Direct Evidence of a Changing Fall-Rate Bias in XBTs Manufactured during 1986–2008

PEDRO N. DINEZIO

Cooperative Institute for Marine and Atmospheric Studies, University of Miami, and NOAA/Atlantic Oceanographic and Meteorological Laboratory, Miami, Florida

GUSTAVO J. GONI

NOAA/Atlantic Oceanographic and Meteorological Laboratory, Miami, Florida

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ABSTRACT

This paper presents direct evidence of systematic depth errors consistent with a fall-rate bias in 52 temperature profiles collected using expendable bathythermographs (XBTs). The profiles were collected using the same recording system and under the same ocean conditions, but with XBTs manufactured during years 1986, 1990, 1991, 1995, and 2008. The depth errors are estimated by comparing each XBT profile with a collocated profile obtained from conductivity–temperature–depth (CTD) casts using a methodology that unambiguously separates depth errors from temperature errors. According to the manufacture date of the probes, the XBT fall-rate error has changed from $(-3.77 \pm 0.57)\%$ of depth in 1986 to $(-1.05 \pm 1.34)\%$ of depth in 2008. The year dependence of the fall-rate bias can be identified with statistical significance (1σ) below 500 m, where the effect of the fall-rate bias is larger. This result is the first direct evidence of changes in the XBT fall-rate characteristics. Therefore, for the 1986–2008 period, the hypothesis that the XBT errors are due to a time-varying fall-rate bias, as hypothesized by Wijffels et al., cannot be rejected. Additional implications for current efforts to correct the historical temperature profile database are discussed.

1. Introduction

Expendable bathythermographs (XBTs) are widely used to observe the upper ocean from ships of opportunity due to their low cost and ease of use. Until the completion of the Argo array in 2007, more than 50% of all temperature profile observations were collected using XBTs. These profiles are a fundamental source of information about ocean changes during much of the observational record. Unlike more costly instruments equipped with pressure sensors, such as conductivity–temperature–depth (CTD) casts or profiling floats, XBTs determine the depth of the temperature observations indirectly using a fall-rate equation (FRE).

Systematic errors in the computed XBT depths have been identified since the mid-1970s (e.g., Seaver and Kuleshov 1982; Roemmich and Cornuelle 1987), but their impact on climate applications was recognized only in the 1990s, after a comprehensive analysis of research-quality CTD and XBT data from several regions of the World Ocean (Hanawa et al. 1995, hereafter H95). H95 study showed that the coefficients in the FRE used at that time resulted in isotherm depths that were too shallow, producing a cold temperature bias in most of the water column.

This issue has regained importance after Gouretski and Koltermann (2007) found a year-dependent warm temperature bias by globally comparing climatologies derived from XBT and CTD/bottle observations. This result was later confirmed and attributed to changes in fall-rate characteristics of the XBT probe due to minor manufacturing changes over time (Wijffels et al. 2008). Removing this year-dependent bias has improved the detection of decadal variability and long-term trends in ocean heat storage (e.g., Wijffels et al. 2008; Levitus et al. 2009; Ishii and Kimoto 2009) and sea level (Domingues et al. 2008).

However, the origin of the XBT errors is still unclear because there is an alternative explanation for

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Corresponding author address: Pedro N. DiNezio, Cooperative Institute for Marine and Atmospheric Studies, Rosenstiel School of Marine and Atmospheric Science, University of Miami, 4600 Rickenbacker Causeway, Miami, FL 33149.
E-mail: pedro.dinezio@noaa.gov

the year-dependence of the warm biases. A more recent study comparing the same XBT and CTD climatologies shows that the year-dependent XBT warm bias might be explained as a superposition of a constant fall-rate bias plus a year-dependent pure thermal bias (Gouretski and Reseghetti 2010). This is an important issue not only because past XBT data need to be adequately corrected, but also because the origin of the errors needs to be identified prior to any attempt to improve the XBT technology.

These studies have examined the year dependence and origin of XBT biases comparing XBT and CTD climatologies. However, because the ocean is thermally stratified, depth errors and pure thermal errors can be confounded. For this reason a definitive answer on this issue will remain elusive if this methodology is used. In contrast, comparing collocated XBT/CTD profiles is the most reliable way to isolate depth errors in XBTs. The vertical temperature gradient of the collocated profiles, which are free from pure temperature errors, can be compared to directly estimate depth errors (e.g., Hanawa and Yoritaka 1987; Hanawa and Yoshikawa 1991; Hanawa and Yasuda 1992; Rual 1991; Hanawa et al. 1995).

In this study we apply this methodology to collocated profiles collected using XBTs manufactured in years 1986, 1990, 1991, 1995, and 2008, but from the same ocean conditions. Using XBTs with different manufacture dates allows us to evaluate whether the XBT fall-rate bias has changed because of manufacture changes during the last 25 years. The profiles were collected in the tropical North Atlantic, a region where layers of homogeneous temperature with a "staircase" structure facilitate the detection of vertical temperature gradients and hence depth errors. Our results are the first direct evidence of changes in the XBT fall-rate bias during 1986–2008, supporting previous results obtained by comparing climatologies (Wijffels et al. 2008; DiNezio and Goni 2010).

2. Data and methods

a. Data

A total of 52 high quality collocated XBT and CTD temperature profiles used in this study were collected in the tropical North Atlantic (Fig. 1) from 11 July to 11 August 2009 during the Prediction and Research Moored Array in the Atlantic (PIRATA) Northeast Extension 2009 (PNE09) cruise. All the XBTs used in this experiment were manufactured by Lockheed Martin Sippican (hereafter Sippican), and obtained using the same data acquisition system consisting of a Sippican hand-launcher model LM-3A, a Mk12 recorder, and a computer. The XBTs were dropped from about 2.5 m, the launching height specified by Sippican to minimize the effect of hydrodynamical transients when the probe enters
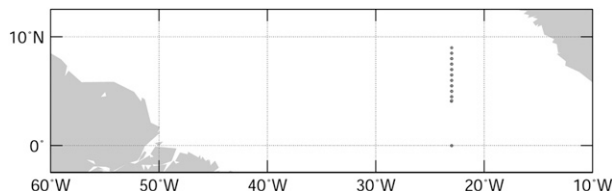

FIG. 1. Locations of collocated XBT–CTD casts in the northeastern tropical Atlantic.

the ocean. Good weather conditions and a very calm sea state prevailed throughout the duration of these collocated casts, contributing to minimizing surface transients. The XBTs used in this experiment had been stored away from excessive heat, sunlight, or moisture according to Sippican specifications, along with the XBTs used for normal operations at National Oceanic and Atmospheric Administration's (NOAA) Atlantic Oceanographic and Atmospheric Laboratory.

The major difference among the XBT profiles obtained in this experiment is the manufacture date of the probes. Another possible difference could result from the fact that we used different XBT models. XBTs manufactured between 1986 and 1995 are model T7 and the XBTs manufactured in 2008 are model DeepBlue (DB). However, these models use the same FRE because the hydrodynamical properties of the XBT probe, such as drag and weight, are the same. Both T7 and DB reach about 750 m, and constitute more than 50% of the XBT archive during the 1990–2010 period. Out of the 40 T7 XBTs deployed in the experiment; 19 were manufactured on 1 April 1986, with serial numbers in the ranges 552664 to 552674 and 552748 to 552759; 21 were manufactured between 1990 and 1995 (one in 3 August 1990, serial number 695092, eight in 23 April 1991, serial numbers in the range 727812 to 727823, and 12 in 11 July 1995, serial numbers in the range 897565 to 897576). The remaining 12 XBTs were DB model manufactured in 26 November 2008, with serial numbers in the range 1085470 to 1085793.

The XBT measures temperature as a function of time t elapsed since the XBT hits the water surface, which is then converted into depth z_{FRE} using the FRE:

$$z_{\mathrm{FRE}} = At - Bt^2. \quad (1)$$

The A and B coefficients in (1) are semiempirical constants related to the hydrodynamics of the probe descent. The A coefficient represents the value of the terminal velocity of the probe, or fall rate and, to first-order, is determined by the drag coefficient and by the mass of the probe in the water. The deceleration term $-Bt^2$ accounts for the reduction of probe mass as the wire pays out and for the increasing drag with depth (Green 1984). We calculated the XBT depths z_{FRE} using the FRE (1) with

the original Sippican coefficients $A = 6.472$ m s^{-1} and $B = 216 \times 10^{-5}$ m s^{-2}, that is, without the stretching factor applied to the FRE after the study of H95, which resulted in a change of coefficients.

We do not expect that the fall-rate characteristics of the probes have changed despite having been stored for more than a decade because they depend on the weight and shape of the probe. However, it is very likely that the accuracy and precision of the XBT thermistor degraded because the shelf time of five years specified by Sippican was exceeded for the XBTs manufactured from 1986 to 1995. This could result in temperature bias. However, the fall-rate characteristics of the probe are not likely to have changed because they depend on weight, shape, and surface roughness of the probe.

The errors in the XBT profiles are evaluated relative to collocated profiles obtained with a dual-sensor CTD profiler because of the much higher accuracy and precision of the CTD pressure and temperature sensors. For instance, the CTD sensors measure temperature and pressure/depth with accuracy of 0.005°C and 1 m, respectively, both of which are much less than the respective accuracies of the XBT. All sensors were calibrated on 21 May 2009, and the results were used to correct the CTD profiles before the comparison with the XBT profiles. A methodology that accounts for the variation of gravity with latitude and depth, and the effect of pressure on density (Saunders 1981), was used to convert CTD pressure into depth z_{CTD}. This methodology neglects the small influence of salinity and temperature on density with an error less than 0.25 m, which is at least one order of magnitude smaller than the hypothesized biases in XBT depth determined via the FRE equation, which is estimated as about 15 m at 700-m depth.

b. Method

Disregarding problems in the recording system, XBT errors originate from 1) the estimation of depth due to deficiencies of the FRE to capture the true hydrodynamics of the probe, and/or 2) temperature errors due to either the finite time response of the thermistor or inaccuracies in the conversion of resistance to temperature by the recording system. There are two main reasons why the FRE could lead to depth errors: 1) fall-rate errors due to inaccurate A and B coefficients resulting from to changes in probe weight or drag, and 2) hydrodynamics of the probe descent that depart from the physical model used to derive the FRE, such as initial transients. Separating depth errors from pure temperature errors is not trivial, even when collocated CTD profiles are available (Green 1984; Hallock and Teague 1992).

For instance, one pair of XBT and CTD profiles obtained on the equator at 23°W shows substantial temperature differences (Fig. 2a, red and blue lines). Note the large differences at about 250 m, which reach about 1°C, are comparable to, or even larger than, decadal or long-term trend. The true XBT depths could be estimated by comparing the depth of isotherms in the XBT and the CTD profile. This is the method used to estimate depth errors from climatological data (e.g., Wijffels et al. 2008). However, a pure temperature bias in the XBTs could introduce a bias in the isotherm depths, even in the absence of depth errors. Differentiating to compute the vertical temperature gradient, $\partial T/\partial z$, effectively removes pure temperature errors that are highly correlated on short vertical lengths. Depth errors can then be estimated by comparing the collocated $\partial T/\partial z$ profiles. This is the essence of the method implemented by H95 based on previous studies (Hanawa and Yoritaka 1987; Hanawa and Yoshikawa 1991; Hanawa and Yasuda 1992; Rual 1991). Analysis of the vertical temperature gradients $\partial T/\partial z$ shows that the $\partial T/\partial z$ profile obtained from the XBT (Fig. 2b, red line) is strikingly similar to that obtained from the CTD (Fig. 2b, blue line). Moreover, the XBT signals are clearly shifted upward at the depths where the temperature differences are largest.

The tropical North Atlantic (Fig. 1), a region where staircase vertical thermal structure can be found at depths down to about 700 m, is ideally suited to implementing this method. The presence of vertical temperature gradients throughout the water column allows the estimation of the true depth of the XBT profiles over the entire depth range. This becomes important to understanding the FRE bias because depth errors due to this type of bias are expected to increase with depth.

The procedure to estimate the depth errors in each XBT profile used in this study consists of the following steps:

1) XBT–CTD pairs. Each XBT profile is paired with its corresponding CTD profile, collected within 6 h and 0.1° of distance in longitude or latitude; 40 out of the 52 XBTs were collected within a 1-h limit. This distance in time can have a significant effect on the profiles from each instrument because of internal waves and other water column disturbances as well as ship drift. However, the XBTs manufactured on different years were not dropped following any systematic pattern with respect to the time of the CTD cast so we do not expect a systematic influence of this effect on the comparison.

2) Interpolation. XBT and CTD profiles are linearly interpolated into 1-m resolution profiles starting at 2 m deep, because some CTD casts do not start collecting data until that depth, down to 800 m.

3) Filtering. The interpolated XBT and CTD profiles are smoothed using a second-order Butterworth filter
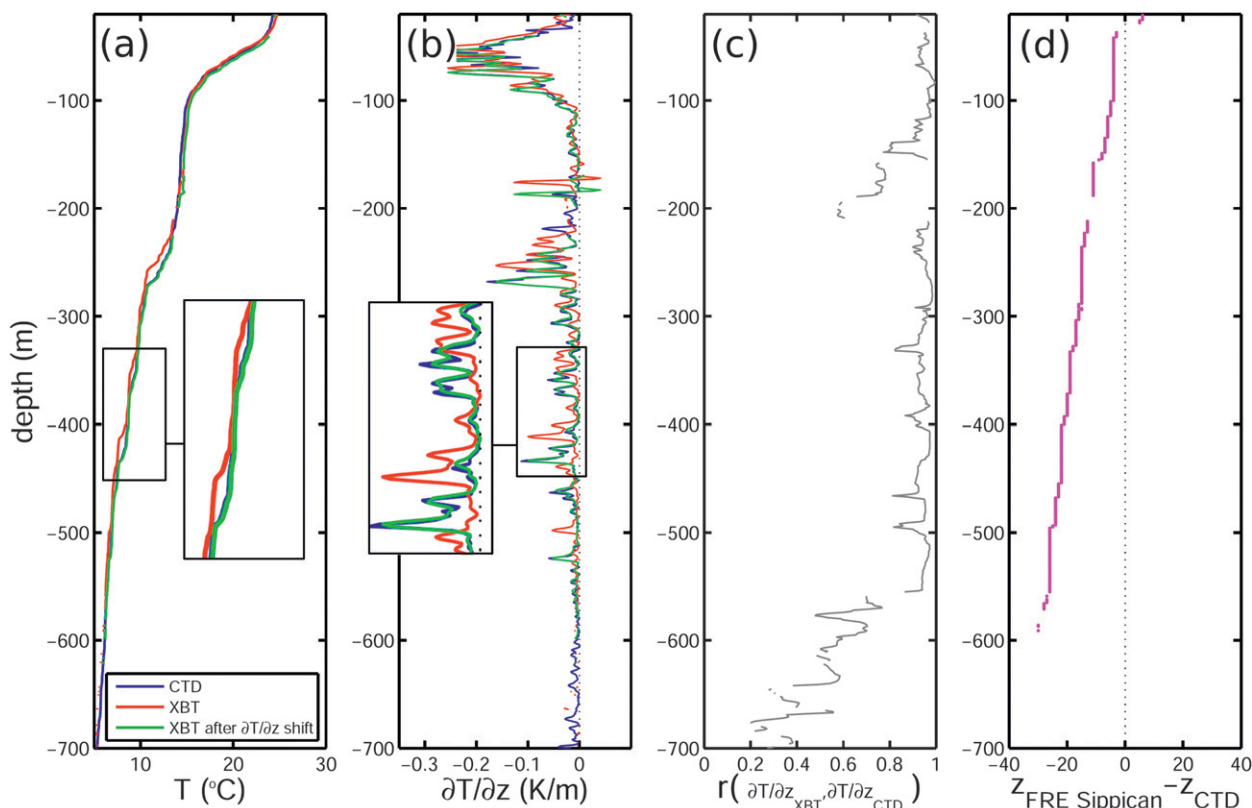
FIG. 2. (a) Temperature profiles and (b) their vertical gradients obtained from a CTD cast (blue) and an XBT cast (red) on the equator at 23°W. (a),(b) The green lines are the adjusted temperature profile and its vertical gradient, resulting from adjustment of the vertical gradient of the XBT profile (red) in order to maximize local correlation with the vertical gradient of the CTD profile. The overall correlation between the vertical gradients of the XBT and CTD profiles goes from 0.72 to 0.97 once the XBT profile is locally adjusted. (c) Maximum correlation coefficient between the XBT and CTD gradient within a 50-m depth window centered at each depth. (d) Vertical shift of the vertical gradient of the XBT profile that maximizes the local correlation between the CTD and XBT gradients. Positive values indicate an upward shift.

with a 5-m low-pass cutoff in order to remove small-scale geophysical and instrumental noise (e.g., spikes).

4) Calculation of temperature gradient. Profiles of vertical temperature gradient are computed using centered differences at each 1-m depth from both filtered CTD and XBT data.

5) Estimation of true XBT depth. The true depth of the XBT temperature profiles $z_{\mathrm{XBT\text{-}adj}}$ is obtained by shifting each XBT depth estimated using the FRE z_{FRE} in order to maximize the correspondence between $\partial T/\partial z_{\mathrm{XBT}}$ and $\partial T/\partial z_{\mathrm{CTD}}$. A 50-m-deep window is centered on each 1-m depth along the $\partial T/\partial z_{\mathrm{XBT}}$ profile and then shifted up and down throughout the entire profile until the maximum correlation with the $\partial T/\partial z_{\mathrm{CTD}}$ profile is found. The maximum correlation between the CTD and the depth-adjusted XBT profile is found always within 50 m because the autocorrelation function of the $\partial T/\partial z$ profiles decays very rapidly. The depth at which the shifted $\partial T/\partial z_{\mathrm{XBT}}$ profile exhibits maximum correlation with the $\partial T/\partial z_{\mathrm{CTD}}$ profile is the actual depth of the $\partial T/\partial z_{\mathrm{XBT}}$ profile, and hence of the

XBT profile. The value of this maximum correlation is used to evaluate the robustness of this estimate of the "true" XBT depth. The CTD depth z_{CTD}, where this correlation is maximum, is the actual depth measured by the XBT $z_{\mathrm{XBT\text{-}adj}}$. We compare this depth with the depth obtained from the FRE z_{FRE} to study the magnitude and vertical distribution of the XBT depth errors. This procedure adjusts the XBT depths at each 1-m level and within a relatively small window compared with the entire profile depth. Therefore, the XBT depth errors are not forced to fit a given vertical distribution. It is noteworthy, however, that the vertical distribution of the $z_{\mathrm{XBT\text{-}adj}}$ minus z_{FRE} differences have such evident linear dependence with depth, already anticipating a fall-rate bias (Fig. 2d).

The implementation of the methodology to estimate $z_{\mathrm{XBT\text{-}adj}}$ from a CTD–XBT pair is illustrated in Fig. 2. As discussed above, this pair of XBT and CTD profiles obtained on the equator at 23°W shows substantial temperature differences (Fig. 2a, red and

blue lines). These differences become more apparent when the vertical gradients are computed (Fig. 2b), which show the maxima in $\partial T/\partial z$ associated with the "stair steps" (see blowups of Fig. 2a and Fig. 1b), generally shifted upward in the XBT profile (red) compared with the CTD profile (blue). The $\partial T/\partial z$ profile obtained after adjusting the XBT depths with the CTD data, $\partial T/\partial z_{\text{XBT-adj}}$ (green), shows a good correspondence with the $\partial T/\partial z_{\text{CTD}}$ profile over most of the depth of the XBT profiles. This correspondence is shown by values of the correlation coefficient, after the depth adjustment, exceeding 0.80 down to about 550 m (Fig. 2c). As a result of the depth adjustment, the total correlation between $\partial T/\partial z_{\text{XBT}}(z)$ and $\partial T/\partial z_{\text{CTD}}(z)$ increases from 0.73 to 0.97 for this individual XBT–CTD pair. Note that the correspondence between the CTD and the depth-adjusted XBT profiles is so good that the blue and green lines are indistinguishable (Fig. 2a). In general, the adjustment of the XBT depths increases the total correlation between $\partial T/\partial z_{\text{XBT}}(z)$ and $\partial T/\partial z_{\text{CTD}}(z)$ in all 52 profiles, with a mean correlation coefficient increasing from 0.77 ± 0.13 to 0.96 ± 0.03 after the depth adjustment (where the uncertainty value is the standard deviation).

For all XBT–CTD pairs, the vertical gradients become increasingly smaller both deeper than 700 m and near the surface, severely limiting the ability of this methodology to estimate the true XBT depths at these depth ranges. In addition, some profiles show low correlation at intermediate depths, such as at 200 m for the 23°W equator profile (Fig. 2c). We used the local correlation coefficient of the z_{FRE} adjustment to determine the estimates of $z_{\text{XBT-adj}}$ that would be used in the identification and quantification of depth errors presented in the next section. Only $z_{\text{XBT-adj}}$ values estimated from adjusted gradients with a correlation of 0.7 or greater (see step 5 or Fig. 2c) were used to estimate the $z_{\text{XBT-adj}}$. The conclusions derived from the analysis of the 52 profiles used here do not change when local correlation cutoffs from 0.6 to 0.8 are used. Using $z_{\text{XBT-adj}}$ estimated from highly correlated portions of the XBT and CTD $\partial T/\partial z$ profiles allows the reduction of the uncertainty in the estimation of the fall-rate bias. Conversely, if a correlation threshold larger than 0.8 is used, the number of $z_{\text{XBT-adj}}$ estimates decreases, resulting in increased uncertainty in the estimation of the fall-rate errors.

6) Visual QC. The adjusted vertical gradients (e.g., Fig. 2b), the correlation between them, the local correlation between the $\partial T/\partial z$ profiles (e.g., Fig. 2c), and the depth dependence of the resulting depth differences,

z_{FRE} minus $z_{\text{XBT-adj}}$, (e.g., Fig. 2d) were visually inspected for all 52 XBT–CTD pairs before proceeding to the analysis of the depth errors as a function of the manufacture date of the XBTs.

7) Estimation of fall-rate and temperature bias. Depth and temperature differences for depths ranging from 20 to 700 m were used to estimate the magnitude of the fall-rate and temperature biases. The methodology used here is unable to detect gradients at depths above and below these limits. The linear depth bias, or fall-rate bias, is computed for each individual profile as the least squares slope of a best-fit straight line adjusting the profile of z_{FRE} minus $z_{\text{XBT-adj}}$ differences. The slope is computed assuming that the differences are zero at the surface ($z = 0$). The fall-rate bias is a percentage of depth, because it is the slope between two depth estimates. The pure temperature bias is the depth-averaged value of the temperature differences between the depth-adjusted XBT profile (T_{XBT}, $z_{\text{XBT-adj}}$) minus the CTD profile (T_{CTD}, z_{CTD}) in units of degrees Celsius.

8) Systematic errors as a function of manufacture date. We analyze the temperature profiles (Fig. 3, left), the associated depth errors (Fig. 3, center), and pure temperature errors (Fig. 3, right) for each three groups of XBTs, separated according to their manufacture year: 1986, 1990–95, and 2008. We also estimate the uncertainty of the fall-rate and temperature biases for each of the manufacture years, using the median as the expected value and the range given by the standard deviation among the individual estimates (Table 1, columns 5, 7, and 8). The median errors avoid the influence of outliers in small sample sizes like these.

3. Results

a. Depth errors

All profiles show depth errors, increasing with depth, that are biased toward negative values ranging from -4% to 0%. The values of -4% obtained for XBTs manufactured on 1986 agree with the cold XBT fall-rate bias identified and corrected after the study of H95. Note that we did not apply the H95 correction to the XBT profiles used in this study. Most of the profiles show depth errors that are highly correlated with depth (Table 1, column 6) suggesting a linear dependence with depth (Figs. 3b, 2e, and 2h). This clear linear dependence indicates a bias in the processes represented by the A coefficient of the FRE; that is, the balance of buoyancy and drag. Thus, the depth errors identified here are consistent with XBTs reaching an actual terminal velocity faster than $A = 6.472$ m s^{-1}; that is, a fall-rate bias. Note that the $-Bt^2$ term in the FRE is much smaller than the At
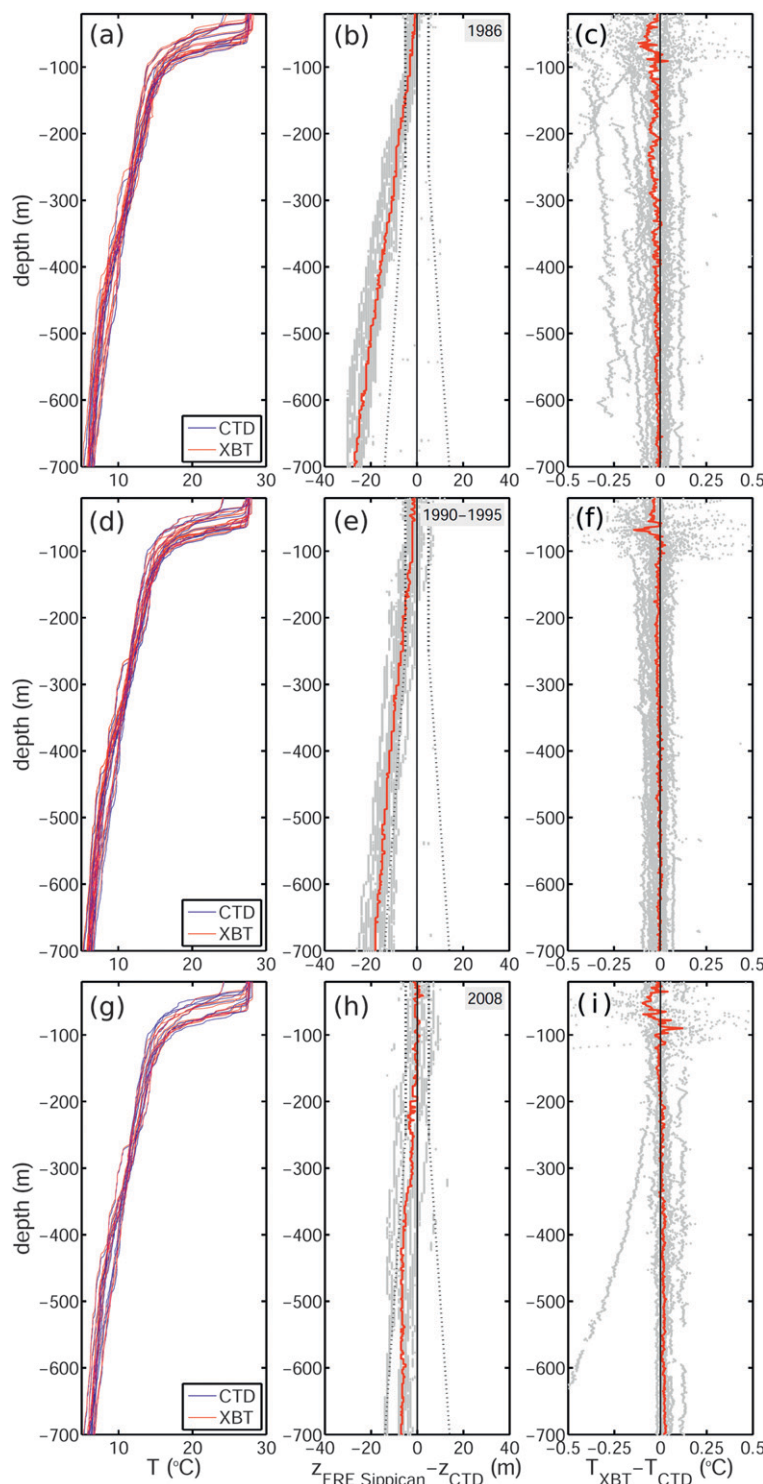
Fig. 3. (left) Temperature profiles obtained from CTDs (blue) and XBTs (red) manufactured in (a) 1986, (d) 1990–95, and (g) 2008. (center) Differences between the depth estimated by the XBT FRE with the original Sippican coefficients minus the true XBT depth estimated using the methodology described in the text (gray dots). The profiles are separated according to the manufacture date of the XBTs: (b) 1986, (e) 1990–95, and (h) 2008. The median value of the depth differences is shown in red. Depth differences are in meters. The dotted lines determine the XBT depth error specified by Sippican: 2% of depth or 5 m, whichever is larger. (right) XBT minus CTD temperature as function of depth after the depth of the XBT profile is adjusted using the methodology described in the text (gray dots). The profiles are separated according to the manufacture date of the XBTs: (c) 1986, (f) 1990–95, and (i) 2008. The median value of the temperature differences is shown in red. Temperature differences are in °C.

TABLE 1. Depth and temperature biases for XBTs manufactured on different years during the 1980s, 1990s, and 2000s.

XBT manufacture date	No. of profiles	Corr coef between $\partial T/\partial z_{CTD}(z)$ and $\partial T/\partial z_{XBT}(z)$		Depth bias			
		Before depth adjustment	After depth adjustment	Magnitude (%)	Corr of depth dependence	Surface offset (m)	Temp bias (°C)
1986	19	0.79 ± 0.12	0.97 ± 0.01	−3.77 ± 0.57	−0.98 ± 0.07	0.20 ± 1.54	−0.03 ± 0.17
1990–95	21	0.77 ± 0.15	0.97 ± 0.01	−2.72 ± 0.50	−0.96 ± 0.08	−0.56 ± 3.03	−0.01 ± 0.04
2008	12	0.74 ± 0.15	0.97 ± 0.02	−1.05 ± 1.34	−0.61 ± 0.46	0.58 ± 4.25	0.01 ± 0.08

term because it is just a correction to account for the loss of mass and the increase in drag with depth.

A clear year-dependence of this bias becomes evident when the depth error estimates from the different profiles are separated into the three groups of years (Fig. 4a). According to our analysis of the 52 collocated XBT–CTD pairs, the median depth bias has changed from $(−3.77 ± 0.57)\%$ to $(−1.05 ± 1.34)\%$ for XBTs manufactured in 1986 and 2008, respectively, with an intermediate value of $(−2.72 ± 0.50)\%$ for 1990–95 (Table 1, column 5). The 1σ uncertainty intervals of these fall-rate bias estimates exhibit a slight overlap. However, the 1σ bounds separate well below 500 m (Fig. 4a), indicating that they represent robust changes in the fall-rate characteristics of the XBT probes with 67% probability. Moreover, the strong linear dependence of the depth errors confirms the hypothesis that these errors are related to variations in the fall rate of the XBT probe.

b. Temperature and start-up errors

Unlike the depth errors, the temperature errors do not show statistically significant biases (Fig. 4b). The amplitude of the uncertainty envelopes, an estimate of the random errors in temperature, does not show a consistent evolution with time; that is, the random errors of the XBTs manufactured in 2008 are larger than those manufactured during 1990–95. These results indicate that the precision of XBTs is very low, but the accuracy is high. The wider error envelopes (low precision) for 1986 could be just the result of one profile with very large temperature errors (Fig. 3c). However, all profiles show temperature errors with almost no depth dependence (Figs. 3c,f,i), supporting the idea that the temperature (random) errors are due to the thermistor. Figure 3i also shows that the depth dependence of the temperature error for 2008 could just be the result of one profile with very large depth dependence. The median of the temperature errors does not exceed 0.03°C, a much smaller value than the 0.1°C accuracy of the thermistor. Thus, our results do not provide evidence for year-dependent systematic temperature errors in XBTs manufactured between 1986 and 2008. The only exception is the seasonal thermocline, where the depth distribution of the median error shows a much

larger and robust underestimation of the temperature, possibly related to the finite-time response of the XBT thermistor (Roemmich and Cornuelle 1987). Note that the thermistors of the XBTs manufactured in 1986 to 1995 may have degraded their accuracy and precision because they exceeded the shelf time.

We also tested the possibility of surface offsets associated with start-up transients. These offsets can be estimated by computing the least squares best-fit line of the depth errors, but allowing for a constant value at $z = 0$. The estimated median values of the implied surface errors are small, not significant, and with uncertainty within the 5 m specified by Sippican (Table 1, column 7) indicating that there are no systematic biases at the surface. During the PNE09 experiment the XBTs were carefully dropped from the depth specified by Sippican to minimize the effect of hydrodynamical transients not captured by the FRE, possibly explaining the absence of this type of errors, which could be more common in profiles collected from ships of opportunity.

4. Conclusions

Using a method that can estimate true XBT depths independent of temperature errors, we have found evidence of a cold XBT fall-rate bias that has changed from $(−3.77 ± 0.57)\%$ to $(−1.05 ± 1.34)\%$ between 1986 and 2008. This work is the first study showing this year dependence using a methodology that can unambiguously separate depth errors from pure temperature errors. A rather large uncertainty is associated with these estimates due to the small number of profiles used (between 12 and 21). However, the year-dependent variations in the fall-rate bias are statistically significant at the 1σ confidence level below 500 m, where the effect of the fall-rate bias is larger. Our results for XBTs manufactured in 2008 also agree with results from experiments performed in 2007 (Goni et al. 2011, manuscript submitted to *J. Atmos. Oceanic Technol.*) showing that the original Sippican FRE coefficients may be more accurate than the H95 correction. Overall, our results indicate that the changes in fall-rate characteristics of the XBT probe may be real with a 67% probability.
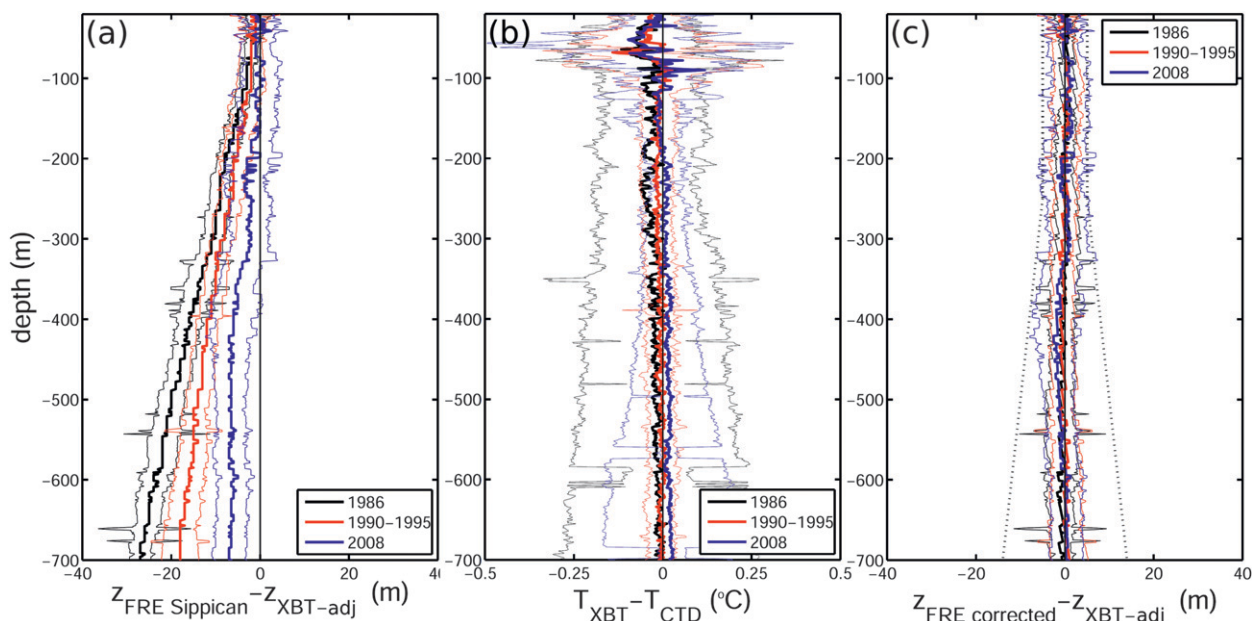
FIG. 4. Vertical profiles of (a) depth errors, (b) temperature errors, and (c) depth errors after fall-rate corrections (solid line) and uncertainty interval (thin lines) of temperature profiles obtained with XBTs manufactured in 1986 (black), 1990–95 (red), and 2008 (blue). The depth-dependent error is the median difference among all profiles with a given manufacture date, and the uncertainty interval is their standard deviation. The depth differences are the depth estimated by the XBT FRE using the original Sippican coefficients minus the true depth estimated using the methodology described in the text. Depth differences are in meters. Temperature differences are in °C. The dotted lines in (c) determine the XBT depth error specified by Sippican: 2% of the depth or 5 m, whichever is larger.

H95 analyzed XBT–CTD pairs collected in several experiments between 1985 and 1992. A total of 161 profiles obtained with T7 XBTs manufactured by Sippican were analyzed. Our estimates of a cold fall-rate bias of $(-3.77 \pm 0.20)\%$ and $(-2.72 \pm 0.20)\%$ for XBTs manufactured in 1986 and in 1990–95, respectively, bracket the -3.52% estimate obtained by H95 for the T7 model. H95 do not provided details on the manufacture dates of these XBTs, but if we assume that they were close to the date of the experiments, then our results are in agreement. The fall-rate bias found here also shows a decrease with time when the XBTs manufactured between 1990 and 1995 are separated into two groups of 9 XBTs for 1990–91 and 12 for 1995. However, the change from $(-2.72 \pm 0.50)\%$ in 1990–91 to $(-2.49 \pm 0.55)\%$ in 1995 is not statistically significant at the 1σ confidence level.

Overall, our results indicate that the H95 correction was adequate for XBTs manufactured between 1986 and 1991, which is close to the 1985 to 1992 range of years covered by the experiments analyzed by H95. Moreover, our results also indicate that the H95 correction may have been no longer adequate as early as 1995, and is clearly inadequate for XBTs manufactured in 2008 when the original Sippican FRE gives smaller depth bias in agreement with previous studies (Wijffels et al. 2008; DiNezio and Goni 2010).

The changes in terminal velocity inferred from our study are indicative of changes in the hydrodynamic characteristics of the XBT probe. These changes could result from manufacturing changes; however, according to Sippican (M. Gifford 2008, personal communication) the only two manufacturing changes made to XBTs in 1995 and 1999 did not have an impact on the fall-rate characteristics of the probe. These changes were implemented in such way that the properties of the XBT probe influencing their hydrodynamics (i.e., weight, roughness, and shape) remained unchanged. A change in the coating process was implemented in 1995. This resulted in a slight reduction of the weight of wire per unit length in air, but without a change in total weight in the water. A net around the spool was added to the probe in 1999 in order to protect the wire during transportation, but without impact on probe weight, roughness, or shape. Sippican regularly conducts tests to ensure the manufacturing stability, including thermistor, wire, and the components of the XBT recording system. However, the XBT profiles are not compared with higher accuracy instruments, such as CTDs, during these tests and instead the XBT profiles are compared among each other in order to ensure stability in the product.

When we separate the XBTs manufactured during 1990–95 into those manufactured in 1990–91 and those

manufactured in 1995 the changes in depth error are $-(2.86 \pm 0.31)\%$ for 1990–91 and $-(2.35 \pm 0.46)\%$ for 1995. This suggests that the decrease in the fall-rate bias was likely to be monotonic between 1986 and 1995. However, because we lack XBTs manufactured between 1995 and 2008, we can rule out that the fall-rate bias may have increased in the intervening years before decreasing again, or that the change in terminal velocity could have occurred as a result of one single change in the manufacturing process.

However, our estimates of fall-rate agree very well with the results of Wijffels et al. (2008). Their results indicate rather sharp jumps in fall-rate values for XBTs deployed between 1990–95 and 1995–2000 (their Fig. 14). Note the distinction between XBTs "deployed" and "manufactured." Their study used the date when the XBT profile was collected (deployed) because there is no metadata of the manufacturing date. Thus, XBTs of different manufacturing dates were likely to be deployed in the same year, resulting in a smoother transition from high to low fall-rate values. Thus, the changes in fall rate could be a result of manufacturing changes on about 1990 and 1995.

No evidence of pure temperature biases was found, apart from a slight cold bias in the seasonal thermocline. However, since we used XBTs that exceeded the shelf life of the thermistor, we cannot rule out the possibility that XBTs also suffer from temperature biases. A suggestion of a cold bias of about 0.1°C in the seasonal thermocline in these profiles could have implications for studying trends in thermal stratification in response to global warming. Because XBTs dominate the earlier part of the climate record prior to 2000, and seem to measure a more diffuse seasonal thermocline, a spurious trend could be introduced when the XBT data are combined with data from more accurate Argo floats available since 2000.

The results discussed here also have an immediate bearing on the discussion as to whether time-varying XBT biases are due to changes in the fall-rate bias or are caused by changes in a pure temperature bias. Our results indicate that, at least for the 1986–2008 period, the hypothesis that the XBT errors are due to a time-varying fall-rate bias, as hypothesized by Wijffels et al. (2008), cannot be rejected. However, it is possible that XBT biases during the earlier part of the record, such as the large temperature biases during the late 1970s through the early 1980s, are due to pure temperature bias introduced by the strip-chart recorder as hypothesized by Gouretski and Reseghetti (2010).

Once the fall-rate bias is corrected, the residual errors show no biases (Fig. 4c). These residual errors estimate the random errors likely to result from the limitations of the FRE to capture the complex hydrodynamics of the descent of the probes. The 1σ envelope of these errors has constant amplitude with depth of about 5 m, much smaller than the 2% specified by Sippican for depths below 250 m. This indicates that smaller uncertainty could be placed on XBT profiles if the fall-rate bias is corrected. This could be achieved for future observations, for instance, if the XBTs had a pressure sensor activated at a given depth, ideally between 600 and 700 m. Our analysis indicates that most of the XBT depth errors result from fall-rate variations and thus are highly correlated with depth. Therefore, just one direct depth observation could be used to estimate the true fall rate of each individual XBT probe and calibrate the FRE for each individual profile. XBTs were designed for naval applications that do not require the accuracy needed to detect global ocean warming. However, adding a single-use pressure sensor would dramatically improve the accuracy of the XBT, rendering it more versatile for future climate applications.

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