Relevance to TOGA of Systematic XBT Errors

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Introduction

Over recent years expendable bathythermographs (XBTs) have become increasingly relied upon in large-scale oceanographic research programs. An assessment of the accuracy of XBTs, and the systems used to drive them, is therefore essential.

The depth accuracy of XBTs has been the subject of many studies [1, 2, 3, 4]. These studies have proposed alternative fall-rate equations to the one specified by the manufacturer on the basis of the errors observed in the depth of the XBT. Other investigators [5, 6] have concentrated on the temperature calibration of the probe thermistors in an effort to improve the accuracy of XBTs.

The aims of this study are to:

- provide further calibrations of XBTs and XBT systems by comparing them with conductivity-temperature-depth (CTD) sensors.
- evaluate the applicability of the various depth-correction algorithms mentioned above.
- examine the implications of the observed depth and temperature errors to a large-scale research program such as TOGA (Tropical Ocean and Global Atmosphere).

Instrumentation and Methods

Two types of digital XBT systems were calibrated against the RV *Franklin*'s Neil Brown CTD Profiler during separate voyages in 1987 (Table 1). Both types of XBT system are used in the CSIRO's Ship-of-Opportunity Program (SOOP). The MK–9 XBT system was used in two configurations for the calibration experiments; with the *Franklin*'s PDP–11 data logging system, and with an HP–85 microcomputer as deployed on ships-of-opportunity. Deep Blue XBTs, from the same batch, were used throughout the calibrations.

The CTD station positions are shown in Fig. 1. Typically, XBTs were dropped 10–20 minutes prior to the descent of the CTD profiler at each station.

The temperature profiles recorded by the CTD Profiler for both voyages are shown in Fig. 2.

Table 1

Calibration Experiment #	Voyage	XBT System Description	XBT Type	Number of XBTs	Number of Corresponding CTDs
1	FR0487	SEAS II/Bathy Systems SA-810 (HP-85)	Deep Blue	17	17
2	FR1087	Sippican MK-9 (HP-85)	Deep Blue	14	3
3	FR1087	Sippican MK-9 (PDP-11)	Deep Blue	12	3

Table 2

DYNAMIC HEIGHT ERROR

Voyage	XBT System	Error in Dynamic Height Relative to 200 m (dyn m)		Error in Dynamic Height Relative to 400 m (dyn m)		Error in Dynamic Height Relative to 700 m (dyn m)	
		Mean	Standard Dev.	Mean	Standard Dev.	Mean	Standard Dev.
FR0487	SEAS II/Bathy Systems SA-810 (HP-85)	0.001 (0.007)	0.007 (0.008)	-0.009 (0.010)	0.013 (0.013)	-0.012 (0.020)	0.013 (0.014)
FR1087	Sippican MK-9 (HP-85)	-0.011 (0.004)	0.007 (0.006)	-0.012 (0.011)	0.009 (0.009)	-0.016 (0.012)	0.011 (0.011)
FR1087	Sippican MK-9 (PDP-11)	-0.011 (0.003)	0.008 (0.009)	-0.013 (0.008)	0.008 (0.008)	-0.019 (0.009)	0.012 (0.011)

( ) after XBT depth correction according to Hanawa and Yoritaka[4].

Table 3

SEAS II MIXED LAYER ANOMALY ANALYSIS 1987
(Estimate)

Index = $T_{max} - T_{5\ metres}$

Total number of drops = 1739
Total number of anomalous drops = 1223
Mean Index for anomalous drops = 0.22

Index Bin	Index >	Range ≤	Frequency	Percentage of Total Drops
0.1	0.05	0.15	625	35.94
0.2	0.15	0.25	315	18.12
0.3	0.25	0.35	133	7.65
0.4	0.35	0.45	44	2.53
≥0.5	0.45	—	106	6.10
			TOTAL = 1223	TOTAL = 70.34

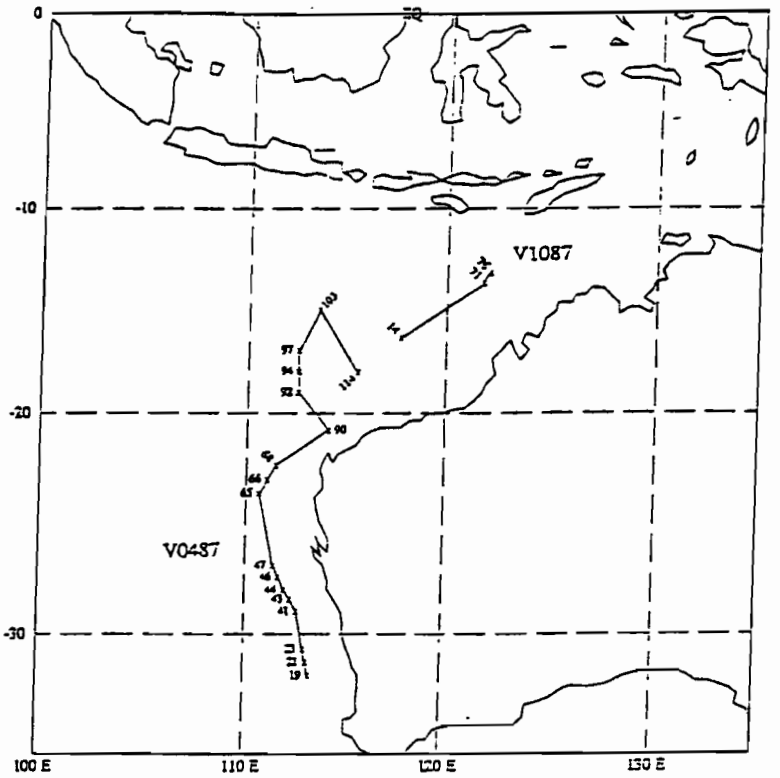

FIG.1. RV Franklin V0487 and V1087 station positions.

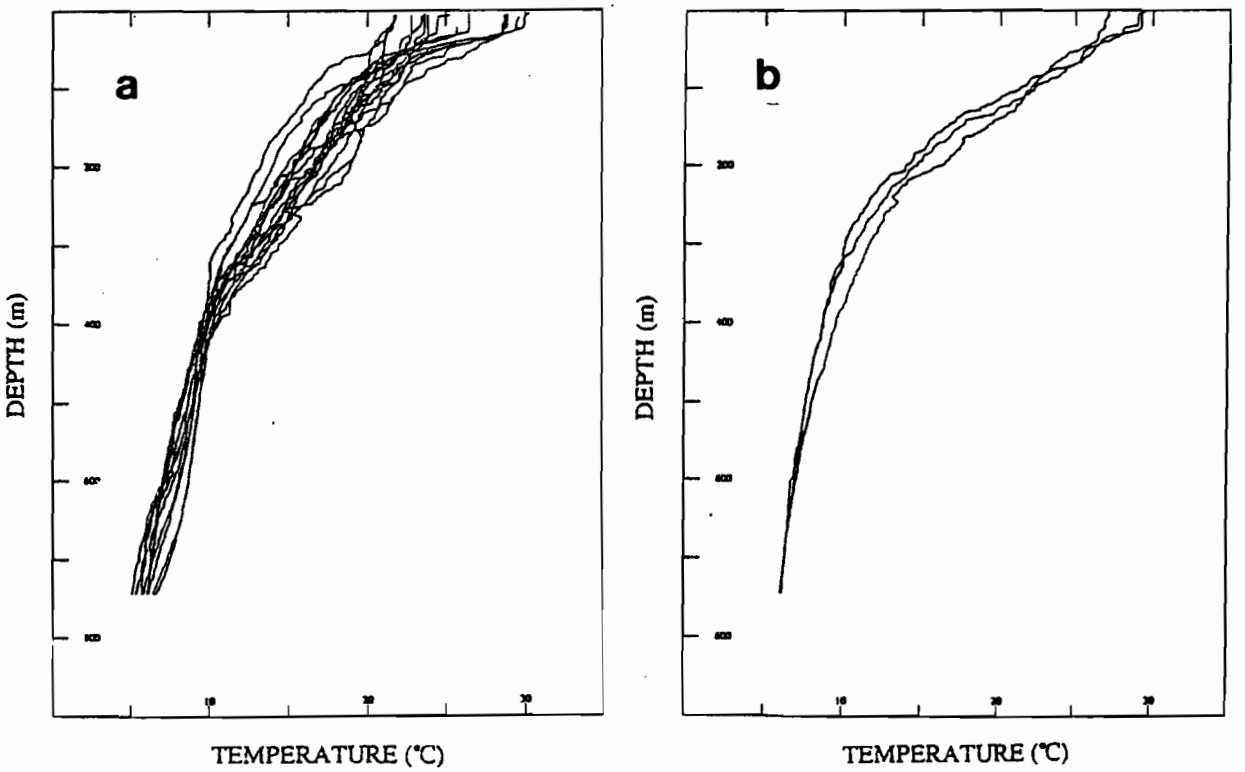

FIG.2. CTD temperature profiles: (a) FR0487, (b) FR1087

Depth and Temperature Errors

(a) Depth Errors

Figs. 3(a) and 4(a) give examples of the average temperature error (T_{XBT}–T_{CTD}) as a function of depth for two of the XBT System/CTD calibration experiments. The characteristic shape of both profiles of temperature error is similar to that found in the experiments of Hanawa and Yoritaka[4]. They found the negative errors in temperature to be mainly due to the errors in depth that result from the XBT falling faster than specified by the manufacturer's fall-rate equation. The largest errors in temperature correspond to the depths of large temperature gradient in the temperature profiles (cf Fig. 2). This is where the depth error due to an incorrect fall-rate has its largest effect.

Figs 3(b) and 4(b) give examples of the average temperature error (T_{XBT}–T_{CTD}) as a function of depth for the same two calibration experiments, however, the depths of the XBTs have been corrected according to the depth-correction algorithm developed by Hanawa and Yoritaka[4]. This algorithm proved to be the most successful at reducing the mean and rms temperature errors for each of the three calibration experiments. The rms temperature error was consistently reduced from above to below the accuracy of the XBT (±0.15°C). The depth-correction algorithm according to Heinmiller et al.[1], on the other hand, actually increased the rms temperature error for each case.

Unfortunately, some errors in temperature still remain at depths corresponding to large temperature gradients, even after the data has been corrected according to Hanawa and Yoritaka[4]. The fall-rate correction of Hanawa and Yoritaka[4] is therefore not totally applicable in the waters of this study, although it does improve the data.

(b) Temperature Errors

Start-up Transients: Large start-up transients in the upper 4 m were observed for the SEAS II XBT System (Fig. 5), and to a lesser extent for the MK–9 XBT System. The mean difference between the first temperature digitisation (0.6 m) and the temperature at 3.9 m (commonly used as the sea surface temperature due to such transients) was –9.50 ± 10.08°C for the SEAS II XBT System, compared to 0.41 ± 0.30°C for the MK–9 XBT System.

SEAS II Mixed Layer Anomaly (Bowing): The need for the comparison of XBT data with a precision CTD sensor was first invoked by the observation of anomalies in the mixed layer temperature profiles recorded by SEAS II XBT Systems deployed in the CSIRO SOOP in the western tropical Pacific. A gradual increase, or "bowing", in temperature was observed as opposed to an isothermal profile. An example is given in Fig. 6. Such anomalies were not present in the data recorded by the MK–9 XBT Systems.

The upper 200 m of the temperature profiles recorded by the SEAS II XBT System and the CTD Profiler during FR0487 are shown in Figs 7(a) and 7(b) respectively. The gradient in temperature in the mixed layer for a single XBT and its corresponding CTD are highlighted to emphasize the "bowing" problem. The corresponding average error in temperature (T_{XBT}–T_{CTD}) in the mixed layer as a function of depth is shown in Fig. 7(c). The mean SEAS II XBT temperature in the mixed layer starts less than and finishes greater than the mixed layer temperature given by the CTD. On examination of each individual XBT/CTD

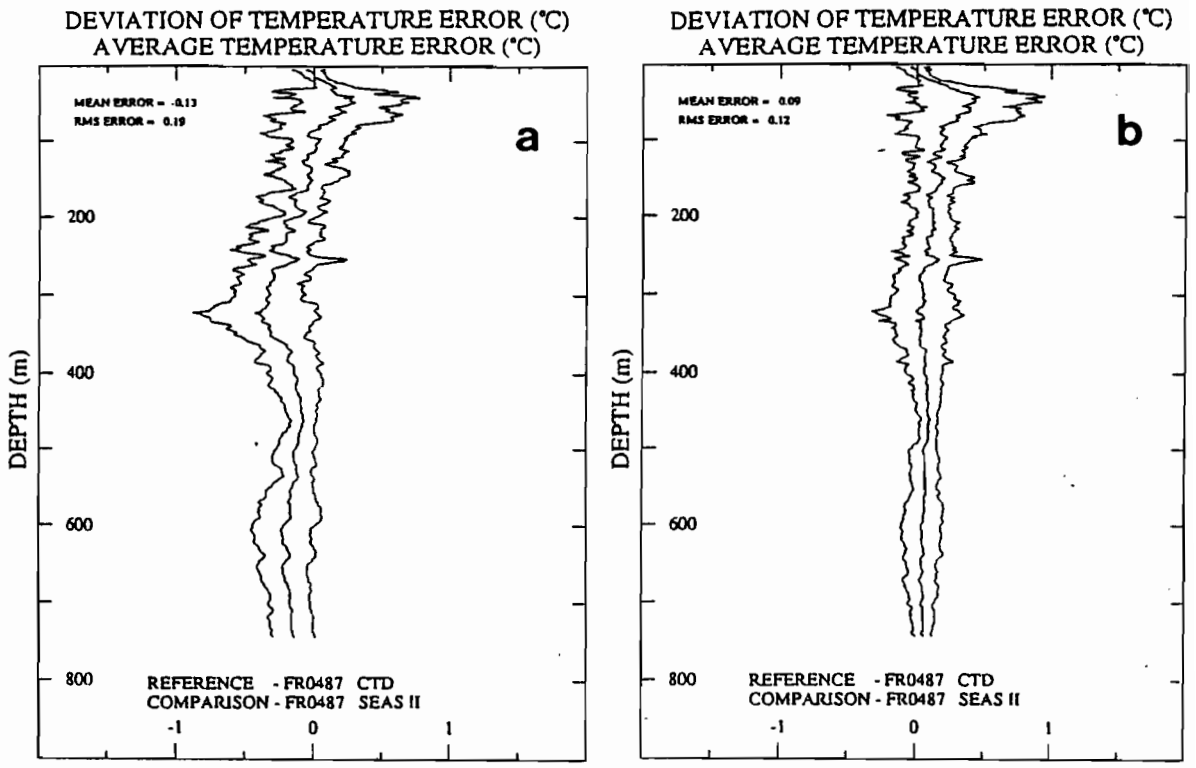

FIG.3. Average temperature error profiles (TXBT-TCTD) for the XBT/CTD comparisons on FR0487 using the SEAS II XBT system; (a) depth uncorrected, (b) depth corrected according to Hanawa and Yoritaka4.

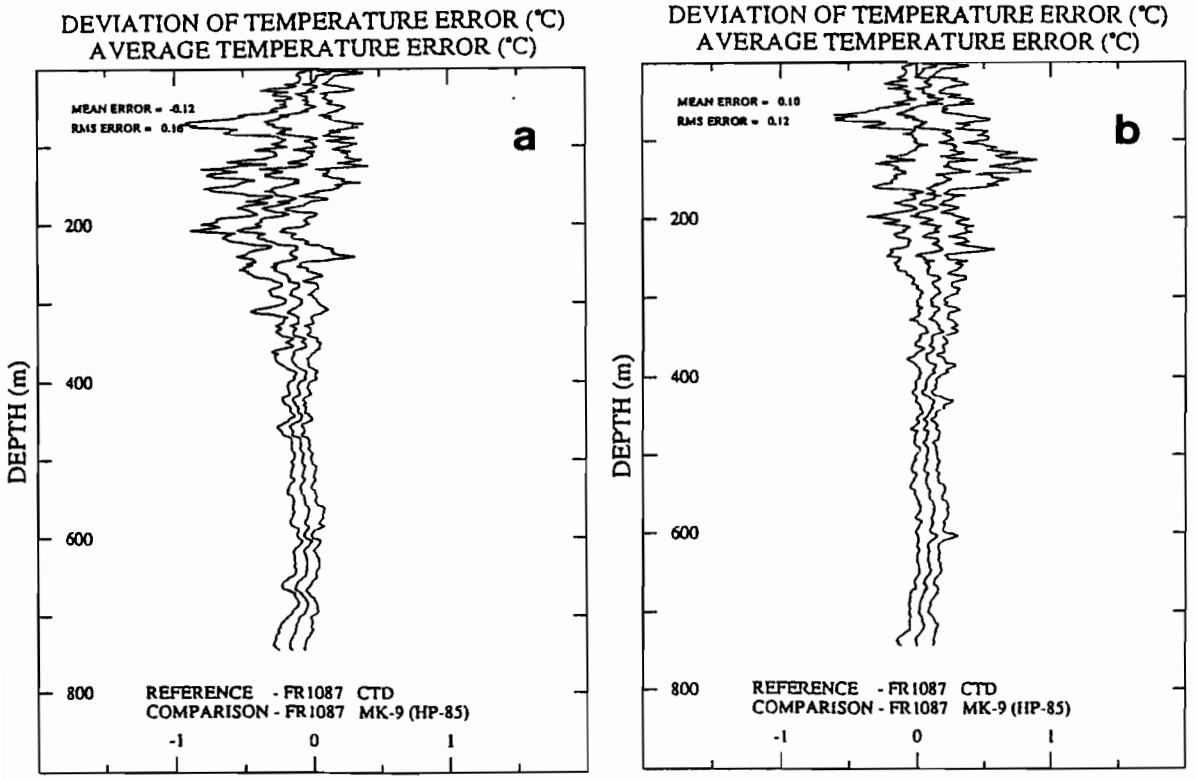

FIG.4. Average temperature error profiles (TXBT-TCTD) for the XBT/CTD comparisons on FR1087 using the MK-9 XBT system; (a) depth uncorrected, (b) depth corrected according to Hanawa and Yoritaka4.

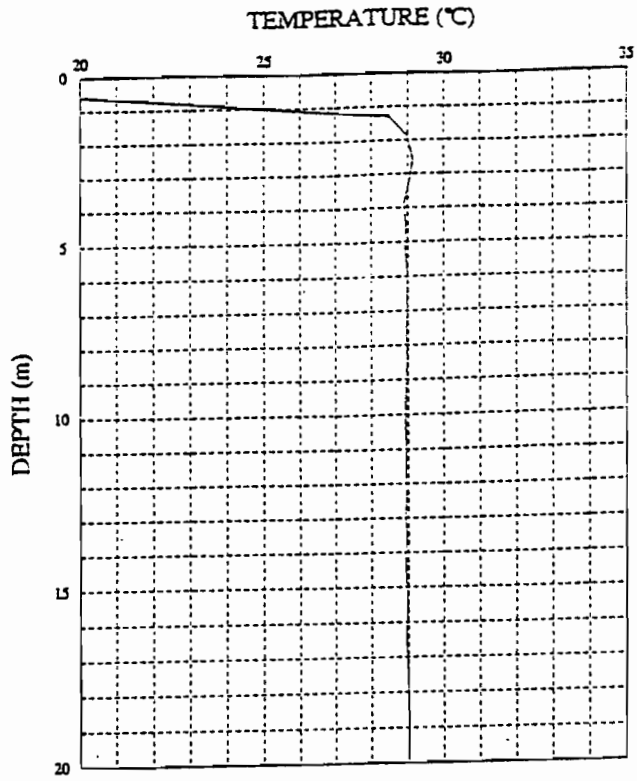

FIG.5. Example of a start-up transient from a SEAS II XBT system.

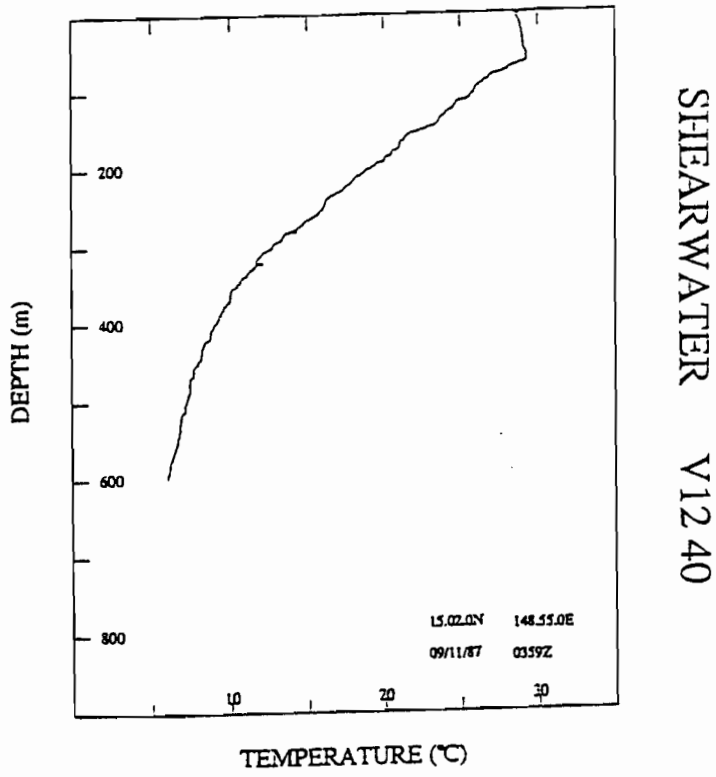

FIG.6. Example of a mixed layer anomaly recorded by a SEAS II XBT system.

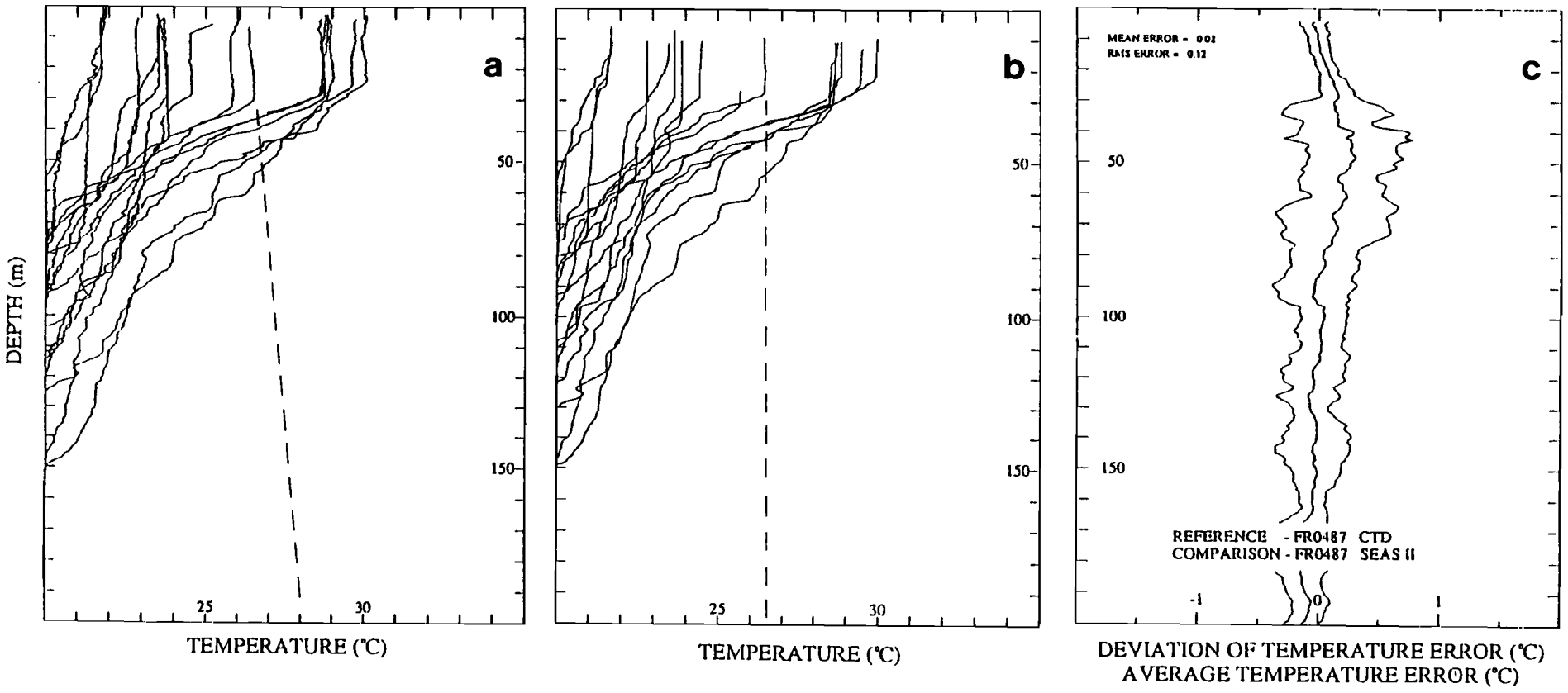

Fig. 7. (a) SEAS II temperature profiles (upper 200 m) for FR0487; (b) CTD temperature profiles (upper 200 m) for FR0487; (c) corresponding average temperature error profile (upper 200 m)

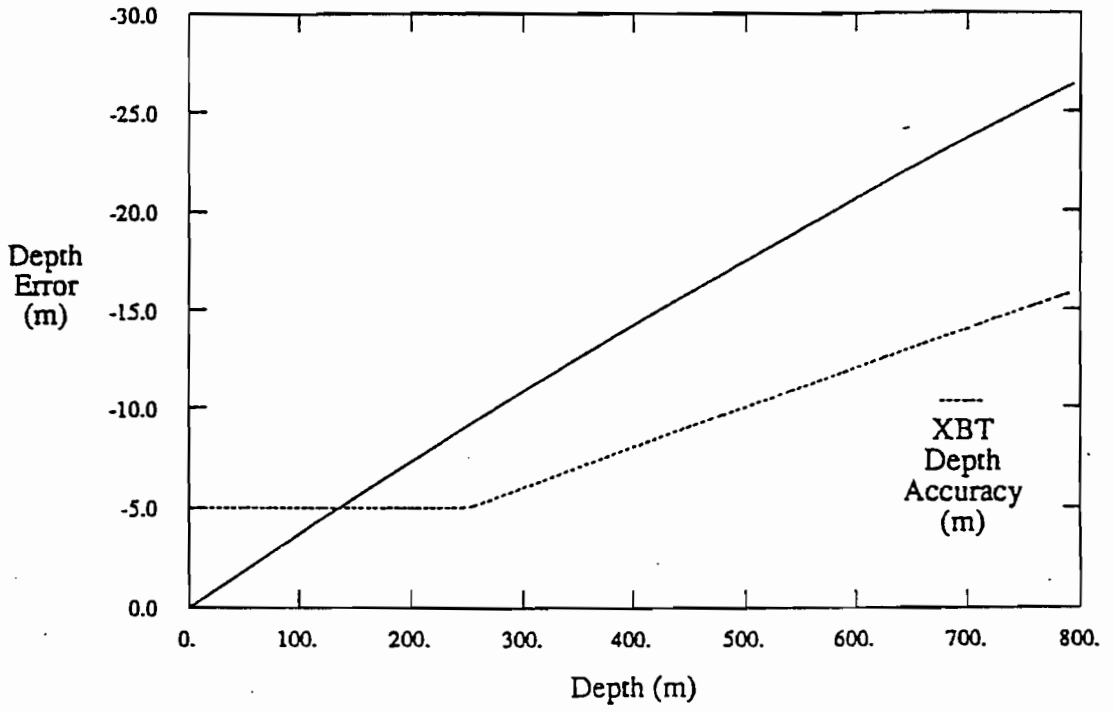

FIG.8. Depth error of the XBT as a function of depth.

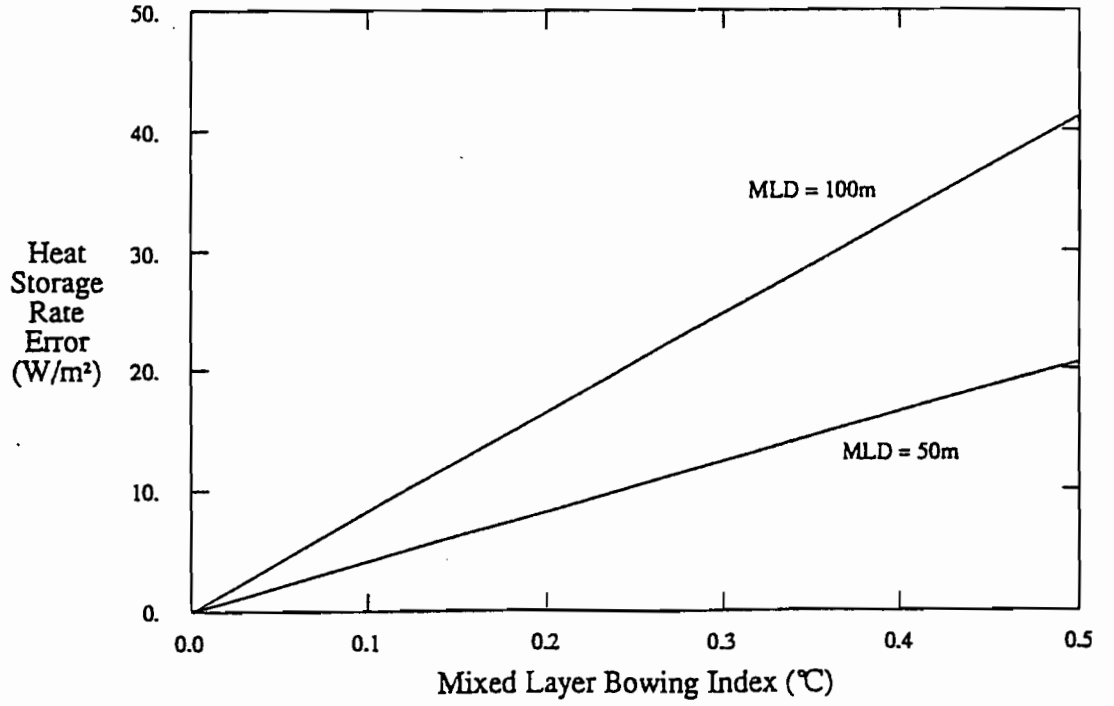

FIG.9. Error in monthly heat storage rate due to the "bowing" problem of the SEAS II XBT system.

comparison, however, the start and finish temperatures of the SEAS II XBT System were found to be randomly distributed in relation to the CTD mixed layer temperature. In some cases the SEAS II temperature starts above the CTD mixed layer temperature and finishes further above it. In other cases, it may start below it and finish equal to it.

The above results indicate a possible drift problem with the electronics of the SEAS II XBT System. The temperature errors may also extend deeper than the mixed layer. We can only distinguish the problem in the mixed layer where the real temperature gradient is zero.

Implications for TOGA

(a) Isotherm Depth Errors

If we assume the corrected depth (z') from Hanawa and Yoritaka[4] to be the true depth of the XBT, then Fig. 8 shows the depth error ($z-z'$) as a function of depth, where z is the depth of the XBT given by the manufacturer. The depth accuracy of the XBT at any given depth is also shown. A 20°C isotherm depth of 200 m, for example, will be measured by an XBT as occurring at a depth of approximately 192.5 m — an error of 7.5 m. The depth error exceeds 25 m at a depth of 800 m, and exceeds the depth accuracy of the XBT (5 m or 2% of the depth, whichever is greater) at a depth of approximately 135 m.

(b) Dynamic Height Errors

Table 2 shows the mean error in dynamic height ($D_{XBT}-D_{CTD}$) relative to 200 m, 400 m and 700 m for the three calibration experiments. The errors are small both before and after the correction for depth of the XBT. Values range from –0.019 dyn m to 0.001 dyn m. Fortunately, the largest temperature gradients in the tropics are shallow enough for errors in temperature, which affect the dynamic height, to be small. The error in depth, which affects the temperature error, is relatively small at these shallower depths.

The depth correction from Hanawa and Yoritaka[4] successfully reduces the error in dynamic height for the MK–9 XBT System, but increases it for the SEAS II XBT System. The additional positive errors in temperature caused by the "bowing" problem of the SEAS II XBT System are possibly cancelling some of the negative errors in temperature that result from errors in depth. The dynamic height error, which depends on temperature, is therefore reduced for the SEAS II XBT System.

(c) Mixed Layer Temperature Errors

A mixed layer bowing index, defined as the maximum temperature of a profile minus the temperature at 5 m, was used to estimate the typical magnitude and frequency of the mixed layer anomaly recorded by the SEAS II XBT Systems deployed in the CSIRO SOOP. The results for the XBT data recorded in 1987 are given in Table 3. Potentially, 34.4% of the data had errors greater than the temperature accuracy of the XBT (±0.15°C). Some profiles recorded indexes of 0.7°C (Fig. 6) and above.

Fig. 9 shows the error in monthly heat storage rates as a function of the potential error in mixed layer temperature due to "bowing". The errors are shown for two characteristic mixed layer depths (MLD). Given the mean index for 1987 from Table 3 of 0.22°C, the corresponding error in the monthly heat storage rate is approximately 18 W/m^2 for a mixed layer depth of 100 m. This is an unacceptable source of error in heat budget studies.

(d) Sea Surface Temperature Errors

The shallowest depth that should be used to estimate sea surface temperature (SST) from an XBT is 3.9 m due to start-up transients. Large errors in SST will be observed otherwise.

Conclusions

- The depth-correction algorithm according to Hanawa and Yoritaka[4] proved the most effective in reducing the mean and rms temperature errors for this data set. However, as neither this correction nor the other corrections that were applied completely reduced the temperature errors observed between the XBTs and CTD Profiler, further studies on the factors that vary the fall-rate of XBTs between different locations will need to be undertaken before a generally applicable depth-correction algorithm will be found. This will have to be done for each type of XBT probe.

- Temperature errors observed in the mixed layer, due to the "bowing" problem associated with the SEAS II XBT System, are a significant source of error for TOGA. A thorough engineering analysis of the electronics of this system is recommended before future use of the system. On the results of this study, CSIRO has replaced the SEAS II units in its SOOP with MK–9 XBT Systems.

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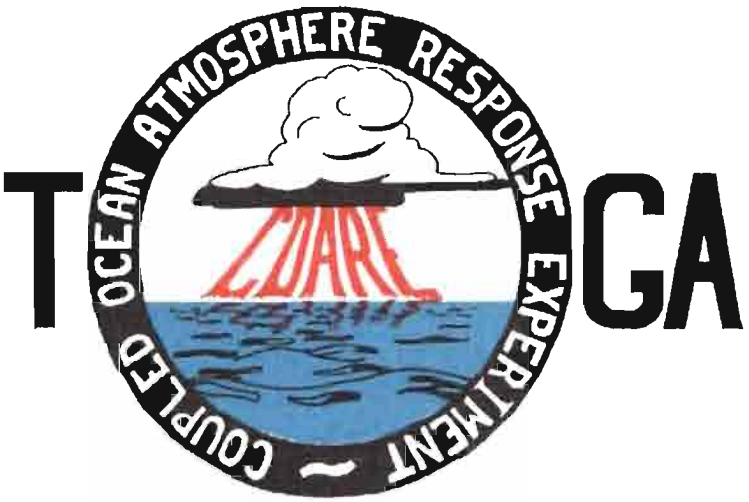

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