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The Temperature and Depth Accuracy of Sippican T-5 XBTs

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The Temperature and Depth Accuracy of Sippican T-5 XBTs

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7 April 1992 and 30 July 1992

ABSTRACT

Thirty-four near-simultaneous pairs of CTD and Sippican model T-5 XBT profiles were obtained during an experiment in the Sargasso Sea during the summer of 1991. The data were analyzed to assess the temperature and fall-rate accuracies of the T-5 probes. The XBT temperatures averaged 0.07°C warmer than CTD temperatures, with some suggestion that the offset might be different for different acquisition systems and that it might be slightly temperature or pressure dependent. When the offset was removed, the differences between CTD and XBT temperatures had a standard deviation of about 0.08°C over a temperature range of 3° – 29°C .

An improved elapsed fall-time-to-depth conversion equation for Sippican T-5's in the Sargasso Sea was found to be $z = 6.705t - 0.001619t^2$, with z the depth in meters and t the elapsed fall time of the probe in seconds. The standard deviation of depth was about 8 m over a depth range of 0 to approximately 1800 m. A cubic fit to the data was equally good or slightly better. Whether a geographically universal fall-rate equation can be devised for each model XBT is still unclear. In addition, now that a number of different manufacturers are introducing their versions of XBTs and XBT acquisition systems onto the market, unresolved questions exist regarding the differences in data taken with these different models.

1. Introduction

The ship-deployed expendable bathythermograph (XBT) is a relatively inexpensive nonrecoverable instrument that yields temperature-versus-depth values down to a maximum of about 1800 m, depending upon the model. XBTs were first introduced in 1965 by Sippican Ocean Systems, and over four million have been sold. Recently, other manufacturers have also begun to enter the market. Global archives are dominated by XBT measurements, and many oceanographic experiments depend upon them as the primary tool for obtaining subsurface measurements. The XBT is truly the "work horse" of physical oceanography. Clearly, knowledge of the accuracy and possible biases of this instrument is very important.

A quick description of the generic XBT will help clarify where some of the inaccuracies and errors in measurements might arise. A thermistor is mounted inside the nose of a small, streamlined, weighted body, which upon deployment is released from its surrounding canister and falls over the side of a ship. As the probe descends, a thin, two-stranded insulated wire unwinds from two spools, one located in the falling body and the other in the canister that remains topside

on board the ship. The thermistor's resistance changes as the probe falls through water of different temperatures, and the varying voltage required to maintain a constant amperage is sensed topside. This variation may be used to generate a trace on a special chart recorder or may be translated by an analog-to-digital (A/D) converter into a digital reading. These readings are then translated into temperature values. Depth is calculated from the assumed fall rate of the weighted body; it is not measured directly. For its XBTs, Sippican Ocean Systems claims an overall temperature accuracy of 0.15°C and a depth accuracy of ± 5 m or 2% of depth, whichever is larger (Sippican Ocean Systems 1991; Sippican Ocean Systems 1992, personal communication).

Temperature inaccuracies and biases may originate 1) in the thermistor itself, 2) in transient responses due to the thermistor time constant (and possibly other electronic components) and to the thermal inertia of the probe, 3) in the voltage changes that may be contaminated by mechanical and electrical interference and by damage to the integrity of the wire insulation, and 4) through errors in converting the topside voltage into either a strip-chart temperature or a digitally recorded temperature. A detailed analysis of many of these problems and how they are manifested in the temperature trace have been described by Blumenthal and Kroner (1978). Roemmich and Cornuelle (1987)

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examined the ultimate accuracy that might be achieved with conventional XBTs with frequent calibration of an electronic digitization system and predeployment calibration of each probe itself. They concluded that total temperature error could be reduced to 0.02°C or less, but depth errors due to fall-rate inaccuracy could degrade this to $0.1^{\circ}\text{--}0.5^{\circ}\text{C}$.

Depth accuracy or lack thereof is due directly to the suitability of the fall-rate equation and to the effect of transients caused by the initial conditions of the probe when it enters the water. Theoretical approaches toward understanding the XBT's fall rate have been given by Green (1984) and Hallock and Teague (1992).

A number of observational studies of the achieved temperature and depth accuracies of various types of XBTs have been published. Most have examined probes made by Sippican Ocean Systems [Hanawa and Yoritaka (1987) being an exception], and most have been T-7's, which have a maximum depth range of about 760 m. One of the first published papers was by Flierl and Robinson (1977), who noted both random and systematic differences in isotherm depths derived from simultaneous CTD (conductivity, temperature, and depth) and Sippican T-7 XBT data in the North Atlantic. Random errors were on the order of 8 db (about 8 m), while systematic differences suggested the XBTs fell more rapidly than expected down to about 400 m, and less rapidly after that. Heinmiller et al. (1983) examined Sippican T-4 (~450 m) and T-7 profiles as compared with simultaneous CTD casts in the tropical Pacific. They found the XBTs to be consistently warmer than the CTDs, and after correcting the temperatures, they found depth-dependent differences between CTD and XBT isotherm depths, with the nominal XBT depth being consistently too shallow below several hundred meters. Both of these studies used XBT paper traces, which may be characterized by somewhat different errors than digitally recorded data.

Hanawa and Yoritaka (1987) compared CTD data from the northwest Pacific with that from T-7 equivalent XBTs made by a Japanese manufacturer and using a digital XBT system. They found lot-dependent temperature biases and proposed a corrected-depth equation. This work was followed by Hanawa and Yoshikawa (1991), who examined the results of five CTD-Japanese T-7 XBT comparison experiments, all in the northwest Pacific but in locales with quite different temperature gradients. They concluded that the nominal fall-rate equation yielded an underestimate of the true depth over much of the profile, and devised a revised equation. They found that different datasets yielded different empirical equations; however, they did not present error bars on the empirical equation coefficients to show that the equations were truly statistically different. Their findings may be relevant to T-7 probes made by other manufacturers, but this needs verification.

Wright and Szabados (1989) examined the temperature and depth accuracies of several types of Sippican XBTs in a part of the northwest tropical Atlantic where salt fingering leads to thermohaline staircases, which are sections of extremely well-mixed layers ranging from several meters to several tens of meters in thickness separated by thin (several meters thick) interfaces. Their data came from modest numbers of T-4, T-5, T-6, T-7, and T-10 probes and four different acquisition systems. The extremely well-mixed layers allowed them to make a very good estimate of the achievable temperature accuracy of the probes and the determination of any sort of bias. All versions of the probes seemed to give temperature values a bit warmer than the CTD values, and these biases varied from system to system, but due to the small sample sizes (5–15 probes), the statistical significance of these differences is equivocal. Particularly relevant to this study, they found a T-5 temperature bias of 0.11°C (standard deviation of 0.06°C) for a Sippican MK-9 acquisition system and 0.24°C (0.17°C) for a Bathysystems unit. For all but the T-5 probes their findings were similar to those of other researchers in indicating that the actual fall rates were faster than the nominal fall rates. The T-5, however, seemed to fall somewhat slower than the nominal rate.

Singer (1990) compared CTD and Sippican T-7 data from the Gulf of Mexico by comparing depths of isotherms. Two different manufacturers' acquisition systems were used, and no attempt was made to check for possible temperature biases. His findings were broadly in agreement with other work in that he found that below about 100 m the nominal fall-rate equation yielded depths that were shallow compared with the CTD depths.

As this review indicates, most past studies have concentrated on the characteristics of T-7 XBTs. The T-7 temperatures appear to be slightly higher than CTD temperatures, and the actual fall rates appear to be somewhat faster than the nominal fall rate supplied by the manufacturers. In our study, we examined 34 T-5 profiles and compared them with 25 concurrent CTD profiles. In section 2, we describe the XBT and CTD datasets and their processing. In section 3, we present our analyses of the temperature and depth errors in the XBT datasets, and in section 4, we summarize our findings and discuss their implications.

2. Data sources and processing

During an experiment in the Sargasso Sea south of Bermuda during summer 1991, 34 Sippican T-5 XBTs were dropped nearly simultaneously with 25 CTD casts in order to develop improved T-5 fall-rate equations for the area and to assess XBT temperature errors or biases. Three different ships were involved, with three different CTD systems and three different XBT systems, as summarized in Table 1. The CTD casts were

TABLE 1. XBT and CTD systems used to acquire data for this study. "Isis" refers to a data acquisition and analysis system developed by the authors.

Platform	USNS <i>Lynch</i>	MV <i>E.T.</i>	R/V <i>Range Rover</i>
XBT System			
Probe	Sippican T-5	Sippican T-5	Sippican T-5
Interface unit	Sippican MK-9	Sippican MK-9	Sippican MK-12 card
Acquisition software	NAVOCEANO	Sippican MK-9 Version 4.1 (vol. I) Version 2.0 (vol. II)	Sippican MK-12 Version 1.0 (vol. I) Version 1.2 (vol. II)
Acquisition computer	Zenith Z-248	Swan 386SX	Zenith Z-248
Processing software	Isis	Isis	Isis
Number profiles:	5	20	9
CTD			
Instrument	NBIS MK III	NBIS MK III	SeaBird Model 9
Interface unit	NBIS Model 1401	NBIS Model 1150	SeaBird Model 11
Acquisition software	EG&G Oceansoft Version 2.02	EG&G Oceansoft Version 2.02	SeaSoft Version 3.3G
Acquisition computer	HP Vectra 286	Swan 386SX	Zenith Z-248
Processing software	Isis CTDPRO2	Isis CTDPRO2	SeaSoft Version 3.3G
Number profiles:	2	13	9

lengthy, going to at least 2000 m, and many to over 5000 m. Hence, "simultaneous" ended up meaning within 8 km and 3.25 h of the nominal start of the CTD cast (Fig. 1). Larger space and time windows led to anomalously large deviations between features measured by the CTDs and corresponding features measured by the XBTs. As it is, there is a certain amount of inherent uncertainty in the results that is due to oceanic, not XBT, variability. This is probably on the order of ± 5 cm in depth (mostly internal wave induced) and $\pm 0.05^\circ$ to $\pm 0.1^\circ\text{C}$ in temperature (assuming a temperature gradient of $0.01^\circ\text{--}0.02^\circ\text{C m}^{-1}$).

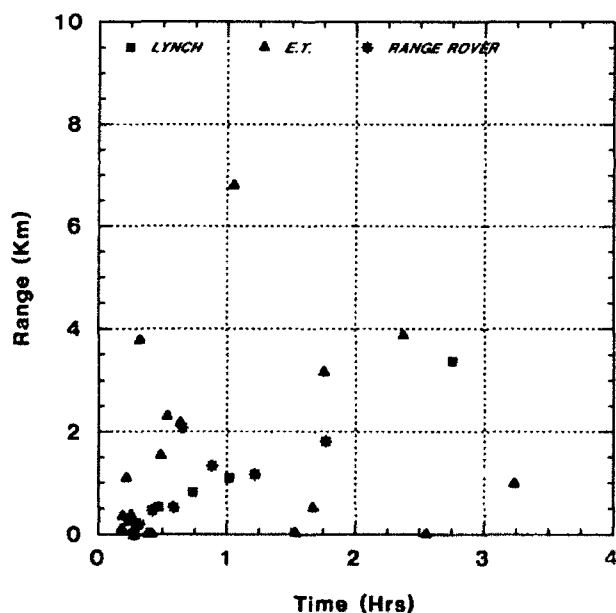


FIG. 1. Temporal and spatial separations between the nominal start of the CTD casts and the deployment of their associated XBTs.

Since this variability is probably randomly distributed, it should not add a bias to the results, but it will increase the achievable error bounds on our estimates.

Standard processing procedures produced temperature (and salinity) versus pressure profiles for the CTD data from all three ships. All CTDs had been recently calibrated, although the second *Lynch* cast was done using the backup CTD whose last calibration date was uncertain but certainly within the previous year. After considering the results of the recent calibrations, we consider the CTD temperatures to be accurate to at least $\pm 0.005^\circ\text{C}$, and pressures to ± 4.5 db. During the processing the samples were "bin averaged" into 1-db bins. Pressure was then converted to depth using the method described in Saunders (1981), and the resulting profiles were interpolated (linearly) to a 1-m depth interval.

Nominal XBT temperatures and depths were calculated by either the Sippican-supplied software in the case of the acquisition systems on board the *E.T.* and *Range Rover* or the NAVOCEANO-supplied software for the system on board the *Lynch* (Table 1). All systems calculated nominal XBT depths from the elapsed fall time of the probe using the manufacturer's supplied equation

$$z = 6.828t - 0.00182t^2,$$

where z is depth in meters and t is elapsed fall time in seconds. Elapsed fall time was later backed out from the depth by solving the above quadratic for t and picking the appropriate root, which is unambiguous. The XBT sampling rate was 10 Hz, leading to a spacing of approximately 64 cm, so the profiles were also linearly interpolated to a 1-m spacing.

Corresponding features on the simultaneous XBT and CTD profiles were matched. Since much of the smaller-scale structure in an ocean profile is masked by the large-scale structure of the thermocline, we

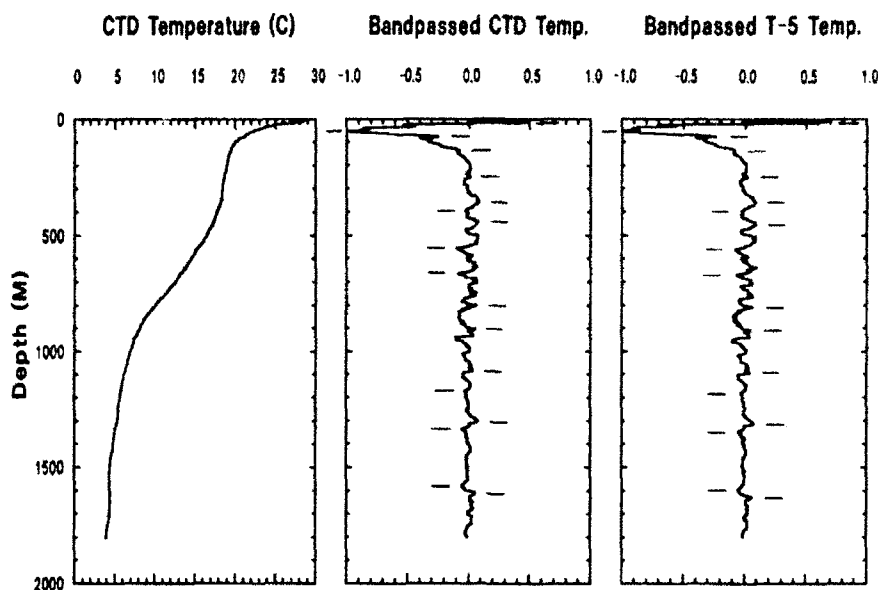


FIG. 2. Example of an unfiltered CTD temperature profile from this study, its bandpass-filtered version, and the bandpass-filtered version of its associated XBT drop. Matched features are indicated on the filtered profiles.

bandpass-filtered both CTD and XBT profiles with a simple boxcar filter, a technique suggested to us by M. Prater and later described in Prater (1991). Half-power points were chosen at 5 and 100 m. An example of this matching of filtered profiles is illustrated in Fig. 2. Features were chosen between approximately 20 and 1775 m, and, as Fig. 2 indicates, they were distributed as evenly over the full water column as possible. Approximately 16 points per profile were selected. The CTD and nominal XBT depths at which the features matched were recorded, along with the *unfiltered* temperature values at those depths. The result was a set of 534 observations, each observation consisting of CTD depth, CTD temperature, XBT nominal depth, XBT elapsed fall time, and XBT temperature. Comparison of the boxcar filter results with other possible filters indicated little if any difference in the resulting set of observations. Because corresponding features were matched, not isotherms, the fall-rate equation findings are not contaminated by errors due to temperature errors, as would be the case if isotherms were matched.

Prater (1991) goes on to describe an intuitively appealing correlation procedure for shifting vertical sections of corresponding filtered profiles up and down in depth until the correlation is maximized and for choosing the depth offset at which the correlation is maximized as the depth offset between the CTD and XBT depths. We tried this procedure but found it gave a considerably larger ambiguity in depth than matching the profiles manually. Perhaps the algorithm can be refined to eliminate this difference, but we opted to use the straightforward direct measurement approach.

3. Results

a. Temperature accuracy

The CTD–XBT feature temperature differences are plotted versus temperature in Fig. 3a. A small temperature correction appears to be needed, which might be a function of true temperature or of depth (probably pressure, in actuality). Correcting by temperature is more useful, since it yields equations of the form $T_{\text{corr}} = a + bT_{\text{XBT}}$ relating corrected XBT temperature to measured XBT temperature (Table 2). One of the acquisition systems (*E.T.*) had a statistically significant dependence on T_{XBT} ; the other two (*Lynch* and *Range Rover*) did not, and for these data, simply correcting with an offset would be justifiable. For consistency we used the linear equations for all datasets. The corrected temperatures are shown (in Fig. 3b) to be significant improvements over the uncorrected temperatures.

Kennelly et al. (1989) and Wright and Szabados (1989) also reported temperature biases with Sippican T-5 XBTs. Kennelly et al. (1989) reported a bias of 0.075°C , and Wright and Szabados (1989) of 0.11° and 0.24°C (different values for different acquisition systems), with the XBT temperatures being warmer than the CTD temperatures. These are of the same magnitude as our mean CTD–XBT differences (Table 2), although perhaps somewhat larger. While we did not record the lot numbers of our XBTs, ours almost certainly did not come from the same lots as the other two studies, since our probes had been obtained at least two to three years later than the probes in the earlier studies. After correcting the temperatures, the pooled

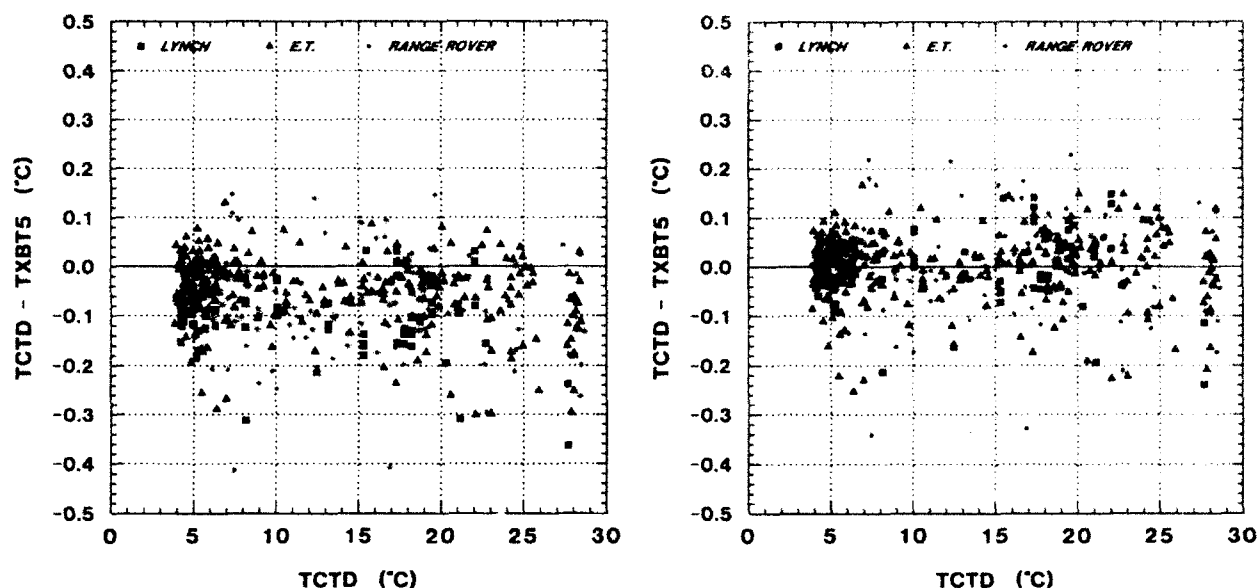


FIG. 3. (a) The difference between CTD temperature minus XBT uncorrected temperature plotted versus CTD depth for all CTD-XBT pairs. The positive and negative 5% of the outliers have been trimmed. Here ■ indicates *Lynch*, ▲ indicates *E.T.*, and • indicates *Range Rover*. (b) Same as (a) except for corrected temperatures.

standard deviation of our XBT temperatures—representing thermistor to thermistor variability and the effects of small-scale changes in the ocean thermal structure between CTD and XBT measurements—was 0.08°C . Kennelly et al. (1989) reported an rms variation of less than 0.1°C , and Wright and Szabados (1989) a standard deviation of 0.06° and 0.17°C .

b. Fall-rate equation

The usually assumed form of the fall-rate equation is a quadratic forced through zero, that is, an equation

of the form $z = at + bt^2$, with t the elapsed fall time. For the XBTs used in this study, the manufacturer—Sippican Ocean Systems—supplies the equation

$$z = 6.828t - 0.00182t^2.$$

The differences between CTD and XBT feature depths from this equation versus CTD depth are plotted in Fig. 4. There is a clear depth-dependent error in the nominal XBT depth. To derive an improved depth versus elapsed XBT fall-time equation, we started by noting the XBT depth for each CTD-XBT matched feature and calculating the XBT elapsed-time value by inverting the manufacturer's fall-rate equation, as described earlier. The CTD depth of that feature is considered the "true" depth, with inherent uncertainty due primarily to internal-wave variability. We ran several regressions of z (true depth) against t (elapsed fall time), assuming five different polynomial regression models. These models were a linear equation, both with and without a constant term; a quadratic equation, also with and without a constant; and a cubic. Quartic and higher models yielded coefficients for the highest-order terms that were not significantly different from zero.

Criteria for selecting the best regression model from among a set of candidates are described in Kleinbaum et al. (1988). The first criterion is based upon selection of the largest sample squared multiple correlation coefficient R^2 , but it gives inconclusive results, since all models have highly significant regressions with R^2 values of greater than 0.999. The fourth criterion, Mallows's C_p , is similarly ambiguous, suggesting only that more than a linear model and less than a sixth-order

TABLE 2. Statistics of the differences between the CTD feature temperatures and the XBT feature temperatures, and the derived correction equations. The corrected temperature is of the form $T_{\text{corr}} = a + bT_{\text{XBT}}$. The asterisk indicates those coefficients not significantly different from 1. After correction, the mean differences were less than 1×10^{-7} . Calculations were done on each platform's dataset individually and then on the pooled dataset. A 10% trim was applied to each dataset to remove outliers.

Platform	Number	Mean T difference before correction	Correction coefficients and values	Standard deviation after correction
<i>Lynch</i>	77	-0.104	$a = -0.08771$ $b = 0.99869^*$	0.069
<i>Range Rover</i>	127	-0.077	$a = -0.06633$ $b = 0.99920^*$	0.092
<i>E.T.</i>	277	-0.052	$a = -0.02038$ $b = 0.99760$	0.070
Pooled	481	-0.067	$a = -0.04193$ $b = 0.99811$	0.079

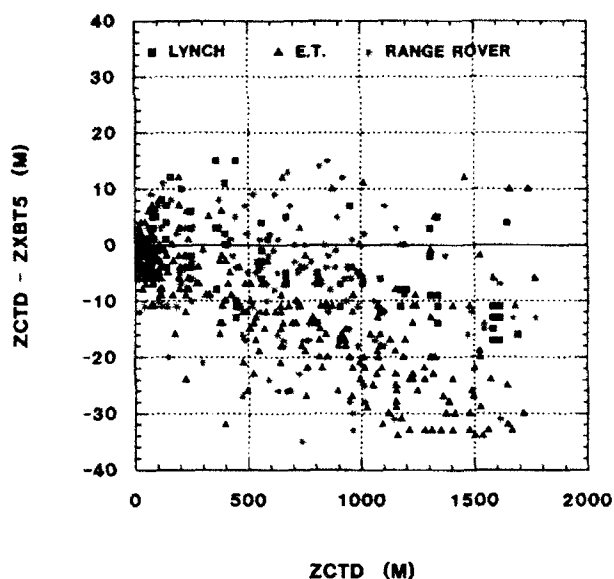


FIG. 4. The difference between CTD depth minus XBT depth plotted versus CTD depth for all CTD-XBT pairs. The positive and negative 5% of the outliers have been trimmed. Here ■ indicates Lynch, ▲ indicates E.T., and * indicates Range Rover.

model is needed. Criteria 2 and 3 proved more useful. Criterion 2 proposes computing a test statistic to compare the highest-order model ("maximum model" or " k -variable model") with lower-order models. If the statistic is not significant, then the lower-order model is adequate. The test statistic F_p is calculated according to

$$F_p = \frac{[SSE(p) - SSE(k)] / (k - p)}{MSE(k)},$$

where k is the number of variables in the highest-order model (3 for a cubic), p is the number of variables in the other models being considered, $SSE(p)$ is the error sum of squares for the p -variable model and $SSE(k)$ for the k -variable model, and $MSE(k)$ is the mean-

square error for the k -variable model. This statistic is compared to an F distribution with $k - p$ and $n - k - 1$ degrees of freedom. The results are summarized in Table 3, along with the statistics using the manufacturer's model. The cubic model is better than the linear models or the manufacturer's fall-rate model at significance levels exceeding 99%, and it is better than the quadratic models at a 95% level but not a 99% level.

The third criterion suggests picking the model that has the smallest error variance, MSE. From Table 3 we see again that the cubic model has a much lower MSE than the linear or manufacturer-supplied models and a slightly lower MSE than the quadratic models.

The quadratic and cubic models both fit our data significantly better than the manufacturer's model, with the cubic being slightly better. Significance tests on the values of the coefficients indicate that for the quadratic model the constant coefficient is not significantly different from zero. This leaves the quadratic forced through zero and the cubic models as the models from which to choose. Both have residuals almost but not perfectly normally distributed, with the residuals from the cubic being slightly closer to a normal distribution (Figs. 5a,b). The cubic model, then, would appear to be the model of choice, but whether or not it is sufficiently better to justify the added complexity of the cubic term is moot. Further studies of this type with larger datasets and improved simultaneity between CTD and XBT measurements are needed to resolve whether a cubic equation is more appropriate than the usually assumed quadratic.

The results for the two best models are summarized in Table 4. The best model was

$$z = -1.803 + 6.795t - 0.002475t^2 + 2.148 \times 10^{-6}t^3,$$

followed by

$$z = 6.705t - 0.001619t^2.$$

TABLE 3. Evaluation of the candidate fall-rate models according to criteria 2 and 3 from Kleinbaum et al. (1988). Criterion 2 considers F_p , the test statistic comparing all other models with the cubic model (the maximum model). Its formula is given in the text. The test statistic is compared with an F distribution whose critical values at a 95% and 99% significance level are given in the last column. Criterion 3 looks for the minimum MSE. The best models are the cubic model and the quadratic forced through zero.

Model	SSE	MSE	F_p	F_{crit} 95%/99%
$z = bt$	0.10322×10^6	0.21417×10^3	487	3.02/4.66
$z = a + bt$	0.77987×10^5	0.16214×10^3	309	3.02/4.66
$z = bt + ct^2$	0.34423×10^5	0.71566×10^2	5.3	3.86/6.69
$z = a + bt + ct^2$	0.34384×10^5	0.71634×10^2	4.7	3.86/6.69
Maximum model: $z = a + bt + ct^2 + dt^3$	0.34047×10^5	0.71080×10^2	—	—
Sippican model: $z = 6.828t - 0.00182t^2$	0.92001×10^5	0.19127×10^3	8.15×10^4	3.86/6.69

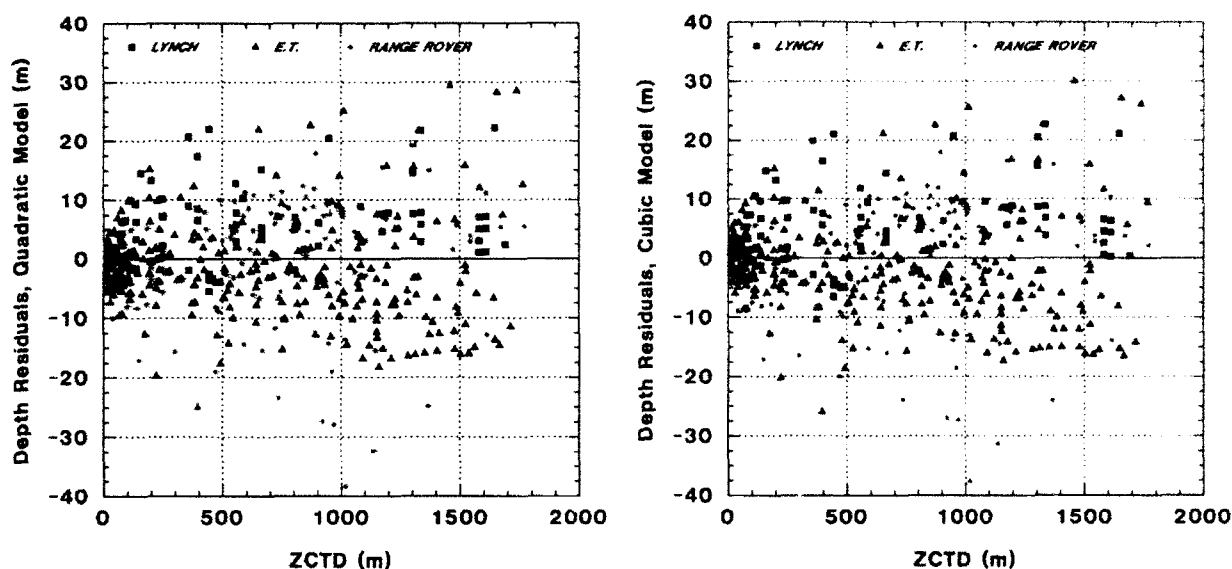


FIG. 5. Residuals for the two best models found in this study: (a) for the quadratic forced through zero; (b) for the cubic model. Comparison with Fig. 4 illustrates the improvement in depth accuracy that is achieved with the new equations.

The difference between the two equations is less than 1 m between about 25 and 250 s. Within the useful depth range of the T-5, the maximum difference is 4.7 m at 290 s (or about 1800 m), the maximum depth of the probe. We tend to prefer the simpler quadratic.

4. Concluding remarks

We have analyzed 34 CTD-T-5 XBT pairs of profiles from the Sargasso Sea to assess the temperature and fall-rate accuracies of the probes. We found temperature to be biased about 0.07°C (XBT warmer), with some suggestion that the offset might be acquisition-system specific. A similar offset was found by Kennelly et al. (1989) and Wright and Szabados (1989). With one of the three datasets, the offset appeared to be tem-

perature (or possibly pressure) dependent, but we do not consider our results conclusive. Once the offset was removed, the temperatures had a standard deviation of about 0.08°C , which lies within the manufacturer's claimed accuracy.

The manufacturer's fall-rate equation,

$$z = 6.828t - 0.00182t^2,$$

was found to be accurate to within $\pm 2\%$ or ± 5 m over all portions of the profile, as claimed (Fig. 4), but two significantly better fall-rate equations were calculated. The cubic equation

$$z = -1.803 + 6.795t - 0.002475t^2 + 2.148 \times 10^{-6}t^3$$

was slightly better in a statistical sense than the quadratic forced through zero.

$$z = 6.705t - 0.001619t^2,$$

although the magnitude of the improvement was small and may not justify the additional complexity. The errors in these equations are nearly depth independent except quite near the surface, with a standard deviation of 8.4 m for both. The significant improvement resulting from the use of these corrections is illustrated in Figs. 6a and 6b.

Several recommendations and observations come out of this study. The question of whether or not there is a small offset in the T-5 temperatures should be resolved, and if so, if it is temperature or pressure dependent. If there is an offset, is it in the thermistors themselves or in the electronics of the acquisition systems? If there is a bias originating in the thermistors themselves, is it lot dependent?

TABLE 4. Summary of the best two fall-rate equations found in this study. The cubic model is slightly better in a statistical sense. The accuracy is taken as the standard deviation of the residuals resulting from the regression calculations (Figs. 5a and 5b).

Coefficient	Estimate	95% confidence interval
Model: $z = bt + ct^2$, accuracy: standard deviation of 8.4 m.		
b	6.705	6.685, 6.726
c	-1.619×10^{-3}	-1.721×10^{-3} , -1.516×10^{-3}
Model: $z = a + bt + ct^2 + dt^3$, accuracy: standard deviation of 8.4 m.		
a	-1.803	-3.710, 0.1035
b	6.795	6.716, 6.873
c	-2.475×10^{-3}	-3.231×10^{-3} , -1.719×10^{-3}
d	2.148×10^{-6}	0.210×10^{-6} , 4.086×10^{-6}

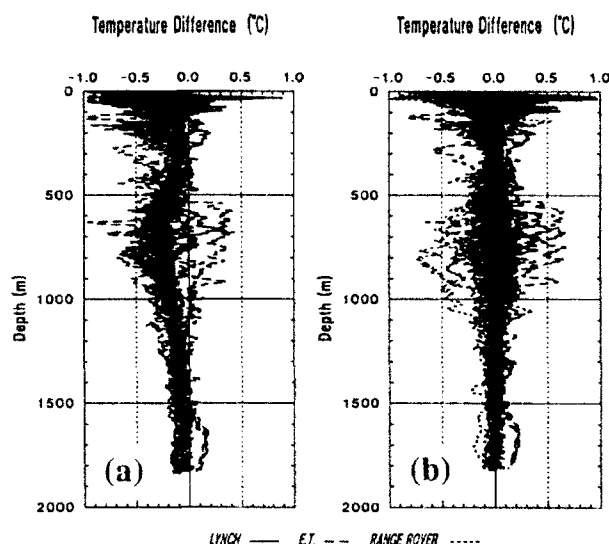


FIG. 6. Mean temperature difference versus depth for the CTD-XBT profile pairs in this study. Panel (a) was computed using uncorrected temperatures and the manufacturer's fall-rate equation. Panel (b) was computed using the temperature corrections and cubic fall-rate equation from this study.

The question of whether or not one fall-rate equation is suitable for all parts of the World Ocean has not been answered. Seaver and Kuleshov (1982) point out the kinematic viscosity of water changes by 42% between 10° and 25°C. This changes the value of the bulk drag coefficient, which, as the analyses of Green (1984) and Hallock and Teague (1992) show, is a major parameter controlling the fall rate of the probe. Will the different temperature structure in various parts of the World Ocean lead to significantly different fall-rate equations? Several years ago the authors examined fall-rate corrections for T-5 XBTs in the northeast Pacific and found a different fall-rate equation for Sippican T-5 XBTs. It was derived from a dataset of poorer quality than the one in this study, so we are uncomfortable asserting it is necessarily more appropriate for the Pacific, and our present equations are appropriate for the Atlantic (or Sargasso Sea, anyway). However, we feel the question is still open as to whether a geographically universal fall-rate equation can be derived for each type of expendable probe.

Both questions of temperature offsets and universal fall-rate equations can probably be answered only by dedicated efforts with sufficiently large numbers of expendables, carefully calibrated CTD systems, and virtual simultaneity between each XBT drop and CTD cast. Most studies—including this one—have used data that were collected during experiments that did not have XBT calibration as their primary purpose. Because of this, compromises had to be made that necessarily qualified the amount and quality of the data

obtained. With the enormous impact XBTs have upon international databases, it seems appropriate that national funding agencies consider sponsoring definitive studies of these instruments.

Our final observation, however, is that the entry into the oceanographic market of a number of suppliers of expendable probes and of data acquisition systems may lower the price of the equipment, but it will complicate the problem of devising accurate temperature and fall-rate conversion equations to maximize XBT accuracy. Each manufacturer's system and each manufacturer's probe has the potential of requiring different conversion equations. Furthermore, as the manufacturers modify their systems and probes so as to improve their competitive position in the marketplace, new conversion equations may be required. The authors have first-hand experience with these problems with air-deployed XBTs (AXBTs); there is every reason to fear the oceanographic community will have to face this problem with the ship-deployed instruments as well. Individual research projects may circumvent these problems by doing an XBT calibration study each time significant numbers of XBTs are deployed or when high accuracies are required, but this will not solve the problem of how to improve the accuracy of the vast amounts of XBT data being sent to international archives.

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REFERENCES

- Blumenthal, B. P., and S. M. Kroner, 1981: Guide to common ship-board expendable bathythermograph (XBT) recording malfunctions. NAVOCEANO reference publication RP-21, Naval Oceanographic Office, SSC MS, 46 pp.
- Flierl, G., and A. R. Robinson, 1977: XBT measurements of the thermal gradient in the MODE eddy. *J. Phys. Oceanogr.*, 7, 300–302.
- Green, A. W., 1984: Bulk dynamics of the expendable bathythermograph (XBT). *Deep-Sea Res.*, 31, 415–426.

- Hallock, Z. R., and W. J. Teague, 1992: The fall rate of the T-7 XBT. *J. Atmos. Oceanic Technol.*, **9**, 470-483.
- Hanawa, K., and H. Yoritaka, 1987: Detection of systematic errors in XBT data and their correction. *J. Oceanogr. Soc. Japan*, **43**, 68-76.
- , and H. Yoshikawa, 1991: Reexamination of the depth error in XBT data. *J. Atmos. Oceanic Technol.*, **8**, 422-429.
- Heinmiller, R. H., C. C. Ebbesmeyer, B. A. Taft, D. B. Olson, and O. P. Nikitin, 1983: Systematic errors in expendable bathythermograph (XBT) profiles. *Deep-Sea Res.*, **30**, 1185-1197.
- Kennelly, M. A., M. D. Prater, and T. B. Sanford, 1989: XBT and XSV data from the Gulf of Cadiz Expedition: R/V *Oceanus* cruise 202. APL-UW TR 8920, 209 pp. [Available from the Applied Physics Laboratory, University of Washington.]
- Kleinbaum, D. G., L. L. Kupper, and K. L. Muller, 1988: *Applied Regression Analysis and Other Multivariable Methods*. 2nd ed. PWS-Kent, 718 pp.
- Prater, M. D., 1991: A method for depth and temperature correction of expendable probes. *J. Atmos. Oceanic Technol.*, **8**, 888-894.
- Roemmich, D., and B. Cornuelle, 1987: Digitization and calibration of the expendable bathythermograph. *Deep-Sea Res.*, **34**, 299-307.
- Saunders, P. M., 1981: Practical conversion of pressure to depth. *J. Phys. Oceanogr.*, **11**, 573-574.
- Seaver, G. A., and A. Kuleshov, 1982: Experimental and analytic error of the expendable bathythermograph. *J. Phys. Oceanogr.*, **12**, 592-600.
- Singer, J. J., 1990: On the error observed in electronically digitized T-7 XBT data. *J. Atmos. Oceanic Technol.*, **7**, 603-611.
- Sippican Ocean Systems, 1991: MK-12 Oceanographic Data Acquisition System Users Manual. Sippican Ocean Systems, 137 pp. [Unpublished document available through Sippican Ocean Systems.]
- Wright, D., and M. Szabados, 1989: Field evaluation of real-time XBT systems. *Oceans 89*, **5**, 1621-1626.