AMERICAN
METEOROLOGICAL
SOCIETY

Bulletin of the American Meteorological Society

The DOI for this manuscript is doi: 10.1175/BAMS-D-15-00031.1

The final published version of this manuscript will replace the preliminary version at the above DOI once it is available.

If you would like to cite this EOR in a separate work, please use the following full citation:

Cheng, L., J. Abraham, G. Goni, T. Boyer, S. Wijffels, R. Cowley, V. Gouretski, F. Reseghetti, S. Kizu, S. Dong, F. Bringas, M. Goes, L. Houpert, J. Sprintall, and J. Zhu, 2015: XBT Science: assessment of instrumental biases and errors. Bull. Amer. Meteor. Soc. doi:10.1175/BAMS-D-15-00031.1, in press.

XBT Science: assessment of instrumental biases and errors

Lijing Cheng[1,*], John Abraham[2], Gustavo Goni[3], Timothy Boyer[4], Susan Wijffels[5], Rebecca Cowley[5], Viktor Gouretski[6], Franco Reseghetti[7], Shoichi Kizu[8], Shenfu Dong[9,3], Francis Bringas[3], Marlos Goes[9,3], Loïc Houpert[10], Janet Sprintall[11], Jiang Zhu[1]

[1.] International Center for Climate and Environment Science, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China
[2.] University of St. Thomas, St. Paul, MN, USA
[3.] Atlantic Oceanographic and Meteorological Laboratory, NOAA, Miami, FL, USA
[4.] National Oceanographic Data Centre, Silver Spring, MD, USA
[5.] CSIRO Oceans & Atmosphere Flagship, Hobart, Tasmania, Australia
[6.] University of Hamburg, KlimaCampus, Hamburg, Germany
[7.] ENEA National Agency for New Technologies, Energy and Sustainable Economic Development, S.Teresa, Italy
[8.] Tohoku University, Sendai, Japan
[9.] CIMAS, University of Miami, Miami, FL, USA
[10.] Scottish Association for Marine Science, Scottish Marine Institute, Oban, UK
[11.] Scripps Institution of Oceanography, UCSD, La Jolla, CA, USA

CORRESPONDING AUTHOR: Lijing Cheng, International Center for Climate and Environment Science, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China, 100029

Email: chenglij@mail.iap.ac.cn

Abstract

eXpendable BathyThermograph (XBT) data were the major component of the ocean temperature profile observations from the late 1960s through early 2000s, and XBTs still continue to provide critical data to monitor surface and subsurface currents, meridional heat transport, and ocean heat content. Systematic errors have been identified in the XBT data, some of which originate from computing the depth in the profile using a theoretically- and experimentally derived fall rate equation (FRE). After in-depth studies of these biases and discussions held in several workshops dedicated to discuss XBT biases, the XBT science community met at the Fourth XBT Science Workshop and concluded that XBT biases consist of: 1) errors in depth values due to the inadequacy of the probe motion description done by standard FRE, and 2) independent pure temperature biases. The depth error and temperature bias are temperature dependent and may depend on the data acquisition and recording system. In addition, the depth bias also includes an offset term. Some biases affecting the XBT-derived temperature profiles vary with manufacturer/probe type and have been shown to have a time dependence. Best practices for historical XBT data corrections, recommendations for future collection of metadata to accompany XBT data, impact of XBT biases on scientific applications, and challenges encountered are presented in this manuscript. Analysis of XBT data shows that, despite the existence of these biases, historical XBT data without bias corrections are still suitable for many scientific applications, and that bias corrected data can be used for climate research.

Capsule Summary

Based on in-depth studies, recommendations for correcting biases in XBT data, and the impact on applications and ongoing research to improve the quality of future XBT data are provided.

INTRODUCTION

eXpendable BathyThermographs (XBTs) are probes that provided the major portion of ocean subsurface temperature observations during the late 1960s through early 2000s. XBTs were designed for naval use, to enable quick collection of a sound velocity profile and as such do not have a high accuracy or precision. The research community quickly adopted the technology, and many millions of profiles have since been collected. The use of the data has changed over time and now XBT data is a valuable resource for climate studies, despite the simplicity of the probe design. More than 38% (41% for all profiles deeper than 100m depth) of upper ocean temperature profiles in the World Ocean Database 2013 (Boyer et al. 2013) were provided by XBTs from 1970 to 2001 (Figure 1). Currently, approximately 18,000 XBTs are deployed every year mostly along fixed transects and in high-density mode, where each transect is repeated approximately 4 times per year and the deployments are carried out every 20-30 km (Figure 2). Scientific studies to monitor the variability of surface and subsurface currents and of meridional heat transport along fixed transects, ocean and climate modeling, ocean data assimilation, and climate change attributions rely strongly on XBT data (Goni et al. 2010; Abraham et al. 2013; Rhein et al. 2013), and XBTs continue to provide critical data with a spatial and temporal sampling that cannot be currently obtained using any other observational platform (Boyer et al. 2013; Abraham et al. 2013).

Biases in XBT data were identified in the 1970s, soon after XBT manufacture began. The quantity of the data makes it highly valuable and therefore, much effort has been expended to correct the known biases. Many authors have attempted to quantify the size of the bias by comparing XBT profiles with co-located high quality data from Conductivity, Temperature, Depth (CTD) instruments (Anderson, 1980;

Flierl and Robinson, 1977; Hallock and Teague, 1992). Hanawa et al. 1995 collected several hundred XBT/CTD comparisons and provided a global correction for XBT data, which was not time-dependent. The community accepted the new coefficients proposed, and data was collected with a mix of both old and new coefficients. In some cases, the coefficients used were not identified in the metadata, compounding the current problem of providing accurate correction schemes. In the 2007 Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC-AR4), (Bindoff et al., 2007) reported a contradiction between observation-based estimate on historical OHC change and models results. For instance, there is a warming decade during late-1970s~early 1980s, which can neither be explained by any existing theory nor be simulated by climate models. Subsequently, Gouretski and Koltermann 2007 identified that XBT biases were time variable and identified a large bias during the 1970s to 1980s, partly explaining the incorrect warming reported during this decade. This study triggered more scrutiny of XBT biases, with many scientists working to identify, quantify, and remove the biases in XBT data and ultimately provide a reliable climate quality data set of subsurface ocean temperatures.

The international XBT science team, formed in 2011, continues efforts to fully understand and correct the XBT bias. A series of workshops have been held: in Miami/United States; 2008, Hamburg/Germany, 2010; and Melbourne/Australia, 2011. Since 2007, several important factors affecting XBT biases have been identified, and more than 10 correction schemes for the historical XBT dataset proposed.

It is timely to summarize the recent progresses in XBT science and provide future guidelines for XBT bias corrections and data applications. Understanding and correcting systematic errors in XBT measurements help to enhance their use for broader ocean and climate studies. On this basis, the Fourth XBT Science Workshop was held in Beijing, China, on November 11-13, 2014, with the participation of 34 experts from 11 countries and 18 universities, laboratories, and organizations. This workshop focused on discussing recent advances in assessing XBT data biases and their impact on applications, and on reaching a consensus to recommend bias corrections for the global XBT data set. In this manuscript, we present a summary of XBT science and key recommendations agreed upon by members of the XBT scientific community for correcting historical XBT data, and for best practices in the future collection of XBT observations.

CORRECTING TIME-DEPENDENT XBT BIASES: RECOMMENDED FACTORS

It has been found that biases in XBT data consist of both systematic depth error and independent pure temperature bias (Reseghetti et al. 2007; Gouretski and Reseghetti 2010; Cowley et al. 2013). These biases have been shown to depend on several parameters, including the probe-type, water temperature, launch height, and data acquisition system, with the total bias being time dependent (Di Nezio and G. Goni, 2011; Gouretski and Reseghetti 2010; Abraham 2012b; Cowley et al. 2013; Cheng et al, 2014; Bringas and Goni, 2015). Variations in manufacturing processes and changes in recording systems are identified as the primary source of time-dependent biases. The exact timing of changes to the XBT system (e.g. analog to digital acquisition system, change of probe nose, thermistor, twin-wire, plastic afterbody, wire-coating, etc) is not known. Further, small variations in the probe physical dimensions over time make it difficult to provide a correct description of the problem. As a result, proposed correction schemes should include a time variation in each of the correction factors.

During the Fourth XBT Science Workshop, the participants agreed that in order to correct systematic errors in the historical XBT dataset, the following corrections (which are equally important) should be performed in order to improve the quality of XBT data:

1) Fall-rate equation coefficients: These are the coefficients in the fall rate equation (FRE). The FRE models the free falling motion of the XBT probe in the water. The FRE has the form: $z(\mathrm{t})=a\mathrm{t}-b\mathrm{t}^2$; where t is the elapsed time of the descent of the probe in the water in seconds, and a and b are fall rate coefficients, representing the initial fall rate and deceleration, respectively (Green 1984). The coefficients a and b in the FRE have been shown to have variability in time (Hanawa and Yoritaka 1987; Hanawa et al. 1995; Gouretski and Reseghetti 2010). Numerous studies show that the depths calculated using the manufacturer coefficients (originally developed by Sippican (main manufacturer of the XBT probes, now acquired by Lockheed Martin)) have a systematic bias (e.g. Flierl and Robinson 1977; Hanawa and Yoritaka 1987; Singer 1990). In the mid-1990s, a research group under the coordination of Integrated Global Ocean Services System (IGOSS) (Hanawa et al. 1995) updated the original FRE coefficients for the most commonly used XBT probe types, based on comparisons with the more accurate collocated data obtained by CTD profilers. These new coefficients were expected to fully correct the fall rate biases. However, it was later shown that the FRE coefficients a and b were time-dependent (Wijffels et al. 2008; Di Nezio and Goni 2011; Cowley et al. 2013; Cheng et al. 2014) and that variations in the FRE coefficients existed due to probe type and manufacturer, which were previously thought to behave identically (Kizu et al. 2005a; 2005b; Gouretski and Reseghetti 2010; Abraham et al. 2012a; Kizu et al. 2011; Cowley et al. 2013;

Cheng et al. 2014). In addition, it has also been shown that the systematic depth errors are a function of water temperature (Thadathil et al. 2002; Kizu et al. 2005b; Cheng et al. 2014). Water viscosity is highly dependent on its temperature, which affects the probe motion. Further studies are needed to correctly quantify this effect.

2) Pure temperature bias correction: The correction of biases not included in the depth estimates and that are temperature dependent. Studies have shown that XBT recording systems have the largest impact on the pure temperature bias. Analog recording systems were mainly used before 1985 and have been found to produce positive pure temperature biases of approximately 0.15°C (Emery et al. 1986), and 0.13°C (Heinmiller 1983; Cowley et al. 2013). Digital systems, which were mainly used after 1989, produced usually smaller biases, in the most cases with positive values ranging from 0.01 to 0.07°C (Emery et al. 1986; Bailey et al. 1989; Wright 1991; Kizu and Hanawa 2002b; Cowley et al. 2013). This pure temperature bias is also due to inaccuracies in the data acquisition system (thermistor, copper wire, cables, digitizer, electronics, and computer) (Heinmiller et al. 1983; Green 1984; Reseghetti et al. 2007). It has been also reported that the pure temperature bias is variable with time and probe type (e.g. Gouretski and Reseghetti 2010; Cowley et al. 2013; Hamon et al. 2013; Cheng et al. 2014). This bias has been observed to robustly increase with the temperature of water flowing past the XBT thermistor (Reverdin et al. 2009; Cowley et al. 2013; Cheng et al. 2014). However, the reason for this temperature dependency and recorder dependency is not yet fully understood.

3) Depth offset correction. Recent studies show that the XBT depth can be better corrected by adding an offset term to the FRE ($Depth=at-bt^2-offset$), which was not allowed conventionally (Cowley et al. 2013; Cheng et al. 2014). This idea was largely introduced for the reduction of subsurface (i.e. 0-50m) depth bias, which could not be achieved only by modifying the two coefficients in the traditional FRE. For the purpose of correcting XBT data, the depth offset has been estimated in previous studies, and considered to originate from various sources (Cowley et al. 2013; Cheng et al. 2014). The original FRE assumes that the XBTs instantly reach their terminal velocity (a) because the coefficient in the quadratic term (b) is much smaller than the coefficient in the linear term. However, recent studies show that this is not true in the early part of the XBT descent (Gouretski and Reseghetti 2010; Cowley et al. 2013; Cheng et al. 2014). The XBT terminal velocity has been assessed and it was determined that the XBTs take up to approximately 1.5s or 20 meters to reach their terminal velocity after they hit the water (e.g. Hallock and Teague 1992; Bringas and Goni 2015). Comparisons between XBT and CTD measurements indicate that there is a depth bias in the initial probe descent period (upper 50 m) (Gouretski and Reseghetti 2010; Cowley et al. 2013; Cheng et al. 2014). Field tests carried out in shallow water (Gouretski and Reseghetti 2010) and in water tanks (Bringas and Goni 2015), and numerical simulations of the XBT falling motion (Abraham et al. 2014; Gorman et al. 2014; Shepard et al. 2014) confirmed this finding. Recent studies confirmed that this depth offset is linked to the initial fall velocity of the XBT in the water, which is a function of the XBT deployment height (Bringas and Goni 2015), and, based on numerical simulations, it has been hypothesized to also depend on the conditions of the probe entry into the water (Abraham et al. 2014; Gorman et al. 2014; Shepard et al. 2014). In addition, one study shows that there may be a time offset that translates into a depth offset at the surface caused by timing errors of the data acquisition system (Thresher, 2014) or malfunctioning of the electronics called “pre-mature start”. An offset term to the FRE that is a function of the deployment height has been proposed (Bringas and Goni, 2015). This offset term is derived from an earlier model (Hallock and Teague, 1992), and it is time dependent during the first 1.5 s of the XBT descent in the water and constant after that. Research is currently underway to further explore additional sources of the depth offset.

THE IMPORTANCE OF METADATA

The dependency of the biases on time (e.g. manufacture date, system changes) and probe type have been highlighted in several studies. There are two major manufacturers of XBT probes, Lockheed Martin Sippican, Inc. in the United States; and the Tsurumi-Seiki Co., Ltd (TSK), in Japan. Each company produces several types of probes with different maximum depths and for different ship speeds. For Sippican, they are T4 (460 m), T5 (1830 m), T6 (460 m), T7 (760 m), Deep Blue (760 m), Fast Deep (1000 m), T10 (200 m), and T11(460 m) (http://www.sippican.com/stuff/contentmgr/files/0dad831400ede7b5f71cf7885fdeb110/sheet/xbtxsv92005.pdf). For TSK manufactured probes, they are T4 (460 m), T5 (1830 m), T6 (460 m), T7 (760 m), and T10 (300 m) (http://www.tsk-jp.com/index.php?page=/product/detail/2/2). Moreover, the maximum depth reached by XBTs is frequently deeper than the nominal values indicated by Sippican and TSK, adding a further contribution to the uncertainty. Their manufacture is fully independent, except for sharing the basic design and using thermistors of a single brand, and their probes have many differences in their structure (Kizu et al. 2005b; 2011).

It has been shown that probe types from different manufacturers have distinct values of bias (Kizu et al. 2005a,b; Ishii et al. 2009; Kizu et al. 2011; Cheng et al.

2014). Therefore, bias corrections for each probe type should be assessed separately. Since a large number of available XBT metadata do not include the information of probe type (Abraham et al. 2013; Cheng et al. 2014), the available metadata, such as institution and country that carried out the deployment, year of deployment, and maximum observed depth, can be used to infer the probe type (Cowley et al. 2013).

MINIMUM REQUIREMENTS FOR XBT METADATA

In addition to the standard requirements for metadata for all oceanographic data (e.g., position and time, platform and instrument type information), it is recommended that the following minimum requirements for XBT metadata are included: fall rate coefficients used in the profile, probe type, probe manufacture date and serial number, manufacturer, launch height, type of recording system and software version. It is critically important that no correction scheme is applied to raw XBT data. All archived data should only contain depths calculated from either the manufacturers or the Hanawa et al 1995 coefficients, and temperatures obtained from the collection system.

CURRENT XBT BIAS CORRECTION SCHEMES

A suite of correction schemes for global historical XBT datasets has been proposed (Hanawa et al. 1995; Wijffels et al. 2008; Levitus et al. 2009; Ishii and Kimoto 2009; Gouretski and Reseghetti 2010; Good 2011; Gouretski 2012; Hamon et al. 2012; Cowley et al. 2013; Cheng et al. 2014). One goal of the Fourth XBT Science Workshop was to assess the respective advantages of each of these schemes. The workshop participants recommended that correction schemes should correctly account for all of the above-discussed parameters, in particular when the XBT data are used for global scale climate research applications. Table 1 lists the factors considered by each scheme. Within these schemes, the above three correction factors (with their two temperature dependent corollaries) along with probe and year variances are explicitly accounted for in only one of them (Cheng et al. 2014), while it is implicitly accounted for in another scheme (Gouretski and Reseghetti 2010). The participants also noted that XBT data sets without all recommended corrections could still be used for several specific applications (discussed below) in which the XBT biases have a minor impact on the results.

At the present time, members of the community recommend the Cheng et al. 2014 corrections be used because the scheme currently provides the most appropriate bias correction strategy as discussed above, including all of the recommended factors. The performance of all the correction schemes is the subject of a soon to be published study lead by the XBT community members. A preliminary inter-comparison among the 10 correction schemes using metrics to define “goodness” of a scheme, indicates that Cheng et al. 2014, Gouretski and Reseghetti 2010 and Levitus et al. 2009 currently outperform other schemes. However, we note that the recommended correction scheme will change as more research leads to improved understanding of the biases and improved quality-control processes. The community will keep scientists informed on updates to the recommended correction scheme.

The online NOAA/NODC-WOD13 selection tool provides the ability to automatically apply to the NOAA/NODC-WOD-13 dataset (Boyer et al., 2013) any of the 10 correction schemes currently available for XBT data.

BIAS-CORRECTED XBT DATA: APPLICATIONS

XBT data have been widely used in oceanography and climate studies over the past 40 years (Goni et al. 2010) and continue to be used for a wide range of critical scientific applications. The impact of the XBT bias on applications and products varies. The main scientific applications of XBT data, and the impact of the application of XBT corrections are shown below. We note that these assessments are based on case studies and, therefore, provide only general guidelines for application of corrections. The use of the best data set available is always preferred, however, data sets that do not contain all of the corrections indicated above are still acceptable for a wide range of oceanographic applications.

1) Global ocean heat content (OHC). OHC is an indicator of the amount of heat stored over a certain depth range in the ocean. The major source of error for historical OHC estimates comes from the XBT biases (Lyman et al. 2010; Boyer et al. 2015). It has been shown that the long-term OHC trend calculated by using uncorrected XBT data was underestimated by a half (Domingues et al. 2008), and created a spurious decadal variation ("the warming decade", Gouretski and Koltermann 2007; Levitus et al. 2009; Rhein et al. 2013) (Figure 3). Uncertainties in OHC (0-700m) estimation induced by different XBT correction schemes range from 8.2 (11.8) to 16.1 (19.6) ZJ (1 ZJ = 1×10^{21} Joules) for 1970-2008 and for years 1993-2008 in parentheses, depending on the mapping technique used (Boyer et al. 2015).

2) Ocean reanalysis/data assimilation. Giese et al. (2010) documented differences in OHC, ocean temperature structure, and velocity of ocean currents due to XBT corrections in the context of global analyses experiments using a Simple Ocean Data Assimilation (SODA) system. The quantified impact of the different correction schemes on these variables show that: the Levitus et al. (2009) scheme reduced the temperature anomalies at 50 m in the eastern equatorial Pacific by 10%–20% and strengthened the zonal currents by ~50% during the 1997-2000 ENSO cycle compared with the Hanawa et al. (1995) correction; while the Wijffels et al. (2008) scheme had little impact on the ENSO representation in the ocean. Therefore, these results indicate that XBT data sets with more accurate correction schemes serve to provide improved estimates of long period ocean signals.

3) Trans-basin ocean meridional heat transport (MHT). Results from numerical model studies carried out for the South Atlantic Ocean (Goes et al. 2015) show that XBT biases need to be corrected in order to detect MHT trends in the South Atlantic. The trends in MHT and meridional overturning circulation (MOC) caused by XBT biases are statistically significant after the 1990s, estimated to be 0.02 PW/decade and 0.3 Sv/decade, respectively. These trends are higher than the actual trends estimated from reanalysis data of 0.006 PW/decade and 0.1 Sv/decade for MHT and MOC, respectively. Therefore, appropriate XBT bias corrections with long-term monitoring may reduce the errors for detection of long-term trends. On the other hand, the errors in the MHT and MOC due to XBT biases are small in comparison to their seasonal and interannual variability. Therefore, XBT data without corrections can still provide reliably assessments of MHT and MOC variability on seasonal-to-interannual time scales (Dong et al. 2009).

4) Geostrophic currents. Geostrophic current estimates show that errors due to pure temperature XBT biases, as estimated for tropical Atlantic currents (Goes et al. 2013b) are very small (<0.02 m/s). The same study shows that the maximum geostrophic velocity errors due to XBT depth biases are likely to be < 0.2 m/s, which is comparable to the errors associated with satellite altimetry estimates of current velocities. Therefore, XBT data without corrections can still provide reliably assessments of geostrophic currents.

5) Mixed layer depth (MLD). Studies carried out in the Mediterranean Sea showed that the Cowley et al. (2013) scheme (applied to 45% of the database) did not significantly affect the estimates of the seasonal cycle of the basin-mean of MLD (Houpert et al. 2014), as the differences of the MLD with and without XBT corrections are two orders of magnitude lower than the amplitude of the seasonal variations. Other studies (Gopalakrishna et al. 2010) examined changes in a particular isotherm depth from XBT data to investigate features of the Arabian Sea and noted that the results were not sensitive to XBT correction.

FUTURE WORK

Extensive progress has been made during the past decades regarding the understanding and assessments of XBT biases and errors. Similarly to corrections made to data obtained from other observational platforms, continuous efforts will be made to improve the XBT data set. In particular, the following steps are recommended:

1) Continue distribution through the main data centers of data with different XBT corrections. At present, the US NOAA/NODC distributes datasets with the 10 different correction schemes (Table 1) applied (http://www.nodc.noaa.gov/cgi-bin/OC5/SELECT/builder.pl), the UK Met Office provides datasets with 3 correction schemes (Good et al. 2013), and the China IAP distributes Cheng et al. (2014) corrected XBT data (http://159.226.119.60/cheng/). Updates to the recommended correction schemes will be posted via the XBT Science Team website (http://www.aoml.noaa.gov/phod/goos/xbtscience/index.php).

Future improvements in the data sets will rely on progress made in the following two areas: (a) Ongoing assessment of XBT biases and errors including a comprehensive intercomparison of the performance of the existing XBT correction schemes, since it is possible that the inclusion of all correction factors does not guarantee providing better data. An intercomparison is currently being undertaken by the XBT community (http://159.226.119.60/cheng/); and (b) Continuous efforts to improve the quality of XBT data with appropriate flags and uncertainties as part of a recently initiated international project: International Quality-controlled Ocean Database (IQuOD) (http://www.iquod.org). The sensitivity of the correction schemes to dataset versions with more data and higher quality control requires more investigation.

2) Require that XBT data originators submit the complete metadata to the major data centers (e.g. NODC). Real time data transmitted via the Global Transmission System (GTS) should preferably be submitted using BUFR format to allow the inclusion of all metadata, which is then archived by the data centers. The metadata must include, in addition to existing requirements for all oceanographic data, information on the fall rate coefficients used in the profile, probe type, probe manufacture date, serial number, manufacturer, launch height, type of recording system, and software version. The metadata recommendations will be submitted to Ship Of Opportunity Programme Implementation Panel (SOOPIP) in the Joint WMO/IOC Technical Commission for Oceanography and Marine Meteorology (JCOMM), International Oceanographic Data and Information Exchange (IODE), for approval and then will be disseminated through these organizations.

3) Recover historical side-by-side XBT/CTD comparison data. Side-by-side XBT/CTD comparisons enable us to accurately assess XBT bias and assess proposed correction schemes (Cowley et al. 2013). A highly valuable collection of historical datasets with XBT and CTD co-located pairs is currently maintained at https://data.csiro.au (DOI: 10.4225/08/543F60A3F1690). All data in the pairs database is also present in the World Ocean Database maintained by US NOAA/NODC (http://www.nodc.noaa.gov/OC5/WOD13/). Ongoing addition of historical XBT/CTD pairs to the pairs database via submission to US NOAA/NODC is strongly encouraged.

4) Assess the cause for the existence of time-varying biases in different probe types. It has been hypothesized that slight differences in probe design may result in probe-type differences (e.g. Kizu et al. 2005b; Kizu et al. 2011). Recent advances in Computational Fluid Dynamics (CFD) may also help to address this question by simulating the real characteristics in XBT probe design to examine the differences in fall rate (Abraham et al. 2012a, 2012b).

5) Further investigate and assess all parameters that contribute to the depth offset. CFD models have identified the launch height (Abraham et al. 2012a, 2012b) and water tank experiments (Bringas and Goni 2015) have identified the initial speed of descent of XBTs in the water (a function of the launch height) as having the largest impact on initial fall rate. Further tests in the ocean have already been conducted to confirm these findings and to investigate other parameters that may impact the value of the offset. The possibility of clock offsets in digital recording systems adding to the depth offset is also being investigated using a precise timing test.

6) Assess the link between water temperature and pure temperature bias, a topic that is rarely discussed in the historical XBT literature. Theoretical analysis, bath calibration, and more side-by-side XBT/CTD tests in water of different temperatures (or different geographical locations) are required to address this.

7) Evaluate why higher positive temperature bias exists in XBT data collected with analog recorders. Intercomparisons of digital devices and still available strip chart recorders may help to evaluate and understand the cause of pure temperature bias and its temporal variability. Well-designed bath tests may also help to confirm the impact of the recorder system on the pure temperature bias. Preservation of old acquisition systems is also desirable for future assessment.

8) Improve and continue communications with the XBT manufacturers in order to improve XBT probes. It has been shown that the depth bias could be reduced when adding one or more pressure switches to XBTs (Goes et al. 2013a). However, the cost of pressure switches precludes their use in a probe that has been designed to provide cost-effective temperature profiles. As a result of this work and after discussions with Sippican, the XBT community recommended that the manufacturers employ tighter controls on probe weight and better calibration of thermistors during the manufacturing process as a more cost-efficient way of reducing biases. In addition, the community will continue to collect XBT and CTD side-by-side data for the most common probe types to continue assessment of XBT biases.

SUMMARY

XBT data make up a significant amount of the global historical upper-ocean temperature profile database and are still used extensively to study ocean boundary currents, ocean heat content, climate change, and meridional heat transport. Some applications for which XBT data are used require these data to be accurately corrected for depth and temperature biases. Bias corrections have been applied successfully to XBT data in ocean heat content studies (e.g. Domingues et al. 2008; Levitus et al. 2012; Boyer et al. 2015). The increasing number of scientific applications for which XBT data are used and the existence of many different bias corrections proposed over the last 30 years highlight the need to propose a corrected historical dataset for climate and oceanographic related studies. This manuscript reports the progress made on XBT bias studies and provides a guide for future data and metadata collection requirements. At the present time, there is one correction scheme (Cheng et al. 2014) that takes account of all the recommended elements. As such, it is currently recommended as the most appropriate correction for XBT data used in calculations of global ocean heat content and ocean reanalysis and data assimilation. Based on previous studies, corrections are not required for calculations of MHT/MOC, geostrophic currents and mixed layer depth calculations.

Similar to data obtained from all observational platforms, efforts will continue to be carried out to improve XBT data quality. The XBT Science Team (http://www.aoml.noaa.gov/phod/goos/xbtscience/index.php) and community will continue working on enhancing our understanding of the XBT fall rate biases by addressing the questions posted above, continuously assessing all available data sets and correction schemes to correct historical and future XBT data, improving the quality of XBT profiles for climate research, and providing future recommendations for XBT bias corrections.

ACKNOWLEDGMENTS. We acknowledge the International Center for Climate and Environment Science (ICCES), Institute of Atmospheric Physics (IAP), Chinese Academy of Sciences (CAS), and Third World Academy of Sciences (TWAS) for supporting the 4th XBT workshop, which provided the opportunity for scientists in the XBT community to meet and discuss XBT biases. L. Cheng and J. Zhu are supported by the project “Structures, Variability and Climatic Impacts of Ocean Circulation and Warm Pool in the Tropical Pacific Ocean” of National Basic Research Program of China (grant no. 41476016), Chinese Academy Sciences’ Project “Western Pacific

Ocean System: Structure, Dynamics and Consequences" (grant no. XDA11010405). Work by G. Goni, S. Dong, F. Bringas, and M. Goes was supported by NOAA/AOML and by the NOAA Climate Program Office.

REFERENCES

Abraham, J. P., J. M. Gorman, F. Reseghetti, E. M. Sparrow, and W. J. Minkowycz, 2012a: Turbulent and Transitional Modeling of Drag on Oceanographic Measurement Devices. *Modelling and Simulation in Engineering*, **2012,** 8. http://dx.doi.org/10.1155/2012/567864.

——, 2012b: Drag Coefficients for Rotating Expendable Bathythermographs and the Impact of Launch Parameters on Depth Predictions. *Numer Heat Tr a-Appl*, **62,** 25-43.

Abraham, J. P., and Coauthors, 2013: A Review of Global Ocean Temperature Observations: Implications for Ocean Heat Content Estimates and Climate Change. *Rev Geophys*, **51,** 450-483, doi: 10.1002/rog.20022.

Abraham, J. P., J. M. Gorman, F. Reseghetti, E. M. Sparrow, J. Spark, T. Shepard, 2014: Modeling and Numerical Simulation of the Forces Acting on a Sphere During Early-Water Entry. *Ocean. Eng.*, **76,** 1-9, doi:10.1016/j.oceaneng.2013.11.015.

Anderson, E. R., 1980: Expendable Bathythermograph(XBT) accuracy studies. *Technical Report 550, Naval Ocean Systems Center, San Diego, California***,** 201pp.

Bailey, R., H. Phillips, and G. Meyers, 1989: Relevance to TOGA of systematic XBT errors. *Proc. Western Pacific International Meeting and Workshop on TOGA COARE*, Noumea, New Caledonia, May 24-30, 1989, 775-784.

Bindoff, N. L. and Coauthors, 2007: Observations: Oceanic Climate Change and Sea

Level, in Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)], *Cambridge University Press, Cambridg, UK.*

Boyer, T., and Coauthors, 2015: Sensitivity of Global Ocean Heat Content Estimates to Mapping Methods, XBT Bias Corrections, and Baseline Climatology. *The 4th XBT workshop: XBT Science and the Way Forward*, Beijing, China, Institute of Atmospheric Physics, Chinese Academy of Sciences. [Available online at http://2014xbtworkshop.csp.escience.cn/dct/page/70005]

Boyer, T. P. , and Coauthors, 2013: World Ocean Database 2013. Sydney Levitus, Ed.; Alexey Mishonov, Technical Ed.; NOAA Atlas NESDIS 72, 209 pp.

Bringas F., and Goni, G., 2015: Early Dynamics of Deep Blue XBT Probes, *J. Atmos. Oceanic Technol.*,, under review.

Cheng, L., J. Zhu, R. Cowley, T. Boyer, and S. Wijffels, 2014: Time, Probe Type and Temperature Variable Bias Corrections to Historical Expendable Bathythermograph Observations. *J. Atmos. Oceanic Technol.*, **31**, 8, 1793-1825.

Cheng, L. J., J. Zhu, F. Reseghetti, and Q. P. Liu, 2011: A New Method to Estimate the Systematical Biases of Expendable Bathythermograph. *J. Atmos. Oceanic Technol.*, **28,** 244-265.

Cowley, R., S. Wijffels, L. Cheng, T. Boyer, and S. Kizu, 2013: Biases in

Expendable Bathythermograph Data: A New View Based on Historical Side-by-Side Comparisons. *J. Atmos. Oceanic Technol.*, **30,** 1195-1225.

Di Nezio, P. N., and G. Goni, 2011: Direct Evidence of Changes in the XBT Fall-rate Bias During 1986-2008. *J. Atmos. Oceanic Technol.*, **28,** 1569-1578.

Domingues, C. M., J. A. Church, N. J. White, P. J. Gleckler, S. E. Wijffels, P. M. Barker, and J. R. Dunn, 2008: Improved estimates of upper-ocean warming and multi-decadal sea-level rise. *Nature*, **453**, 1090-U1096.

Dong, S. S. L. Garzoli, M. O. Baringer, C. S. Meinen, and G. J. Goni, 2009: The Atlantic Meridional Overturning Circulation and its Northward Heat Transport in the South Atlantic. *Geophys. Res. Lett.*, **36**, L20606, doi:10.1029/2009GL039356.

Emery, W. J., W. Lee, W. Zenk, and M. J., 1986: A low-cost digital XBT system and its application to the real-time computation of dynamic height. *J. Atmos. Oceanic Technol.*, **3,** 75-83.

Flierl, G. R., and A. R. Robinson, 1977: XBT measurements of thermal gradients in the MODE eddy. *J. Phys. Oceanogr.*, **7**, 300-302.

Giese, B. S., G. A. Chepurin, J. A. Carton, T. P. Boyer, and H. F. Seidel, 2010: Impact of Bathythermograph Temperature Bias Models on an Ocean Reanalysis. *J. Climate*, **24**.

Goes, M., G. Goni, and K. Keller, 2013a: Reducing Biases in XBT Measurements by Including Discrete Information from Pressure Switches. *J. Atmos. Oceanic Technol.*, **30,** 810-824.

Goes, M., G. J. Goni, V. Hormann, and R. C. Perez, 2013b: Variability of eastward currents in the equatorial Atlantic during 1993-2010. *J. Geophys. Res.*, **118,** 3026-3045.

Goes, M. M., M. Baringer, and G. Goni, 2015: The impact of historical biases on the XBT-derived meridional overturning circulation estimates at 34°S, *Geophys. Res. Let.*, doi:10.1002/2014GL061802.

Goni G.J., and Coauthors, 2010: The Ship Of Opportunity Program. In Proceedings of the "OceanObs'09: Sustained Ocean Observations and Information for Society" Conference (Vol. 2), Venice, Italy, 21-25 September 2009, Hall, J., Harrison D.E. and Stammer, D., Eds., ESA Publication WPP-306.

Good, S. A., 2011: Depth Biases in XBT Data Diagnosed Using Bathymetry Data. *J. Atmos. Oceanic Technol.*, **28,** 287-300.

Good, S. A., M. J. Martin, and N. A. Rayner, 2013: EN4: Quality controlled ocean temperature and salinity profiles and monthly objective analyses with uncertainty estimates, *J Geophys Res-Oceans*, **118**, 6704-6716.

Gopalakrishna V., and Coauthors, 2010: Observed intra-seasonal to interannual variability of the upper ocean thermal structure in the southeastern Arabian Sea during 2002-2008, *Deep-Sea Res Pt I*, **76**, 6, 739-754, doi:10.1016/j.dsr.2010.03.010.

Gorman, J. M., J. P. Abraham, D. B. Schwalbach, T. S. Shepard, J. R. Stark, and F. Reseghetti, 2014: Experimental Verification of Drag Forces on Spherical Objects Entering Water. *J Mar. Ocean Biol. Ocean*, **3**, 2, http://dx.doi.org/10.4172/2324-8661.1000126.

Gouretski, V., 2012: Using GEBCO digital bathymetry to infer depth biases in the XBT data. *Deep-Sea Res Pt I*, **62,** 40-52.

Gouretski, V., and K. P. Koltermann, 2007: How much is the ocean really warming? *Geophys. Res. Lett.*, **34**, L01610, doi:10.1029/2006GL027834.

Gouretski, V., and F. Reseghetti, 2010: On depth and temperature biases in bathythermograph data: Development of a new correction scheme based on analysis of a global ocean database. *Deep-Sea Res Pt I*, **57,** 812-833.

Green, A. W., 1984: Bulk Dynamics of the Expendable Bathythermograph (Xbt). *Deep-Sea Res Pt I* **31,** 415-426.

Hallock, Z. R., and W. J. Teague, 1992: The fall-rate of the T7 XBT. *J. Atmos. Oceanic Technol.*, **9,** 470–483.

Hamon, M., G. Reverdin, and P. Y. Le Traon, 2012: Empirical correction of XBT data. *J. Atmos. Oceanic Technol.*, **29,** 960-973.

Hanawa, K., and H. Yoritaka, 1987: Detection of systematic errors in XBT data and their correction. *J. Oceanogr. Soc. Japan*, **43**, 68-76.

Hanawa, K., P. Rual, R. Bailey, A. Sy, and M. Szabados, 1995: A New Depth Time Equation for Sippican or Tsk T-7, T-6 and T-4 Expendable Bathythermographs (Xbt). *Deep-Sea Res. Pt I*, **42,** 1423-1451.

Heinmiller, R., C. Ebbesmeyer, B. Taft, T. Olson, Nikitin, O., 1983: Systematic errors in expendable bathythermograph (XBT) profiles. *J. Oceanogr.*, **65,** 287-299.

Houpert, L., and Coauthors, 2014: Seasonal cycle of the mixed layer, the seasonal thermocline and the upper-ocean heat storage rate in the Mediterranean Sea derived from observations. *Prog. Oceanogr*., **132**, 333-352, doi: 10.1016/j.pocean.2014.11.004.

Ishii, M., and M. Kimoto, 2009: Reevaluation of historical ocean heat content variations with time-varying XBT and MBT depth bias corrections. *J. Oceanogr.*, **65,** 287-299.

Kizu, S., and K. Hanawa, 2002a: Start-up transient of XBT measurement. *Deep-Sea Res. Pt I*, **49,** 935-940.

——, 2002b: Recorder-dependent temperature error of expendable bathythermograph. *J. Oceanogr.*, **58,** 469-476.

Kizu, S., H. Yoritaka and K. Hanawa, 2005a: A new fall-rate equation for T-5 expendable bathythermograph (XBT) by TSK. *J. Oceanogr.*, **61**, 115-121.

Kizu, S., S. Ito, and T. Watanabe, 2005b: Inter-manufacturer difference and temperature dependency of the fall-rate of T-5 expendable bathythermograph. *J. Oceanogr.*, **61,** 905-912.

Kizu, S., C. Sukigara, and K. Hanawa, 2011: Comparison of the fall rate and structure of recent T-7 XBT manufactured by Sippican and TSK. *Ocean Sci.*, **7,** 231-244.

Levitus, S., J. I. Antonov, T. P. Boyer, R. A. Locarnini, H. E. Garcia, and A. V. Mishonov, 2009: Global ocean heat content 1955-2008 in light of recently revealed instrumentation problems. *Geophys. Res. Lett.*, **36**, L07608, doi:10.1029/2008GL037155.

Levitus, S., and Coauthors, 2012: World ocean heat content and thermosteric sea level change (0-2000 m), 1955-2010. *Geophys. Res. Lett.*, **39**, L10603, doi: 10.1029/2012GL051106

Lyman, J. M., S. Good, V. Gouretski, M. Ishii, G. Johnson, M. Palmer, D. Smith, and J. Willis, 2010: Robust warming of the global upper ocean. *Nature*, **465,** 334-337.

Reseghetti, F., M. Borghini, and G. M. R. Manzella, 2007: Factors affecting the quality of XBT data - results of analyses on profiles from the Western Mediterranean Sea. *Ocean Sci.*, **3,** 59-75.

Reverdin, G., F. Marin, B. Bourles, and P. L'Herminier, 2009: XBT Temperature Errors during French Research Cruises (1999-2007). *J. Atmos. Oceanic Technol.*, **26,** 2462-2473.

Rhein, M., and Coauthors, 2013: Observations: Ocean. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. *Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.*

Roemmich, D., B. Cornuelle, 1987: Digitization and calibration of the expendable bathy thermograph. *Deep-Sea Research*, 34, 229-307.

Shepard, T., J. Abraham, D. Schwalbach, S. Kane, D. Siglin, and T. Harrington, 2014: Velocity and Density Effect on Impact Force during Water Entry of Sphere. *Geophysics & Remote Sensing*, **3**, 2169-0049.

Singer, J. J., 1990: On the error observed in electronically digitized T-7 XBT data. *J. Atmos. Oceanic Technol.*, **7**, 603-611.

Thadathil, P., A. K. Saran, V. V. Gopalakrishna, P. Vethamony, N. Araligidad, and R. Bailey, 2002: XBT fall rate in waters of extreme temperature: A case study in the Antarctic Ocean. *J. Atmos. Oceanic Technol.*, **19**, 391-396.

Thresher, A, 2014: Mk21 and Devil/Quoll timing test. *The 4th XBT workshop: XBT*

Science and the Way Forward, Beijing, China, Institute of Atmospheric Physics, Chinese Academy of Sciences. [Available online at http://2014xbtworkshop.csp.escience.cn/dct/page/70005]

Wijffels, S. E., J. Willis, C. Domingues, P. Barker, N. White, A. Gronell, K. Ridgway, J. Church, 2008: Changing Expendable Bathythermograph Fall Rates and Their Impact on Estimates of Thermosteric Sea Level Rise. *J. Climate*, **21,** 5657-5672.

Wright, D. M., 1991: Field evaluation of the XBT bowing phenomenon. *OOD Data Report 91-2, Ocean Observations Division/Office of Ocean Services, National Ocean Service, NOAA, 12 pp.*

Table 1. Summary of the ten of the available correction schemes that analyzed historical and global XBT datasets. The check mark denotes whether a factor has been considered by a given scheme. And the check mark inside a square indicates a scheme partly or implicitly considering the specific factor.

Factors		Cheng et al. 2014	Gouretski & Reseghetti 2010	Levitus et al. 2009	Gouretski 2012	Hamon et al. 2012	Good 2011	Cowley et al. 2013	Cowley et al. 2013 CH	Ishii and Kimio, 2009	Wijffels et al. 2008
Pure temperature bias	Pure temperature bias correction	✓	✓	✓	✓	✓		✓	✓		
	Time-variable	✓	✓		✓	✓		✓	✓		
	Temperature dependency	✓	✓			☑Cold & warm water					
Depth bias	Depth bias correction	✓	✓		✓	✓	✓	✓	✓	✓	✓
	Time-variable	✓	✓		✓	✓	✓	✓	✓	✓	✓
	Surface depth bias	✓	✓		✓	✓		✓	✓		
	Temperature dependency	✓	☑								
Probe Type	Sippican	T7/DB; T4/T6; T5; T10	T4/T6; T7/DB		T10; T4/T6; T7/DB	Deep; Shallow	T4; T7; T10	T4/T6; T7/DB	T4/T6; T7/DB;	T7; T4; T6; T5; T10; FD;	Deep; Shallow
	TSK	T4/T6; T5; T7						TSK	TSK	T4; T6; T7	
	Unknown	Deep Unknown; Shallow Unknown			Deep Unknown; Shallow Unknown		Unknown				

Figures Caption Lists

Fig. 1. Percentage of different instruments in the ocean subsurface temperature observation system from 1966 to 2013 (based on WOD2013). Data include Expendable Bathythermograph (XBT); Profiling Floats (PFL); Autonomous Pinniped Bathythermographs (APB); Mechanical Bathythermographs (MBT); Ocean Station Data (OSD); High Resolution CTD/XCTD (CTD); Drifting Buoys (DRB); Undulating Oceanographic Recorder (UOR); Glider data (GLD); Moored Buoys (MRB).

Fig.2. Location of approximately 35,000 global XBT deployments during 2013-2014. Colors indicate the length of time the currently operated transect has been maintained.

Fig. 3. Upper (0-700m) Ocean Heat Content (OHC) calculated using corrected and uncorrected XBT data (black curve). The XBT data is corrected using ten of the schemes including CH14 (Cheng et al. 2014), L09 (Levitus et al. 2009), GR10 (Gouretski and Reseghetti, 2010), W08 (Wijffels et al. 2008), IK09 (Ishii and Kimoto, 2009); GD11 (Good 2011); G12 (Gouretski 2012); H12 (Hamon et al. 2012); CW13 (Cowley et al. 2013) and CWCH (CH method in Cowley et al. 2013). The annual mean of global OHC anomaly (OHCA) is calculated by simply averaging the 1^{o} by 1^{o} grid means of OHCA over the global ocean.

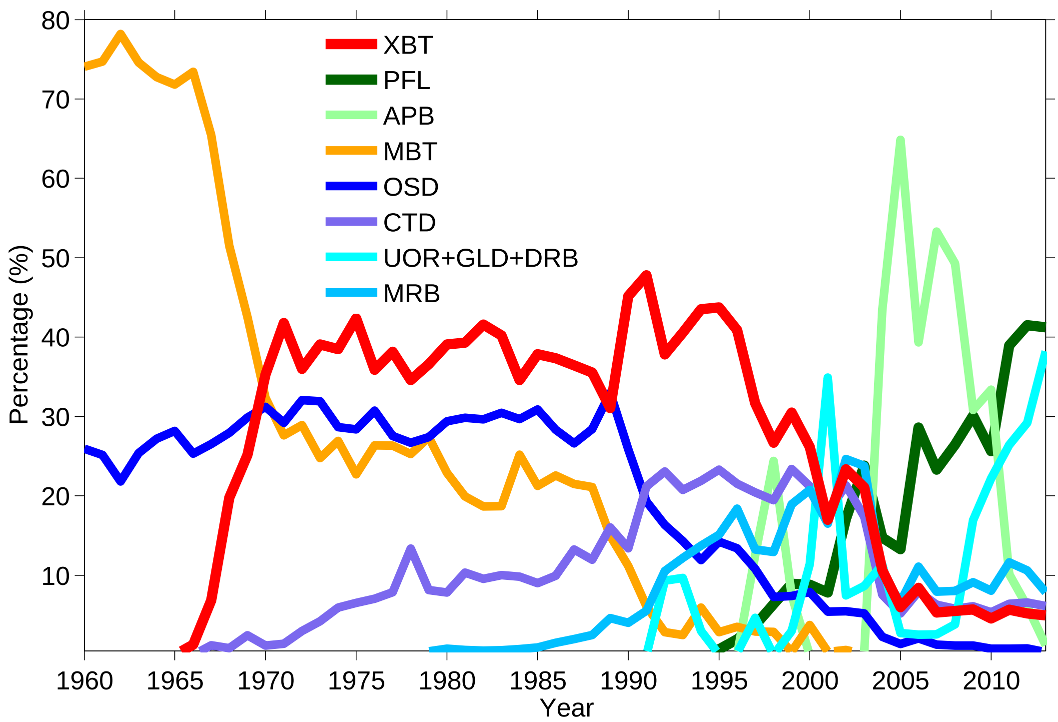

Fig. 1. Percentage of different instruments in the ocean subsurface temperature observation system from 1966 to 2013 (based on WOD2013). Data include Expendable Bathythermograph (XBT); Profiling Floats (PFL); Autonomous Pinniped Bathythermographs (APB); Mechanical Bathythermographs (MBT); Ocean Station Data (OSD); High Resolution CTD/XCTD (CTD); Drifting Buoys (DRB); Undulating Oceanographic Recorder (UOR); Glider data (GLD); Moored Buoys (MRB).

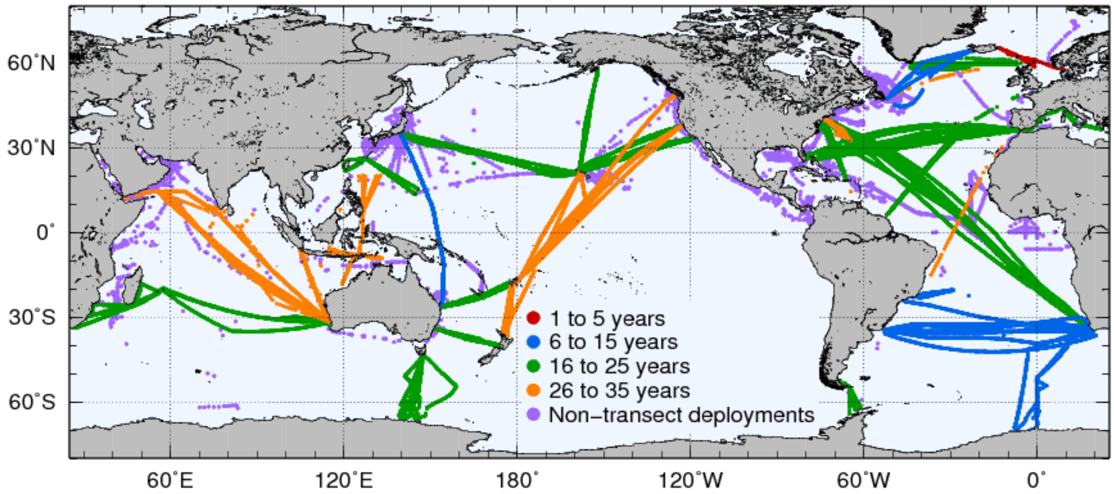

Fig.2. Location of approximately 35,000 global XBT deployments during 2013-2014. Colors indicate the length of time the currently operated transect has been maintained.

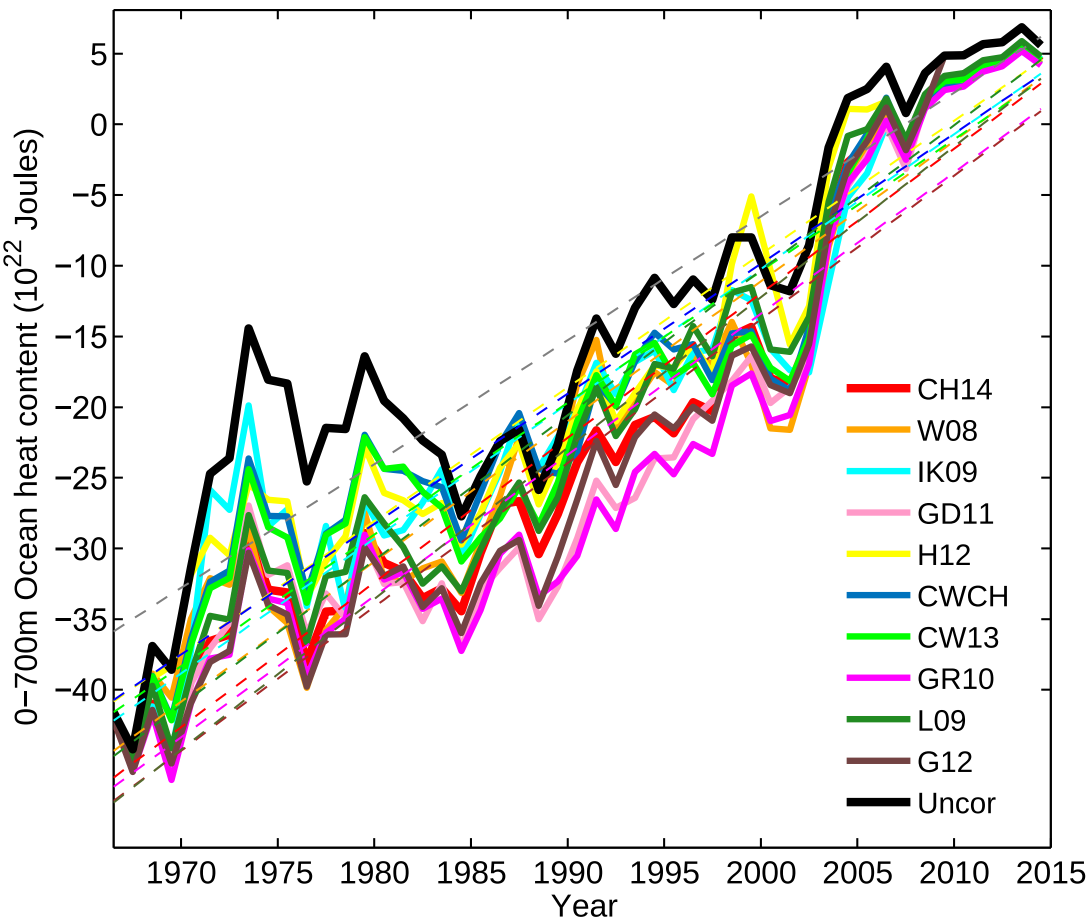

Fig. 3. Upper (0-700m) Ocean Heat Content (OHC) calculated using corrected and uncorrected XBT data (black curve). The XBT data is corrected using ten of the schemes including CH14 (Cheng et al. 2014), L09 (Levitus et al. 2009), GR10 (Gouretski and Reseghetti, 2010), W08 (Wijffels et al. 2008), IK09 (Ishii and Kimoto, 2009); GD11 (Good 2011); G12 (Gouretski 2012); H12 (Hamon et al. 2012); CW13 (Cowley et al. 2013) and CWCH (CH method in Cowley et al. 2013). The annual mean of global OHC anomaly (OHCA) is calculated by simply averaging the 1^{o} by 1^{o} grid means of OHCA over the global ocean.