Quantification of the Effect of Water Temperature on the Fall Rate of Expendable Bathythermographs

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ABSTRACT

A very large portion of the historical information on ocean temperatures has been measured using expendable bathythermograph (XBT) devices. For decades, these devices provided the majority of global information. It is, therefore, important to quantify their accuracy and identify biases in this important historical dataset. Here, calculations are made of the influence of water temperature on the rate of descent of the XBT devices into the ocean waters. In colder regions, the larger viscosity of the water is expected to cause a greater drag force on the device, which would slow the descent. It was found through computational fluid dynamic models that the impact of temperature and viscosity on the probe descent is approximately 2.2% for water temperatures that range from 0°C to 27°C. Probe-specific temperature-dependent fall rate equations were applied to 269 collocated XBT/conductivity–temperature–depth (CTD) measurements from two different research cruises. It was found that the probe-specific descent equations were an improvement over the uncorrected method. Next, in an effort to automate the process, the fall rate coefficients were related to the topmost measured temperature in the water column. With this relationship, comparisons were made between the probe-specific descent calculations and 2937 high-resolution XBT–CTD pairs. It was found that the new methodology outperformed the standard fall rate equation. The new method was also compared with an independent correction method that was previously published. It was found that both new methods were improvements upon the industry-standard fall rate calculation. Subsequent calculations using the top-100-m water temperature were performed and were found to be statistically insignificant compared to the proposed simplified method.

1. Introduction

Measurements of the earth’s climate system are crucial to the understanding of past and potential future climates. In particular, with human emissions of greenhouse gases, the earth is out of energy balance (Domingues et al. 2008; Abraham et al. 2013; Durack et al. 2014; Roemmich et al. 2015; Trenberth et al. 2014, 2015). Although the studies listed here are not exhaustive, they reflect various approaches to quantifying the ongoing energy imbalance.

Insofar as approximately 90% of the energy imbalance is manifested by ocean heat content changes (Church et al. 2011; Nuccitelli et al. 2012; Abraham et al. 2014a), accounting for the earth’s energy imbalance is largely an issue of ocean heat content measurements.

The creation of a long-lasting and high-quality dataset is challenging in part because climate records must be generated over many years and decades in order to quantify long-term trends and superimposed natural climatic variability (Lyman et al. 2010; Cheng and Zhu...
One of the most important datasets for long-term ocean measurements is from expendable bathymeterograph devices (XBT). These devices are launched into ocean waters and descend through the water while tethered to an onboard data collection system. As they descend, the XBTs transmit temperature information to the data collection system. Depth is not measured directly but rather is inferred from a time–depth relationship fall rate equation (FRE). The FRE takes the form

\[
\text{Depth} = At + Bt^2. \tag{1}
\]

Accurate measurements of the XBT depth is important for quantifying various oceanic properties and processes, such as heat content (Abraham et al. 2013) and overturning and oceanic heat transport (Goes et al. 2015).

The coefficients in Eq. (1) have been specified by the XBT manufacturers [Sippican Inc. and Tsurumi Seiki (TSK) Co.] as \(A = 6.472 \text{ m s}^{-1}\) and \(B = -0.00216 \text{ m s}^{-2}\) for the Deep Blue, T4, T6, and T7 devices (and for the TSK Co. counterparts). Other coefficients are suggested for different XBT types. However, since the 1960s, several studies have identified systematic biases in XBT data (Hazelworth 1966), mainly due to the inaccuracy of the fall rate coefficients (Flierl and Robinson 1977; Seaver and Kuleshov 1982). Therefore, many experiments were constructed by comparing the XBT profiles with collocated conductivity–temperature–depth (CTD) devices, aiming to quantify the value of XBT bias (e.g., Hanawa and Yoritaka, 1987; Hanawa and Yoshikawa 1991; Hallock and Teague 1991). Over time it became apparent that XBT biases vary temporally and between probe types, which make it difficult to obtain a global value of XBT bias. In 1995, Hanawa et al. (1995) calculated XBT depth bias by using hundreds of XBT–CTD comparisons. The recommendations made by Hanawa et al. (1995, hereafter H95) were reported in the Intergovernmental Oceanographic Commission (IOC) technical series (Hanawa et al. 1994) and were subsequently accepted by the XBT community as updated coefficients \(A = 6.691 \text{ m s}^{-1}\) and \(B = -0.00225 \text{ m s}^{-2}\). These FRE coefficients are termed H95 coefficients and are recommended for the Deep Blue, T4, T6, and T7 devices (and for the TSK counterparts). Other coefficients are suggested for different XBT styles. Since the H95 coefficients were determined, the historical XBT record contains profiles collected with both the manufacturer coefficients and the H95 values.

The reassessment of the FRE coefficients was thought to solve the fall rate problem. However, more and more evidence indicates that many factors can affect the XBT descent rate through the ocean waters, so that under circumstances that differ from those of the calibrating experiments, other coefficients or corrections may be necessary. Many studies have been performed to quantify the biases among the global XBT datasets using statistical analyses (Wijffels et al. 2008; Ishii and Kimoto 2009; Levitus et al. 2009; Gouretski and Reseghetti 2010; Good 2011; Cowley et al. 2013; Cheng et al. 2014). All these studies correct for a fall rate bias and some also include a temperature bias. In some cases the fall rate bias is constant but in others it varies with time. Until recently, there has been no consensus on the best method of correction, but the XBT science community is in the process of assessing the schemes (Cheng et al. 2016).

In addition to improvements to the values of the FRE coefficients, inclusion of more terms has been studied. Some research has included an offset term to the standard FRE because there is a depth bias in the upper 50 m that has been shown to be dependent on drop height in very recent work (Bringas and Goni 2015). In this study, no offset term was included in the FRE; however, the influence of drop height will nevertheless be directly incorporated into the model as described later.

It has been suspected for a long time that the water temperature could influence the fall rate of the XBT probe in the ocean: as water temperature decreases (and viscosity increases), the linear term (the initial fall rate of the XBT probe) will change and the acceleration may also be affected. Seaver and Kuleshov (1982) proposed a first numerical bias model, taking into account the impact of water temperature, which regulates the fall rate via viscosity. By constructing an XBT–CTD test (10 XBT–CTD pairs) in cold waters, Thadathil et al. (2002) indicates a slower fall rate in colder water. Kizu et al. (2005) investigated the temperature dependency of the fall rate for T5 devices produced by both TSK and Sippican. In addition, by using \(\sim 4000\) side-by-side XBT–CTD pairs collected by Cowley et al. (2013), Cheng et al. (2014) investigated the effect of temperature on fall rate [coefficient \(A\) in Eq.(1)]; they found that the initial fall rate \(A\) increases linearly with upper-0–100-m averaged temperature. Abraham et al. (2012a) used numerical simulation in a similar study and found a similar temperature dependency in numerical models.

All of these independent studies indicate that the water temperature could impact the XBT fall rate,
and so it is a key task to parameterize this effect in XBT correction schemes. In this study, a novel method is proposed to create probe-specific FRE coefficients by taking into account the influence of water temperature.

Here, the two prior methods of Stark et al. (2011) and Cowley et al. (2013, hereafter C13) are employed to further investigate and quantify the impact of water temperature on the linear FRE coefficients $A$ and $B$. Using collocated XBT and CTD profiles from two modern voyages, the viability of the new method is assessed. Then, a new technique to easily and quickly create probe-specific FRE coefficients is presented. Finally, this new method is applied to a large dataset (2937 CTD–XBT high-resolution Sippican T4/T6/T7/DB pairs) and an assessment of the new method is made. Comparisons are made with fall rates calculated using the standard H95 FRE coefficients.

2. Numerical model

The model is based on that first articulated in Stark et al. (2011) and Abraham et al. (2011). A computational fluid dynamic analysis was made of the probe descending into the water. In the model, the effects of impact forces are neglected. While prior research has shown these can affect the depth, particularly in the upper layers of the oceans, their magnitude is difficult to assess and ultimately results in a depth offset (Shepard et al. 2014; Schwalbach et al. 2014; Gorman et al. 2014; Abraham et al. 2014b; Bringas and Goni 2015). For the present calculations, the drop heights were 0.5 m (R/V Southern Surveyor experiments) and 3.0 m [ice-breaker (IB) Aurora Australis experiments]. These heights were used to calculate the velocity of the probe at the time of impact with the water. Subsequently, the drag forces as described in Stark et al. (2011), Gorman et al. (2014), and Abraham et al. (2012a,b) were used. No extra impact force effects were employed. No other depth offsets were used.

The basis for the calculation is an instantaneous force–momentum balance as the device falls into the water. This is expressed as

$$F_{\text{net}} = F_{\text{buoy}} - F_{\text{drag}} = \frac{d(m_p V)}{dt} = m_p \frac{d(V)}{dt} + V \frac{d(m_p)}{dt},$$

where the buoyancy and drag forces are reflected by the subscripts on the force terms. These two forces are obtained by Eqs. (3) and (4), respectively,

$$F_{\text{buoy}} = (m_p - m_w)g,$$

and

$$F_{\text{drag}} = C_d \frac{1}{2} \rho V^2 \times \text{Area},$$

where the symbol $C_d$ is a drag coefficient, $F$ is the drag force, $\rho$ is the fluid density, $V$ is the probe velocity, and Area is the frontal area of the probe. The drag coefficient is dependent upon the Reynolds number (Re), which characterizes the descent. The Reynolds number is, in turn, determined by the velocity of the object and the viscosity of the fluid in the neighboring region.

Mathematically, the dependence of the drag coefficient can be expressed as

$$C_d = \text{function(Re)} = \text{function}(T, V, \mu).$$

The symbols $T$, $V$, and $\mu$ represent temperature, velocity and viscosity of the fluid, respectively. The density and viscosity of the fluid are determined at each time step by knowledge of the temperature at that time step, recorded by the XBT. As a result of previous studies already listed, quantitative information for the drag coefficients are known for broad ranges of Reynolds numbers. The method takes in temperatures from the XBT descent, calculates an initial velocity based on the drop height and, consequently, a Reynolds number characterizing the flow around the probe. From the Reynolds number, a drag coefficient and a drag force are determined. This information is used in a force balance to update the probe velocity at subsequent times. The forward-stepping algorithm is continued until the ultimate depth of the probe is reached.

Mathematically, as derived in Stark et al. (2011), the forward-stepping algorithm leads to

$$V^{\text{new}} = V + \frac{\Delta t}{m_p} \left[ (m_p - m_w)g - C_d \frac{1}{2} \rho V^2 \times \text{Area} - V \frac{dm_p}{dx} \right].$$

A requirement is the initial velocity of the probe at the time of impact with the water and the water temperature—that initial velocity is dependent upon the drop height of the probe; its calculation is based on acceleration of the probe caused by Earth’s gravity, and air resistance is neglected. Consequently, the first value of velocity is

$$V_{\text{initial}} = \sqrt{2g(\text{drop height})},$$

where the symbol $g$ is the gravitational acceleration. The initial temperature of the water is taken to be that
recorded at the 4-m depth for reasons that will be discussed later.

In Eq. (6), the symbols \( m \), \( \Delta t \), and \( x \) correspond to the mass, calculation time step, and depth, respectively. The subscripts \( p \) and \( w \) refer to the probe and the displaced water, respectively. The calculations provide a relationship of probe-specific time and depth. This relationship is fitted with a quadratic trend of the form

\[
\text{depth} = Br^2 + At, \tag{8}
\]

where \( A \) and \( B \) correspond to the probe-specific fall rate equation of Eq. (1).

3. Results

XBT and collocated CTD pairs were sourced from the version 2 XBT and CTD pairs database (Cowley et al. 2014). All XBT data used in this study were high resolution (~0.6-m depth intervals) and from Sippican Deep Blue (DB), T7, T6, or T4 probes.

a. Initial assessment of the method

The above-mentioned method was applied to 190 Sippican DB XBT casts from an IB *Aurora Australis* (2012) voyage and 79 casts from an R/V *Southern Surveyor* voyage (2009). The profiles were collected over a wide latitude range and, consequently, a wide range of temperatures, as illustrated in Fig. 1. Deployment heights were approximately 3 m from the IB *Aurora Australis* and 0.5 m from the R/V *Southern Surveyor*. Insofar as the numerical method requires the initial velocity of the probe upon impact with the water, the differing drop heights lead to differences in the initial velocities. However, the method naturally accounts for these differences in the algorithm, as indicated in Eq. (7).

This small dataset of 269 profile pairs was used to do an initial assessment of the proposed correction. New values for coefficients \( A \) and \( B \) of the FRE were derived, applied to the XBT profiles in this small dataset and new depths were calculated. As a result, the new depths now incorporate the effect of water temperature. Results
were then compared with near-collocated CTD temperatures using the method of C13.

The H95 depth errors (Fig. 2a) are large and biased positively in all temperature ranges from these two voyages. After applying the new temperature-dependent FRE coefficients to the XBTs, the temperature/depth error is reduced to around zero in the upper 300 m (Fig. 2b). Below 300 m the temperature/depth biases are reduced, but now they become negative. The C13 method (Fig. 2c) also reduces the depth bias. Residual biases in the data with the H95 coefficients are large, particularly in the warmer waters (Fig. 3a). Application of the temperature-dependent coefficients (Fig. 3b) and the C13 correction (Fig. 3c) result in a much reduced temperature/depth bias.

b. Application of a simplified automatic method

The approach outlined in the preceding sections requires computationally expensive calculations to be performed for each probe cast. Boyer et al. (2013) contains more than 2,254,000 XBT profiles from 1965 to 2014. To reduce the computational overhead of the calculations, a simplified and more automatic method was explored. The approach here uses the temperature measured near the ocean surface (at a depth of 4 m). These depths are sufficient so that thermal equilibration of the XBT sensor has occurred (Roemmich and Cornuelle 1987; Bailey et al. 1989). The temperature at 4 m is chosen to be representative of the temperature in the surface’s mixed layers, which varies over the first several meters to hundreds of meters in the ocean. An alternative is to use an average value of the top 100 m, which is discussed further in section 3d.

The simplified method involves a correlation of the recorded water temperature at 4-m depths and the depth-averaged coefficients \([A\) and \([B\) from Eq. (1)]. With the sole input of the near-surface temperature (the first recorded temperature measurement from the XBT device), it is feasible to automatically recalculate all linear coefficients and subsequently correct all FREs. As a result of this simplified method, each XBT probe would be assigned unique A and B FRE coefficients.

Before presentation of the simplified method, the necessity must be justified. The time-stepping calculation expressed in Eq. (6) is a forward-stepping integration that must be completed for each measured temperature from the XBT drop. For an XBT drop depth of 700 m, this requires approximately 1100 time steps per probe. Each time step requires 11 separate calculations so that in total, slightly more than 12,000
calculations are required for each probe. A preferred approach would be a simplified method wherein existing programs are used with easy-to-make modifications. Since the current depth calculations are made using the traditional FRE [Eq. (8)], that approach will form the basis of the new simplified method.

It is recognized that the new coefficient in the FRE will depend on temperature throughout the descent of the device. Prior work such as Cheng et al. (2014) attempted to relate the temperature throughout some depth (the upper 100 m for instance) to biases in the initial velocity (term $A$). They found a temperature dependency of the initial fall rate with a linear factor of 0.0025 (T7/DB) and 0.0050 (T4/T6) as shown in Fig. 4a. This result shows good agreement with our study. In an earlier work (Kizu et al. 2005), the dependency of depth error on water temperature is approximately estimated to be about 2 m°C$^{-1}$ in the upper 1000 m. When assuming a linear relationship between fall rate and water temperature, the relationship between fall rate and temperature is 0.0131 m s$^{-1}$°C$^{-1}$ (also shown in Fig. 4a), which is larger than our study. But the Kizu et al. (2005) result is obtained from TSK T5 XBTs, the design of which is different from Sippican T4/T6 and T7/DB probes. For example, there is more wire on the T5s to allow them to reach deeper depths, and there is a different manufacturer drop rate ($A = 6.828$, $B = -1.82$). So, the fall rate for T5 probes will likely have a different temperature dependency compared with other probe types.

The approach here is different. It is to find probe-specific FRE coefficients based on the calculation procedure outlined in Eq. (6) and without the need to perform iterative calculations. If such a goal were achieved, then the methodology could be easily applied to all archived XBT measurements in an automated fashion. The only reasonable way to achieve this goal is to avoid reliance on any subsurface properties of the water and to require only information that is obtained prior to the drop or with the first measurement.

The correlation between the linear coefficient and the 4-m near-surface temperature is provided in Fig. 4a, and the corresponding correlation of the quadratic term is found in Fig. 4b. There, 269 data points from the initial test cases are shown by data symbols. Solid circles are used for data obtained from the Aurora Australis cruise (drop height of 3 m), and open circles correspond to Southern Surveyor Southern Cruise (drop height of 0.5 m). The more shallow drop heights from the Southern Surveyor correspond to warmer waters, which are expected to lead to faster descent through the ocean waters.
because of the lower water viscosity. The Aurora drops were performed in cooler waters and, consequently, it is expected that the FRE coefficients give a slower descent. These two expectations are realized in the figure. No quality-control exclusion was applied; every XBT cast was included in the correlation. The fitted question is quadratic and is included in the figure. A quadratic fit was selected over other potential options. First, the quadratic fit does a reasonable job of matching the values of the data and the shape of the dependency. Second, there is some physical basis for the selection. When the temperature dependencies of the density and the viscosity are combined, it is found that there is an inverse dependency of the Reynolds number on the temperature. Since the drag coefficient has been shown to vary quadratically with the Reynolds number (Stark et al. 2011; Abraham et al. 2012a, b, 2013), the result is an expected quadratic relationship between temperature and fall rate, with the second-order term having a negative sign. This expectation was realized in Fig. 4.

Compared with Cheng et al. (2014) and Kizu et al. (2005), all of these studies agree that the fall rate increases with temperature, indicating the impact of viscosity. But the result from using the numerical model shows better agreement with Cheng et al. (2014) and weaker agreement with Kizu et al. (2005). This comparison suggests there are still some uncertainties for the quantification of

FIG. 4. (a) Correlation of the FRE linear coefficient with 4-m near-surface temperature (in black for the results of this study). For comparison, the linear correlation between fall rate and 0–100-m averaged temperatures from Cheng et al. (2014) is shown in solid pink for T7/DB and dashed pink for T4/T6. Results from Kizu et al. (2005) are shown in green. The three curves are adjusted to zero in 15°C for better comparison. Among the data, solid circles are for 3-m drop heights and open circles are for 0.5-m drop heights. (b) Correlation of the quadratic coefficient with 4-m near-surface temperature. Among the data, solid circles are for 3-m drop heights and open circles are for 0.5-m drop heights.
temperature dependence. However, the aforementioned studies use very different methodologies; here a physics-based approach is taken. The mutually reinforcing conclusions are indicative of the robustness of the finding.

The correlation was used for all 4-m near-surface temperatures below 27°C. For temperatures in excess of 27°C, a constant value of 6.607 was used for the linear FRE term (because the quadratic fit would lead to a physically unreasonable decrease in the linear coefficient for temperatures above 27°C).

Using the temperature-varying $A$ values derived from the fit in Fig. 4a and $B$ values from Fig. 4b, a new set of depths can be calculated. It should be noted that a comparison calculation was performed with values of the $A$ coefficient calculated from Fig. 4a and constant $B$ values equal to $-0.002484$, and the results were nearly identical to those that will be shown. Consequently, it was found that the variation of $B$ had a much smaller impact on the FRE compared to the variation in $A$.

c. Comparison of the simplified automatic method with other methods

A comparison between the new FRE coefficients (temperature-varying $A$ and $B$) and the H95 FRE coefficients was made using 2937 XBT/CTD profile pairs. The XBT profiles are Sippican T4, T6, T7, and Deep Blue probe types (the most abundant probe types historically) and are limited to high-resolution pairs ($\leq 1$-m depth intervals in XBT and $\leq 2$-m depth intervals in CTD). Low-resolution pairs are excluded because of the higher uncertainty in estimating depth errors using the method of C13.

Application of the temperature-specific $A$ and $B$ coefficients to the XBT profiles makes considerable improvement to the data compared to the H95 coefficients, at all water depths and temperature ranges (Figs. 5 and 6). Overall, the depth errors tend to be overcorrected at depth in the new method, while in the C13 method they remain undercorrected (Figs. 5 and 6).

Next, attention is turned to temperature residuals between XBT and CTD profiles. As found by many previous studies (Reseghetti et al. 2007; Gouretski and Reseghetti 2010; C13; Cheng et al. 2014, 2016), there is a pure temperature bias in XBT data that is independent of the depth bias. Many studies calculate temperature residuals after correcting the depth bias as an approximate of pure temperature bias. Based on this method, the C13 method indicates that pure temperature bias is largely consistent over depth. Therefore, it is also valuable to examine the temperature residuals after applying the new method in this study. It is seen that both the current analysis and the C13 approach reduce the total temperature difference between XBT and CTD (Figs. 7 and 8),
and the residuals show more depth consistency than H95. It should be noted that the temperature bias correction of the C13 method has not been applied in this study.

Warmer waters generally have a larger depth error when calculated with H95 coefficients, and these errors are noticeably reduced with both the current method and with the C13 method (Fig. 7). In deeper waters, the current method performs consistently across nearly all temperature ranges, with the two warmest categories having a negative residual at depth (within 300–800 m). The C13 method temperature residual tends to grow with increasing depth in the 7.5°–15.5°C range (Fig. 7c). Furthermore, both C13 and the current method show a similar distribution of temperature residuals (Fig. 8), despite the methods being very different. And both methods show a more confined distribution of the temperature residuals, indicating that removal of depth error significantly reduces the total temperature error.

d. Statistical comparison

A statistical investigation was made to quantitatively compare the performance of the three approaches. Figure 9 shows the mean and 1σ values for depth error and temperature residuals with depth for all methods. Both the present method and C13 improve on the H95 coefficients. Using the H95 coefficients, an increasing depth bias with depth is observed (XBTs deeper than CTDs), which is ~10 m at 900 m (1%). Using the current method, the mean depth bias is reduced, but it is reversed at depth (XBT depths are shallower than CTD depths). C13 shows a small positive bias over 0–900 m. Both methods reduce the depth error to less than 5 m at 900 m (0.5%). The standard deviation in depth errors is greatest in H95 and lowest in C13; however, all three methods have similar values.

The mean temperature residuals in H95 are around 0.1°C and are mostly constant with depth. Similarly, the C13 residuals are constant with depth but are lower than H95 (0.03°C), indicating there exists a pure temperature bias. The current method reduces the total temperature biases significantly (to 0.005°C) but not consistently over the depth range. This might be because the new method undercorrects the depth error in shallow water and overcorrects at depth. C13 has a lower standard deviation in the temperature residuals in the upper layers than the present approach (Fig. 9b), and all three methods have a similar standard deviation over the remaining depths.
e. Alternate simplified model using top-100-m average temperature

The method outlined in the preceding sections correlates the fall rate coefficients against the near-surface temperature. It remains to be determined whether other choices of correlating temperatures would provide improved results. To test this, the calculations were repeated and the coefficients \(A\) and \(B\) were correlated with the average temperature in the upper 100 m of water, as used in Cheng et al. (2014). This alternate approach provides some added complexity because it is not assumed that the standard FRE coefficients are correct. Consequently, it is not known when the device reaches a depth of 100 m. To overcome this issue, we have opted to use the H95 FRE coefficients to estimate the 100-m depth. We average the temperature over this estimated depth and correlate the coefficients against this estimated 100-m average temperature.

From this process, a counterpart to Fig. 4 was obtained. Equations (9a) and (9b) provide the correlation of \(A\) against the 4-m subsurface temperature (from Fig. 4a) and against the upper-100-m average temperature, respectively. Similarly, Eqs. (10a) and (10b) provide the quadratic coefficient \(B\) as a function of subsurface and 100-m temperatures, respectively:

\[ A = -0.000229T^2 + 0.01249T + 6.439, \]

using the 4-m near surface temperature \((9a)\)

for subsurface temperatures less than 27°C and 6.607 when the subsurface temperature exceeds 27°C;

\[ A = -0.000208T^2 + 0.01173T + 6.449, \]

using the 0-100-m average temperature \((9b)\)

for 100-m average temperatures less than 26°C and 6.6123 when the 100-m temperature exceeds 26°C;

\[ B = 4.14 \times 10^{-7}T^2 - 2.54 \times 10^{-5}T - 0.002319, \]

using the 4-m near-surface temperature \((10a)\)

\[ B = 3.65 \times 10^{-7}T^2 - 2.42 \times 10^{-5}T - 0.002334, \]

using the 0-100-m average temperature. \((10b)\)

When these new coefficients are applied to the large dataset, it is found that the results are insignificantly different from those already presented in Figs. 5–9. For the results using the 4-m subsurface temperature, the depth-averaged error is \(-3.578 \pm 6.746\) m and the temperature error is \(-0.00753 \pm 0.1656\) °C. The corresponding depth and temperature errors when the top 100-m average temperature is used are \(-3.630 \pm 6.588\) m.
and $-0.005^{\circ}C \pm 0.163^{\circ}C$, respectively. At 700-m depth, using the 100-m average temperature results in an additional 0.23-m overcorrection at 700 m, which is negligible when compared to the overall correction in the mean depth error from H95 depths (6.5 m at 700 m for H95 and $-3.9$ m at 700 m for the 4-m temperature calculation results) (Fig. 9). Similarly, at 700-m depth, the difference in temperature bias is negligible between the two methods ($0.0008^{\circ}C$) compared to the correction observed in Fig. 9. Because of the simplicity of the first proposed method and the similarity of the results, we recommend the correlations indicated in Fig. 4 and in Eqs. (9a) and (10a).

**f. Discussion**

When the results of both parts of the present study are considered as a whole, it becomes clear that the new method is an improvement upon the uncorrected H95 approach. However, when compared with recent techniques, the new method undercorrects in shallow water and overcorrects at depth. Tests with inclusion of an offset term in the FRE have indicated that the offset has a significant effect on the corrections. By refining the application and value of the offset term (perhaps related to deployment height and impact forces when the probe first enters the water), the results of this method might be improved. Future studies will investigate this potential. Guidance for the importance of the inclusion of offset terms is obtained from Bringas and Goni (2015), who show that such terms are particularly important for launch heights that differ from those upon which the FREs were obtained.

The new approach is theoretically and numerically constructed; it is not formulated from experimental results. Insofar as the temperature dependency affects the drag forces, that dependency appears in the final results. So, there is a potential to use this new approach to provide further improvements to FREs.

The new method also quantifies the rate of change of the linear term with the 4-m near-surface temperature. The relationship is shown graphically in Fig. 10. There it is seen that for the coldest waters, the linear term changes approximately $0.2\% \ deg^{-1}$ change in 4-m near-surface temperature. On the other hand, for warmer waters, the influence on the linear term is much reduced and falls to zero at temperatures above 27$^{\circ}C$. The cumulative effect
on the linear term, over the span of temperatures shown in Fig. 4a, is approximately 2.2%.

4. Concluding remarks

Here, numerical simulations based on a computational fluid dynamic calculation have been performed to quantify the effect of water temperature on the fall rate of XBT devices. The focus of the study is to quantify the influence of temperature on the linear term ($A$) and the quadratic term ($B$) in the FRE. A test case including 269 casts was analyzed and individual FRE coefficients were obtained for every XBT profile. These coefficients were then input into the FRE and depths recalculated for a large number of XBT casts collocated with CTDs. Comparing each XBT with its CTD pair, it was found that the probe-specific calculations were an improvement compared to the uncorrected H95 FRE. In particular, depth and temperature errors were reduced throughout the entire depth.

While the method is an improvement, the time and effort required for individual simulations renders the technique impractical for large-scale corrections. To simplify and speed up the process, a correlation was found between the uppermost water temperature and the coefficients in the FRE—that correlation was used to automatically obtain coefficients for each profile. These new coefficients were applied to an independent dataset of 2937 casts. These corrected XBT casts were compared with their collocated CTD casts, and the depth and temperature residuals were further compared with H95 depth and temperature residuals. It was found that the simplified correction reduced both temperature and depth errors over the H95 coefficients.

The present work is a temperature-dependent recal culation of fall rate based on theory, while C13 is a time-dependent linear correction applied to H95 depths based on observed data. Both methods reduce biases in XBT data despite being very different in nature. Future investigations into the inclusion of an offset term in the FRE could improve the current method performance.

![Fig. 9. Mean (solid lines) and 1σ values (dashed lines) in (a) depth and (b) temperature for the three methodologies.](image-url)

![Fig. 10. Change of linear FRE coefficient with sea surface temperature.](image-url)
One potential use of the new method is that it allows for quantification of the sensitivity of the linear FRE coefficient with temperature. It is seen that that term may change by up to 2.2% as the water temperature changes.

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