LETTERS

Robust warming of the global upper ocean

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A large (~10^{23} J) multi-decadal globally averaged warming signal in the upper 300 m of the world's oceans was reported roughly a decade ago[1] and is attributed to warming associated with anthropogenic greenhouse gases[2,3]. The majority of the Earth's total energy uptake during recent decades has occurred in the upper ocean[3], but the underlying uncertainties in ocean warming are unclear, limiting our ability to assess closure of sea-level budgets[4–7], the global radiation imbalance[8] and climate models[5]. For example, several teams have recently produced different multi-year estimates of the annually averaged global integral of upper-ocean heat content anomalies (hereafter OHCA curves) or, equivalently, the thermosteric sea-level rise[5,9–16]. Patterns of interannual variability, in particular, differ among methods. Here we examine several sources of uncertainty that contribute to differences among OHCA curves from 1993 to 2008, focusing on the difficulties of correcting biases in expendable bathythermograph (XBT) data. XBT data constitute the majority of the *in situ* measurements of upper-ocean heat content from 1967 to 2002, and we find that the uncertainty due to choice of XBT bias correction dominates among-method variability in OHCA curves during our 1993–2008 study period. Accounting for multiple sources of uncertainty, a composite of several OHCA curves using different XBT bias corrections still yields a statistically significant linear warming trend for 1993–2008 of 0.64 W m^{-2} (calculated for the Earth's entire surface area), with a 90-per-cent confidence interval of 0.53–0.75 W m^{-2}.

A host of choices must be made when computing OHCA curves. These choices include how to quality-control the data, which mapping technique to use, which baseline mean climatology to use, which annual cycle to remove, how to treat unsampled or undersampled areas, and how to correct biases in data from XBTs and other instruments. The several teams working on the problem around the world make their own choices and have produced apparently different OHCA curves[16].

We assess the differences arising from these choices by overlaying the curves produced by each team (Fig. 1). For this gross comparison, the curves are aligned by removing their individual means for 1993–2006, the time period over which most of the curves overlap. The curves show significant warming of the global upper ocean for the past 16 yr. Most of their warming rates (Table 1) are consistent, agreeing within their published uncertainties.

However, there are differences in interannual variability among the curves. For example, from 1997 to 1998 (during a strong El Niño) some curves appear to show cooling, some seem to show warming and others seem to show no change. Other years show similar variations among curves. Offsets among the curves may originate from differences in the reference period from which the heat content anomalies are computed, making it difficult to assess differences among the curves.

The individual OHCA curves all flatten out after around 2003, with some variability among curves in the year in which this levelling occurs. The causes of this flattening are unclear, but sea surface temperatures have been roughly constant since 2000[17]. Although sea level has continued to rise steadily during this period, an increase in the amount of water added to the ocean by melting continental ice in recent years may account for most of this rise even with very little change in ocean heat content[6,7,18]. However, this resolution of the sea-level budget leaves the global energy budget with a large residual for this time period, because it takes less energy to melt ice than to warm the ocean for the equivalent sea-level rise[18,19].

The flattening of OHCA curves also occurs around the time (2004) that the Argo array of autonomous profiling floats first achieved near-global coverage[20] and became the primary source of OHCA data. The Argo array affords year-round sampling of the temperature and salinity of the ice-free oceans over the 0–2,000-m layer, with a nominal separation of 3° in latitude and longitude. The transition from an ocean temperature record consisting primarily of ship-based XBT data to one dominated by high-quality conductivity–temperature–depth (CTD) instrument data from Argo floats occurred between

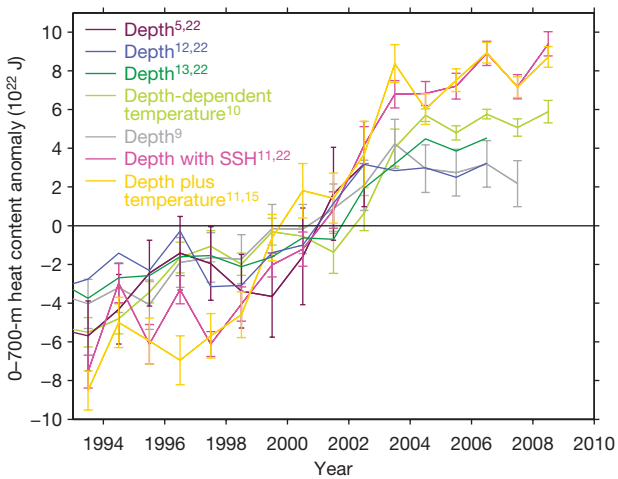

Figure 1 | OHCA curves using published methods. Globally integrated annual average OHCA curves from 0 to 700 m, estimated using methods published in papers cited in the key. All OHCA curves are estimated using different baseline climatologies, mapping methods and XBT corrections (first reference). Types of XBT bias corrections used include depth, depth-dependent temperature and depth with sea surface height (SSH; second reference, if different from first). Each curve has had its 1993–2006 mean removed to aid comparison, except for the depth[5,22] curve, which has been aligned with the 1993–2002 mean of the other curves. Error bars, 1 s.e.m. (Supplementary Information).

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Table 1 | Warming rate bounds at 90% confidence

Type of XBT bias correction	Warming rate normalized to area of the Earth (W m^{-2})	Effective degrees of freedom
XBT depth plus temperature[11,15]	0.89–0.95	6.4
XBT depth-dependent temperature[10]	0.52–0.58	5.4
XBT depth[9]	0.35–0.45	7.2
XBT depth with SSH[11,22]	0.78–0.90	4.9
XBT depth[12,22]	0.26–0.42	5.0
XBT depth[13,22]	0.36–0.50	4.3

Confidence intervals are estimated from slopes of uncertainty-weighted lines fitted to the OHCA curves in Fig. 1 for the years 1993–2006 (Supplementary Information). If no uncertainties are plotted in Fig. 1 then the uncertainties of the pink curve were used in the weighted least-squares fit. The first reference in the first column is for the mapping method and the second (if different from the first) is for the XBT correction. For details on the effective degrees of freedom, see Supplementary Information. SSH, sea surface height.

roughly 2000 and 2005[9], and marked a revolution in ocean observing. Argo has dramatically increased the sampling in the Southern Ocean since 2004[11]. However, we find that this region continues to warm from 2004 to 2008 (not shown) and apparently did not contribute to the flattening of the OHCA curves. The fact that this transition occurred at the same time as the flattening could be coincidental, but also raises the possibility of a yet-undiscovered bias in the observing system.

The XBT was designed primarily to estimate ocean sound speed for submarine warfare. As XBT data began to be used for more sensitive climate research of the sort discussed here, partly correctable temporal and spatial biases in both XBT temperature and XBT depth were discovered[9,10,15,21,22].

We compare the effects of five different methods of correcting these XBT biases in OHCA curves. All the methods attempt to eliminate the XBT biases by comparing XBT data with higher-accuracy data from different platforms, mainly CTD and bottle data from ships and Argo floats; one method in addition uses satellite-derived sea surface height[22]. The corrections vary in time and in the types of bias they are designed to remove. Biases can result from a variety of problems with XBTs and how they are deployed, and they can affect both the depths and the temperatures that make up a profile[23]. One example is estimating how the rate at which the XBTs fall through the water has changed over time as the instruments have subtly changed, as this fall rate is used to infer the depths of the temperature measurements. Choices that have been made are to focus on the fall-rate issue and obtain corrections to the observation depths[9,22], to correct both temperature and depth biases using depth-dependent adjustments to the temperature measurements[10], and to obtain adjustments for both the depths and the temperatures[15].

A further difficulty in estimating XBT bias adjustments is that there are multiple types and manufacturers of XBTs, each with its own bias history. However, the XBT metadata are incomplete. For example, XBT type and manufacturer were not recorded for about half the data archive[9,24]. These partial metadata make consistent application of the different XBT corrections difficult.

We acquired five differently assembled, quality-controlled XBT data sets, each used to produce a different OHCA curve. Each research team supplied their own bias-corrected XBT data for this study, ensuring that the XBT corrections are applied in the manner intended. Additionally, we apply four of the XBT corrections to the same EN3 (version 2a; http://www.metoffice.gov.uk/hadobs/en3) XBT data set[12,13,25] using published corrections (Fig. 2, dotted lines). Each of these nine corrected XBT data sets are combined with other non-XBT *in situ* data and mapped using the same method (Fig. 2, solid lines; Supplementary Information), relative to the same 1993–2002 reference period. This procedure ensures that remaining differences are entirely due to differences in XBT bias corrections and XBT quality control. These differences are used to help determine the uncertainties in OHCA estimates (Supplementary Information).

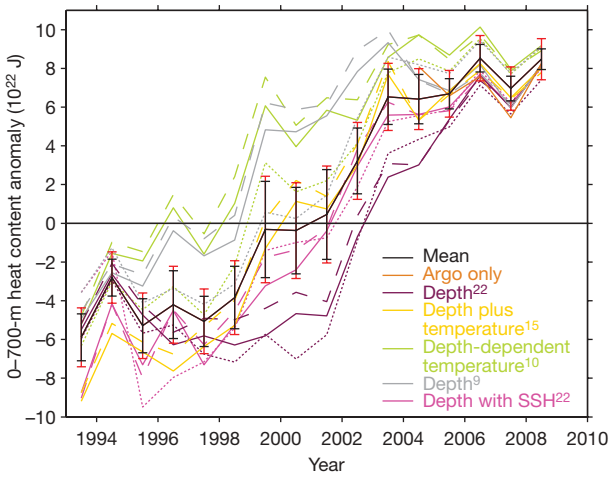

Figure 2 | OHCA curves produced using the same mapping technique. Solid lines are OHCA curves with a single 1993–2002 climatology and variously corrected XBT data provided by individual research teams. Dashed and dotted lines show the same thing as the solid lines, but using a single 2005–2008 climatology (dashed) or applying different published XBT corrections to the identical EN3 (version 2a) XBT data set (dotted). The key describes the type of XBT bias correction, with references. The trend estimate of the mean curve (black line; red error bars, 90% confidence intervals) is 0.64 ± 0.11 W m^{-2} and has 5.7 effective degrees of freedom (Supplementary Information); red error bars show the overall uncertainty, determined from combining all of the individual uncertainties in Fig. 3 assuming they are uncorrelated. Black error bars show XBT correction and XBT quality-control uncertainty from Fig. 3. The difference between the global means of the two climatologies has been added to the dashed lines.

A mean (Supplementary Information) of the nine resulting 16-yr OHCA curves (Fig. 2, black line) has the same general shape as the curves in Fig. 1: a decadal warming with a flattening after 2003. Unlike Fig. 1, these curves can be compared directly and net offsets among the different curves reflect biases due to differences in XBT bias correction and quality control.

Argo has greatly improved the spatial and temporal sampling of the global ocean[11]. This impact is most striking in the Southern Ocean, where there have historically been few observations, especially during the austral winter, owing to the remote location and harsh environment. The anthropogenic-warming signal is thought to be large in the Southern Ocean because of the role of varying air–sea fluxes in the formation regions of bottom and intermediate waters[26–29]. However, the poor historical sampling there means that it is difficult to define an adequate baseline climatology for the Southern Ocean. Recent modelling results suggest that increased sampling in the Southern Ocean could lead to an artificial reduction in OHCA[30]. To assess the sensitivity of the time series to the reference period, the OHCA curves are also computed using a climatology for 2005–2008 (Fig. 2, dashed lines), a period when the Southern Ocean was fairly well sampled by Argo floats. Because the global ocean was warmer for this period than for 1993–2002, for comparison the curves relative to the 2005–2008 climatology are shifted here by 7.7×10^{22} J, which is the difference in global heat content between the two climatologies. The remaining differences among the OHCA curves produced using the two different climatologies are negligible and therefore add little to the overall uncertainty.

We also estimate uncertainty associated with mapping methodology, effects of irregular or sparse geographical sampling, and the use of different climatologies (Fig. 3; Supplementary Information). These uncertainty estimates are combined, assuming that they are uncorrelated, to produce an overall uncertainty in the OHCA curve (Fig. 3, red line). From 1995 to 2004, the XBT uncertainty dominates, increasing from 1994 to 1999 as the number of coincident XBT–CTD measurement pairs decreases[10,15,22], and reaching a peak of about

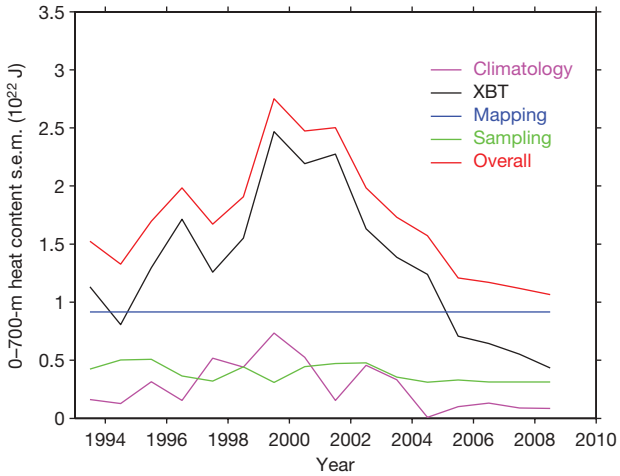

Figure 3 | Uncertainties in OHCA. Estimates of uncertainties (described in Supplementary Information) arising from the choice of climatology (magenta line), the method of XBT correction and XBT quality control (black line), the choice of mapping methodology (blue line) and the effects of irregular and sparse sampling (green line). All uncertainties are displayed as 1 s.e.m. The overall uncertainty, calculated by combining the individual uncertainties assuming they are uncorrelated, is also shown (red line).

2.4×10^{22} J lasting from 1999 to 2000, with smaller contributions to the overall uncertainty from the other terms. The XBT uncertainty begins to decrease after 2000, as the Argo array of profiling floats reaches maturity, decreasing the relative contribution of XBT data to the OHCA estimates.

We fit a line using weighted least squares (Supplementary Information) to the mean OHCA curve (Fig. 2, black line), using the overall uncertainty (Fig. 2, red error bars) for each year in the fit. These uncertainties are large enough that interannual variations, such as the 2003–2008 flattening, are statistically meaningless. We estimate a warming rate of $0.63 \pm 0.28\ \mathrm{W\,m^{-2}}$ (uncertainties at the 90% confidence level) for 1993–2003, which is slightly (but not significantly) higher than the value of $0.5 \pm 0.18\ \mathrm{W\,m^{-2}}$ stated in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. The fit to the entire 16-yr record, including the well-sampled Argo years, yields a more robust warming rate of $0.64 \pm 0.11\ \mathrm{W\,m^{-2}}$. The large uncertainties in OHCA introduced by the XBTs would undoubtedly have a similar effect on trends in thermosteric sea level (not shown).

Since the Fourth Assessment Report, the discovery of a time-varying bias in XBT data has prompted re-evaluations of the rate of upper-ocean warming. We have carried out an intercomparison of these estimates of ocean warming and made a comprehensive estimate of the total uncertainty. We find that uncertainties in XBT bias corrections are the dominant error source over the period 1993–2008, which limits our ability to resolve interannual changes in ocean heat content. However, despite these uncertainties, we still find a robust warming over the 16-yr record. We are optimistic that with more work the uncertainty associated with XBT bias corrections may be reduced in future, possibly leaving the mapping methodology, which is also improvable, as the largest uncertainty.

METHODS SUMMARY

We obtained Argo data from the US Argo Global Data Assembly Center (http://www.usgodae.org/argo/argo.html) and non-Argo and non-XBT data from the World Ocean Database 2005 (WOD05)[24]. We downloaded both Argo float and WOD05 data on 14 September 2009. We estimate anomalies by taking differences both from a mean all-year climatology and from a seasonal cycle defined by the quarterly annual cycle from the World Ocean Database 2001 (WOD01). (WOD05 and WOD01 can be found at http://www.nodc.noaa.gov/OC5.) We estimate baseline climatologies for different time periods using corrected XBT data[10] and by mapping all available data using an objective mapping technique[11]. Unless otherwise stated, we map and integrate anomalies using a weighting that assumes unsampled areas have the same OHCA as the mean of the sampled areas[11], which slightly increases our trend estimates relative to previously reported values.

The 90% confidence intervals given for the OHCA trend estimates in Fig. 2 and Table 1 are computed from weighted least-squares fits (Supplementary Information).

We focus on the period from 1993 onwards because the sampling uncertainty during this time period is well defined and relatively small[11]; there are sufficiently few profiles from mechanical bathythermographs, which have their own biases[9]; and the XBT correction that uses satellite-derived sea surface height is available only from 1993[22].

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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