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Recorder-Dependent Temperature Error of Expendable Bathythermograph

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The accuracy of temperature measurement by the expendable bathythermograph (XBT) is examined for five types of recorders by comparison with co-located CTD measurements and statistical analysis of temperature profiles including an isothermal layer. A positive temperature error increasing downward is occasionally detected for two types of Japanese recorder which have been commonly used among Japanese oceanographic institutions and marine observatories. This error resembles to that reported by Bailey *et al.* (1989) and Wright (1991) for a different type of recorders, although its cause is not clearly understood. The irregular occurrence of the error suggests that the problem is not solely due to the recorders but rather by some inconsistency of the whole measuring system including them, an XBT probe and sea water. The error is estimated to increase at a rate of *O* (0.1°C/100 m), and it could be close to 1°C at the deepest part of the profiles (760 m for Tsurumi T-7).

Keywords:
· Expendable bathythermograph,
· XBT,
· temperature measurement,
· VOS monitoring.

1. Introduction

The expendable bathythermograph (XBT) has been widely used since the 1970s for measuring temperature profiles of the upper ocean. At present, the significant parts of this measurement depend upon the reliability of XBTs. However, it seems that the precision of XBT-measured temperature has not been well examined in the field experiments though the great amounts of attention has been paid to the depth error in the time-depth conversion (e.g. Hanawa *et al*., 1995).

Bailey *et al*. (1989) reported that the temperature measured by XBTs using a Bathy Systems Inc., 810 recorder gradually *increased* with depth in a surface mixed layer. Since a different type of recorder did not indicate such unrealistic profiles (Bailey *et al*., 1989) and increasing the electrical current reduced the magnitude and occurrence of bowing (Wright, 1991), it was concluded that this downward-positive temperature error, called "bowing", was caused by a combination of low electrical current to excite the XBT and a slight leakage of the wire insulation (Wright, 1991). However, the Japanese XBT systems commonly used among Japanese oceanographic institutions and marine observatories have never been examined in this regards.

Tohoku University has been using XBTs to conduct upper ocean monitoring across the Kuroshio (Hanawa *et al*., 1996) and between Japan and Hawaii for many years. From routine processing of the hundreds of temperature profiles obtained, we noticed that a similar gradual downward increase of XBT-measured temperature was occasionally observed in the winter surface mixed layer of the sea south and southeast of Japan. This is a very unrealistic finding on account of vigorous wind stirring and deep convection during winter and minor variation of salinity in the layer in those regions.

We therefore performed a detailed systematic survey on accuracy of temperature measured by XBT systems by comparing co-located measurements by XBT and CTD (Conductivity-Temperature-Depth recorder) and also by analyzing many XBT profiles taken by ourselves and other organizations with recorders of various types. In this paper, we demonstrate that a similar temperature error as that reported by Bailey *et al*. (1989) does indeed occasionally occur for recorders of two particular types but not for others.

Section 2 gives information on the data obtained for this investigation. The results and discussions are given in Section 3. Conclusions are described in Section 4.

2. Data

Sixty-three pairs of co-located measurements by XBT and CTD obtained during five research cruises during 1985 through 1993 by the R/V *Hakuho Maru* and the

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Table 1. Sources of co-located XBT and CTD measurements. See the text for details.

Name of R/V and cruise	XBT recorder	XBT probe	Number of pairs
Hakuho Maru (KH-85-5)	ORI handmade	TSK T-7	15
Hakuho Maru (KH-87-1)	ORI handmade	TSK T-7	9
Hakuho Maru (KH-93-2)	Z-60-16 II	TSK T-7	12
Tansei Maru (KT-87-13)	Z-60-16 II	TSK T-7	8
Tansei Maru (KT-89-9)	Z-60-16 II	TSK T-7/T-6	19

R/V *Tansei Maru* of the Ocean Research Institute (ORI), the University of Tokyo, were used in this study, and are listed in Table 1.

We also used more than 1000 XBT profiles from the North Pacific measured by five types of recorders, as shown in Table 2. They were either obtained from the two monitoring programs, namely the Tokyo-Ogasawara Line Experiment (TOLEX; Hanawa *et al*., 1996) and the Japan-Hawaii Monitoring Program (JAHMP) conducted by ourselves, or provided by the Japan Meteorological Agency (JMA), the National Research Institute of Fisheries Science (NRIFS), Tokai University (courtesy of Professor Kutsuwada), and the US National Oceanic and Atmospheric Administration (NOAA).

All of the TOLEX-XBT data prior to March 2001 were obtained by a Z-60-16 II recorder manufactured by Murayama Denki Co., Ltd. An MK-130 recorder of Tsurumi Seiki Co., Ltd., has been used since then. Three different recorders have been used in the JAHMP-XBT measurement. A Z-60-16 III recorder was used in October 1998 cruise. In the three cruises in 1999, a Z-60-16 II, the same type but different recorder from that used in TOLEX, was used. An MK-130 recorder has been used since 2000.

On the research cruises of the two ORI research vessels, a handmade ORI recorder and Z-60-16 II(s) were used (Kitagawa *et al*., 1981; Hanawa and Yoshikawa, 1991). Since we do not have exact information about the instruments used during the cruises, the number of recorders used is not known. Since the Z-60-16 II used in TOLEX had never been unloaded since 1988 until its replacement by MK-130, it is considered that the Z-60-16 II(s) used in the ORI research cruises was (were) not the same equipment as the one used in TOLEX. However, it is unclear whether or not the Z-60-16 II recorder used in JAHMP was also used in some of the ORI cruises.

The handmade ORI recorder is a prototype of the commercial model, the Z-60-16 II (Murayama Denki Co., Ltd., personal communication), and the Z-60-16 III is an improvement on the Z-60-16 II. For the manufacturing confidentiality, however, detail is not open to the public. According to the limited information, these two types seem to be basically of the same design, except that the type III possesses a self-calibration function to prevent long-term trend of the circuit characteristics. The type II does not have such capability, but no degradation severe enough to violate the initial specifications was found for the older model, either (Murayama Denki Co., Ltd., personal communication). Also, the temperature "observed" by a recorder before entry into the water is between 0°C and 10°C (this varies seasonally) for the type II, but is constantly about 15°C for the type III. Therefore, the older type tends to take a longer time for the start-up transient (this term is explained in Subsection 3.2). In this study, Z-60-16 II and III are considered as different models. The MK-130 has completely different circuit from Z-60-16 II and III (Tsurumi Seiki Co., Ltd., personal communication).

The types of recorder used by the other organizations are summarized in Table 2. The data provided by JMA were collected by their four research vessels which used either Z-60-16 II or III. The data from Tokai University and NRIFS were obtained by a single Z-60-16 II, respectively. The data from NOAA were collected by volunteer observing ships (VOS) which carried either an MK-9 or an MK-12 recorder manufactured by Sippican Co., Ltd. If we assume that ships with different call signs used different equipment, then at least five MK-9s and eleven MK-12s were used.

In summary, the XBT data used were obtained by at least four Z-60-16 III recorders (used in 1998-JAHMP and three JMA research vessels), at least six Z-60-16 II (including the handmade-ORI) recorders (used in TOLEX, 1999-JAHMP, the ORI cruises, the JMA R/V *Ryofu Maru*, the Tokai University R/V *Bosei Maru*, and the NRIFS R/V *Soyo Maru*), two MK-130s (used in JAHMP since 2000 and TOLEX since March, 2001), at least five MK-9s and at least eleven MK-12s.

All XBT data used here are so-called "raw" data except for those from the JMA R/V *Seifu Maru*, which were already interpolated to a one meter interval when provided. The XBT data from the Subarctic Gyre Experiment (SAGE) were taken at a sampling rate of 10 Hz while the others were taken at 20 Hz. All profiles were obtained in the subtropical North Pacific (south of 35°N and west of 160°W) and adjacent seas near Japan.

All CTD data used in this study were obtained by a Neil Brown Instrument Systems Inc., (NBIS) Mark IIIb instrument, except for KH-93-2 when Sea-Bird Electronics Inc., (SBE) model 11-plus was used.

3. Results

3.1 Comparison with CTD measurements

Comparison is made between each of the 63 pairs of XBT and CTD measurements obtained during the five research cruises of the ORI research vessels. The time-depth conversion for XBTs is performed according to the fall-rate equation of Hanawa *et al*. (1995). In order to avoid the influence of depth error due to the conversion, a careful profile-to-profile comparison was done by drawing a graph for each pair. An example is shown in Fig. 1 to describe the procedure.

First, at least a few remarkable points are chosen by eye in the profiles for each pair (hereafter "marks") from the whole range of depth (indicated by circles in Fig. 1(a)). The marks should be well defined in both profiles and should accurately correspond to each other. Secondly, the temperatures by XBT and CTD are read for each mark and paired with depth by CTD. The pressure-to-depth conversion for CTD was done by the method of Hanawa and Yoritaka (1987). Then, assuming that the temperature measured by CTD is the true value, the error of XBT temperature is calculated for each depth. The depth-temperature error are plotted in Fig. 1(b) for the example. The procedure is performed similarly for each of the remaining pairs.

XBT and CTD measurements were performed almost concurrently at the same position for each pair. An XBT probe was dropped when the CTD reached 100 m depth in its downward path. The ships were drifting during the measurements. The difference in time and position between XBT and CTD measurements is thus considered to be minimal.

The results per cruise are shown in Fig. 2. The tendency of error is clearly cruise-dependent. The error profiles from KT-87-13 (Fig. 2(d)) and KT-89-9 (Fig. 2(e)) agree well, with one exception. There is no significant difference between the results from T-6 probes and those from T-7 probes for the latter cruise. However, about half of those from KH-93-2 (Fig. 2(c)) record a large error, which increases almost linearly with depth. One of these profiles shows a linear and consistent increase of temperature error from the sea surface, but others indicate similar errors, which rather start to grow from some depth. In contrast, all XBT profiles from KH-87-1 (Fig. 2(b)) show a small but consistent negative error.

The profiles from KH-85-5 (Fig. 2(a)) can be separated into two groups: one with a small and the other with a constant negative error. Hanawa and Yoritaka (1987)

Table 2. Sources of XBT data provided for the present investigation. JAMSTEC is the abbreviation of Japan Marine Science and Technology Center. SAGE is Subarctic Gyre Experiment. See the text for details.

Name of R/V and cruise	Organization	Recorder	Probe	Number of casts ($MLD > 30$ m)	Number of cases ($\Delta T_{max} > 0.05$)	Number of cases ($\Delta T_{max} > 0.1$)
TOLEX (–Jan., 2001)	Tohoku Univ. and JAMSTEC	Z-60-16 II	TSK T-7	370	275 (74%)	58
TOLEX (Mar., 2001–)	Tohoku Univ. and JAMSTEC	MK-130	TSK T-7	15	0 (0%)	0
JAHMP (Oct., 1998)	Tohoku Univ.	Z-60-16 III	TSK T-7	67	31 (46%)	5
JAHMP (1999)	Tohoku Univ.	Z-60-16 II	TSK T-7	116	76 (66%)	8
JAHMP (2000–)	Tohoku Univ.	MK-130	TSK T-7	182	4 (5%)	2
Ryofu Maru (1997–2001)	JMA	Z-60-16 II	TSK T-7	153	111 (73%)	26
Seifu Maru (2000)	JMA	Z-60-16 III	TSK T-7	10	3 (30%)	1
Shunpu Maru (1997–2000)	JMA	Z-60-16 III	TSK T-7	122	39 (32%)	4
Chofu Maru (1999–2001)	JMA	Z-60-16 III	TSK T-7	54	9 (17%)	0
Soyo Maru (2000)	NRIFS	Z-60-16 II	TSK T-7	23	11 (48%)	1
Bosei Maru (1996–1999)	Tokai Univ.	Z-60-16 II	TSK T-7	14	6 (43%)	0
SAGE (1998–2001; 5 ships)	NOAA (via JMA)	MK-9	Sippican Deep Blue	57	2 (4%)	0
SAGE (1998–2001; 11 ships)	NOAA (via JMA)	MK-12	Sippican Deep Blue	526	20 (4%)	1

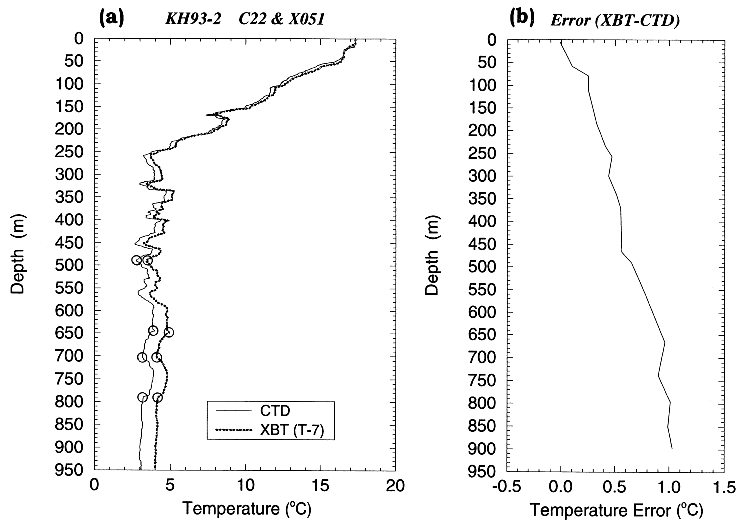

Fig. 1. (a) An example of temperature profiles and (b) estimated error profiles by co-located XBT (thick dotted line) and CTD (thin solid line) measurement. Circles in (a) show examples (not all) of chosen "marks" to estimate the temperature error of XBT measurement (see text).

confirmed that the two different behaviors found in KH-85-5 are caused by the poor quality of a group of XBT probes which displayed a negative error. However, these negative errors (Fig. 2(a)) do not seem to increase with depth as those found in the profiles from KH-93-2 (Fig. 2(c)).

A positive increase of temperature error with depth was reported by Bailey *et al*. (1989) and is known as "bowing". The origin of the name is unclear, but it may come from the bending of the vertical temperature profile, which should be straight in the mixed layer. The cause of the problem was concluded to be a combination of low electrical current to excite the XBT and a slight leakage of the wire insulation (Wright, 1991).

All XBT profiles in this comparison were taken by either the ORI handmade or Z-60-16 II instruments, which are virtually identical. If we assume that all XBT profiles were taken by a single recorder in each ORI cruise, which is usual, the figures can be interpreted as showing the error characteristic of individual recorders of this type. The present comparison indicates that a similar increase of temperature error with depth ("bowing") occasionally happens for this type of recorder. However, it should be noted that the error does not always occur, nor at a constant rate, even with a single recorder. This irregularity may suggest that the problem is not solely caused by a recorder but rather by some inconsistency of the whole measuring system, possibly including an XBT probe and sea water.

3.2 *Mixed layer profile analysis*

We also investigated the dependence of the occurrence of the positive temperature error on types of recorder by using a number of profiles obtained in the North Pacific. Since no CTD measurements were available for this purpose, a different approach was adopted.

In the sea south and southeast of Japan, a well-mixed surface layer develops in winter in response to the great amount of heat release to the atmosphere and strong mixing by wind. The thickness of the layer often exceeds 200 m and the temperature variation in the layer is very small. We used this uniformity of temperature in the winter mixed layer as a reference.

Only temperature profiles taken from October to April were used, since profiles in summer include only a thin isothermal layer which does not allow us to detect a small temperature error. The procedure is as follows.

The top 10 m in every profile are removed from the analysis. Usually, an XBT probe takes a few seconds after entry to the water to display the correct temperature of the surrounding water. This process is called "start-up transient" (Roemmich and Cornuelle, 1987; Bailey *et al*., 1989), and UNESCO (1997) recommended not to use XBT-measured temperature from the surface to 4 m depth. Thadathil *et al*. (1999) showed good agreement between temperature measured by some XBT system and CTD at 5 meter depth in the Indian Ocean. Kizu and Hanawa (2002) suggested that the depth of the adjustment differed for different recorder types and that 4 m might not be deep enough for some recorders to complete the transient. The temperatures obtained at depths from 4–10 m have therefore been also discarded.

Anomaly of temperature at each depth, $\Delta T(z)$, is calculated using temperature at 10 m depth as a reference.

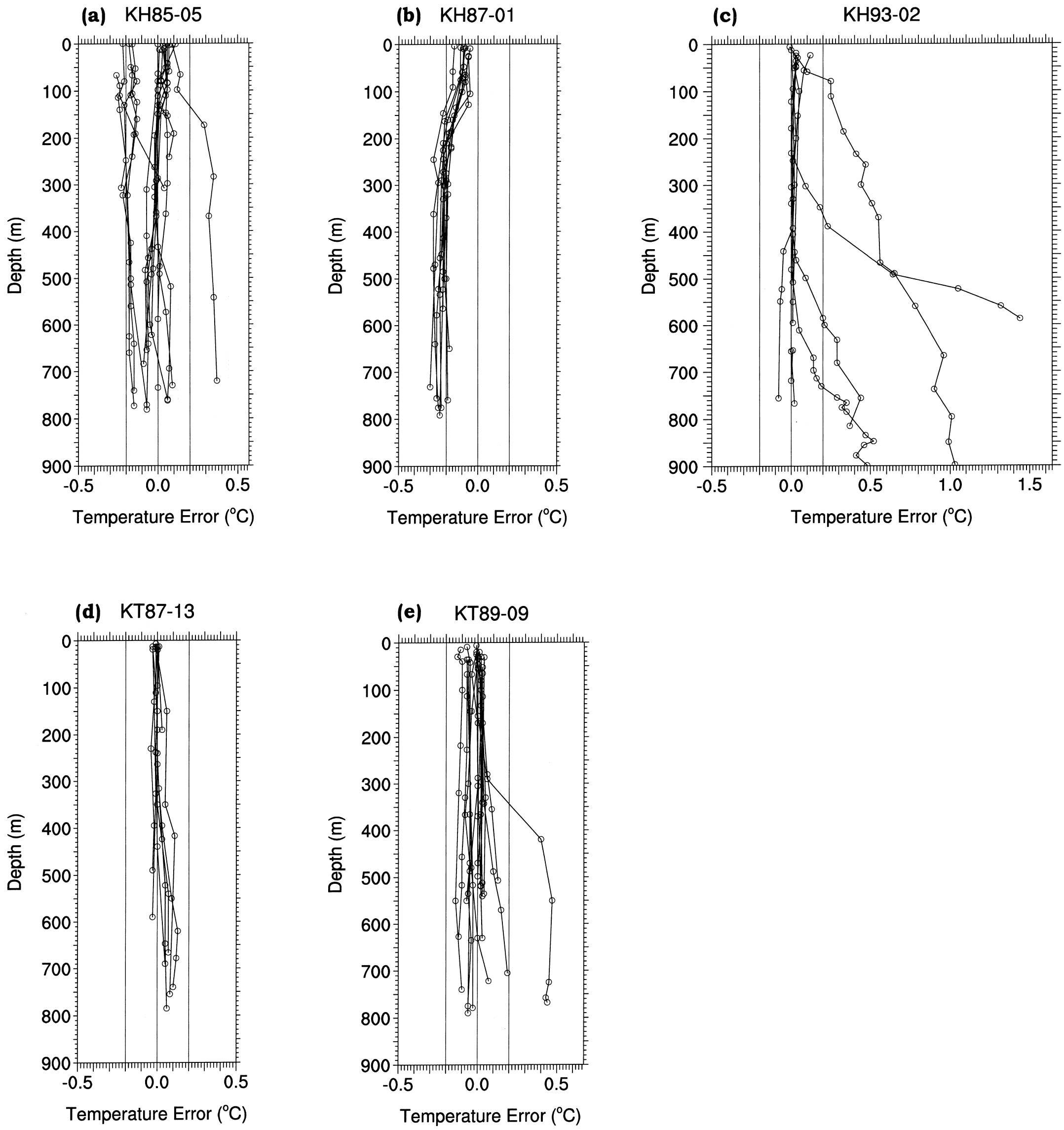

Fig. 2. The error profiles for each of the ORI research cruises shown in Table 1. (a) KH-85-5. (b) KH-87-1. (c) KH-93-2. (d) KT-87-13. (e) KT-89-9. The circles indicates the depth of marks chosen for the error estimation. For KH-93-2 (c), two cases with almost zero error are omitted in the figure.

Spike-like, narrow fluctuations which are occasionally observed are removed by a seven-term median filter (covering approximately 1 m on both sides), and the thickness of the isothermal layer below 10 m depth is defined for each profile by $-0.05°C < \Delta T < 0.5°C$. This thickness is referred to as the *MLD* (Mixed Layer Depth) hereafter. The reason for taking a larger positive margin in the definition is that the current investigation basically aims to detect downward-positive temperature error under general oceanic conditions with warm water on top. The largest positive temperature anomaly, ΔT_{max}, at the base of the isothermal layer is stored with its depth if $MLD > 30$ m.

Finally, all results were checked graphically profile by profile, and a case was removed when the calculated ΔT_{max} seemed to be due to different reasons than being caused by the instrumental error of the present interest. The remaining profiles are those characterized by temperature gradually increasing downward with ΔT_{max} at some depths. A typical example is shown in Fig. 3.

Frequency of occurrence is summarized in Table 2 for conditions $\Delta T_{max} \geq 0.05°$ and $\Delta T_{max} \geq 0.1°$ by recorder or by cruise. It is shown that Z-60-16 II most frequently observed profiles with temperature increasing downward. Z-60-16 III observed these unrealistic profiles less frequently than Z-60-16 II but much more than the other

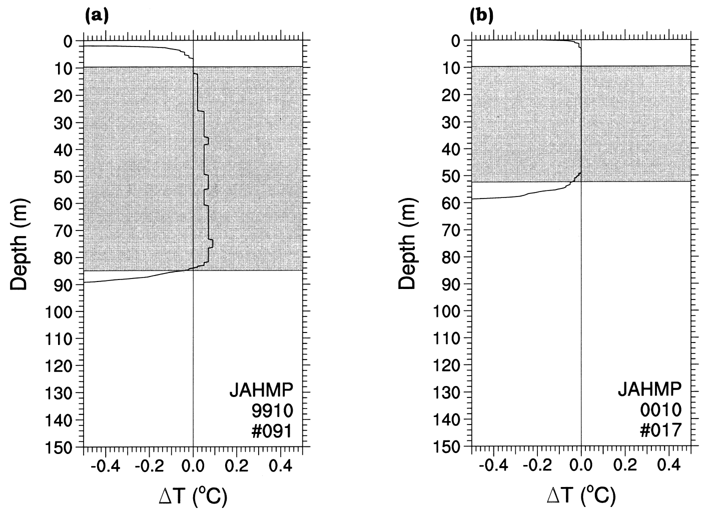

Fig. 3. Typical temperature profiles (a) with and (b) without a downward increase of temperature in the assumed isothermal layer (shaded). Obtained from JAHMP-XBT measurement with (a) Z-60-16 II (Oct., 1999) and (b) MK-130 (Oct., 2000).

three types of recorder, Sippican MK-9, MK-12, and Tsurumi MK-130. The error tends to increase with depth but its rate seems to be very variable. The magnitude of error is therefore variable as well, but is estimated to be *O* (0.1°C) in the isothermal surface layer with typical thickness of 100 m.

Not all of these profiles may be caused by instrumental error, since such a profile might result from proper compensation of density by variation of salinity. However, a gradual quasi-linear increase of temperature in the mixed layer is generally very implausible. In addition, the large statistical difference among the groups of profiles taken along virtually the same cruise track and in the same season with different types of recorder in TOLEX and JAHMP suggests that a major part of the difference can be attributed to some instrumental problem of Z-60-16 II and III. It should be noted, however, that the accuracy of analog/digital (A/D) conversion of at least one of the Z-60-16s which observed such unrealistic profiles was still better than 0.03°C in the laboratory after having been in use for more than 10 years. This suggests that the problem was not solely caused by the recorder.

We cannot identify downward-negative temperature error, such as those observed during some of the ORI cruises (see Fig. 2(b)), by the present methodology, since the water temperature generally decreases downward in the ocean. For the same reason, the frequency of detecting positive ΔT_{max} should depend on *MLD*. The more frequency discovery of the phenomena in TOLEX than in JAHMP may be explained by the fact that an isothermal layer thicker than 100 m was observed 125 times by TOLEX Z-60-16 II but only twice by JAHMP Z-60-16s. It should be noted that almost all of the KH-93-2 cases (Fig. 2(c)) could not be identified in the absence of CTD measurements for comparison because none of them include a thick mixed layer and some of them started from well below the sea surface.

4. Summary and Discussion

The present mixed layer analysis has shown that a downward-positive temperature error occasionally occurs when Z-60-16 II or III are used, while it is seldom observed by MK-9, MK-12, and MK-130 instruments. It is not clear from the present analysis, however, if an error of opposite sign exists for any types of recorder examined. The cause of the former error is not revealed because of insufficient information about the circuit design of instruments, but the error profile is very similar in appearance to the "bowing" suggested by Bailey *et al*. (1989) for another type of recorder.

It is difficult to conclude that the problem is really type-dependent rather than recorder-dependent, since only a small number of recorders (mostly fewer than ten) have been tested for any types in this investigation. The problem may be in fact recorder-dependent and also could be cast-dependent, as may be inferred from the fact that the error was not always observed, nor at a constant rate, even with a single recorder. However, we nevertheless conclude that the problem is basically type-dependent, given the great difference between the statistics for the five different recorder types.

The cause of bowing for the Bathy Systems Inc., 810 recorder was the low electrical current (12 micro-amperes) used to excite the XBT (Bailey *et al*., 1989; Wright, 1991). The system at this current level is likely sensitive to a slight leakage of the wire insulation. It was confirmed that the magnitude and occurrence of bowing was reduced substantially by increasing the current to 200 micro-amperes. Murayama Z-60-16 II and III are excited by constant electrical current of 50 micro-amperes, which is higher by only a factor of four than the 810 recorder. It may thus be plausible that the present phenomenon was also caused by a similar reason.

This remark is also supported by the irregularity with which the phenomenon occurs. If the error were caused solely by the poor calibration of a particular recorder, the phenomenon should have occurred for every drop in a similar way. Furthermore, since the accuracy of A/D conversion of the types of recorder in question was stably remained within the nominal precision after long-term use, the problem was probably not caused by poor calibration of the recorders as “A/D converters”. It should be noted that Murayama’s calibration was not performed using an XBT probe but rather with equivalent resistances which cover the whole range of temperature measurement.

Therefore, it is concluded that the problem was caused by some electrical inconsistency of the whole measuring system, including an XBT probe and the sea water, possibly with a very slight leakage of the wire insulation, which can only affect the accuracy of measurement when a recorder is used in the real ocean. The impact of such small probe-by-probe quality variation may be different for different types of recorders, which is partly suggested by the manufacturer’s information.

The mixed layer profile analysis does not allow us to assume that the detected temperature error grows further in the deeper part of the ocean. It may increase, decrease or stay at a certain level of error at depths, depending on its cause. Since the comparison with CTD measurements shows no error profile with a downward-decreasing tendency, however, it should be reasonable to consider that the error, when it occurs, does not diminish with depth. Further, if the error increases with depth at a rate of 0.1°C per 100 m, as estimated, it can be close to 1°C at the end of a profile by T-7, as shown in Fig. 2(c).

An error of the order of 0.1°C in the variable surface layer may not be a significant problem. Indeed, most of the identified errors are within the nominal accuracy of an XBT probe, 0.2°C (for TSK probes), except for some shown by comparison with CTD (Figs. 2(b) and (c)). If the error increases with depth, however, it could be more serious in the deeper part of the ocean where temperature variation is generally small.

The present investigation strongly indicates the importance of recording the type and preferably also the serial number of the recorder used in the individual XBT measurement (so-called “meta” data). If data are obtained by the type of recorder which could suffer from such systematic error, it is recommended to inspect the profile in detail. An isothermal layer, if any, could be helpful for the purpose. However, not a few XBT data in the past lack such information so that the users are not alerted that there is any possibility of error with the data to be used.

Our results suggest that such an established instrument as the XBT can still suffer from an unknown type of instrumental error. We should finally point out that this sort of problem could be resolved or at least discovered quicker if manufacturers and users keep better communication. In the present case, Murayama has never tested the instrument under actual oceanic conditions, and the users have almost never doubted the recorder’s specifications nor sent back the quality information on the data to the manufacturer. This episode eloquently recounts the past and the present situation in Japan, which should be improved in the future for a better quality control of the instruments, a key to a better understanding of the environment.

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References

Bailey, R., H. Phillips and G. Meyers (1989): Relevance to TOGA of systematic XBT errors. p. 775–784. In *Proc. of the Western Pacific International Meeting and Workshop on TOGA COARE*, ed. by J. Picaut and R. Lukas, Noumea.

Hanawa, K. and H. Yoritaka (1987): Detection of systematic errors in XBT data and their correction. *J. Oceanogr. Soc. Japan*, **43**, 68–76.

Hanawa, K. and Y. Yoshikawa (1991): Reexamination of the depth error in XBT data. *J. Atmos. Ocean. Tech.*, **8**(3), 422–429.

Hanawa, K., P. Rual, R. Bailey, A. Sy and M. Szabados (1995): A new depth-time equation for Sippican or TSK *T*-7, *T*-6 and *T*-4 expendable bathythermographs (XBT). *Deep-Sea Res.*, **42**(8), 1423–1451.

Hanawa, K., Y. Yoshikawa and T. Taneda (1996): TOLEX-ADCP monitoring. *Geophys. Res. Lett.*, **23**(18), 2429–2432.

Kitagawa, S., T. Taira and T. Teramoto (1981): A digital data logger for the XBT. *La mer*, **19**, 165–170 (in Japanese with English abstract and captions).

Kizu, S. and K. Hanawa (2002): Start-up transient of XBT measurement by three types of Japanese recorder system. *Deep-Sea Res.* (in press).

Roemmich, D. and B. Cornuelle (1987): Digitization and calibration of the expendable bathythermograph. *Deep-Sea Res.*, **34**(2), 299–307.
Thadathil, P., A. K. Ghosh, J. Pattanaik and L. Ratnakaran (1999): A quality-control procedure for surface temperature and surface layer inversion in the XBT data archive from the Indian Ocean. *J. Atmos. Ocean. Tech.*, **16**, 980–982.
UNESCO (1997): First Session of the Joint IOC-WMO IGOSS Ship-of-Opportunity Programme Implementation Panel. Cape Town, South Africa, 16–18 April 1997.
Wright, D. M. (1991): Field evaluation of the XBT bowing phenomenon. OOD Data Report 91-2, Ocean Observations Division/Office of Ocean Services, National Ocean Service, NOAA, 12 pp.