Pergamon

DEEP-SEA RESEARCH
PART I

Deep-Sea Research I 45 (1998) 819–827

Instruments and methods

# An evaluation of XBT depth equations for the Indian Ocean

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Received 18 April 1997; received in revised form 11 September 1997

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## Abstract

For the purpose of finding XBT depth equations applicable to the entire Indian Ocean we carried out experiments through the collection of controlled XBT-CTD data on four cruises. These experiments were conducted in various locations of the Indian Ocean with highly variable physicochemical conditions. We estimated the mean depth error to vary from $-2$ to $-27$ m in a depth range of 0–750 m, which is comparable to that reported by Hanawa, Rual, Bailey, Sy and Szabados (1995, *Deep-Sea Research I* 43 (8), 1423–1451; hereafter referred to as HN-95), but is much higher than the manufacturer's specified accuracy. The coefficients of the mean depth-time equation derived from the present data set do not differ significantly from HN-95. Depth error does not seem to be influenced by regional water characteristics. Our analysis confirms the applicability of the HN-95 equation for Indian Ocean as well. © 1998 Elsevier Science Ltd. All rights reserved.

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## 1. Introduction

Extensive XBT data sets are being generated in the world oceans under several international programmes, such as TOGA, CLIVAR, and WOCE, and the Indian Ocean is no exception. There have been a number of XBT depth error analyses comparing XBT depths with those of STD/CTD, since the latter are very reliable (Flierl and Robinson, 1977; Seaver and Kuleshov, 1982; Heinmiller et al., 1983).

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PII: S0967-0637(97)00100-3

Revised depth-time equations have been suggested for improving the depth accuracies using different techniques and data sets (Heinmiller et al., 1983; Green, 1984; Singer, 1990; Hanawa and Yoshikawa, 1991; Hanawa and Yasuda, 1992). A comprehensive study by Hanawa et al. (1995) (HN-95 hereafter) critically examines the XBT depth errors of T4, T6 and T7 probes based on a large set of simultaneous XBT-CTD data from different oceanic regions of the world. They proposed a common depth-time equation for T4, T6, and T7 probes that reduces the mean depth error to less than 1 m in the range 0–800 m. However, random errors still exist and are found to exceed manufacturer's stipulated error.

The Indian Ocean represents highly contrasting environments with respect to T–S characteristics: the Arabian Sea, the central Indian Ocean and the Bay of Bengal in particular, and the suitability of the HN-95 equation cannot be ascertained since it was based on little data from the Indian Ocean, and that was only from the far southeastern region. Hence, we undertook an experiment to derive a depth-error equation for the Indian Ocean. We have computed the XBT depth errors from four different data sets using the temperature error-free method proposed by HN-95, obtained a depth-time equation and compared with that of HN-95. Dependence of depth error, if any, on fall rate variation caused by water characteristics and kinematic viscosity was also examined.

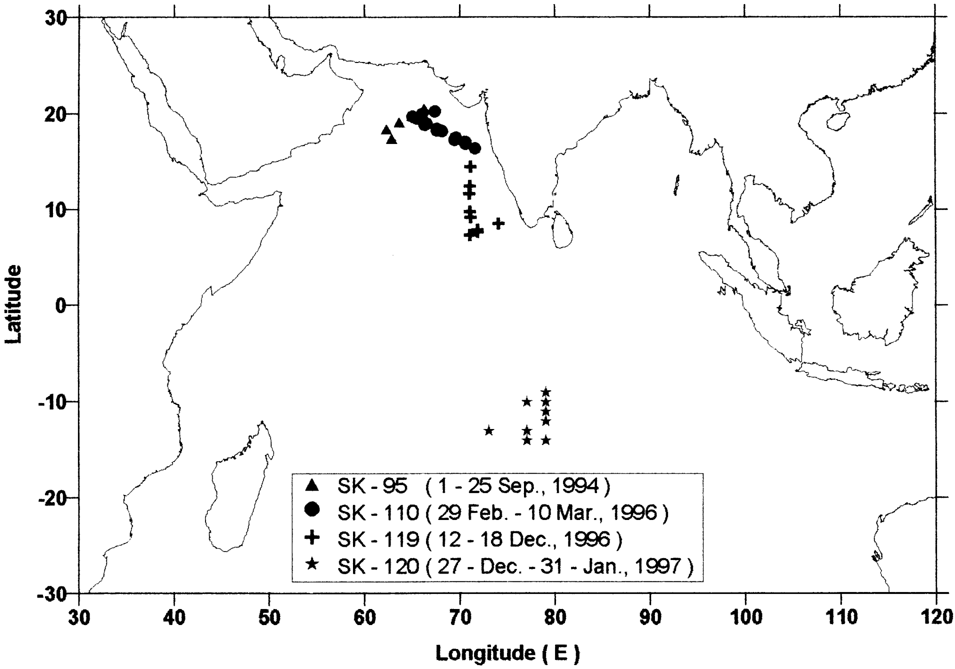

Fig. 1. Station locations of XBT-CTD controlled data sets.

## 2. Methodology

Controlled XBT-CTD experiments were carried out during separate cruises in the Indian Ocean representing contrasting southwest and northeast monsoon seasons. In all the experiments, T-7 Sippican XBT probes and Neil Brown CTD were used. The station positions occupied during different cruises with the respective periods of the experiments are given in Fig. 1. A T7-XBT takes about 120 s to reach its maximum range of 750 m, whereas a CTD cast in the same depth range takes nearly 40 min. Therefore, for obtaining nearly coincident profiles of both XBT and CTD, the XBT probes were launched when the CTD was operational at about 100 m depth. Under this controlled operation we could make both XBT and CTD coincident, at least at some depth.

Pre-cruise calibration of the CTD was done in the shore laboratory. All XBT and CTD temperature profiles were critically examined for their quality. The raw XBT and CTD data were interpolated to 1 m intervals, and then a seven-point median filter was applied to remove the spikes, of the order of 2 m vertical depth range, in the temperature profiles. Subsequently the method proposed by HN-95 was adopted for further processing.

## 3. Results

Mean depth errors for the data of individual cruises are given in Fig. 2 with the corresponding standard deviations. Among the data sets the highest depth error of −2 to −30 m was found for the SK 110 data set while the lowest error of −2 to −20 m was found for SK 119, for a depth range of 750 m. For SK-95 and SK-120 the error fell between these limits with similar features. The mean depth error, however, occurred outside the stipulated error bar, indicating that the coefficients supplied by the manufacturers are not adequate. The observed mean errors are comparable to those reported by HN-95.

The fall rate for each profile was corrected based on the existing depth error to derive the new depth–time relation. New coefficients of “$a$” [associated with elapsed time $t$, in equation (1)] and “$b$” [associated with elapsed time $t^2$ in equation (1)] of the depth–time relation are estimated for individual profiles based on least-squares fit between corrected depth and the corresponding elapsed time.

Scatter plot of depth versus estimated elapsed time for the entire data set is given in Fig. 3. The solid line represents the mean curve obtained from the present data set, and the dashed line is that of the manufacturer. The manufacturer’s equation underestimates the fall rate. The mean depth–time equation for the present data set, obtained using the mean $a$ and $b$ coefficients, was as follows:

$$Z = 6.694t - 0.00222t^2. \tag{1}$$

The new depth equation given by HN-95 is

$$Z = 6.691t - 0.00225t^2 \tag{2}$$

where $Z$ is the new corrected XBT depth in metres at the elapsed time $t$ in seconds.

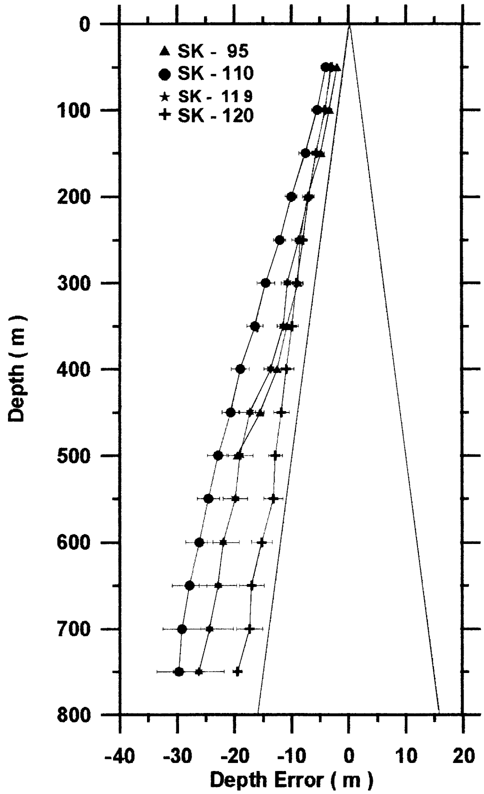

Fig. 2. Mean depth error in XBT data set of different cruises.

The mean *a* and *b* coefficients in equation (1) did not differ significantly from those proposed by HN-95. Figure 4 represents the corrected XBT data using coefficients *a* and *b* from the present data (open circles) and the HN-95 coefficients (filled circles) along with the mean depth error (curve with + sign) computed for the four cruises. Mean depth error varied from −2 to −27 m. After corrections, in both cases, the mean depth error is nearly zero, though a random error of 10 m still exists.

## 4. Discussion

On all four cruises, the XBT fell faster than the rate given by the manufacturer, and the resulting depth error falls outside the specified error bars. The correction based on the regression equation (1) and the resulting residual error and those based on the HN-95 equation, do not differ much (Fig. 4). This implies that though the global equation of HN-95 yielded a slightly higher fall rate, as shown by the positive residual error, it reduces the mean depth error so that the resulting error is well within the specified bars.

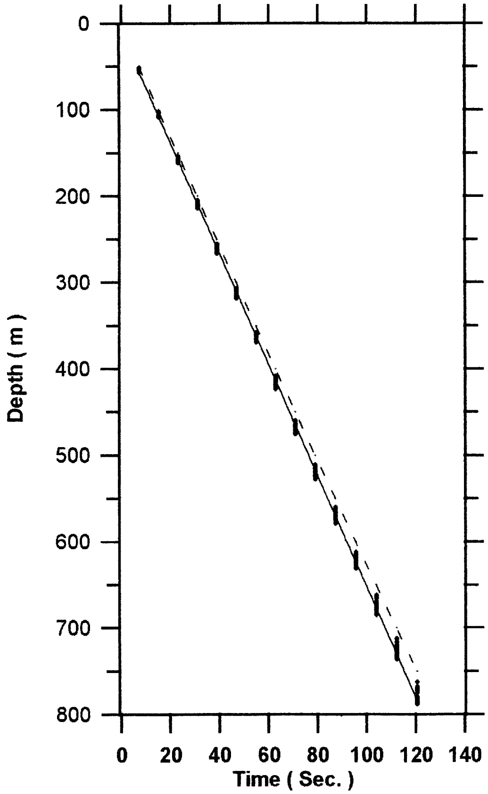

Fig. 3. Scatter plot of depth versus elapsed time obtained from the present data. (Broken line shows the manufacturer's equation and the solid line is based on the equation from the present study).

Since the fall rate equation is basically derived from a least-squares fit between the depth and the elapsed time of the probe, the scatter in *a* and *b* coefficients on an *a*–*b* plane has considerable significance to depth error. Hanawa and Yasuda (1992) pointed out that when the *a* and *b* distribution follows a linear form, the depth difference with respect to a reference equation does not vary significantly, though the individual values of *a* and *b* could be different. For a given data set the *a*–*b* relationship also indicates the validity of the deduced depth errors that are used to find *a* and *b*. The present error analysis showed that the *a* and *b* distribution has a linear trend (Fig. 5). Thus, *a* and *b* coefficients of this work and those of HN-95 are similar. While *a* and *b* coefficients of HN-95 for combined T4/T6/T7 XBT types are 6.691 and 0.00225; the same for T7 XBTs from the present data sets are 6.694 and 0.00222 [equations (1) and (2)].

To avoid inconsistency in the processed data, HN-95 recommended that the archives not be corrected until a unified equation is arrived at. The present comprehensive data set from the Indian Ocean could be of much use in finalising a global

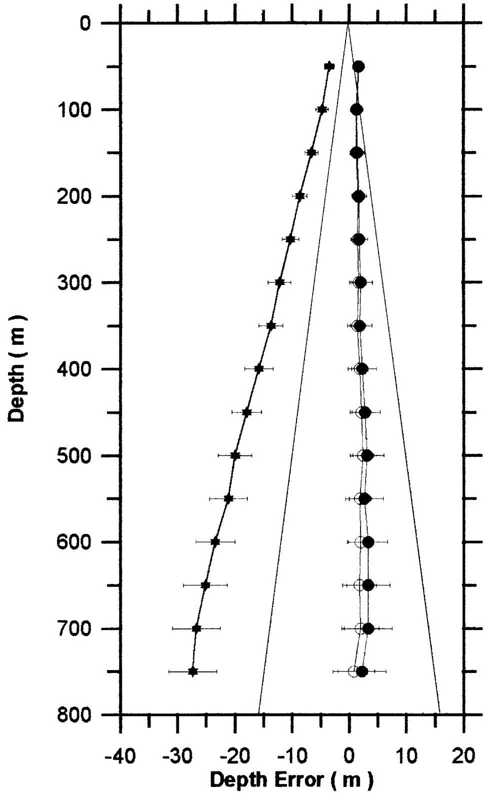

Fig. 4. Mean depth error for the combined data (star) and depth error after correction of the XBT depth based on equation (1) (open circle) and equation (2) (solid circle).

equation. However, for the end users of combination of XBT and CTD data, we recommend the use of equation (1) (from the present study) or equation (2) (HN-95), to remove the pseudo-undulation in the thermal structure (derived from combined CTD and XBT data) caused by the systematic error in XBT depth. The HN-95 data set (both CTD and XBT) was a digitally recorded type. Application of the HN-95 equation for the strip chart XBT records may not provide the expected accuracy as in the case of digital types. This is because the older style strip chart recorder may induce additional errors associated with the chart recorder mechanism (Kroner and Blumenthal, 1978). However, a recent study of Ridgway (1995) compared the archived XBT data (consisting of both digital and strip chat recorder types) and hydrographic data (consisting of both CTD and Nansen Cast types) collected in the Tasman Sea off Eastern Australia and found that the HN-95 equation could remove the systematic error in the archived XBT data.

The observed depth error can be attributed to regional (dependence on water masses through buoyancy and viscosity) and “non-regional” probe wire pull on the

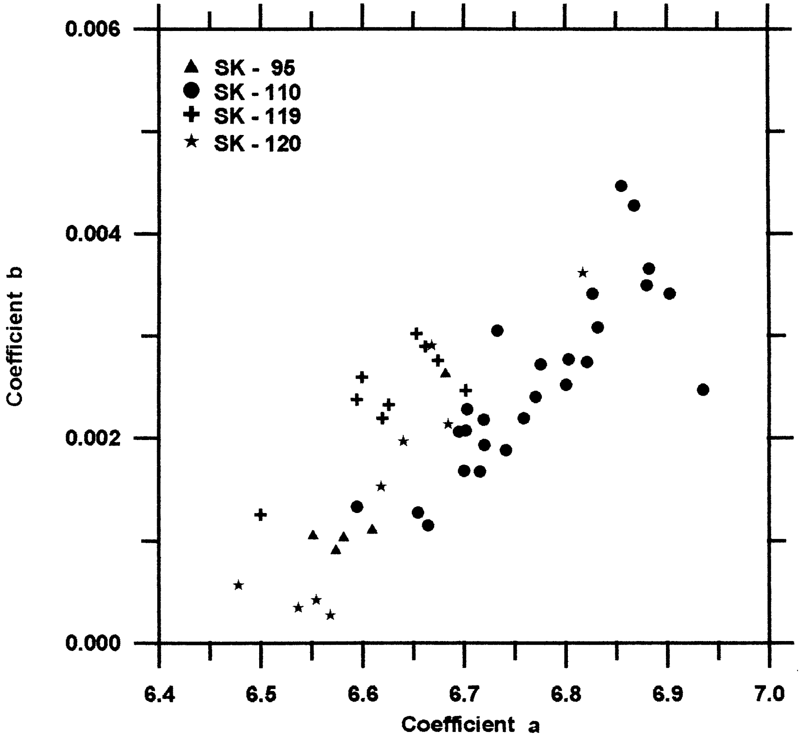

Fig. 5. Scatter diagram of the *a* and *b* coefficients.

one hand and dynamic variations (batch to batch variations) on the other hand. The effect of ocean salinity and temperature on density, and thus probe buoyancy, is of second-order importance in affecting the fall rate. The probe dynamics vary considerably due to viscosity change (Seaver and Kuleshov, 1982). Viscosity is, to the first order, inversely proportional to the temperature.

HN-95, using the comprehensive data set distributed over different water masses, examined the fall rate variation (coefficient *a*) caused by change in water temperature. They found that out of nine data sets, three (northwest tropical atlantic—nwta, northwest Pacific—nwp, and northeast atlantic—nea) showed considerable variations in fall rate due to change in viscosity. They could not draw any valid conclusion based on those results as in the same data, three other data sets showed some inverse relationship.

Our results also do not exhibit any dependence of fall rate on temperature. We plotted the mean T–S (Fig. 6) of each cruise and compared them with the mean depth error of corresponding cruises (Fig. 2). The error did not show any regional dependence on either water mass or viscosity. If the fall rate depends on regional water masses, either through buoyancy or through viscosity, then it would have been

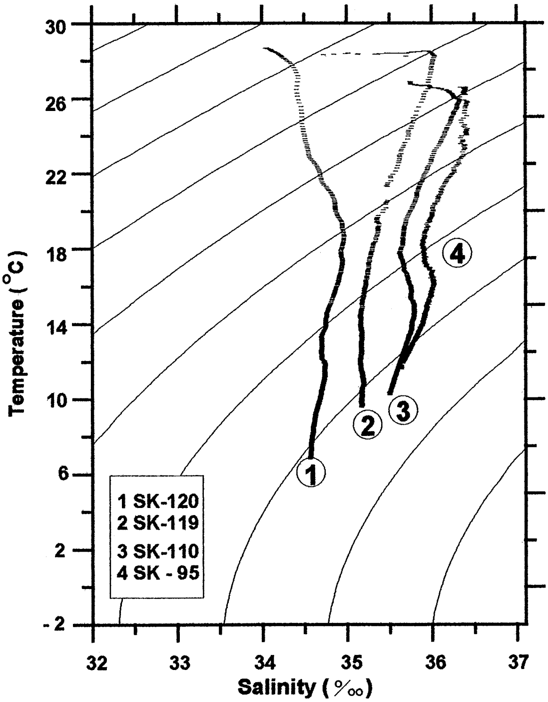

Fig. 6. Mean T–S diagrams for individual cruises.

minimum (maximum error) in SK-95 and SK-110 and maximum (least error) for SK-120. However, it was not the case.

Now the question remaining to be addressed, not within the scope of this study, is what obscures the viscosity dependence on fall rate. Is it wire pull or batch to batch variations? These have to be examined adequately with additional field experiments considering these aspects.

## Acknowledgements

We gratefully acknowledge Dr. E. Desa, Director, National Institute of Oceanography for his encouragement in undertaking this study. This work was partially supported by Department of Ocean Development, Government of India, through the MARSIS (Marine Remote Sensing Information System) project. Authors are grateful to Dr. S. R. Shetye and Shri. D. Sunder for pre-cruise calibration of the temperature sensor and to Dr. Ramesh Babu, Chief scientist of SK-120 cruise for making the SK-120 XBT-CTD data available to us. We are also grateful to anonymous reviewers for their useful comments.

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