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Inter-manufacturer Difference and Temperature Dependency of the Fall-Rate of T-5 Expendable Bathythermograph

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The fall-rate of the T-5 expendable bathythermograph (XBT) produced by Tsurumi Seiki (TSK) Co., Ltd and that by Sippican Inc., are intercompared by a series of contemporaneous and colocated measurements with conductivity-temperature-depth (CTD) profilers. It is confirmed that the fall-rates of the two manufacturers' T-5 differ by about 5 percent, despite the fact that they had been believed to be identical for many years. The cause of the difference is discussed on the basis of a detailed cross-examination of the two T-5 models. It is found for the first time that the two models are different in several respects. The manufacturer's fall-rate equation is only applicable to the Sippican T-5, for which Boyd and Linzell's (1993) equation seems to be slightly more accurate. Kizu *et al.*'s (2005) equation gives a clearly less biased depth than the manufacturers' equation for the TSK T-5. It is also found that the fall-rates of both T-5 models are dependent on water temperature, perhaps because of viscosity. The temperature-dependency of the fall-rate of the TSK T-5 is larger than that of the Sippican T-5.

Keywords:
· T-5,
· XBT,
· expendable bathythermograph,
· fall-rate equation,
· time-depth conversion equation,
· temperature measurement,
· VOS monitoring,
· water viscosity.

1. Introduction

The expendable bathythermograph (XBT) is a free-fall instrument for measuring the temperature structure of the upper ocean. It has been enjoying widespread popularity in the world ocean since the mid-1970s because of its simple operation (Conkright *et al.*, 2002).

Because the XBT probes carry no pressure sensors, we need an equation to calculate the depth of individual sampling points from the time elapsed since a probe hits the water surface after its deployment from a platform. The equation, often referred to as a time-depth conversion equation or a fall-rate equation, generally takes the form

$$d(t) = at - bt^2, \quad (1)$$

where $d(t)$ is the depth in meters at a time, t, in seconds. The equation contains two empirical constants, a and b, that are defined by the manufacturers or other authors for individual XBT models with different shape and weight in the water.

T-5 is an XBT model with the longest profiling range (nominally down to 1830 meters depth) of all XBT types available in the market. Various XBT models including T-5s are supplied by two manufacturers: Sippican Inc., and Tsurumi Seiki (TSK) Co., Ltd. Some model names (i.e., T-5, T-6, T-7 and T-10) are shared by the two manufacturers, but their products are not exactly the same and are equipped with wires of different density. The difference in weight of the wire has reportedly been compensated for by different hollowing inside the metal ogive weight (Tsurumi Seiki, personal communication, 2003). Therefore, a single set of coefficients, a and b, is used for both the manufacturers' probes that share a common name. The coefficients recommended by the manufacturers for the T-5 are $a = 6.828$ m s^{-1} and $b = 0.00182$ m s^{-2}.

However, the validity of the manufacturers' coefficients for the T-5 has never been established and has been debated for years among oceanographers. The users of the TSK T-5 probes (Ishii *et al.*, unpublished manuscript, 1994) claimed that the coefficients had a systematic bias, while those of the Sippican T-5 probes (Boyd and Linzell, 1993, hereafter BL93; Sy, unpublished manuscript, 2000)

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Table 1. Coefficients of published fall-rate equations for the T-5 probes. The form of the equations is given in Eq. (1). Note that the equation by KYH05 is for the TSK T-5 while the other two are not limited to the T-5 by a particular manufacturer.

	a	*b*
Manufacturers	6.828	0.00182
Boyd and Linzell (1993; BL93)	6.705	0.001619
Kizu *et al*. (2005; KYH05)	6.54071	0.0018691

Table 2. Scale factors for a simple conversion of depth to KYH05 from the two preceeding fall-rate equations. Depth by KYH05 is obtained by multiplying the factors to the depth (leftmost) by the original equation used in the time-depth conversion. Note that the factors are slightly depth-dependent, and that the equation by KYH05 is for the TSK T-5.

Depth (m)	Manufacturer to KYH05	BL93 to KYH05
250	0.9572	0.9738
500	0.9565	0.9722
750	0.9558	0.9704
1000	0.9550	0.9685
1250	0.9542	0.9666
1500	0.9533	0.9646
1750	0.9524	0.9625

identified a much smaller bias or none. Kizu *et al*. (2005, hereafter KYH05) confirmed this discrepancy with a large number of comparisons between either TSK or Sippican T-5 and conductivity-temperature-depth (CTD) profilers. Nevertheless, there has been no proof or even reasonable explanation of why the two manufacturers' T-5s, which had been reported to behave the same in the water, should fall at different speeds. The previous coefficients defined for the T-5 probes are listed in Table 1, and scale factors are given in Table 2 for a simple depth conversion to KYH05 from the preceding two equations.

Now, the global ocean temperature archive owes much to the precision of the XBT measurement. The majority of the thermal information of the upper ocean has been provided by the XBTs over the last three decades. Therefore, any systematic depth bias of the fall-rate equations as well as the temperature error of the sensor must be minimized for the precise detection of climatic change.

It should also be noted that all the previous studies made only CTD-TSK or CTD-Sippican comparisons. None of them gave a direct comparison of the two T-5 models, by which we could judge more clearly if the disagreement is real or not. This is what we have done, as reported in this article. A series of concurrent measurements by the TSK T-5, the Sippican T-5 and well-maintained CTD profilers have been conducted in the open ocean for the first time. We have also examined the structure of each model in detail. The fall-rates of the two T-5 models are found to be clearly different and dependent on water temperature, and their causes are discussed based on a detailed examination of the two models.

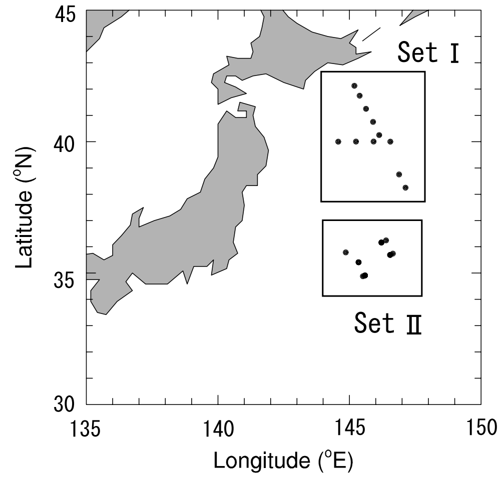


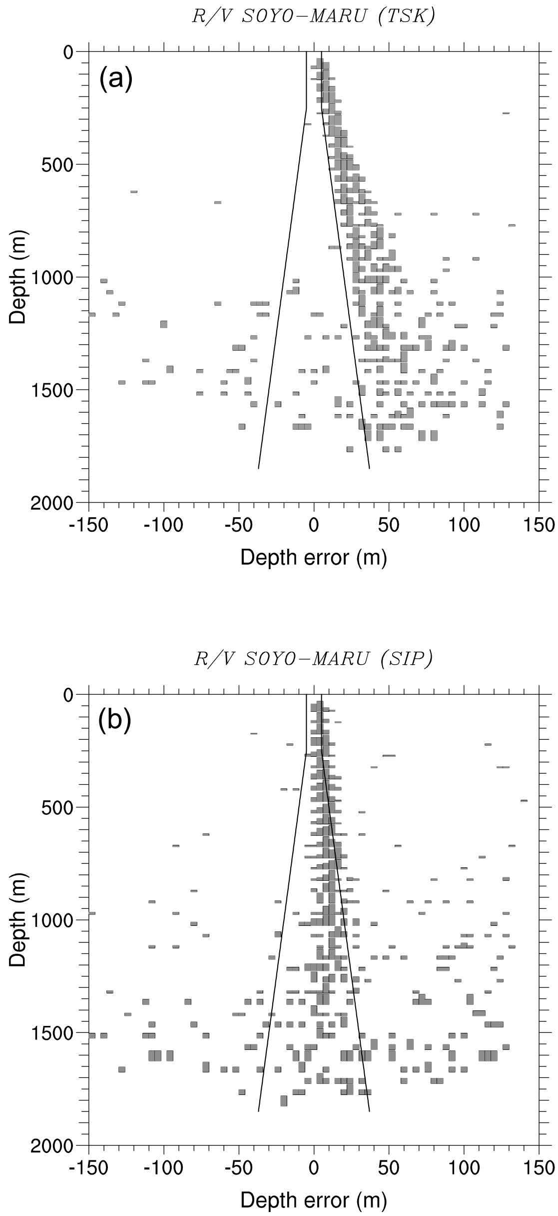
Fig. 1. Locations of measurements (dots). Sets I and II were obtained during the cruises of *R/V Wakataka-Maru* and *R/V Soyo-Maru*, respectively.

2. Measurements and Results

2.1 Intercomparison of temperature profiles

Twenty-three nearly-simultaneous and collocated measurements by CTD profilers and the two manufacturers' T-5 were conducted during two cruises from August to September 2003 near Japan by two research vessels: *R/V Soyo-Maru* of National Research Institute of Fisheries Science and *R/V Wakataka-Maru* of Tohoku National Fisheries Research Institute. Twelve pairs of profiles were taken by the former, and the rest (eleven) by the latter. The locations of the measurements are shown in Fig. 1. A few of the XBT profiles are incomplete, probably due to accidental contact of the wire with the hull, but we obtained a full range of data for the remaining casts. The CTD profilers used on both the vessels are SBE-9 (SeaBird).

For each set of measurements, a first T-5, produced by either TSK or Sippican, was released when the CTD equipment passed 100 meter depth on its downward path. Immediately after the first one finished, a T-5 produced by the other manufacturer was launched. The TSK T-5 was released first in the first half of each cruise, and the order of deployment was inverted in the second half. A single TSK MK-130 deck unit was used to operate all T-5 measurements in each cruise.



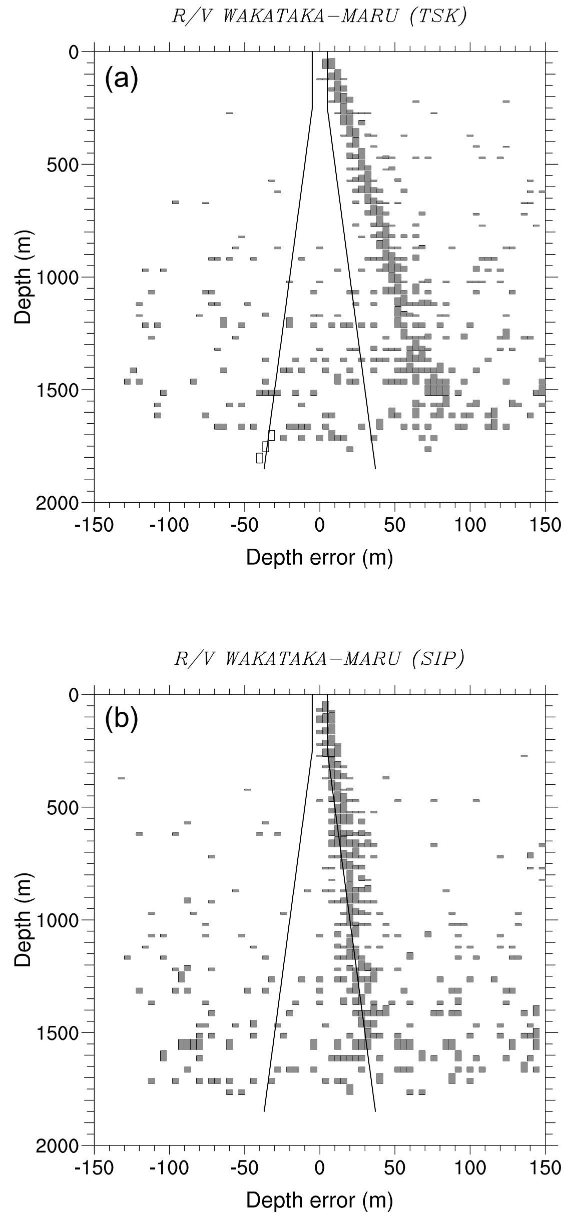


Fig. 2. Estimated depth error of Eq. (1) for the data obtained by *R/V Soyo-Maru* cruise. For (a) the TSK T-5 and (b) the Sippican T-5. Positive depth error means that the T-5 depth is greater than the CTD depth. Vertical bars indicate the relative frequency of occurrence of the depth error at individual depth. Solid lines indicate the nominal depth error by the manufacturers. Note that the manufacturers' fall-rate equation is used in the depth calculation.

Fig. 3. As Fig. 2 but for the *R/V Wakataka-Maru* cruise. See Fig. 2 for details.

Since only about 5 minutes is required to complete an individual measurement by the T-5, the time difference between the two T-5 measurements at a depth is less than 10 minutes. The CTD was still around a depth of 800 meters on its downward path when the second T-5 finished. The time difference between the measurements by either T-5 and CTD is thus less than 30 minutes. The ship drift during one set of measurements was less than one nautical mile.

It is confirmed that the order of deployment did not systematically affect the estimation of depth error. We have also compared the CTD temperature profiles on its upward and downward paths, and the estimated depth bias was larger than the natural variation of temperature during individual sets of measurement.

The sampling rate of the temperature measurement by the T-5 is 20 Hz, which translates into a vertical reso-

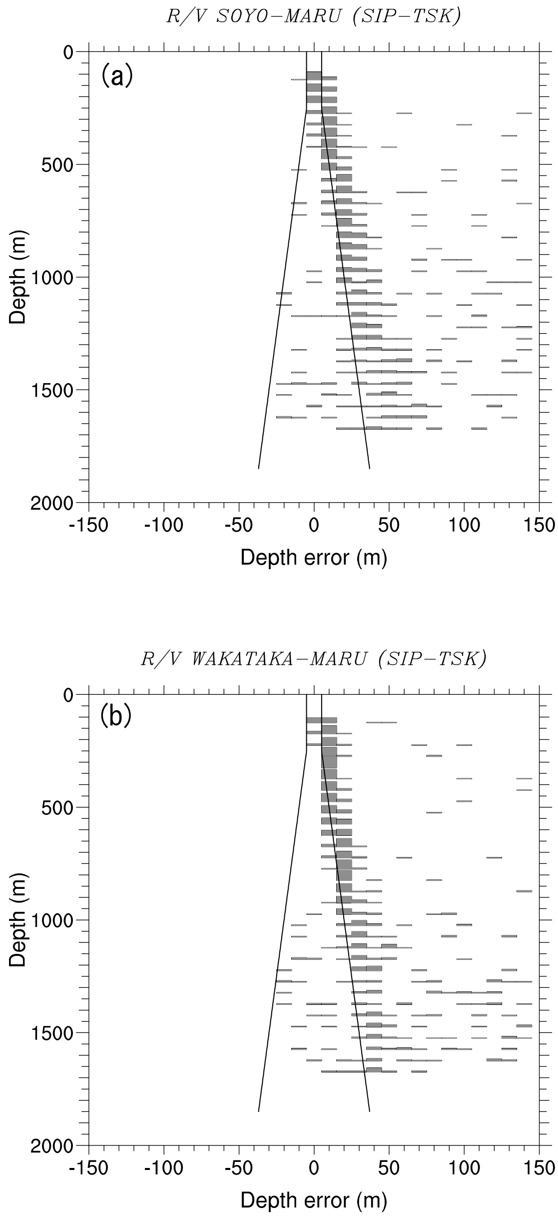


Fig. 4. Depth difference between the TSK T-5 and the Sippican T-5 as a function of CTD depth. (a) The *R/V Soyo-Maru* cruise and (b) the *R/V Wakataka-Maru* cruise. See Fig. 2 for explanation of symbols and lines.

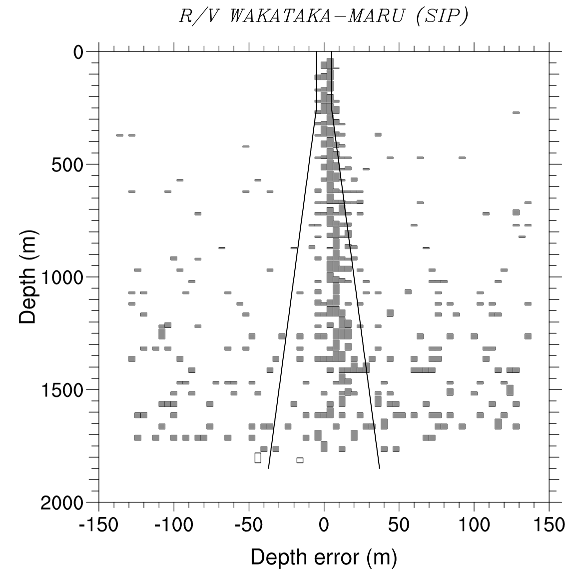


Fig. 5. Depth error of BL93's fall-rate equation for the data taken by Sippican T-5 during the *R/V Wakataka-Maru* cruise. See Fig. 2 for details.

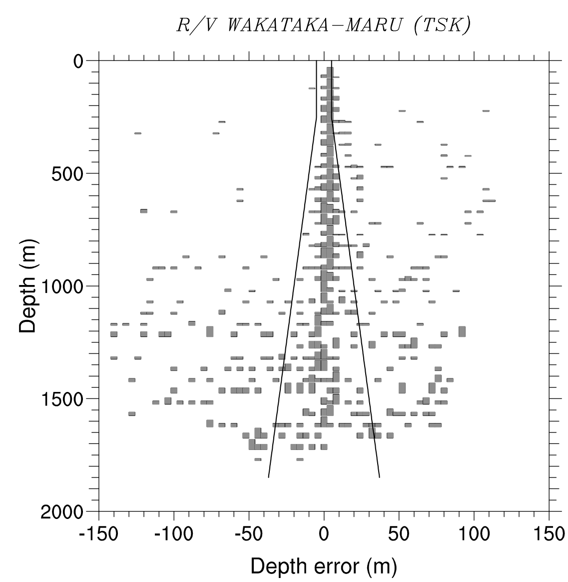


Fig. 6. Depth error of KYH05's equation for the data taken by TSK T-5 during the *R/V Wakataka-Maru* cruise. See Fig. 2 for explanation of symbols and lines.

lution of about 30 centimeters. The depth resolution of the CTD measurement is one decibar.

We followed the method of KYH05 (a modified version of Hanawa *et al*., 1995) to estimate the accuracy of the manufacturers' fall-rate equation, assuming that the CTD measurement has no depth and temperature error. The CTD profilers used in this investigation had been calibrated routinely, and the nominal accuracy (0.003 mmho/cm, 0.001°C and 0.015% for conductivity, temperature and pressure, respectively) was maintained throughout our investigation. Vertical temperature gradients (hereafter TG) are calculated at an interval of one meter for both XBT and CTD data. The error of depth is estimated by searching for a depth offset which gives the smallest difference between TG profile by either T-5 and

Table 3. Results of examination of the two T-5 models. A: total weight of a probe in water with full wire. B: as A but without wire. C: POC (position of centroid) measured from the noze of a probe in water with full wire. D: as C but without wire. E: total length of a probe. All numerical items are given in the form of mean ± standard deviation. Weights are in grams and lengths are in milimeters.

Manufacturer	A	B	C	D	E
Sippican	714.3 ± 1.7	520.8 ± 0.4	63.9 ± 0.5	43.8 ± 0.8	342.9 ± 0.07
TSK	725.5 ± 1.7	539.7 ± 0.6	69.1 ± 1.7	43.2 ± 0.4	343.8 ± 0.04

that by CTD. The latitudinal variation of gravity and the density variation of seawater were accounted for in the calculation. See KYH05 for more details.

The estimated error of depth is shown in Figs. 2 and 3 for the two cruises. It is shown that the manufacturers' fall-rate equation systematically overestimates the depth for the TSK T-5 in both the cruises. The error is far beyond the nominal accuracy of depth given by the manufacturers (the maximum of 5 meters or 2 percent of depth). However, the error for the Sippican T-5 is mostly within the range of nominal accuracy. These results support KYH05 and other previous reports.

Figure 4 shows the depth difference between the TSK T-5 and the Sippican T-5 for each pair. The difference increases linearly with depth, clearly indicating that the Sippican T-5 falls faster than the TSK T-5.

The fall-rate equations by BL93 and KYH05 are also tested for the Sippican T-5 and the TSK T-5, respectively, and the results are shown individually in Figs. 5 and 6. BL93's equation shows slightly better agreement with CTD measurement than the manufacturers' equation for the Sippican T-5. KYH05's equation significantly reduces the positive depth bias by the manufacturers' equation for the TSK T-5.

2.2 *Probe examination*

The weight and dimensions of the two T-5 models were thoroughly investigated in September 2003 by courtesy of TSK Co., Ltd. The total weight and the position of the centroid (center of weight, hereafter POC) were measured in faucet water for each of seven TSK T-5 probes and seven Sippican T-5 probes that were provided by individual manufacturers, so that the weight balance of the two models could be intercompared. All the probes were then dismantled, and the weight and dimensions of the separate parts were also measured.

We used faucet water rather than seawater to suppress the change of weight due to oxidation. The effect of salinity on the density of water is negligible compared to the difference between the average density of an XBT probe and that of the water.

The total weight and POC in the water with full and without wire, and the total length of a T-5 probe given by each manufacturer are shown in Table 3. A TSK T-5 probe with full wire is heavier in the water by about 11 grams than a Sippican T-5 probe. The difference in weight without wire is 19 grams. The latter weight difference comes wholly from the difference in the mass of the metal ogive weight. TSK checks the total weight of every probe in the air, and their allowance is ±2 grams (TSK, personal communication, 2003). Probe-to-probe differences for the TSK T-5 were actually very small in our examination. These facts mean that the differences between the TSK probes and the Sippican probes can be considered significant if a similar allowance is assumed for the Sippican's probes, though some batch-to-batch difference might exist.

An unexpected observation is that a Sippican T-5 that had fallen faster is *lighter* than a TSK T-5. If we suppose that a heavier instrument should sink faster in the water column, the result should have been opposite. This strongly suggests that the falling motion of either or both of the T-5 models in the water is much more complicated than the simple free-fall motion of a point mass.

Another marked difference is in the balance of weight. When the wire was fully wound, POC of the TSK T-5 lies 5 millimeters behind that of the Sippican T-5 in the water. This difference is largely caused by the different length of the probe spool: the TSK T-5 has a longer spool to wind thicker wire than the Sippican's. The difference in the mass of wire is mostly but not perfectly compensated by the deficit of metal weight, and differences still remain in POC and the total weight. When the wire was removed, the difference in POC almost vanishes in the water. Therefore, it is inferred that the difference in nose-to-tail weight balance and hence vertical alignment between the TSK T-5 and the Sippican T-5 is largest at the beginning of measurement (i.e. near the water surface) and becomes smaller with depth. In contrast, the difference in the total weight increases slightly (about 8 grams) when the wire is unreeled from the probes as they sink.

The difference in outer radius between the two models is smaller than 1 millimeter throughout the length of the metal ogive weight (TSK, unpublished manuscript, 2003). The difference in the total length is also negligible. However, the Sippican T-5 has a center hole about one millimeter (10 percent) wider than the TSK T-5. Therefore, it may still be plausible that the two T-5 models are subject to different drag forces by the water passing through the central hole.

Green (1984) comprehensively discussed the motion of XBTs and suggested that an XBT probe can wobble rather than fall straight in the water. This is plausible indeed for the TSK probes, which have often been observed to take slant paths after entry into the water (TSK, personal communication, 2003). It is not known, however, if the Sippican T-5 shows similar kinematic behaviour. We suggest that the difference in the weight balance and the size of the central hole could be responsible for the different fall-rate of the two models, but further investigation would require laboratory experiments in a deep tank and/or the accurate simulation of their motion, both of which are beyond the scope of this study.

It is not known whether the aforementioned discussion applies to the other types of XBT. The chemical composition (i.e., density) of the metal ogive weight and the wire are common among all types of XBT produced by the individual manufacturers. Therefore, it is possible that the change of the weight balance of a probe unreeling wire in the water is different between all the TSK probes and the Sippican probes that share the same model name. However, the inter-manufacturer difference may be smaller for the other types of XBT since the difference in length of the wire spool is only associated with T-5 (TSK, personal communication, 2003) and much shorter wire of the other XBT models makes up less of the total probe weight.

2.3 Temperature dependency

The primary objective of the *R/V Soyo-Maru* cruise was to measure the frontal structure of the Kuroshio Extension. We benefit greatly from this because we could obtain a wide range of temperature profiles from closely spaced areas where gravity can be assumed to be constant.

All of the CTD temperature profiles obtained by the *R/V Soyo-Maru* cruise are shown in Fig. 7. There are two groups with markedly different water temperatures: Group A with higher temperatures from the southern side of a front and Group B with lower temperatures obtained from the northern side. The temperature difference averaged from the surface to 1,000 meter depth is about 10°C.

The depth errors of BL93 for the Sippican T-5 and that of KYH05 for the TSK T-5 are shown in Figs. 8 and 9, respectively, for individual temperature groups. For both the T-5 models, it is evident that the groups from lower temperatures show better estimation of depth compared with those from higher temperatures. Both the T-5 models fall faster in the water of higher temperature.

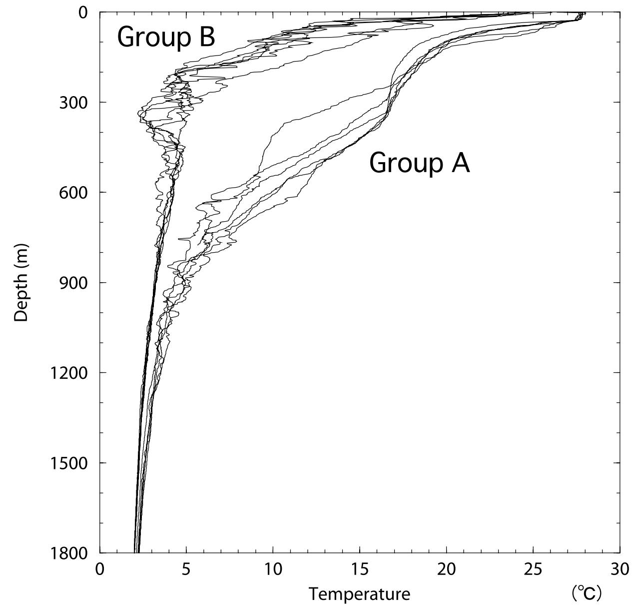


Fig. 7. All temperature profiles obtained by CTD profilers during the *R/V Soyo-Maru* cruise. Group A from warm water region and Group B from cold water region.

Moreover, the TSK T-5 is more sensitive to the water temperature than the Sippican T-5: the depth error of the former is larger than the latter. It is inferred that the depth error would remain significant unless the temperature dependency is included in the equation, although further modification of the coefficients of the fall-rate equation in its present form (Eq. (1)) might be effective in reducing the mean bias.

The warm water group has shown less-scattered results than the cold one. This originated from our method, which uses the vertical temperature gradient. The water columns with warmer water on top (Group A; Figs. 8(a) and 9(a)) have larger temperature gradients than the cold water columns that have relatively uniform thermal structure (Group B; Figs. 8(b) and 9(b)). Therefore, the mismatch of vertical temperature profile tends to occur more frequently for the cold water group than the warm water group.

The difference in depth error of the TSK T-5 between the two temperature groups is about 20 meters at 1000 meter depth. The average water temperature difference between the two groups over the upper 1000 meters is roughly 10°C, and the effect of salinity on the water viscosity is neglegible compared to that of temperature. Therefore, the dependency of depth error on water temperature is estimated to be about 2 m/°C at that depth (0.2%/°C) if we assume a linear relationship between the fall-rate and water temperature.

Seaver and Kuleshov (1982) noticed that the fall-rate

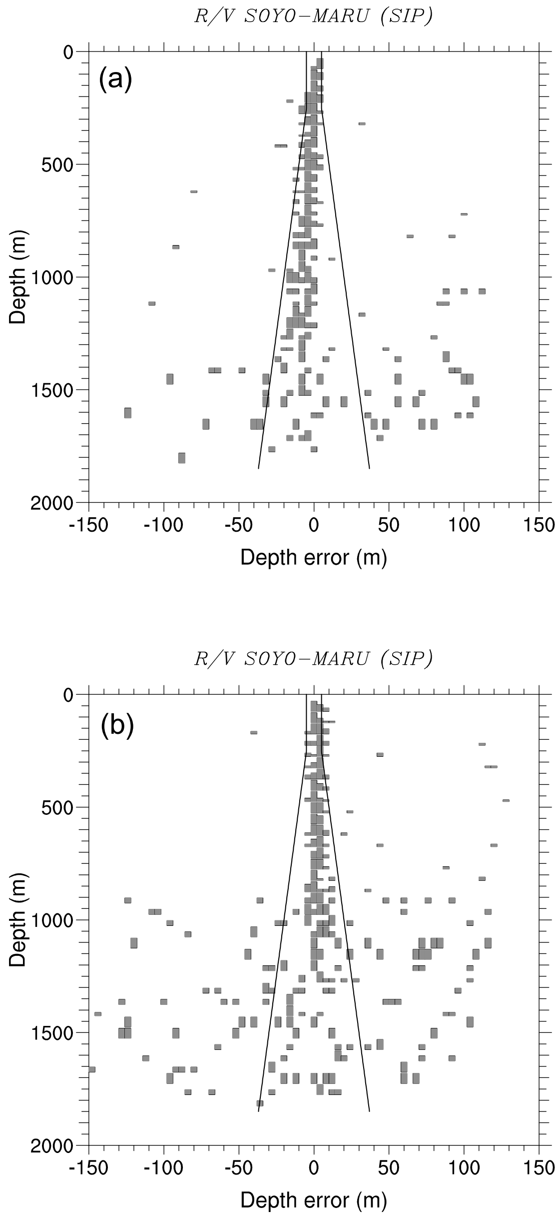


Fig. 8. As Fig. 5 but shown separately by water temperature. (a) Warm temperature group (Group A in Fig. 7) and (b) cold temperature group (Group B in Fig. 7).

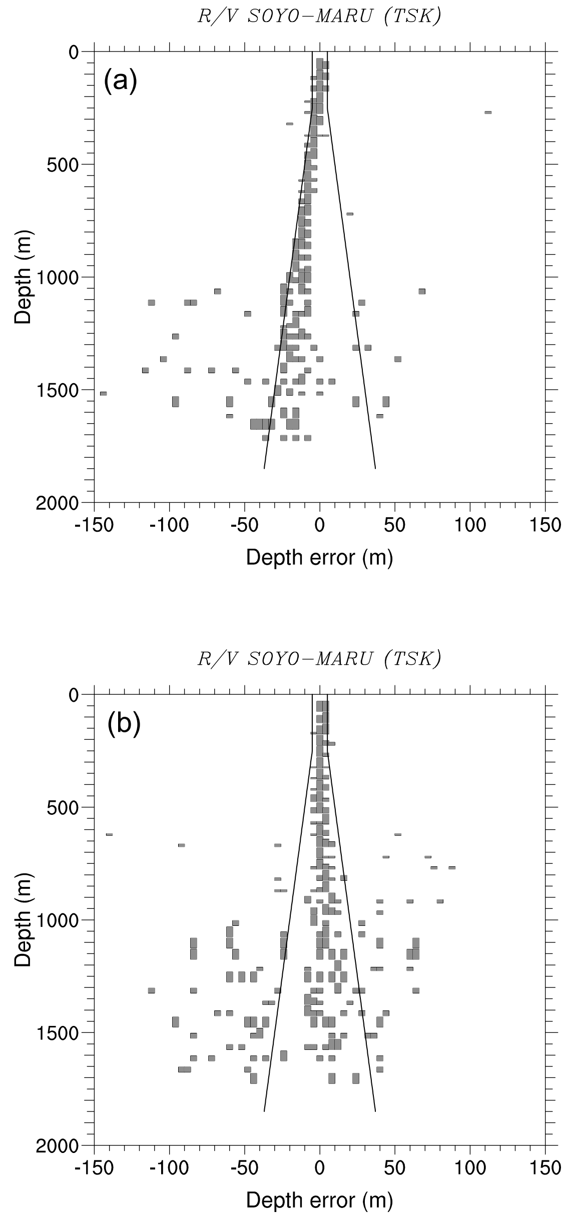


Fig. 9. As Fig. 6 but shown separately by water temperature. (a) Warm temperature group (Group A in Fig. 7) and (b) cold temperature group (Group B in Fig. 7).

of T-5 as well as T-7 might decrease in water at low temperatures. Because they just compared the depth of particular isotherms obtained by XBT measurement to that obtained by CTD measurement, however, they claimed that their results were not free from the temperature error of XBT measurements. The present study has avoided this by using not the temperature itself but the vertical temperature gradient, and confirms their suggestion by direct comparison. Hanawa *et al*. (1995) and Thadathil *et al*. (1998) tried to estimate the temperature dependency of the fall-rate of T-7 probes, but they failed, perhaps because of large scatter among data sets due to various causes such as batch-to-batch differences in the instruments or varying measurement conditions. Thadathil *et al*. (2002) noted that the fall-rate of T-7 is smaller at extremely low temperatures. Therefore, such temperature-dependency of the fall-rate may be common, at least qualitatively, for other types of expendable bathythermographs.

3. Concluding Remarks

It is confirmed that the manufacturers' fall-rate equation overestimates depth by about 5 percent when applied to the TSK T-5. This is more than double the nominal depth accuracy quoted by the manufacturers. For the Sippican T-5, however, the equation gives a much smaller depth error that is almost within the nominal depth accuracy.

More important is that the inter-manufacturer difference has been demonstrated for the first time by direct intercomparison between the two manufacturers' probes: the T-5 models of the two manufacturers are by no means the same. It is strongly recommended that the TSK T-5 and the Sippican T-5 are clearly identified and distinguished in all data sets. The manufacturers' fall-rate equation can only be applied to the Sippican T-5, and KYH05's equation should be used for the TSK T-5. Boyd and Linzell's (1993) fall-rate equation seems to give a slightly less biased depth than the manufacturers' equation for the Sippican T-5.

It should be noted, however, that even KYH05 may not guarantee the nominal depth accuracy for the TSK T-5 in the sea of extremely high/low temperatures, considering that the fall-rate of the TSK T-5 is substantially dependent on water temperature. The cause of this dependency is believed to be viscosity, but more detailed investigation will be necessary to confirm this effect quantitatively. The temperature dependency of the fall-rate is much smaller in the case of the Sippican T-5, but still appreciable.

We request TSK not to make any modifications to their models which may reduce the systematic depth bias. This is very important in order to avoid generating another seed of confusion within the oceanographic community. The metadata of the available ocean data set is often incomplete, and adding new types of instruments or modifying older designs can sometimes make things more difficult. It is more desirable now to understand the behaviour of the present models as they are, and provide such information to the users.

Finally, it is recommended that the impact of the manufacturer-to-manufacturer difference and temperature dependency of the fall-rate of the T-5 probes is quantitatively estimated in the available/future temperature archives. Unfortunately, this is practically impossible in the present situation, where a substantial number of temperature reports do not include exact identification of the instrument used. Whenever compiling a high-quality data set, therefore, it is vitally important to keep accurate metadata of individual measurement, not just as supplemental information but rather as a key of identification in case of any possible discovery of such problems in particular instruments.

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