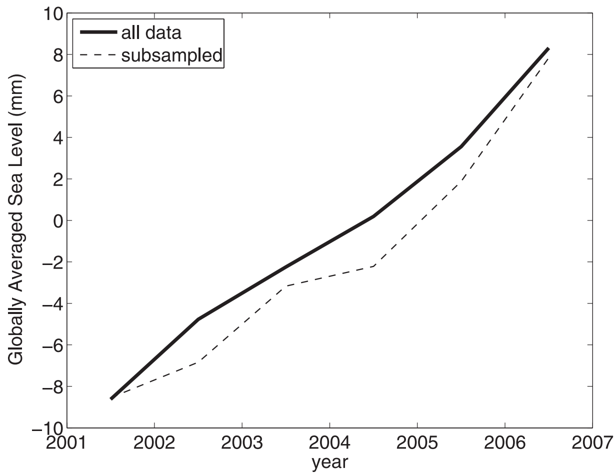

FIG. 5. Globally averaged sea level from altimeter data. Comparing sea level estimated by averaging over the Aviso maps of SSH (solid line) vs that from Aviso data subsampled at in situ data locations, mapped, and globally averaged (dashed line) illustrates the effect of changing in situ data distributions during the spinup of the Argo array on estimates of the global mean.

slightly farther below the fully sampled estimate between 2003 and 2004, it increases more rapidly than the fully sampled estimate between 2005 and 2006. It should be noted that SSH is only a proxy for OHCA, as it contains mass, freshwater, and deep temperature signals that are not in upper OHCA. Nevertheless, this result suggests that the increased sampling of the Southern Ocean by the Argo array did not cause a significant bias in the OHCA estimates. This finding is consistent with those of Lyman and Johnson (2008), who present a more detailed look at the effect of historical in situ sampling patterns on OHCA in the context of Aviso SSH.

5. Discussion and conclusions

Systematic pressure errors have been identified in real-time temperature and salinity profiles from a small number of Argo floats. These errors were caused by problems with processing of the Argo data, and corrected versions of many of the affected profiles have been supplied by the float provider. Profiles that remain uncorrected, however, may be unsuitable for many oceanographic analyses. Recent scientific results that relied heavily on real-time Argo data in the tropical and subtropical Atlantic downloaded prior to 31 October 2007 (W. B. Owens and C. Schmid, personal communication 2007) may require re-examination for sensitivity to these errors. Argo data users should be aware that real-time Argo data only undergo rudimentary checks, and only delayed-mode Argo data have undergone rigorous quality control and been examined by the float providers. Although details will vary depending on the application, users of real-time Argo data may wish to apply quality control procedures such as those described by Willis et al. (2008) for making estimates of globally averaged quantities such as globally averaged OHCA or steric sea level.

Most of the rapid cooling reported by Lyman et al. (2006) is demonstrated to be the result of the combination of this cold bias in the spurious Argo data and the transition from an ocean-observing system dominated by warm-biased XBT data to one dominated by Argo data. Furthermore, these systematic errors are shown to be significantly larger than estimated sampling errors in OHCA. It is also shown that sampling changes from the Argo array in the Southern Ocean are unlikely to have made a significant contribution to the spurious cooling.

OHCA does not appear to exhibit significant warming or cooling between 2003 and 2006. However, without fully addressing the XBT bias, it does not seem prudent to combine XBT data with data from the Argo array to produce a long-term estimate of OHCA. Furthermore, only in 2003 did Argo coverage become adequate to determine the global integral without including XBT profiles. For these reasons, OHCA variability is not estimated prior to 2003 in the present analysis.

Here errors in the fall-rate equations are proposed to be the primary cause of the XBT warm bias. For the study period, XBT probes are found to assign temperatures to depths that are about 2% too deep. In the global integral, this fall-rate error is consistent with results here—that XBT-based OHCA estimates are biased warm by about 73×10^{21} J relative to Argo-based estimates during this period.

The cooling reported by Lyman et al. (2006) would have implied a very rapid increase in the rate of ice melt in order to account for the fairly steady increase in global mean sea level rise observed by satellite altimeters over the past several years. The absence of a significant cooling signal in the OHCA analyses presented here brings estimates of upper-ocean thermosteric sea level variability into closer agreement with altimeter-derived measurements of global mean sea level rise. Nevertheless, some discrepancy remains in the globally averaged sea level budget, and observations of the rate of ocean mass increase and upper-ocean warming are still too small to fully account for recent rates of sea level rise (Willis et al. 2008). Temperature changes in the deep ocean (e.g., Johnson et al. 2007) may account for some of that discrepancy, at least over multidecadal time scales (Domingues et al. 2008).

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Program (http://www.nodc.noaa.gov). Float data were collected and made freely available by Argo (a pilot program of the Global Ocean Observing System) and contributing national programs (http://www.argo.net/). Altimeter products used herein were produced by Ssalto/Duacs as part of the Environment and Climate EU Enact project (EVK2-CT2001-00117) and distributed by Aviso, with support from CNES. This research was carried out in part at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. JML and GCJ were supported by the NOAA/Climate Program Office and the NOAA/Office of Oceanic and Atmospheric Research. Comments from multiple anonymous reviewers improved the manuscript. The findings and conclusions in this article are those of the authors and do not necessarily represent the views of the National Oceanic and Atmospheric Administration.

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