XBT Fall Rate in Waters of Extreme Temperature: A Case Study in the Antarctic Ocean

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ABSTRACT

XBT fall-rate variation in waters of extreme temperature and the resulting depth error has been addressed using controlled XBT–CTD datasets collected from two cruises in the Southern Ocean. Mean depth errors deduced from both the datasets are significantly different from those reported earlier for tropical and subtropical regions. The comprehensive study of Hanawa et al. (making use of controlled XBT–CTD data, mostly from tropical and subtropical waters) showed that the manufacturer's equation underestimates the probe's fall rate. This is manifested by the mean negative depth error reported from this region. However, results from the present study show that the manufacturer's equation slightly overestimates the fall rate in this region, as indicated by the small positive error (5–10 m).

In order to provide theoretical support to the observed depth error, an analytical approach is adopted based on the viscosity effect on the probe's fall rate. Observed as well as analytical results suggest that the probe has a decelerating tendency due to the viscosity effect in high-latitude waters, and the existing correction scheme is not appropriate for XBT data from regions of such extreme low temperature.

The existing correction scheme is valid for tropical and subtropical waters of negative depth error zones. However, for XBT data from high-latitude waters it is reasonable not to correct XBT data based on the existing scheme until the exact nature of depth error from this region is known. Though the mean depth errors from both the datasets show nearly identical values, it is necessary to conduct more controlled XBT–CTD experiments in this region in order to substantiate the exact nature of error for this region and then develop an appropriate depth-correction scheme.

1. Introduction

The existence of depth error in expendable bathythermograph (XBT) data, caused by manufacturer fall-rate equations, has been reported in many earlier studies. Hanawa et al. (1995) made a comprehensive experimental study of the XBT depth error using a large set of simultaneous XBT–CTD data from different oceanic regions and proposed a new depth equation, common to T4, T6, and T7 probes. However, their equation was based on sparse data from the Indian Ocean. Subsequently, Thadathil et al. (1998) examined the validity of the new depth equation for the Indian Ocean region by collecting more controlled XBT–CTD datasets and confirmed its suitability for the Indian Ocean, as well. However, the applicability of the new depth equation in waters of extreme low temperatures, such as the Antarctic and Arctic Oceans, has not yet been examined due to lack of controlled XBT–CTD data.

Seaver and Kuleshov (1982, hereafter SK) developed an analytical model to find out the XBT depth error and compared it with the observed error, derived from the POLYMODE XBT–CTD datasets. In the analytical model, they attributed the depth error to the probe's retardation, caused by increasing viscosity during its descent through deeper layers of decreasing temperature. Hanawa et al. (1995, hereafter HN95) and Thadathil et al. (1998, hereafter T98), in their experimental studies, tried to find out the effect of temperatures (viscosity) on fall rate by comparing the regional mean temperature with the mean depth error, deduced from XBT–CTD datasets for different regions. Their observed depth error did not show any marked dependence of fall rate on regional water temperature. This could be due to the following.

1) Profile-to-profile vertical temperature structure of

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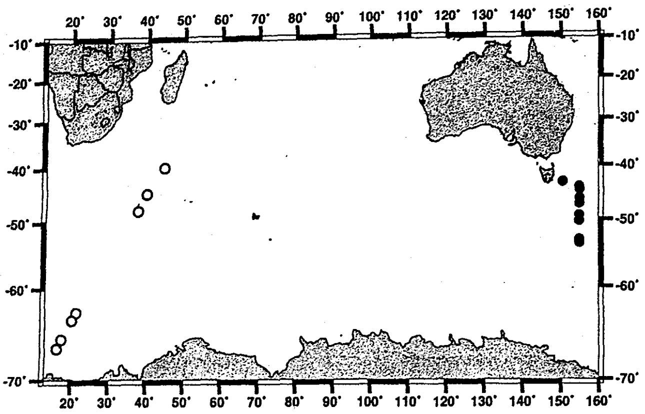

FIG. 1. Station locations of the XBT–CTD data sets used in the present study. Stations under the Indian and Australian expeditions are shown as open and solid circles, respectively.

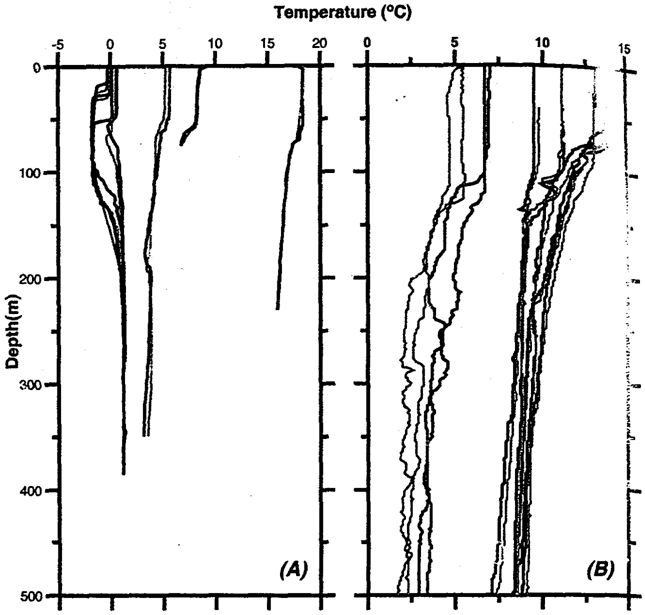

FIG. 2. Composite profiles of XBT (red line) and CTD (black line) temperature data collected during (a) the Indian expedition, and (b) the Australian expedition.

the various regional datasets is not significantly and consistently different enough to bring out the regional effect of viscosity on fall rate.

2) Wire-pull, or stretch, and batch-to-batch variation of the probe dynamics also obscure the viscosity effect on fall rate.
3) The regional mean temperature is uncorrelated with the mean depth error derived from vertical anomalies.

Simultaneous observations of XBT–CTD data from high-latitude waters (low temperature) are expected to resolve the dependence of vertical viscosity on fall rate. With this objective, we collected controlled XBT–CTD data from the Antarctic and subantarctic waters and the details of the two datasets used in this study are given in section 2. In order to provide theoretical support for the observed depth error, we adopted the analytical approach of SK, after reviewing the same in the light of more accurate experimental results of HN-95 and T-98. While section 3 gives details of the analytical approach, the observed depth error is addressed in section 4 followed by discussion in section 5.

2. XBT–CTD data

During the XVIII Indian Scientific Expedition to Antarctica (14 December 1998–30 March 1999), controlled XBT–CTD observations were carried out on board Marine Vessel *Polar Bird* in the Southern Ocean. In order to obtain nearly coincident temperature profiles of both CTD and XBT, Sippican-made, T-7 XBT probes were launched when the CTD operational depth was about 100 m (T98). A Sea-Bird (SBE-19) shallow-water-type CTD having a depth range of 500 m was used. We could not operate the deep CTD due to winch constraints on the vessel. At some stations the CTD cast could not be completed due to very strong currents and wave conditions. The second dataset of controlled XBT–CTD data from the Southern Ocean, collected on board Australian Polar Supply Vessel *Aurora Australis* during the Commonwealth Scientific Industrial Research Organisation (CSIRO) Climate Change Research Program (CCRP) in April 1993 and existing in the CSIRO data archive, has been subsequently incorporated for depth error analysis in the present study. Locations of XBT–CTD stations during the expeditions of India (open circle) and Australia (solid circle) are shown in Fig. 1. Composite profiles of XBT (red line) and CTD (black line) temperature data collected during the Indian and Australian expeditions are given in Figs. 2a and 2b, respectively.

3. Analytical depth error

Decreasing temperature with ocean depth and the resulting increase in kinematic viscosity decelerates the XBT probe (SK). The viscosity of seawater, to the first order, is inversely proportional to temperature. The sa-

TABLE 1.

Reference	Fall-rate equation	Coefficient a	Coefficient b
Manufacturer	$Z = 6.472t - 0.00216t^2$	6.472	0.00216
HN95	$Z = 6.691t - 0.00225t^2$	6.691	0.00225
T98	$Z = 6.694t - 0.00222t^2$	6.694	0.00222
NEA dataset of HN95	$Z = 6.561t - 0.00179t^2$	6.561	0.00179

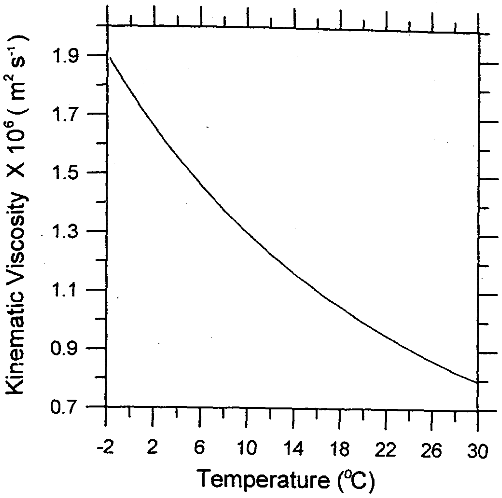

FIG. 3. Relation between temperature and kinematic viscosity.

linity effect on viscosity is very small (Horne 1969). Millero (1974) examined the viscosity of seawater as a function of temperature and salinity, and this relation is used to compute kinematic viscosity in the present study. Figure 3 shows the relation between temperature and viscosity. Assuming that the probe diameter L and seawater density ρ are constants, the probe drag friction d could be expressed as:

$$d = \rho U^2 \left(\frac{UL}{\nu}\right)^{1/n}, \tag{1}$$

where U is probe terminal velocity, ν is kinematic viscosity, and n is the number representing the flow type. Approximating the probe's fall regime in the transition region in between laminar and turbulent boundary layers (Schlichting 1955) and considering d as a constant, SK derived the XBT depth error by taking the partial derivative of Eq. (1). Therefore, Eq. (1) becomes

$$\Delta U = -\frac{1}{2n-1}\frac{U\Delta\nu}{\nu} \tag{2}$$

$$\Delta D = \int \Delta U\, dt, \tag{3}$$

where ΔU is fall-rate error, $\Delta\nu$ is change in viscosity with depth, and ΔD is systematic depth error. Considering different layers, the depth error for each layer (ΔD_i) can be obtained:

$$\Delta D_i = -\frac{1}{2n-1}\frac{\Delta\nu U}{\nu}\int dt$$
$$= -\frac{1}{2n-1}\frac{(\nu_{\mathrm{ml}} - \nu_{\mathrm{ref}})}{\nu}Ut \tag{4}$$

$$\Delta D = \sum_{i=1}^{N} \Delta D_i \tag{5}$$

where ν_{ml} is viscosity in the mixed layer and ν_{ref} is the viscosity at reference level, where the change in depth error with depth is zero and N is the number of layers considered. For the T98 dataset, ν_{ref} corresponds to viscosity at 700 m. In the present study, ν_{ref} is taken as viscosity at 300-m depth. At depths greater than 300 m, change in depth error will be negligible because the viscosity change (caused by very small variation in vertical temperature) is too small to alter the fall rate.

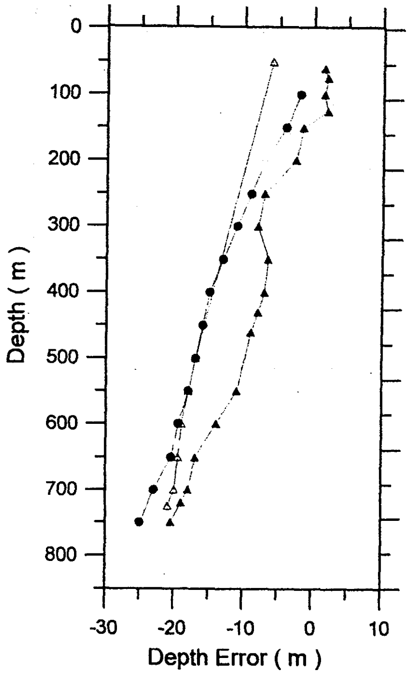

FIG. 4. HN95 observed error (solid circle) along with the SK analytical (open triangle) and observed (solid triangle) errors for the POLYMODE region.

Fall-rate equations, which we refer to a number of times in this and subsequent sections, are presented in Table 1 for better comparison of the analytical and observed errors. For a given type of probe, the depth–time equation provided by the XBT manufacturer is of the form $Z = at - bt^2$, where Z is the depth and t is the elapsed time in seconds starting when the probe hits the surface; a and b are positive coefficients. The linear coefficient a is a function of the hydrodynamic characteristics of the probe in the water, while the quadratic coefficient b is a function of change in mass of the probe (unreeling of the wire) and change of water characteristics (density and viscosity gradients) with depth (Green 1984).

Before addressing the observed and analytical XBT depth error in the Antarctic region, the analytical depth error of SK is reevaluated by comparing it with the observed error of SK and HN95, both from the POLYMODE region. Figure 4 represents the HN95 observed error (solid circle) along with the analytical and observed error of SK (open and solid triangles, respectively) for the POLYMODE region. The analytical depth error of SK is more comparable to the experimental error of HN95 than to the experimental error of SK. For T98 data, also, the observed and analytical depth errors

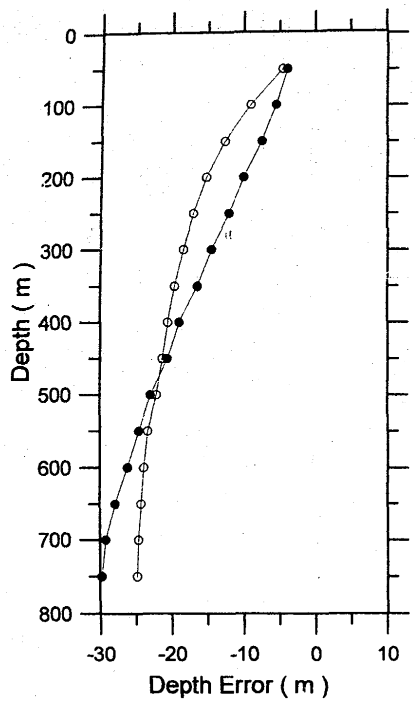

FIG. 5. Observed (solid circle) and analytical (open circle) errors for T98 dataset.

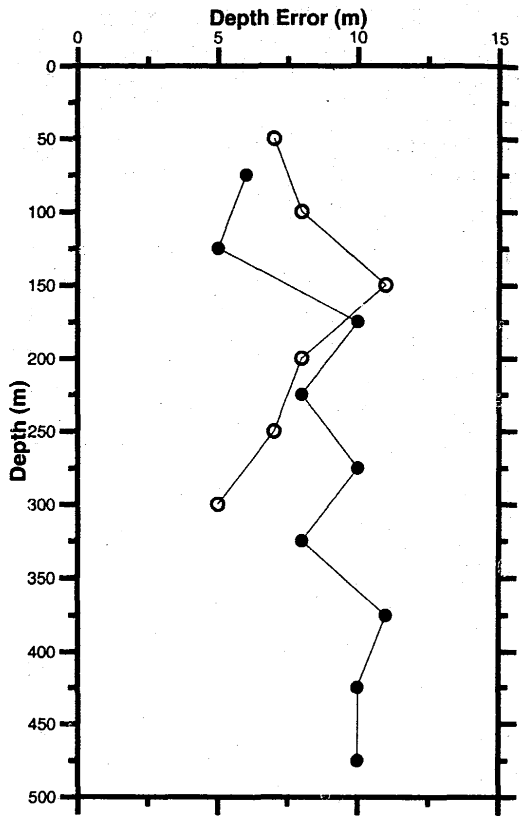

FIG. 6. Observed mean depth errors derived from the two datasets of the Indian (solid circle) and Australian (open circle) expeditions.

(filled and open circles, respectively, in Fig. 5) are in reasonable agreement. While the analytical and experimental depth errors are in reasonable agreement for HN95 and T98, the discrepancy between analytical and experimental results is larger in the case of SK. This discrepancy between the analytical and observed depth errors of SK and, at the same time, the better agreement between SK analytical and observed errors of HN95 and T98 could be due to the following.

1) SK deduced the depth error experimentally from the observed XBT–CTD data based on selected isotherms. Compared to the temperature error-free method of HN95, the SK method is likely to have depth errors caused by undulations of the isotherms and also due to error in observed temperature (Hanawa and Yasuda 1992).
2) XBT data from a strip-chart recorder, as in the case of SK data, include additional depth errors in the reading due to variations in the speed of the chart control mechanism.

The above facts suggest that the analytical approach of SK represents near-realistic depth errors and could be used to discern the general trend of XBT depth error due to the viscosity effect on probe fall rate.

4. Experimental error

Raw XBT data were interpolated to 1-m intervals, and then a seven-point median filter was applied to both CTD and XBT data to remove spikes. The quality control procedure of Thadathil et al. (2001) has been adopted for XBT data. From the quality controlled and filtered dataset, the depth error down to 300 m has been deduced using the HN95 method. The observed mean depth errors derived from the two datasets are given in Fig. 6, where the curves with solid and open circles represent mean depth errors of datasets collected during Indian and Australian expeditions, respectively. In both the cases, the error is positive (in contrast to the negative errors of HN95 and T98) and varies from 5 to 10 m, without showing any systematic dependence on depth as in the cases of HN95 and T98.

5. Discussion

XBT–CTD experiments conducted in tropical and subtropical waters (HN95; T98) revealed that the manufacturer's equation underestimates the probe's fall rate in these regions. This is manifested by the negative depth error, which increases with depth. Similar XBT–CTD experiments in high latitudes (Antarctic and subantarctic waters) show that the manufacturer's equation slightly overestimates the fall rate of XBT probes in this region. The small positive depth error curve in Fig. 6 suggests that the probes fall at a velocity slightly lower than the fall rate proposed by the manufacturer.

The observed behavior of the probe's fall rate in waters of significantly different temperatures as well as the resulting depth errors are in accordance with the theo-

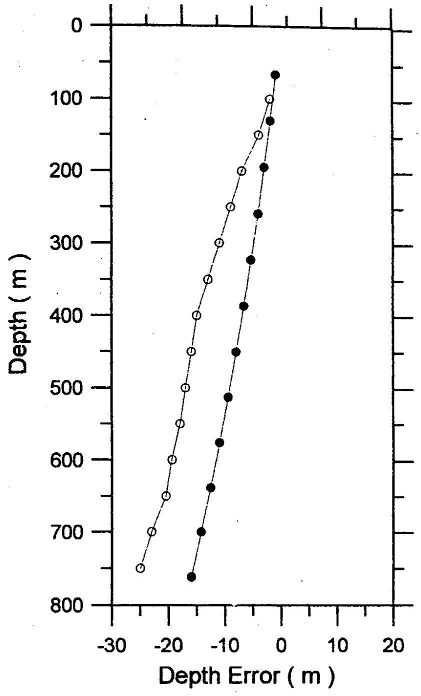

FIG. 7. Mean depth error for the combined dataset of HN95 (open circle) along with the depth error for NEA dataset (solid circle).

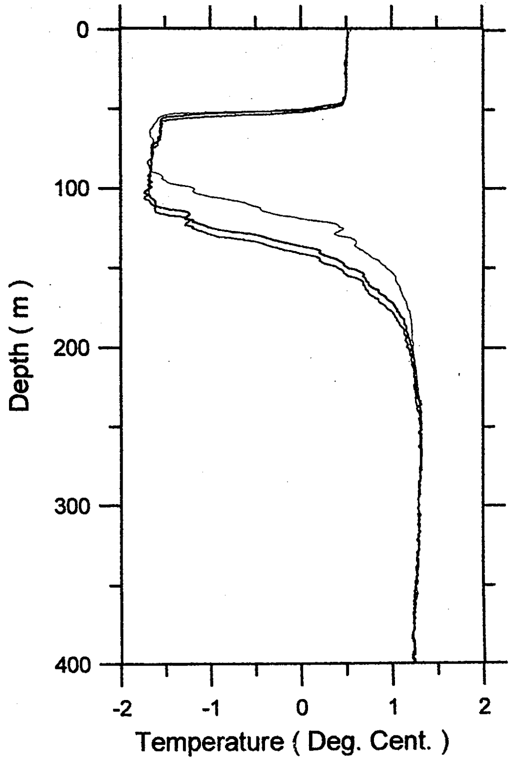

FIG. 8. Typical profiles of XBT (gray) and CTD (blue) data from the Antarctic Ocean along with the corrected XBT profile (red) using a new depth equation.

retical variation in probe's fall rate (discussed elsewhere). In tropical and subtropical waters, the XBT probes traverse through water columns of higher temperature, and the probe's deceleration is less marked due to the lower viscosity. On the other hand, in waters of high latitudes, the probes decelerate significantly owing to the higher viscosity of the water column. Such deceleration of the probe in accordance with the SK theory could also be seen for the northeastern Atlantic (NEA) dataset of HN95, the only dataset from the higher latitudes ($\gtrsim$45°). We reproduced the mean depth error for the NEA dataset using the *a* and *b* coefficients (Table 1) of the fall-rate equation for this dataset, given by HN95. This is plotted in Fig. 7 (open circle), along with the mean error curve for the combined dataset of HN95 (solid). Depth error for the NEA dataset is significantly smaller than that of the combined dataset, suggesting that the probe's deceleration is higher in NEA waters.

The new depth equation of HN95 is being used for depth correction for global XBT data. However, in the context of the results from the present study, depth correction of XBT data from high-latitude waters using the new depth equation has to be reassessed, as it can only increase the existing depth error. This is illustrated in Fig. 8 (the temperature profiles of XBT and CTD from the Antarctic region are presented in gray and blue, respectively). The corrected XBT temperature profile, based on the new depth equation, is presented in red. The shift of the corrected XBT profile further away from the CTD profile in Fig. 8 suggests that the correction further increases the existing depth error.

These observed and analytical results of fall rate in lower latitudes (warm waters) and higher latitudes (cold waters) suggest the existence of the following three oceanic zones based on the probe's fall-rate behavior:

1) zones where probes fall faster than the manufacturer's fall rate, which causes negative depth error and requires depth correction;
2) zones where the probes fall in accordance with the manufacturer's fall rate and require no depth correction; and
3) zones where probes fall slower than the manufacturer's fall rate, which causes positive depth error and requires depth correction.

Based on the SK theory and using the CTD data (temperature and salinity) collected from tropical to Antarctic waters during the Indian expedition, we computed the analytical depth error for different latitudes from the tropical to polar regions, and the results are presented in Fig. 9, along with the corresponding temperature profiles (CTD). Solid lines represent depth error and dashed lines represent temperature. The three different zones of fall rate and associated depth errors, as we discussed above, could be seen in the analytical error curves.

Studies of HN95 and T98 have already established that tropical and subtropical waters are of negative depth error zones and that the existing correction scheme is valid. However, for XBT data from high-latitude waters it is reasonable not to correct XBT data based on the existing scheme until we know more about the nature of depth error from this region. Though the mean depth

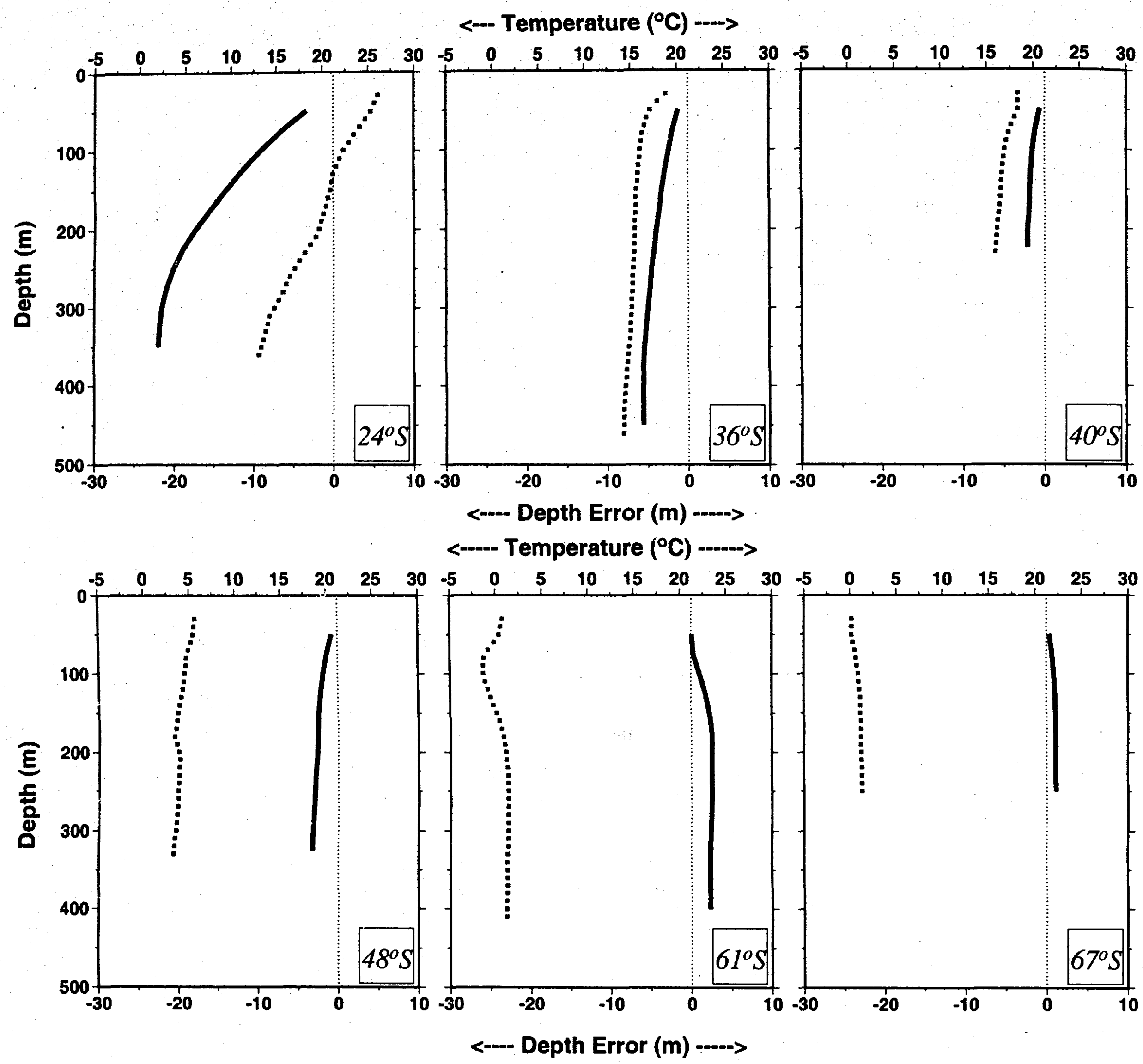

FIG. 9. Analytical depth errors for different latitudes from the tropical to polar regions along with the corresponding temperature profiles. Solid lines represent depth error and dashed lines represent temperature.

errors from both the datasets show near-identical values, it is necessary to conduct more controlled XBT–CTD experiments in this region in order to substantiate the exact nature of error for this region and develope an appropriate depth-correction scheme.

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