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A New Fall-Rate Equation for T-5 Expendable Bathythermograph (XBT) by TSK

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The accuracy of the manufacturer's fall-rate equation for the T-5 Model of expendable bathythermograph (XBT) has been investigated based on about 300 collocated pairs of XBT-CTD (Conductivity-Temperature-Depth profiler) measurements in various climatological regions. We found that the equation systematically overestimates depth by about 5% for the T-5 produced by Tsurumi Seiki, Co. Ltd. (TSK), but almost no bias is associated with the T-5 produced by Sippican, Inc., in USA. The cause of this difference is not clear, because the two manufacturers' T-5 probes are reported to have identical shape and weight in water. We propose a new fall-rate equation for the TSK T-5: $z(t) = 6.54071t - 0.0018691t^2$, where $z(t)$ is depth in meters at time, t, in seconds.

Keywords:
· T-5,
· XBT,
· expendable bathythermograph,
· fall-rate equation,
· temperature measurement,
· VOS monitoring.

1. Introduction

The expendable bathythermograph (XBT) is a free-fall instrument for measuring the water temperature of the upper ocean. It has enjoyed widespread popularity since the mid 1970s (Conkright *et al.*, 2002) because of its simple operation. The global ocean temperature archive now owes much to the precision of the XBT measurement.

XBT is dropped from the air into the water. Since the instrument carries no pressure sensor, we always need to infer the depth of individual temperature measurements according to time elapsed from the instance when the instrument (a probe) hits the water surface, by using the time-depth conversion equation. The equation, often also referred to as the "fall-rate" equation, often takes the form of

$$z(t) = at - bt^2, \tag{1}$$

where $z(t)$ is depth (downward positive) in meters at the elapsed time, t, in seconds. The first term on the right-hand side generally dominates the second term, indicating that an XBT probe falls at an approximately constant speed in water. The second term corrects for the loss of mass due to the release of wire from the freely-falling probe. The equation includes two empirical constants, a and b, that differ for different XBT models with different structures and weights in water.

The T-5 probe can reach the greatest depth (nominally 1830 meters) among all XBT types in the market, and the model is supplied by two manufacturers: Sippican, Inc., in USA, and Tsurumi Seiki, Co., Ltd. (TSK) in Japan. The probes manufactured by TSK and Sippican are equipped with wire of different quality, but the two manufacturers' probes are reported to have an identical total weight in seawater (Tsurumi Seiki, personal communication). The outer shape of the probes is also reported to be the same. Therefore, the following fall-rate equation supplied by Sippican:

$$z(t) = 6.828t - 0.00182t^2, \tag{2}$$

has been commonly used for T-5 probes made by both the manufacturers.

However, the reliability of this equation does not seem to have been established among users in different countries. Japanese oceanographers have long shared a common feeling that Eq. (2) has a systematic bias. Ishii (unpublished manuscript, 1994) reported that the bias was depth-dependent and reached as much as 50 meters at 1000 meter depth, according to the result of a field investigation near Alaska. Boyd and Linzell (1993; hereafter BL93) identified a smaller but systematic bias for Sippican T-5, and proposed a new equation:

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Table 1. XBT data used in the present investigation.

Group #	Institute	Platform	Period	Area	XBT	CTD	Number of pairs
1	Tohoku Univ.	*R/V Hakuho-Maru*	Sep., 1994	SE of Japan	TSK T-5	SBE-9	24
2	Tohoku Univ.	*R/V Wakataka-Maru*	Jan.–Feb., 2002	Off Sanriku	TSK T-5	SBE-9	20
3	JAMSTEC	*R/V Alpha Helix*	Jul.–Aug., 1995	Off Alaska	TSK T-5	SBE-9	10
4	JAMSTEC	*R/V Kaiyo*	Jan., 1995	Off Mindanao	TSK T-5	SBE-9	14
5	various	various	1977–1998	global	Sippican T-5 (see text)	various (see text)	224

$$z(t) = 6.705t - 0.001619t^2, \qquad (3)$$

based on 34 comparisons with a CTD profiler in the Sargasso Sea. However, Sy (unpublished manuscript, 2000) reported at the 3rd Session of SOOPIP (Ship-of-Opportunity Programme Implementation Panel) that Eq. (2) had no appreciable bias for Sippican T-5, according to a survey conducted in the Atlantic Ocean. These inconsistent results cause confusion, but no report in the published literature has examined this issue in greater detail.

This article reports an investigation of the validity of Eq. (2) first for the TSK T-5 using several tens of side-by-side comparisons with CTD profilers. The equation was also tested for the Sippican T-5 by collecting near-collocated pairs of XBT and CTD measurements from an available oceanographic data set. We found that the equation does have a systematic bias when applied to the TSK T-5, whereas this is not likely with the Sippican T-5. We have estimated the error of using Eq. (2) with the former T-5, and we here propose a new fall-rate equation.

2. Data

We prepared five groups of data for the present investigation, as shown in Table 1 and Fig. 1. Data in Groups 1 through 4 were obtained individually from a single research cruise in a specific region and period. They are all side-by-side XBT-CTD measurements, and all XBT profiles were taken by TSK T-5 probes. We assume that a single CTD equipment was used during each of the cruises, though detailed information is not given for some of them.

At each time of measurement, a T-5 probe was released when the CTD passed 100 meter depth on its downward path so that the difference of time between the two measurements is minimized. The vertical resolution of XBT measurement is approximately one meter for all pairs in Groups 1 through 4. That of the CTD measurement is about one decibar for Groups 1 through 3 and two decibars for Group 4.

Data in Group 5 was collected from the World Ocean Database 2001 (WOD2001) which contains oceanographic observations by various institutions throughout the world (Conkright *et al.*, 2002). Because the XBT and

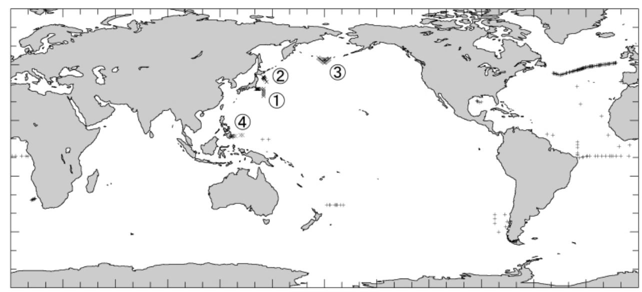

Fig. 1. Locations of XBT-CTD measurement used in this investigation. Groups 1 through 4 are marked by crosses and circled numbers, and Group 5 by plus signs.

CTD measurements in this group were not conducted side-by-side, we selected and paired only those taken within three nautical miles in space and one day in time from each other.

The types of XBT probe and CTD profiler are only partially known from metadata of WOD2001. We tried to collect information from data suppliers individually and confirmed that a majority of data in Group 5 was obtained during the trans-North-Atlantic research cruises by German vessels using the Sippican T-5 (Sy, personal communication). We assume that Sippican probes were also used in the rest of the XBT measurements in Group 5 because the group includes no reports from Asian institutions, which use mostly TSK probes.

We required the maximum depth of the reported profile to be greater than 1,200 meters in order to exclude data by models other than T-5. We also required the number of reported data points in the vertical to be greater than 800 for a single profile to eliminate data from coarse sampling (e.g. inflection points only). All of the paired XBT and CTD temperature profiles have been carefully screened to preclude those containing instrumental error and other errors which likely arose from conditions of measurement. Natural variability (e.g. internal waves) could degrade the precision of comparison, but we believe that this influence is small because most of the data were obtained away from coasts and shelf regions where internal waves prevail.

3. Analysis

We basically followed the method of Hanawa *et al.* (1995; hereafter H95) to estimate the accuracy of Eq. (2). The method of H95 was designed for the fall-rate issue of T-7 (for 760 m measurement), T-4 and T-6 (for 460 m measurement) type probes. A few modifications have been made here to apply the method to T-5, which can descend much deeper. The flow of analysis is outlined below.

First, both XBT and CTD data were linearly interpolated to exact one meter interval in the vertical. Eq. (2) was used for XBT data in this step. Because temperature was recorded as a function of pressure in all CTD measurements, we used the following equation (Saunders, 1981) for the pressure-to-depth conversion:

$$d_{ctd} = \int_0^p \frac{\alpha dp}{g_s + \frac{1}{2}\gamma p}, \tag{4}$$

where d_{ctd} is depth, α is the specific volume calculated according to Saunders and Fofonoff (1976), p is the CTD-measured pressure in decibars,

$$g_s = 9.780318(1 + 5.3024 \times 10^{-3}\sin^2\phi - 5.9 \times 10^{-6}\sin^2 2\phi) \quad [\mathrm{ms}^{-2}] \tag{5}$$

is the surface value of gravitational acceleration, g, as a function of latitude, ϕ, and γ is the increase of gravity with depth. H95 used a simplified form of Eq. (4):

$$d_{ctd} = 0.993p, \tag{6}$$

by assuming a constant density and gravity. However, we chose Eq. (4) instead of Eq. (6) primarily because the latitudinal variation of gravity (about 0.5 percent from equator to pole) is not negligible in the present investigation. Density variation of seawater is also accounted for, though its influence is estimated to be relatively small (mostly less than 0.3 percent). These errors in Eq. (6) could be ignored in the case of T-7 and other short wire type probes, but that is not the case for T-5 for much deeper measurements. Since $\gamma p/2$ is negligible compared to g_s in Eq. (4), it was omitted in later calculation.

Second, two types of filters were applied in sequence to each profile: (i) a seven-point Median filter for removing spike-wise noise, and (ii) a low-pass linear cosine Hanning filter for smoothing out small-scale variation. See H95 for more detail information on these filtering processes. Third, vertical temperature gradients (hereafter TG) were calculated at one meter intervals for the filtered XBT and CTD profiles. These are referred to as TGX and TGC, respectively, hereafter.

Fourth, the depth error of Eq. (2) was estimated as follows. The absolute value of difference between the TGX profile and TGC profile was vertically integrated over a fixed width of depth, $2\Delta z$, centered at the depth of XBT measurement, z_{xbt}, by Eq. (2), for various depth offset, D, given for the TGC profile. The depth error of Eq. (2) was defined as a value of D which gives the minimum vertically-integrated difference. If there is no depth error, D should be zero. In other words, the range of vertical integration of the difference was gradually shifted up and down, looking for a depth offset which gives the greatest similarity between the two TG profiles. We set Δz = 25 m. The fourth step was repeated at a depth interval of 50 meters. The uppermost 50 meter layer was not used in the analysis in order to remove the start-up transient of XBT (Kizu and Hanawa, 2002a).

Using profiles of vertical gradient of temperature is beneficial because of its insensitivity to accuracy of temperature measured by XBT (H95). Kizu and Hanawa (2002b) reported that the same type of recorder as one used in Group 1 often showed behaviour called "bowing", a gradual increase of temperature error with depth, but the influence of this problem should be small in the present investigation where the profiles are compared in a relatively small range of depth (50 meters).

4. Results and Discussion

The estimated error of Eq. (2) is shown in Fig. 2 as a function of depth for each group. The frequency of occurrence of error is indicated by vertical bars in each graph. The nominal accuracy of depth given by the manufacturers, the minimum of 5 meters or 2 percent of depth, is indicated by solid lines.

Figure 2 shows that Eq. (2) systematically overestimates depth for the TSK T-5. The bias is about 5 percent on average, which is a few times larger than the nominal error of depth. In contrast, Group 5 shows almost no systematic bias for the Sippican T-5. The cause of the much larger pair-to-pair difference for the last group is not clear, but we believe that the limited reliability of metadata and hence the limited quality of match-ups of this group could make determination of depth error much more difficult than for the other four groups, which were obtained by well-controlled side-by-side measurement.

The present method for detection of depth error does not work satisfactorily in deep oceans where vertical variation of temperature is small and does not change significantly with depth. The poorest result was obtained for Group 3, which was taken in seas with very uniform temperature in the vertical (not shown).

There are differences between the groups. The estimated error is larger for Group 2 than Group 1. The two groups were obtained in seas only several degrees of latitude apart (Fig. 1), but with very different temperatures, as shown in Fig. 4. Considering that TSK probes are supplied with very high precision of total weight (<2 grams;

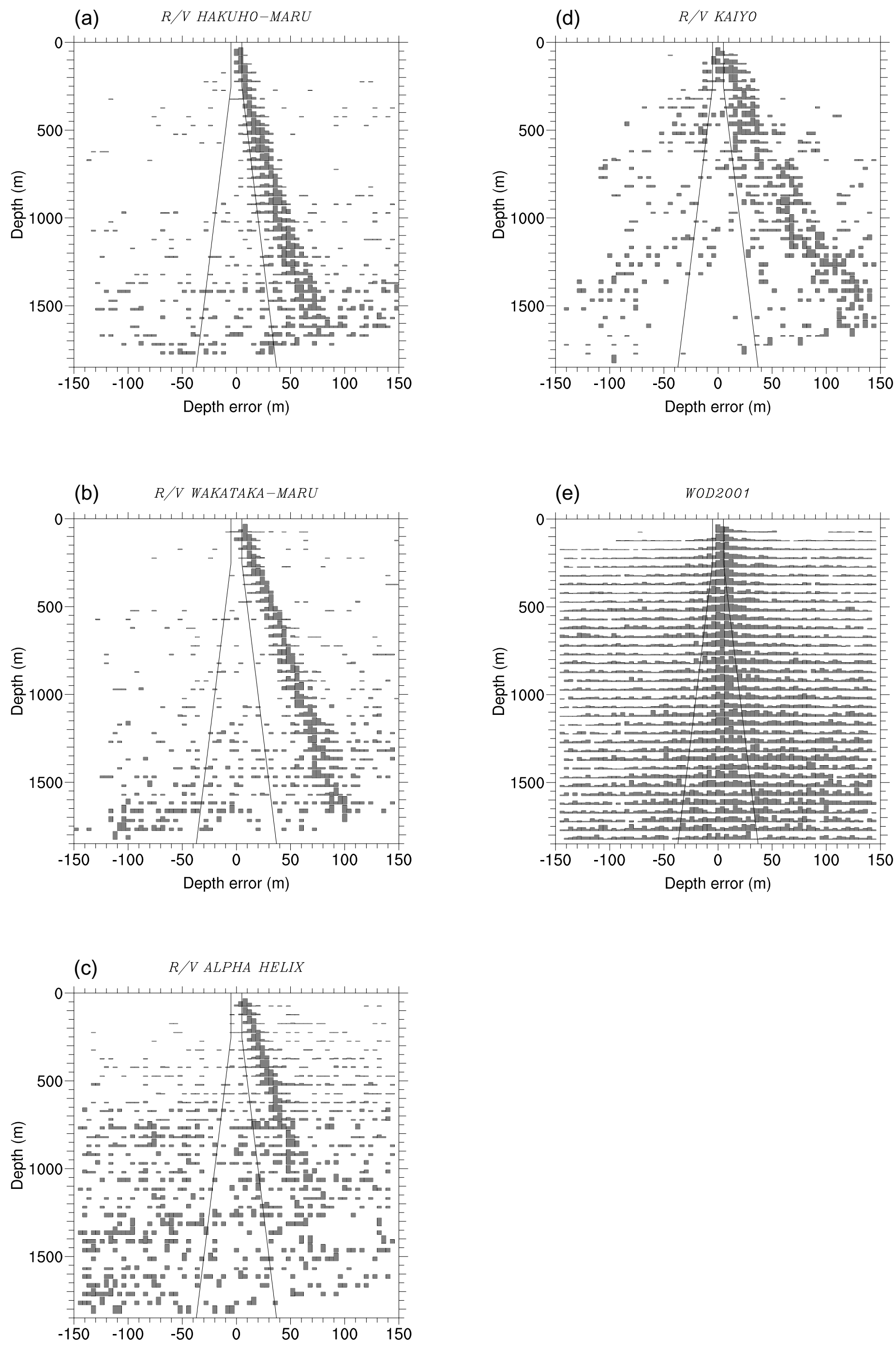

Fig. 2. Depth error of Eq. (2) as a function of depth. Frequency of occurrence of error is shown by bars, which are arbitrarily scaled for each bin of depth. The manufacturers' nominal accuracy is shown by solid lines. (a) Group 1, (b) Group 2, (c) Group 3, (d) Group 4, and (e) Group 5.

TSK, personal communication), it is plausible that the differences between the two groups are due to the differences in viscosity of seawater, as discussed by Seaver and Kuleshov (1982) and Thadathil *et al*. (2002). A detailed inspection reveals that the error profile for Group 1 (Fig. 2(a)) curves in a depth range of 300 to 500 meters, where water temperature changes rapidly in the vertical (Fig. 4(a)). In contrast, the temperature profiles of Group 2

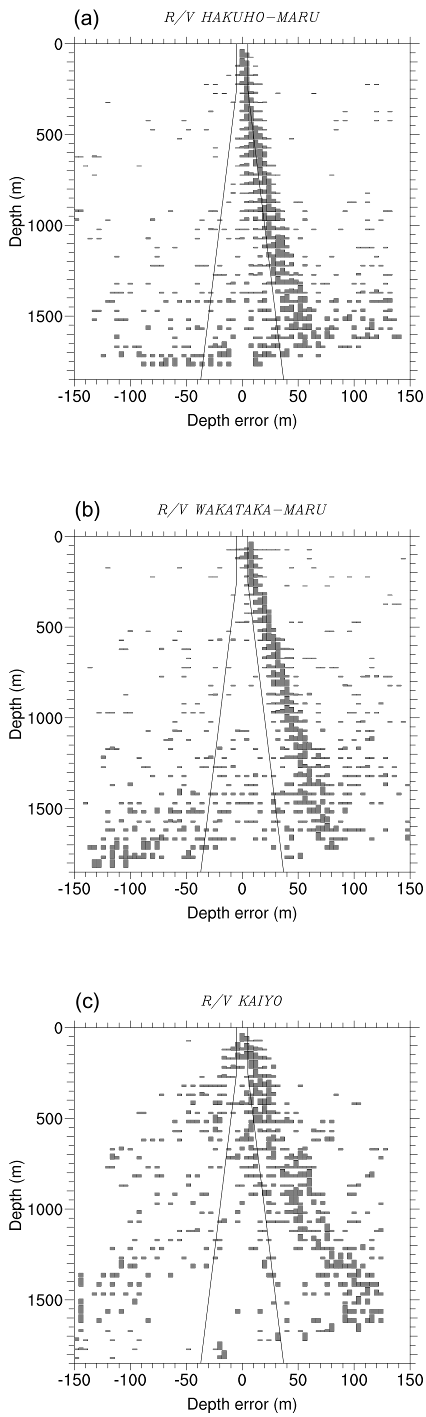

Fig. 3. As Fig. 2(a) but of Eq. (3) and for Groups 1, 2 and 4 only. (a) Group 1, (b) Group 2, and (c) Group 4.

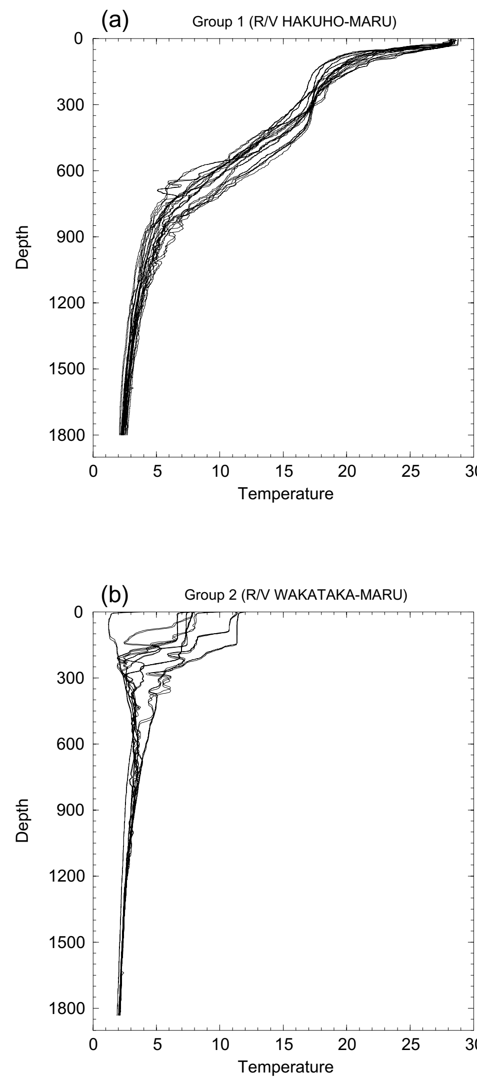

Fig. 4. Temperature profiles in Group 1 (a) and Group 2 (b).

include no such thermocline (Fig. 4(b)), and the estimated error seems to be a more linear function of depth (Fig. 2(b)).

Equation (3) was also tested, and the results are shown in Fig. 3 for Groups 1, 2 and 4. The depth bias of this equation is smaller than that by Eq. (2) but still out of the nominal accuracy of depth given by the manufacturers.

The mean error of depth was calculated every 50 meters of depth for each profile in Groups 1, 2 and 4, and a quadratic least-square fit forced through zero was applied to individual XBT-CTD pairs. The reason for eliminating Group 3 from the fit is its limited vertical coverage. Data obtained from depth greater than 1,400 meters and outliers in Fig. 2 were also excluded prior to the fit. The resulting coefficients a and b are shown in Fig. 5 with variation of depth at 500 and 1800 meter depth. By taking an average for a and b coefficients, respectively, a new fall-rate equation for the TSK T-5 was retrieved:

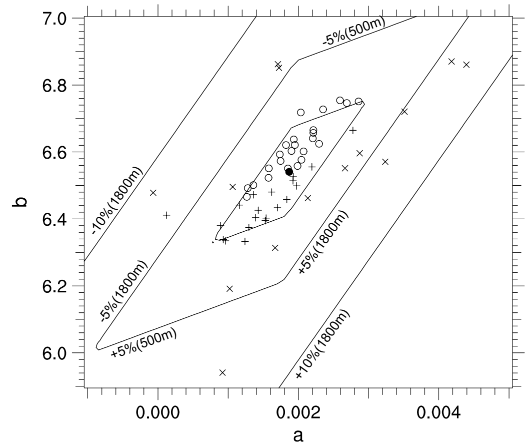

Fig. 5. Variation of coefficients estimated by least-squares fit to individual error profiles. The coefficients obtained from Groups 1, 2 and 4 are indicated by open circles, plus signs and crosses, respectively. The grand average is shown by the closed circle. Parallelograms show 2 (innermost), 5 (middle) and 10 (outermost) percent deviations from Eq. (7) at 500 and 1800 meter depth.

$$z(t) = 6.54071t - 0.0018691t^2. \tag{7}$$

The coefficients of Eq. (7) are also shown in Fig. 5. Variation of coefficients obtained from individual pairs in Group 1 and Group 2 translates into mostly within 2 percent of depth, namely the nominal accuracy given by the manufacturers. However, coefficients obtained from Group 4 vary more extensively, suggesting that the differences among groups may be too large to be covered by a simple unique fall-rate equation with 2 percent error.

The estimated error of Eq. (7) is shown in Fig. 6 as a function of depth for Groups 1 through 4. The error stays mostly within the manufacturers' nominal accuracy for Groups 1 through 3. However, the new equation still has a slight systematic bias for individual groups. We suggest that this difference among groups might be caused by the variation of water temperature (i.e. viscosity), but more detailed discussion would require a more precise estimation of the influence of water temperature on the complex dynamics of XBT probes in the ocean (Green, 1984).

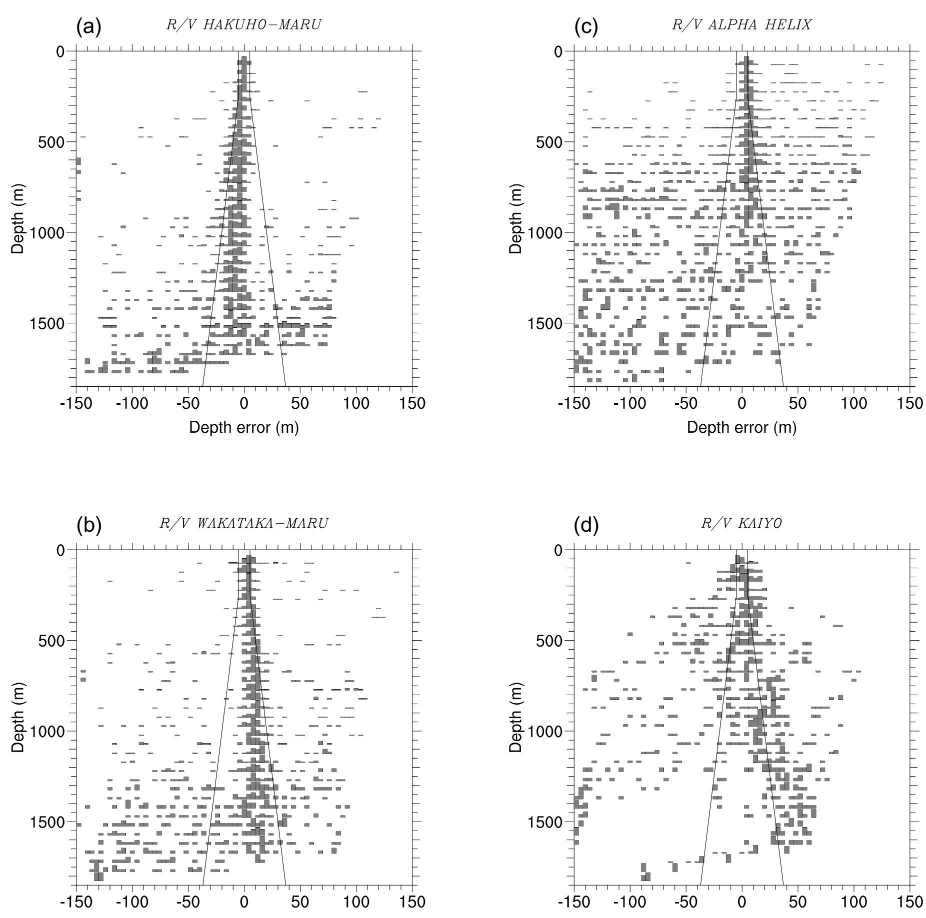

Fig. 6. As Fig. 2 but for Eq. (7) and for Groups 1 through 4 only. (a) Group 1, (b) Group 2, (c) Group 3, and (d) Group 4.

5. Concluding Remarks

It has been shown that the manufacturer's fall-rate equation systematically overestimates depth when applied to the TSK T-5 by about 5 percent, which is more than double the nominal accuracy given by the manufacturers. This confirms the common experience shared among Japanese oceanographers for many years. The new equation proposed here is effective in reducing that bias, but more validation may have to be conducted to assess the overall accuracy of the equation because group-to-group variation is also large. The suggested possibility that the fall-rate may depend on water temperature (i.e. viscosity) would further complicate the problem because, in that case, we could not know temperature and depth independently from XBT measurement alone.

On the other hand, almost no bias is identified with the manufacturer's equation applied to the Sippican T-5, and this supports Sy (unpublished manuscript, 2000). However, we cannot clarify whether Eq. (3) is more accurate than Eq. (2) for the Sippican T-5 because of large scatter among data sets.

It is now very likely that the two T-5 Models made by the two manufacturers (TSK and Sippican) have systematic differences in the fall-rate. The reason is not clear, however, because the two manufacturers' probes have been reported and are believed to possess identical shape and weight, and are hence expected to behave similarly in water. It should also be noted that all of the past and the present investigation is based on either TSK T-5 versus CTD or Sippican T-5 versus CTD comparison. Direct comparison between the two T-5 Models is desired in future, and further examination is needed to explain the detected difference between these two models.

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