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Instruments and Methods

Evaluation of the fall rates of the present and developmental XCTDs

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Abstract

The fall rates of the current types of expendable conductivity-temperature-depth (XCTD) profilers and one under development are evaluated based on a series of co-located measurements with conventional conductivity-temperature-depth (CTD) profilers in the North Pacific. The types of probes investigated are the XCTD-1, the XCTD-2, the XCTD-3, and the XCTD-5 manufactured by Tsurumi Seiki Co., Ltd. It is confirmed that the present manufacturer's fall-rate coefficients for the XCTD-1/2 satisfy the accuracy guarantee of 2% of depth, at depth greater than 20 m. The coefficients of all XCTD types tested are dependent on water temperature, and the probes tend to fall slightly faster in warmer water. New sets of coefficients are given for the individual types, in a form that includes a correction for water temperature. It is also found that the ring hood structure of the XCTD-1/2 is effective in stabilizing the fall rates. The newer XCTD-3/5, which lack the hood, show larger scatter in the fall rate and occasionally violates the guaranteed depth accuracy.

Keywords: XCTD; Expendable conductivity-temperature-depth profiler; Fall-rate equation; Temperature measurement; Salinity measurement; VOS monitoring

1. Introduction

The expendable conductivity-temperature-depth profiler (XCTD) is a free-fall instrument for measuring the temperature and salinity profiles of the upper ocean. The development of the instrument was initiated during the 1970s independently by two companies, Sippican Inc., USA, and Tsurumi Seiki Co., Ltd. (TSK), Japan. After a number of improvements in the sensor unit and the probe body, the two companies individually started selling their own products by the mid-1990s (Lancaster, 1988; TSK, unpublished manuscript).

The Sippican XCTDs and the TSK XCTDs are different in many aspects. The year-to-year status of the instrument under development is given in the activity report (IOC, 1995, 1997) of the Integrated Global Ocean Services System (IGOSS) Task Team for Quality Control of Automated Systems

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(TT/QCAS). Numerous studies to evaluate the XCTDs were conducted in the sea by the two companies and independent oceanographers using the probes from one company or the other (e.g. Hallock and Teague, 1990; Sy, 1993, 1996, 1998; Johnson, 1995; Mizuno et al., 1995; Albèrola et al., 1996; Mizuno and Watanabe, 1998; Gilson et al., 2000; Watanabe and Sekimoto, 2002; TSK, unpublished manuscript). Eventually, the two companies held a field test to compare overall performance of their XCTDs, and they agreed to supply only TSK XCTDs in the world market from 1999.

Because the XCTD probes carry no pressure sensors, an equation is needed to estimate depth from the time elapsed after the probe hits the water surface. The equation, variously referred to as a time-depth conversion equation, a fall-rate equation, or a depth formula, generally takes the following quadratic form:

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

where $d(t)$ is the depth in meters at elapsed time, t, in seconds. The equation contains two empirical coefficients, a and b. The second term is included to represent the deceleration due to the loss of probe weight as the wire is spooled out. Therefore, the two coefficients should be positive when $d(t)$ is taken to be positive downward.

The primary specifications of the TSK XCTDs evaluated in this article are presented in Table 1. Currently available in the market are the XCTD-1, the XCTD-2, and the XCTD-3. The XCTD-2F has been sold only to the Japan Coast Guard. TSK has been developing a new type, temporally named as the XCTD-5, which would enable deep temperature/salinity profiling from fast-cruising vessels. Crucial for the size of the two coefficients, a and b, are total weight of probe, profiling range (i.e. length of probe wire), diameter (i.e. line density) of wire, and the form of the probe body.

The only difference between the XCTD-2 and the XCTD-2F is that the latter has longer canister wire, which makes the latter available on a faster platform. All the other dimensions are identical, as are the probe weights and hence the expected fall rates.

The thickness of the wire has been changed twice in the development of the TSK XCTD family. The first change occurred when the company developed the XCTD-2, with a profiling range (1850 m) longer than that of the already existed XCTD-1 (1000 m). The second change was made to obtain higher signal transfer rate in the development of the XCTD-3/5.

The XCTD-1, the XCTD-2, and the XCTD-2F have the same outer shape of probe. They have a ring hood at the end of the after-body (top of Fig. 1) for stabilizing the attitude of the probe as it descends. In contrast, the hood is not attached to the XCTD-3/5 (bottom of Fig. 1), which consequently have higher falling rates than the XCTD-1/2.

The change in probe shape and the second change in diameter of the wire enabled quicker measurement on faster vessels while not changing the length of the canister and hence the design of the launching unit. On the other hand, whether and how the hood-free structure of the newer two types affects the stability of their fall rate are not well known, and are points of concern in the present investigation.

The fall rates of TSK XCTDs have been estimated by several studies in the past. Originally, TSK obtained a set of coefficients for the XCTD-1 (simply called "XCTD" at that time) based on its own comparison with CTD profiles at sea (TSK, unpublished manuscript). Mizuno and Watanabe

Table 1
Specifications of the TSK XCTDs that are currently available or under development

Model	Speed (kt)	Range (m)	Probe weight (g)	Wire length (m)	Wire diameter (mm)	Ring hood	Manufacturer's a	Manufacturer's b
XCTD-1	12	1000	688	1025	0.09	Yes	3.42543	4.7×10^{-4}
XCTD-2	3.5	1850	682	1954	0.07	Yes	3.43898[a]	3.1×10^{-4}[a]
XCTD-2F	8	1850	682	1954	0.07	Yes	3.43898	3.1×10^{-4}
XCTD-3	20	1000	687	1025	0.09	No	5.07598	7.2×10^{-4}
XCTD-5	8	1850	773	1915	0.09	No	N/A	N/A

Speed allowance, profiling range, initial probe weight in fresh water, the length and diameter of probe wire, and the coefficients of the manufacturer's fall-rate equations installed in the TS-MK-130 XCTD system. The XCTD-2F is for Japan Coast Guard only.

[a]For probes with serial numbers smaller than 05011071 and not 04120989 nor 04120990, the coefficients are $a = 3.3997$ and $b = 3.0 \times 10^{-4}$.

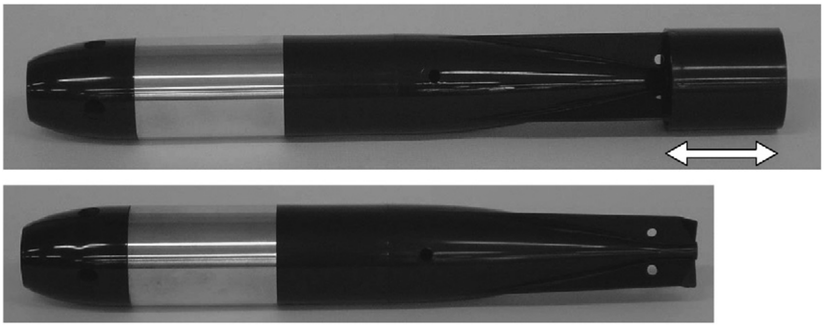

Fig. 1. Photos of the XCTD-1 (top) and the XCTD-3 (bottom). The left panels are side view, and the right ones are slant-rear view. Both types have three fins with 120° separated from each other, and only the former type has a tube-shaped ring hood attached to the rear end of the probe (as shown by an arrow), which covers the rear part of the fins. Because of this difference, the XCTD-1/2 probes are longer (377 mm) than the XCTD-3/5 (319 mm). The nose shape, outer curvature and diameter of the probe body (51 mm) are identical for all types of TSK XCTDs.

(1998) also obtained a ''tentative'' set of coefficients for the XCTD-1, $a = 3.426$ and $b = 4.7 \times 10^{-4}$, by applying the sophisticated method of Hanawa et al. (1995) to six side-by-side comparisons with CTD profiles. Watanabe and Sekimoto (2002) similarly estimated coefficients for the XCTD-2, $a = 3.4005$ and $b = 3.2 \times 10^{-4}$, from nine comparisons with CTD profiles. Koso et al. (2005) deduced those for the XCTD-2F, $a = 3.4390$ and $b = 3.1 \times 10^{-4}$, based on 20 comparisons with CTD profiles but by a different methodologies.

The coefficients obtained by Mizuno and Watanabe (1998) are now used for the XCTD-1 in the manufacturer's TS-MK-130 XCTD System. Those by Koso et al. (2005) are similarly adopted for the XCTD-2 and the XCTD-2F. These are hereafter referred to as the present manufacturer's coefficients for the individual types. Strictly speaking, however, the choice of coefficients in the manufacturer's operating system has been made according to the serial number rather than type (model name) of the probe (see Table 1 for details). Therefore, users who wish to recover data with time as a vertical coordinate from already depth-converted data should refer to the serial number of the probe, which is recorded in the header section of the data files.

The manufacturer's coefficients for the XCTD-3 were obtained by TSK based on comparison with the XCTD-1 profiles. In other words, they have not been tested against any calibrated CTD. Similarly, no fall-rate coefficients have been given yet for the XCTD-5.

The primary purpose of the present study was twofold: (1) to evaluate the accuracy of the present manufacturer's coefficients for the XCTD-1 and the XCTD-2 by utilizing a greater number of comparisons with CTD profiles, and (2) to provide the fall-rate coefficients for each of the other two types, the XCTD-3 and the XCTD-5.

At the beginning of this investigation, TSK was thinking of changing the way by which the probe wire is fastened to the probe spool of the XCTD-1/2, from the present aqueous resin adhesive to a plastic net, mainly for the sake of production efficiency. Therefore, we obtained data by the XCTD-1/2 probes with the two kinds of binding to investigate whether this modification could cause any significant change of the fall rate. However, preliminary analysis revealed that the probes of a type with different binding did not show statistically significant difference in the fall rate. Therefore, the difference in the wire binding is ignored in the following. The XCTD-2F probes used in the present study are the adhesion type, and the XCTD-3/5 probes are the net type. For further information, the expendable bathythermograph (XBT) produced by Sippican uses the net and those produced by TSK uses the adhesion.

2. Methods

2.1. Data and measurements

A series of side-by-side measurements by CTD profilers and the five types of XCTD probes (the XCTD-1, the XCTD-2, the XCTD-2F, the XCTD-3 and the XCTD-5) was conducted in various parts of the North Pacific (Fig. 2) by several institutions and agencies. The fundamental information about the cruises and the number of co-located measurements made in the present investigation are given for each XCTD type in Table 2.

Three research cruises by T/S *Oshoro Maru*, Hokkaido University, provided 131 XCTD measurements at 32 CTD stations (Group A) in the northern North Pacific under the direction of the second author of this article. The third author and his colleagues conducted a similar set of 94 side-by-side measurements at 18 CTD stations (Group B) in the Kuroshio Extension region during the KH06-1 cruise of R/V *Hakuho Maru*, the Japan Agency for Marine-Earth Science and Technology (JAMSTEC). All types except the XCTD-2F were included in both Groups A and B.

In addition, the Japan Coast Guard provided the authors with similarly co-located measurements by the XCTD-2F (Group C). In this set, 36 comparisons were made during the seafloor geodetic survey off the coast of Honshu Island, Japan. Also, the fifth author provided sets of comparison between the XCTD-1 or the XCTD-2 and CTD profiles as summarized in Table 2 (Group D).

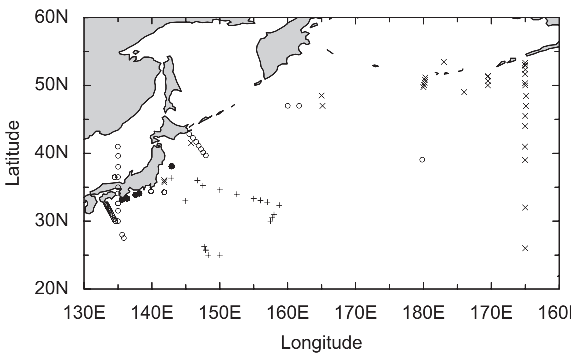

Fig. 2. Locations of the XCTD/CTD comparisons used in the present investigation. Crosses, pluses, solid circles and open circles indicate positions of Groups A, B, C and D, respectively.

All the XCTD data used were taken when the vessels were under CTD operation (i.e. almost in stationary situation), basically following the standard procedure documented by Sy and Wright (2000). In Groups A and B, multiple types of XCTD probes were tested at a single CTD station. Typically, first XCTD probe was released shortly after CTD entered the water. Immediately after the first XCTD measurement finished, another XCTD probe (of different type) was launched. Four or six types, depending on case, were launched in this way at individual CTD stations of Groups A and B.

The CTD temperature profiles obtained from Groups A–C are shown in Fig. 3. Most profiles from Group A (Fig. 3a) are characterized by low surface temperature and small temperature change in the vertical. In contrast, those in Group B (Fig. 3b) were obtained mostly in the subtropics, where surface temperature is higher and hence the thermal stratification is stronger over a greater range of depth. Group C (Fig. 3c) consists of three types of profiles: a low-temperature profiles obtained off northeastern Japan, a high-temperature ones collected in and at the offshore side of the Kuroshio, and intermediate-temperature ones taken on the coastal side of the Kuroshio.

Approximately 5 (for the XCTD-1/3) or 10 min (for the XCTD-2/5) were required to complete one XCTD measurement. The time difference between an individual XCTD cast and the CTD

Table 2
The list of cruises involved and the number of XCTD/CTD measurement pairs made in this investigation

ID	Vessel	Period	CTD	Type of XCTD				
				1	2	2F	3	5
Group A	R/V *Oshoro-Maru*	November 2003	SBE19	0	3	0	0	0
		August 2004	SBE9+	0	6	0	0	0
		June–August 2005	SBE9	36	36	0	24	24
Group B	R/V *Hakuho-Maru*	March 2006	SBE9	29	29	0	18	17
Group C	Various (JCG)	April–September 2004	SBE19+	0	0	35	0	0
		February 2005	SBE19+	0	0	1	0	0
Group D	Various	1997–2002	Various	42	20	0	0	0
Total				107 (93)	130 (119)		42 (35)	41 (35)

The number of profiles eventually used for the determination of fall-rate coefficients are given in parenthesis in the last line of the table.

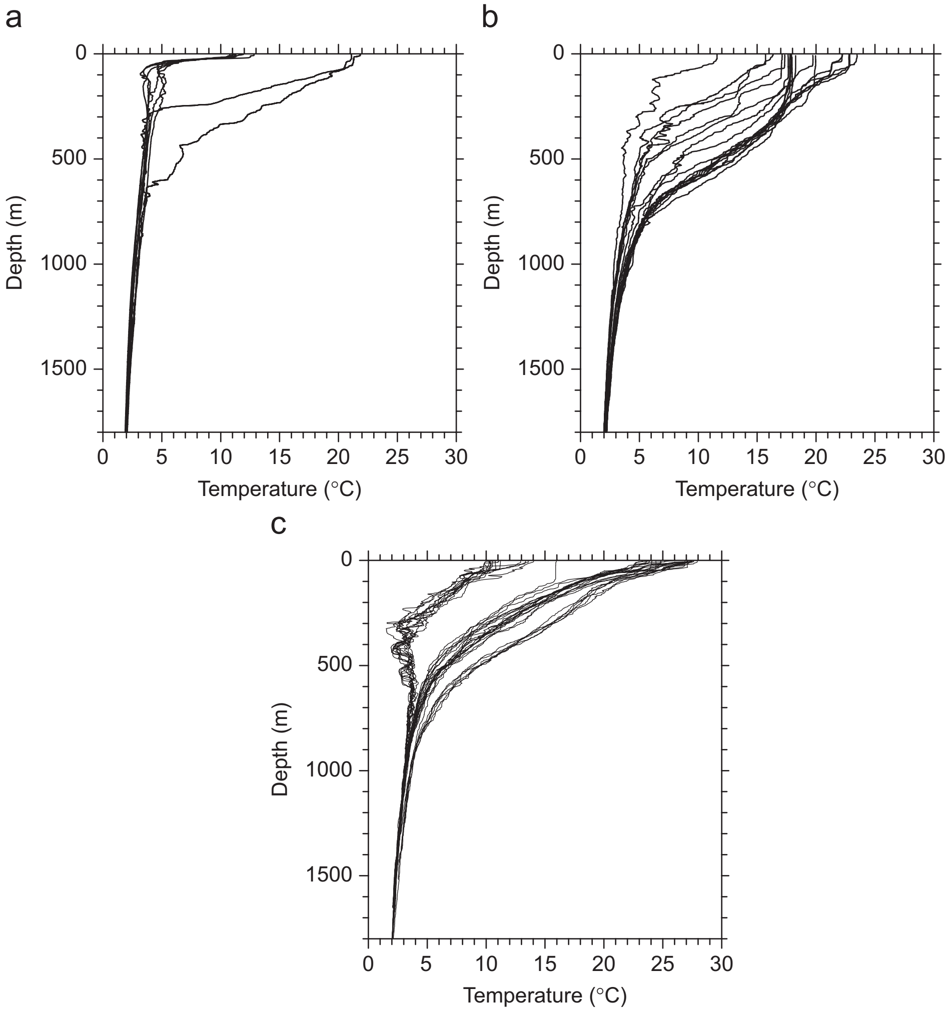

Fig. 3. CTD temperature profiles obtained from (a) Group A, (b) Group B and (c) Group C.

measurement to be compared therefore varies from several minutes to about half an hour. Most of the CTD data paired with the XCTD profiles in this study were obtained during the descent of the instrument, but those during the ascent, if available, were also used to minimize the time difference. The drift of the vessel during a set of measurements at a CTD station was usually less than half a kilometer, and always less than 4 km.

The probes were launched from the lower deck of the vessels at several meters above the water surface, though the precise height varied from case to case depending on the structure of the vessel and the sea state. Several XCTD profiles were incomplete, perhaps because of accidental contact of the wire with the hull, wire breaking, or insufficient water depth, but we could obtain a full range of data for the remaining casts. One XCTD-5 probe malfunctioned, but all the other probes worked without problem.

In all the experiments, a TSK TS-MK-130 System was used to control the XCTD measurements. Time-to-depth conversion was made on board by following the standard procedure according to the manufacturer's equation to make "ALL" files from "RAW" files, which are not depth-converted. The "RAW" files were also stored, but the "ALL" files were used in the analysis because the detailed format of the former was not available. The first author is fully responsible for all of the post-measurement analysis. The method of analysis is described in the following section.

The sampling rate of the XCTD measurements by the TS-MK-130 is 25 Hz. This translates into a vertical resolution of about 14 cm for the XCTD-1/2 and about 20 cm for the XCTD-3/5. The vertical resolution of the CTD data is 1 decibar or 1 m.

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 believed to be maintained throughout the investigation.

Actually, profiles of Group C were used in the Koso et al. (2005) to obtain their fall-rate coefficients for the XCTD-2 and the XCTD-2F. They estimated the fall rates by comparing XCTD/CTD depths where the vertical gradient of temperature has peaks. They confined their analysis to a depth range from the surface to 1000 m depth because of technical difficulty in finding good "marks" to be used in their peak-detection method in deeper layers. They eventually selected 20 XCTD/CTD pairs out of a total of 36 co-located measurements to determine their final coefficients. Their data set is included in the present evaluation for two purposes: (1) to increase the number of XCTD/CTD comparisons for the XCTD-2/2F and (2) to compare the results obtained with different methodology.

2.2. Detection of depth error

In order to estimate the accuracy of the manufacturer's fall-rate equation, the method of Hanawa

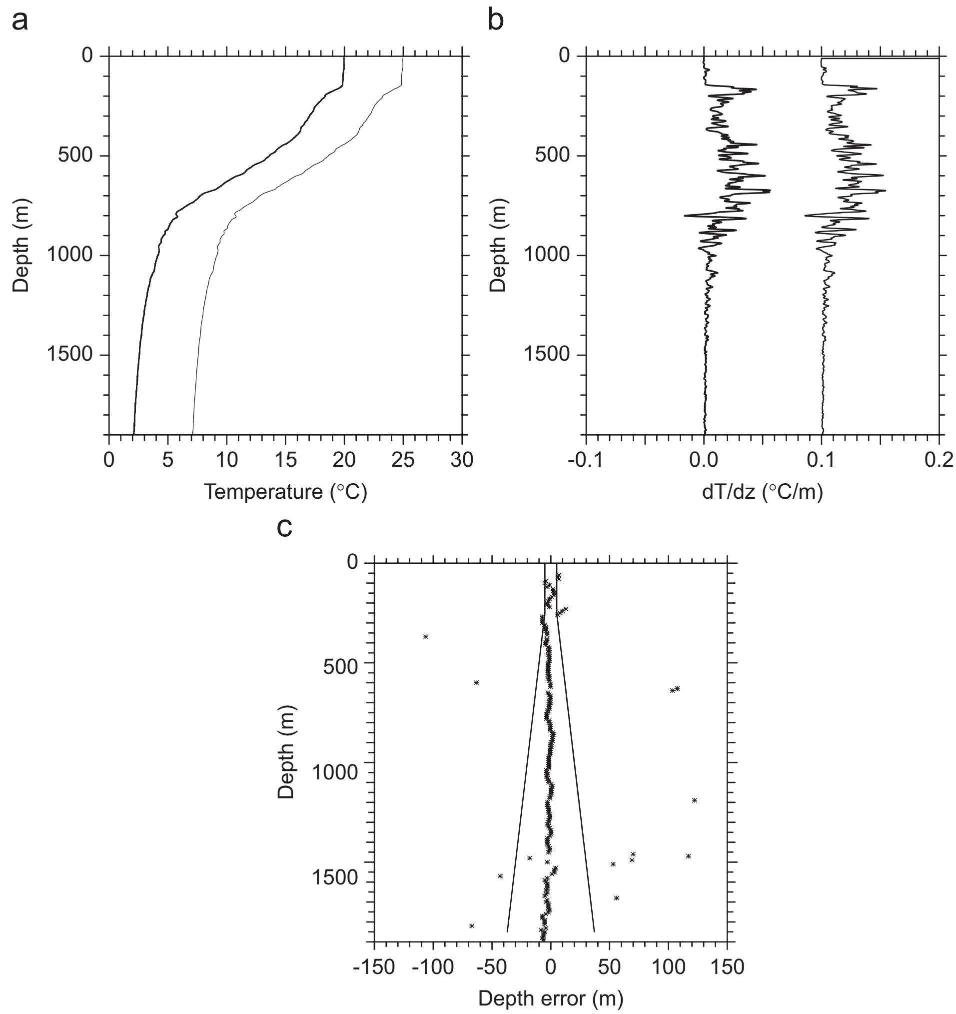

Fig. 4. Examples showing how the method detects depth error in two typical cases (see also Fig. 5). A case from Group B with many thermal structures in the vertical. (a) Temperature profiles of XCTD (left) and CTD (right). CTD profile is shifted by offset of 5 °C. (b) Vertical gradient of temperature by XCTD (left) and CTD (right). The profile by CTD is shifted by offset of 0.1 °C/m. (c) Vertical distribution of depth error detected by the present method. Solid lines in (c) indicate the manufacturer's guaranteed depth accuracy.

et al. (1995) is applied, with some modification, to the temperature profiles of XCTD/CTD pairs. Temperature rather than conductivity is chosen simply because the latter is greatly sensitive to the former.

Firstly, the individual temperature profiles are processed with a 7-point median filter to remove spikes. Secondly, they are interpolated at 1-m interval, and thirdly smoothed with a 41-point Hanning filter. The choice of (especially the second) filter is rather arbitrary, and the decision is made according to a compromise between advantage (good vertical resolution) and disadvantage (higher noise) of retaining high-wave-number structures in profiles for estimating the depth error of given equations. Fourthly, the vertical gradient of temperature is calculated for the total depth range of individual XCTD and CTD profiles. Finally, the error of depth is estimated by searching for a depth offset that gives the smallest difference between the profile of temperature gradient by XCTD measurement and that by co-located CTD measurement. See Hanawa et al. (1995) for further details.

A slight change from Hanawa et al. (1995) is that the latitudinal variation of gravity is accounted in the present study. This, however, causes change of only a few tenths of a percent in depth over the latitudinal range considered here. All of the CTD measurements are assumed to be free from errors in both depth and temperature.

Two examples (Figs. 4 and 5) show how the method detects depth error in profiles with different vertical homogeneity. The CTD profile in Fig. 4a was obtained in the subtropics (Group B) and

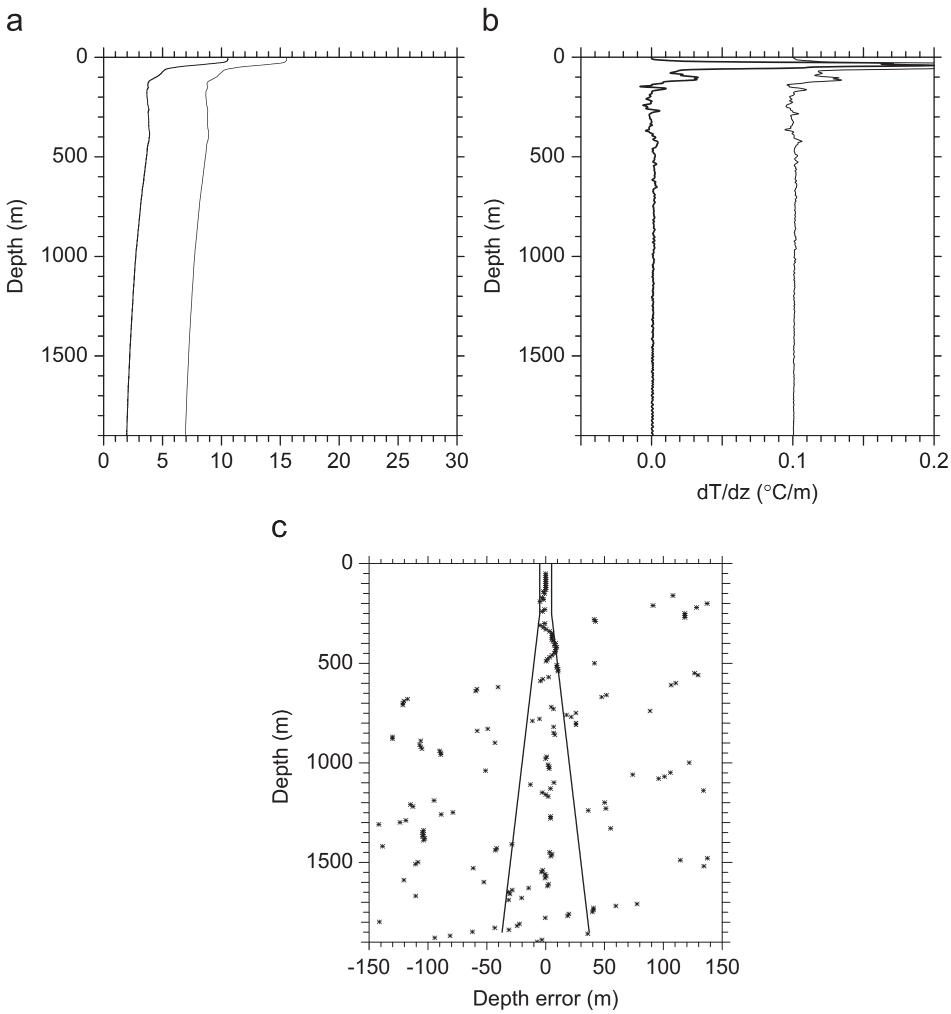

Fig. 5. Same as Fig. 4 but for a case in Group A with high vertical homogeneity.

includes many thermal structures with good size of vertical gradient in most part of the profiling range (Fig. 4b). Fig. 4c shows that the present method can provide a "plausible" vertical plot of depth error (XCTD depth minus CTD depth) and that almost no depth bias is identified in this case.

In contrast, for a profile (Fig. 5a) obtained from the subarctic sea (Group A) with high vertical homogeneity (Fig. 5b), the method can only marginally trace the vertical distribution of depth error (Fig. 5c). This is obviously because the method of Hanawa et al. (1995) entirely relies on the vertical change of the vertical temperature gradient to detect depth error. A numerical experiment (not shown here) indicates that adding noise of 0.01 °C to a CTD temperature profile from Group A can violate the detection of depth error. This does not happen in the case of "well-stratified" profiles like that shown in Fig. 4a. The poor results in Fig. 5c demonstrate that the method of Hanawa et al. (1995) can fail with profiles of high vertical homogeneity that often occur in high-latitude oceans. In this investigation, therefore, careful inspection is made profile-by-profile to remove erroneous points prior to the final derivation of the fall-rate coefficients.

3. Results and discussions

3.1. Evaluation of the manufacturer's coefficients

The estimated error of depth by the manufacturer's fall-rate coefficients is shown in Fig. 6 for each type of XCTD from Group A. Positive error (rightward bias) indicates overestimation of depth (i.e. depth by XCTD is greater than that by CTD). In other words, a positive error means that the probe fell slower than the applied coefficients tell. Here, the results are given in a form of histogram rather than a profile-by-profile fashion.

For all types except for the XCTD-3, the error of the manufacturer's coefficients is well within the nominal accuracy (i.e. tolerance), maximum of 2% or 5 m, defined by the manufacturer. The detected depth difference occasionally exceeds ±5 m near the surface, but it is very difficult to judge whether the difference should be attributed to instrumental inaccuracy because natural variability (e.g. waves) could cause a difference of this magnitude during the time between measurements by XCTD and CTD. The small bias down to greater depths supports the use of the manufacturer's coefficients, and the depth accuracy is actually shown to be much higher than 2% of the depth, except near the surface.

In contrast, the depth error detected for the XCTD-3 shows much larger scatter than the XCTD-1/2, and the error occasionally exceeds the present accuracy guarantee. The cause of this difference between the XCTD-3 and the XCTD-1/2 will be discussed in Section 3.3 in more detail.

Figs. 7 and 8 show the corresponding results for Group B and the XCTD-2F from Group C, respectively. Again, the error stays within the guaranteed accuracy envelope for the XCTD-1/2. Small bias in Fig. 8 means that the fall-rate coefficients of Koso et al. (2005) for the XCTD-2 (originally developed by using the XCTD-2F) are justified by a second method of error estimation. The errors for the XCTD-3 are again greater than those for the XCTD-1/2, but the manufacturer's fall-rate coefficients did not result in a significant depth bias.

The least-square-mean fitting is applied to the results of depth error detection to obtain a set of coefficients, a and b in Eq. (1), for individual profiles. Careful screening was made beforehand to remove outliers as aforementioned. The fitting is allowed only when the points are available over a depth range at least from the surface to 600 m depth for the XCTD-1/3 and to 1200 m depth for the XCTD-2/5. When the number of available points is smaller than 40, that profile is discarded from the fitting and further analysis. The number of profiles eventually used in the determination of fall-rate coefficients is given for each XCTD type in Table 2.

The sample size, average and standard deviation of the coefficients in each of Groups A–C are shown in Table 3 for the XCTD-1 and the XCTD-2/2F. Similar summaries are given in Table 4 for the XCTD-3 and the XCTD-5. The standard deviation of error in Group A is generally larger than that in Groups B and C for all types shown. This again suggests the limited applicability of the present methodology, which uses the change of vertical temperature gradient, in the northern sea where temperature varies little at depth (Fig. 3a).

The standard deviations of the a coefficient for the XCTD-3/5 (Table 4) are much larger than those of the XCTD-1/2 (Table 3) in either group. This difference can be attributed to the difference in probe shape as discussed in Section 3.3.

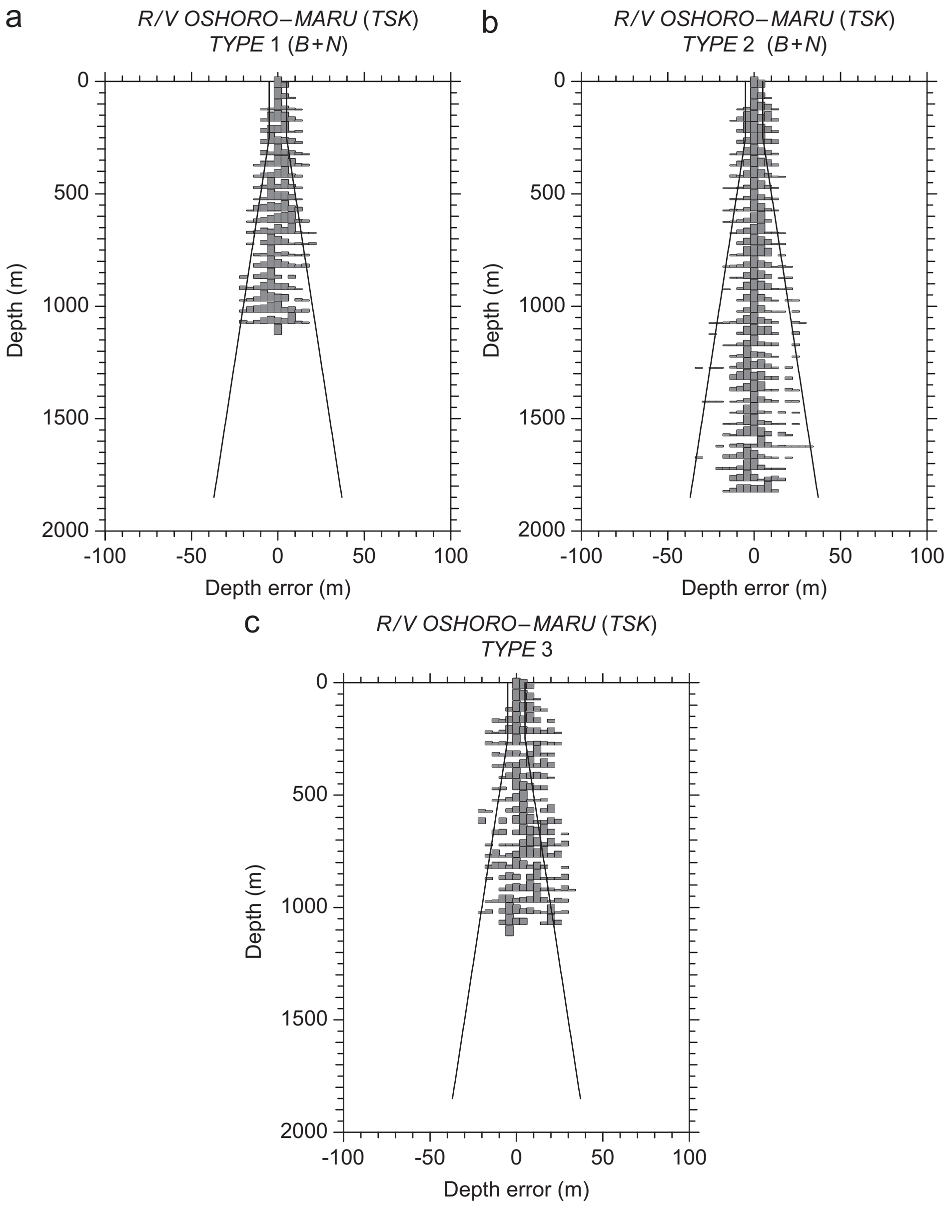

Fig. 6. The depth error of the manufacturer's fall-rate coefficients for individual XCTD types in Group A. The vertical axis is the depth by CTD, and the horizontal axis is the error of depth estimated by the present analysis. (a) The XCTD-1, (b) the XCTD-2, and (c) the XCTD-3. Vertical bars, scaled arbitrarily, indicate relative frequency of occurrence of the depth error in each depth bin (50 m). Solid lines denote the manufacturer's guaranteed depth accuracy (maximum of 5 m and 2% of the depth).

3.2. Water temperature and fall rate

Figs. 6–8 show that the depth error estimated for the XCTD-1/2 is substantially smaller than the nominal accuracy of 2% of depth except near the surface. Although the XCTD-3 shows larger scatter that occasionally exceeds the guarantee, the manufacturer's present fall-rate coefficients well satisfy the specification and are almost bias-free statistically.

The issue to be examined here is whether the fall rate of XCTDs varies with water temperature as shown in the literature for XBTs (e.g. Thadathil et al., 2002; Kizu et al., 2005). Figs. 9–12 show the profile-by-profile relation between the water temperature averaged over the surface 500 m, T_{500}, and the fall-rate coefficients. Here, T_{500} is chosen as an indicator of water temperature integrated over a range of depth, rather than temperature at a particular depth

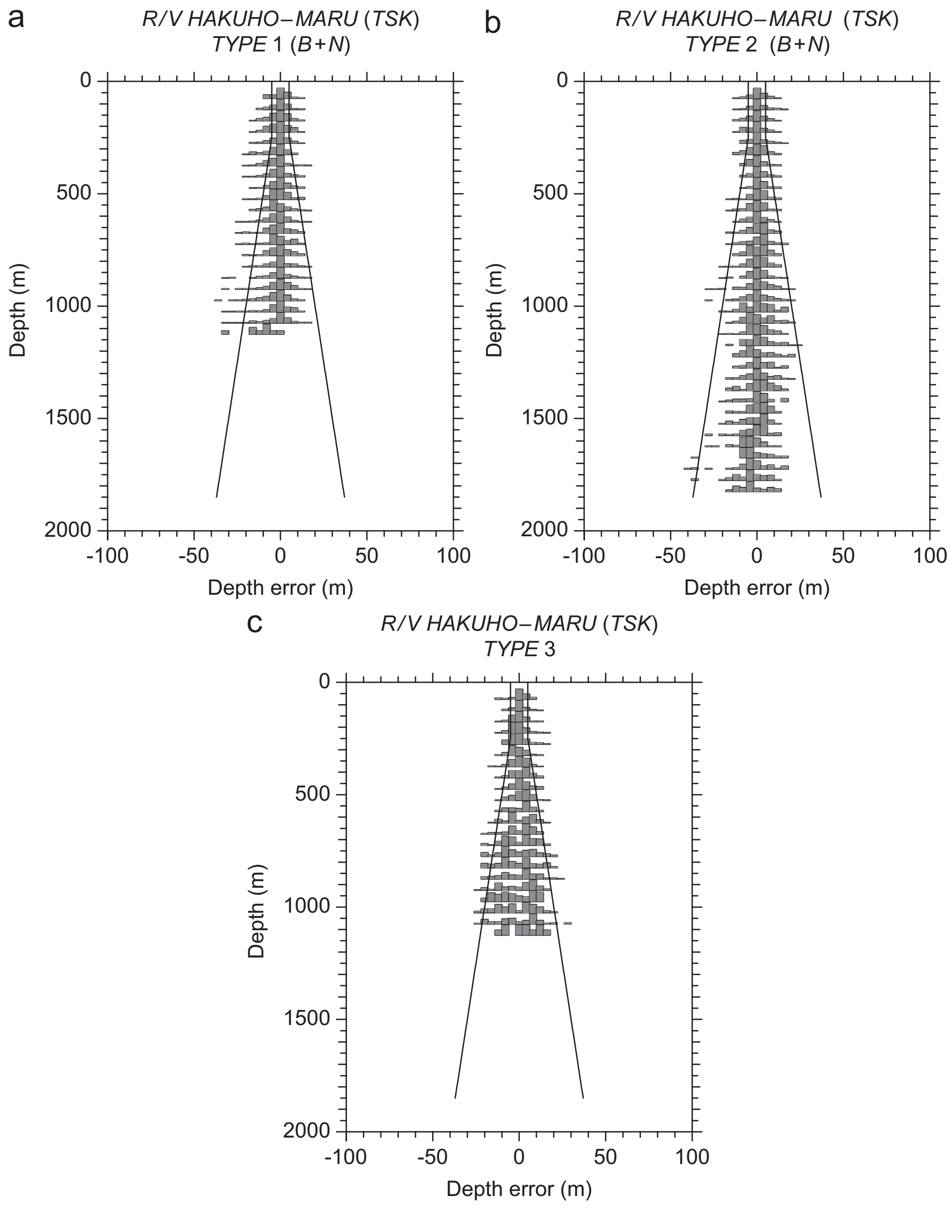

Fig. 7. Same as Fig. 6 but for Group B. (a) The XCTD-1, (b) the XCTD-2, and (c) the XCTD-3.

level. Note that the two subsets (binder and net) of the XCTD-1 are merged, and so are the two XCTD-2 subtypes and the XCTD-2F.

A positive correlation is found between the *a* coefficient and T_{500} for all types including the XCTD-5 (Figs. 9a–12a). In other words, all tested types of XCTD probes tend to have slightly larger initial fall rates in warmer water. The correlation coefficients are $r = 0.41$ ($N = 93$), 0.21 (119), 0.44 (35), and 0.31 (35) for the XCTD-1, the XCTD-2, the XCTD-3, and the XCTD-5, respectively, and those except the last are statistically significant at the 95% level.

The correlation between the *b* coefficient and T_{500} is also positive for all types (Figs. 9b–12b) but is less significant. The correlation coefficients are $r = 0.36$, 0.17, 0.24, and 0.12 for the XCTD-1, the XCTD-2, the XCTD-3, and the XCTD-5, respectively. All except the one for the XCTD-1 is insignificant at the 95% level. The present measurements or analysis may not be accurate enough to detect a subtle temperature dependency of the *b* coefficient.

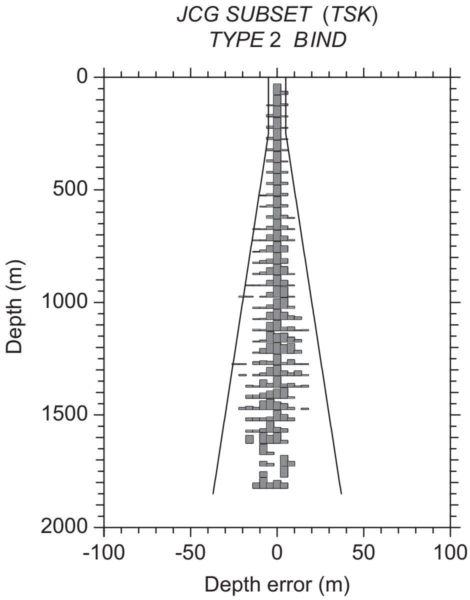

Fig. 8. Same as Fig. 6 but for Group C. Note that only the XCTD-2F is tested in this set.

Table 3
The mean and standard deviation of the a and b coefficients for the XCTD-1 and the XCTD-2/2F in Groups A–C

	XCTD-1		XCTD-2/2F		
	Group A	Group B	Group A	Group B	Group C
a (ave.)	3.4018	3.4392	3.4293	3.4329	3.4345
b (ave.)	2.95E−4	4.96E−4	2.85E−4	3.04E−4	2.93E−4
a (std.)	0.0589	0.0291	0.0280	0.0267	0.0195
b (std.)	4.74E−4	1.05E−4	6.77E−5	7.34E−5	5.99E−5
N	25	28	40	27	36

N is the sample size.

Table 4
Same as Table 3 but for the XCTD-3 and the XCTD-5

	XCTD-3		XCTD-5	
	Group A	Group B	Group A	Group B
a (ave.)	4.9724	5.0644	5.0318	5.0621
b (ave.)	4.04E−4	6.54E−4	4.38E−4	4.57E−4
a (std.)	0.1213	0.0513	0.0863	0.0550
b (std.)	5.22E−4	2.92E−4	3.22E−4	2.82E−4
N	17	18	18	17

The choice of T_{500} is arbitrary but is thought to be justified because similarly significant positive correlation is also obtained when T_{500} is replaced by some other temperature averaged from the surface to various levels down to 1000 m depth. The change of correlation by changing the depth range is only marginal.

The overall change of fall rates with temperature is around 1% for the XCTD-1/2 but can exceed 2% for the XCTD-3 in some depth levels. The manufacturer's coefficients are within the range of the fall rates in the present results and coincide best with those at moderate to high water temperatures. It is therefore suggested that the manufacturer's coefficients may give slightly biased depth information in water of low temperature.

The temperature dependency of the fall rate was identified very clearly by Kizu et al. (2005) for the T-5 XBT. Also, Thadathil et al. (2002) noted that the fall rate of T-7 is smaller at extremely low temperatures. Although it has been difficult to estimate the size of the temperature dependency for the short-range profiles by T-7 (e.g. Seaver and Kuleshov, 1982; Hanawa et al., 1995; Thadathil et al., 1998), it is now more plausible that the change of water viscosity with temperature ($\nu = 1.787 \times 10^{-6}\,\mathrm{m^2\,s^{-1}}$ at 0 °C to $\nu = 1.004 \times 10^{-6}\,\mathrm{m^2\,s^{-1}}$ at 20 °C) can have a noticeable effect on the fall rate of those free-falling probes. The size of temperature dependency of fall rates is smaller for XCTDs than the TSK T-5 that was reported by Kizu et al. (2005). The reason is not clear, but it may be caused by the structural difference between XCTDs and XBTs.

The present results show that both the a and b coefficients increase as T_{500} increases. This suggests that the XCTD probes fall faster initially but also decelerate faster in the subtropical sea where the probes experience higher T_{500} but greater decrease of temperature with depth (Fig. 3). A primary cause of the b coefficients should obviously be the weight loss, but the larger b coefficient in water of greater T_{500} may be attributed to such thermal structure of the ocean. In other words, it is likely that the second-order term may partially be caused by the increase of water viscosity with depth.

Because of the large scatter, particularly in the samples at low temperatures, precise estimation of the size of the temperature dependency of the fall rates is still difficult. Since the detection of depth error is fully dependent on the comparison between CTD and XCTD temperature-gradient profiles, the large scatter in water of low temperature is naturally expected. The linear regression in Figs. 9–12 give rough estimates of the value for each type, but more accurate estimation would require a different kind of approach which does not depend too much on vertical gradient of temperature.

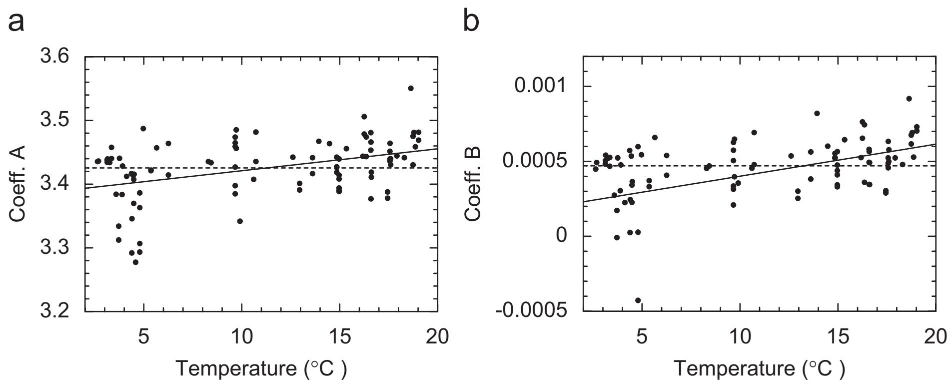

Fig. 9. The temperature dependency of (a) a and (b) b coefficients for the XCTD-1. The vertical axis is T_{500}, the temperature vertically averaged from the surface to 500 m depth. The temperature (horizontal axis) is in degrees Celsius. Solid lines show regression lines for individual types, of which slope is given as a_1 in Table 5. Dashed lines show the manufacture's coefficients.

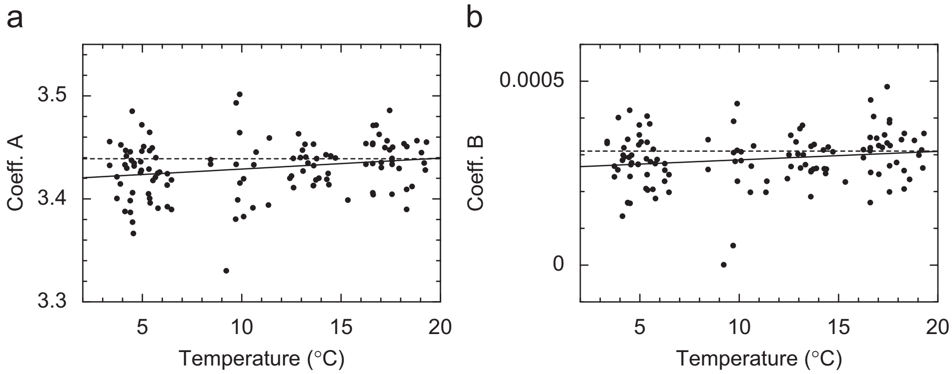

Fig. 10. Same as Fig. 9 but for the XCTD-2.

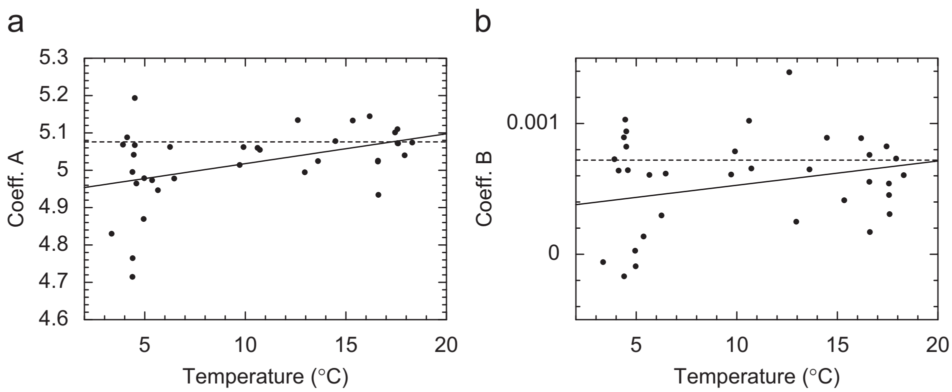

Fig. 11. Same as Fig. 9 but for the XCTD-3.

3.3. Effect of probe shape on fall rate

The sensitivity of the a coefficient to water temperature for the XCTD-1/2 is smaller than that for the XCTD-3/5. This difference is thought to be caused by the structural difference between the former two types and the latter two (Fig. 1).

As shown in Table 1, the initial weight of an XCTD-3 probe is virtually the same as that of an XCTD-1 probe or an XCTD-2, and an XCTD-5

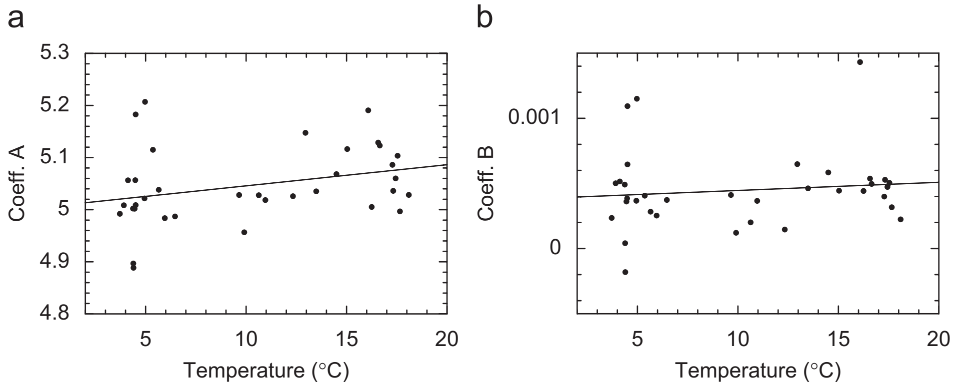

Fig. 12. Same as Fig. 9 but for the XCTD-5.

probe weighs more than any of those three types by about 11%. All of the present XCTD probes have a circular flat nose separated from the side by an almost right-angle corner, and all types of XCTD have the same girth. The only structural difference between the XCTD-1/2 and the XCTD-3/5 is the ring hood, as described earlier.

The ring hood is attached to the former two types for keeping the upright attitude of the probe by "braking" and giving stable rotation at the rear end. The hood is absent from the latter two types for the sake of obtaining higher fall rates to shorten the time of measurement, while not forcing any modification to the length of the probe and the launching unit. The trade-off is likely to be loss of stability of the attitude and the fall rate, which is observed in the difference in the scatter of estimated depth errors between different types (Figs. 6–8).

Kizu et al. (2005) found a larger temperature impact on the fall rate of the TSK T-5 than on that of the Sippican T-5. In that case, the structural difference between the two products was much less visible: the centroid of a TSK T-5 is located only 6 mm behind that of a Sippican T-5. They speculated that the TSK T-5 has higher sensitivity to water temperature because of reduced stability of the attitude compared to the Sippican T-5.

The lack of a "rear brake" in the XCTD-3/5 is actually common to the XBT probes. However, a crucial difference between XCTD and XBT is at the front end of the probes. The role of the rear brake may be more important for the former because it has nose much rougher than the latter, acting as a "front brake".

Both the present results for the XCTDs and those for the T-5 XBT in Kizu et al. (2005) suggest that losing vertical stability during fall causes higher sensitivity to water viscosity. This hypothesis is not proven theoretically, however, and more precise knowledge of the flow around the falling probes, which is beyond the scope of this investigation, would be necessary to provide more quantitative information about the temperature dependency of fall rates of expendable probes with different shapes.

3.4. Determining new coefficients

The present investigation shows that the manufacturer's fall-rate coefficients for the XCTD-1/2 probes satisfy the guaranteed depth accuracy. The XCTD-3 probes also show no clear indication of systematic bias of the present formula for that type. A problem with the XCTD-3/5 is that they showed large probe-to-probe (or cast-to-cast) differences, as discussed in the previous subsection.

Proposing new coefficients is sometimes not meaningful, because analyzing new data sets often results in a new set of coefficients that are numerically different but do not provide a statistically significant improvement from the existing ones. However, clear identification of the temperature dependency of the two coefficients (Figs. 9 and 12) motivates us to evaluate the feasibility of the temperature correction. The aim of deriving new fall-rate coefficients in the following is not to recommend immediate replacement of the present manufacturer's coefficients but rather to document the present knowledge about the temperature dependency of the coefficients for the future.

Here, a new form

$$d(t) = a(T)t - b(T)t^2 \quad (2)$$

is considered. The coefficients, a and b, are respectively linear functions of water temperature, T, in degrees Celsius:

$$a(T) = a_0 + a_1 T, \tag{3}$$

$$b(T) = b_0 + b_1 T, \tag{4}$$

where a_0 and b_0 are the value of coefficients at 0 °C, and a_1 and b_1 are the coefficients of sensitivity of a and b to T. Again T_{500} is used as T in Eqs. (2)–(4). Different depth ranges are also tested, but the results of regression did not significantly differ because of the presence of large scatter (Figs. 9–12) in the temperature-coefficient relation. Although the correlation between the b coefficient and water temperature is less significant, the temperature dependency is accounted for in both the coefficients. The four constants, a_0, b_0, a_1 and b_1, are derived by the least-square fit and given for each XCTD type in Table 5.

The probability that each of the present manufacturer's equation and the new equation satisfies the nominal depth accuracy (2%) is estimated by calculating a ratio of the number of data points that stay inside this tolerance to the total number of data points used for the determination of depth error. The improvement by including the temperature effect is negligible (only tenths of a percent), however, suggesting that the dependencies of the two coefficients on temperature (Figs. 9–12) largely cancel each other. The present results show that the effect of water temperature on the overall fall rates of XCTDs is too small to be corrected for in a simple quadratic fall-rate equation, at the presence of large scatter among individual casts.

The accurate determination of the temperature effect obviously requires more precisely "simultaneous" XCTD/CTD comparison in circumstance free from natural variability, which may not be achievable in the real ocean. The users who only concerns the overall depth accuracy should use the manufacturer's present coefficients until more precise knowledge about the temperature effect becomes available.

For depth range deeper than 300 m, the accuracy of depth by the XCTD-1/2 is estimated to be higher than 2% by a probability of more than 95%, and even higher than 1% by a probability of more than 70%. On the other hand, that by the XCTD-3/5 is higher than 2% by a probability of around 85%, and higher than 1% by a probability of only about 50%.

Table 5
Temperature dependency of the fall rate of each XCTD type, estimated by linear regression

Type	a_0	a_1 (K^{-1})	b_0	b_1 (K^{-1})	N_p
XCTD-1	3.387	3.4e−3	1.87e−4	2.14e−5	93
XCTD-2	3.418	1.1e−3	2.63e−4	2.31e−6	119
XCTD-3	4.938	8.0e−3	3.42e−4	1.85e−5	35
XCTD-5	5.005	4.1e−3	3.83e−4	6.27e−6	35

The constants a_0 and b_0 are the values of a and b at 0 °C. The sensitivity of a and b coefficients to water temperature is given as a_1 and b_1. The number of profiles used in the regression (the number of points in Figs. 9–12) is shown as N_p for each type.

4. Concluding remarks

The present fall-rate coefficients for the XCTD-1/2 by the manufacturer (Mizuno and Watanabe, 1998; Koso et al., 2005) are found to statistically satisfy the guaranteed depth accuracy. It is also shown that the fall-rate coefficients of all types of XCTD are dependent on water temperature. The change of fall rates with temperature is marginal (1–2% for 15 K difference in T_{500}), but the positive correlation between the a coefficients and water temperature is significant at the 95% level for all XCTD types except for the XCTD-5. Therefore, new fall-rate coefficients are presented for each type as an idea to correct for the temperature effect.

It is suggested that a ring hood at the end of afterbody is effective in stabilizing the fall rates of the XCTD probes with the present "flat-nose" form. The XCTD-1/2 with the hood and the XCTD-3/5 without it exhibit very different statistical results, and the former two types seem to have an advantage in obtaining constant speed in water. Further study would be necessary, however, to theoretically quantify the impact of this structural difference.

Since the hood structure slows the falling probe, on the other hand, the cruising speed of the platform is limited when the XCTD-1/2 is used. There is an increased demand for XCTD probes that can be used on a high-speed platform, but allowing a higher speed by using low fall-rate probes requires longer canister wire, which is likely to force a modification of the size of the canister and hence the launching unit, and also possibly the revision of on-board systems via the change of transfer rate through the wire. Removal of the ring hood from the XCTD-3/5 has been a quick solution to avoid this, but it seems that the ring-free structure resulted in losing stable fall rates in the water.

Another solution to achieve higher speed allowance is to abandon the flat nose and take a streamlined form like that of XBTs. But this choice may cause unstable wobbling of the probe during descent, as reported for XBTs in previous studies (e.g. Green, 1984). It is also known by the manufacturer's experience that the flat nose with an angled edge helps the probe achieve constant fall rates by generating turbulence at the corner. More investigation is necessary for the full development of XCTDs suitable to high-speed platforms.

The effect of water temperature on the falling probe is still not well understood. It is likely that the viscosity of water, which varies considerably with temperature, plays a substantial role. However, its quantitative estimation requires more precise measurement of the flow around the falling probe, and this may not be achievable in the actual ocean at the presence of natural variation. Numerical modeling of the flow might also be helpful but is beyond the scope of this investigation.

The present analysis covers a temperature range from about 4 °C to about 19 °C in terms of T_{500}. The behavior of the XCTD probes under more extreme temperatures near freezing point, that are common in the polar ocean, for instance, is another issue to be examined. An easy lesson from the present investigation is the importance of testing probes under a wide range of oceanic conditions.

A final remark is to address the importance of keeping metadata of good quality. The choice of fall-rate coefficients has been made according to the serial number of the XCTD probe, as aforementioned. In other words, the number information is crucial when one attempts to recalculate the depth of XCTD profiles that are already depth-converted. Therefore, it is strongly recommended that the serial number of the XCTDs be recorded in any data archive.

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