Open Access

Effect of Temperature and Salinity on Sound Speed in the Central Arabian Sea

M. M. Ali[1,*], Sarika Jain[1] and Radhika Ramachandran[2]

[1]*National Remote Sensing Centre, Hyderabad, India*

[2]*Department of Space, New Delhi, India*

Abstract: Sound speed in the oceans depends on temperature, salinity, and pressure and has large seasonal and spatial variations. Since temperature and salinity variations are large compared to pressure, we studied the relative importance of these two parameters on sound speed by analyzing the hourly profiles for one year (16 October 1994 – 22 October 1995) up to 250 m depth from the Woods Hole Oceanographic Institution mooring in the central Arabian Sea (15.5° N, 61.5° E). We replaced the mooring temperature and salinity profiles with the climatological values and observed that the impact of temperature change is significant compared to that of salinity. This study provides an opportunity to utilise relatively more number of temperature measurements from XBT (expendable bathy thermograph) along with climatological salinities in the central Arabian Sea.

Keywords: Central Arabian Sea, sound speed, temperature, salinity.

1. INTRODUCTION

The important applications of sound speed profiles (SSPs) are in a wide range of scientific strategic applications like detection of underwater targets and acoustic communications. Under favourable conditions, shadow zones that have important bearing on strategic applications are created below the sonic layer depth (SLD), which is the layer of near surface maximum sound speed. Sound speed in the oceans that is dependent on temperature, salinity and pressure varies seasonally and spatially. Pressure that can be derived from depth does not vary significantly from season to season or from place to place; it changes only with depth. However, temperature and salinity (T/S) have both temporal and spatial variations.

In the absence of salinometer measurements, sound speed profiles (SSPs) are estimated from T/S observations. To compute the sound speed from *in situ* T/S profiles, many empirical equations are available. Some of them are Wilson's equation [1], Del Grosso's Algorithm [2], Mackenzie equation [3], Coppens equation [4], UNESCO (United Nations Educational, Scientific and Cultural Organization) algorithm [5], Medwin and Clay formula [6] and by Leroy *et al.* [7]. The international standard algorithm, often known as the UNESCO algorithm, is due to Chen and Millero [8].

Since the combined T/S data from CTD (conductivity, temperature and depth) or thermister chain are always sparse compared to temperature profiles alone from XBT (expendable bathy thermograph), it is important to explore the possibility of utilizing more number of temperature profiles alone by studying the relative importance of temperature and salinity on sound speed. The large number of measurements from XBTs has been used together with available T-S relationships in many oceanic regions to infer salinity from temperature data [9-14]. Ali *et al.* [15] proposed a different approach to combine temperature from XBT and climatological salinities from Levitus and Boyer [16]. They demonstrated the approach by replacing the CTD salinities with the climatological salinities. In this article, we studied the relative influence of T/S on sound speeds using Woods Hole Oceanographic Institution (WHOI) hourly observations. We also replaced the CTD salinity values with climatology to infer the errors involved in the estimation of sound speed in case XBT temperatures and climatological salinities are used. However, the errors in XBT measurements [eg. 17-21] are not considered in this exercise.

2. DATA AND METHODS

The data used in the present analysis are: (i) T/S profiles at central Arabian Sea mooring (15.5° N, 61.5° E; Fig. (**1**)) deployed by WHOI during 16 October 1994 – 22 October 1995 [22]: (hereunder WHOI data), (ii) monthly climatological temperature profiles from Antonov *et al.* [23] and (iii) monthly salinity profiles form Locarnini *et al.* [24] (hereunder these two climatological profiles will be referred as Levitus climatology).

Out of all the WHOI temperature measurements available at several depths, only those depths where these measurements are available throughout the period were considered. Thus, 27 depths selected for temperature are 1.4, 1.8, 1.91, 2.4, 3.5, 4.5, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 80, 90, 100, 125, 175, 200, 225 and 250 m. However, the salinity measurements are available at fewer depths and the six depths selected for salinity measurements are 1.4, 10, 35,

*Address correspondence to this author at the National Remote Sensing Centre; Tel: 919949045110; Fax: 914023879869;
E-mail: mmali73@yahoo.com, mmali@nrsc.gov.in

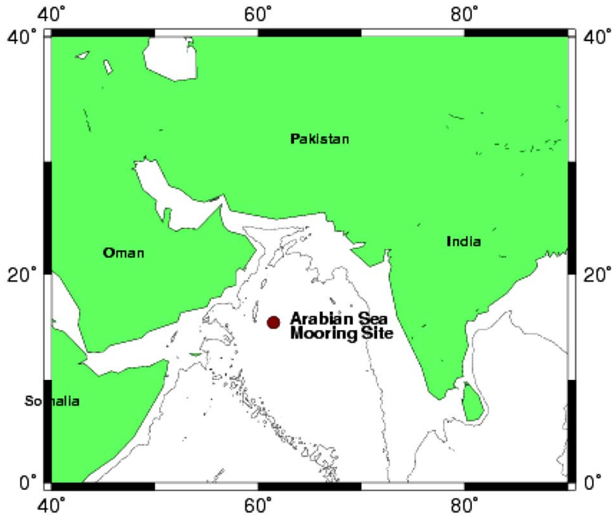

Fig. (1). Location of the WHOI Mooring along with the grid used for climatological sound speed estimations.

100, 200, and 250 m. Since the vertical resolution of salinity values was poor as compared to temperature values, salinity measurements were linearly interpolated to the temperature depths. Overall, 8578 profiles were analyzed in this study.

The UNESCO algorithm originally developed by *Chen and Milero* [8] and modified by *Wong and Zhu* [5] was used to estimate the sound speed using temperature (in ºC), pressure (in bars) and salinity (in psu) at all the 27 depths. This algorithm is valid for a temperature range of 0 to 40 °C, salinity range of 0 to 40 psu and pressure range of 0 to 1000 bar. This algorithm uses pressure as a variable for sound speed calculation in place of depth; hence, depth values have been converted in to pressure following Leroy and Parthiot [25].

From these hourly estimations, we obtained annual mean values of sound speed. In order to study the effect of T/S on sound speed, we have considered the maximum and minimum values of these two parameters at each depth occurring within the entire one year WHOI data set. Sound speeds were computed using these minimum and maximum values of temperatures and salinities. These profiles are compared with the average sound speeds computed using measured T/S profiles. Besides, four more sound speeds are simulated: two by considering maximum and minimum temperature profile with mean salinities and two more by considering maximum and minimum salinities with mean temperatures.

Similarly, using monthly Levitus climatological values, we computed monthly mean sound speeds at 0, 50 and 100 m depth from which we obtained seasonal averages at the one degree grid centered around the mooring location (Fig. **1**). The seasons are divided as winter (December–February), pre-monsoon (March – May), southwest monsoon (June–September) and post-monsoon (October–November).

3. RESULTS AND DISCUSSIONS

3.1. Effect of Temperature

The SSP obtained by using maximum temperatures and mean salinities at each depth is on the right side of the annual mean SSP (Fig. **2a**). Similar profile with minimum temperatures and average salinities is on the left side of the mean profile. The difference of sound speed at various depths due to the changes in temperature could be as large as 9 m/s at 250 m to 26 m/s at 140 m depth. From this study we can conclude that Effect of temperature change on sound speed is significant.

3.2. Effect of Salinity

Similarly, the two SSPs obtained by using the maximum and minimum salinities at each depth in the entire one-year dataset along with the average temperature profile are almost equal to the annual average SSP (Fig. **2b**). The three profiles almost coincide indicating that the annual variations in salinity do not significantly affect the SSP. Thus, it can be concluded that deviations in salinity, even on an annual basis, do not influence sound speed significantly.

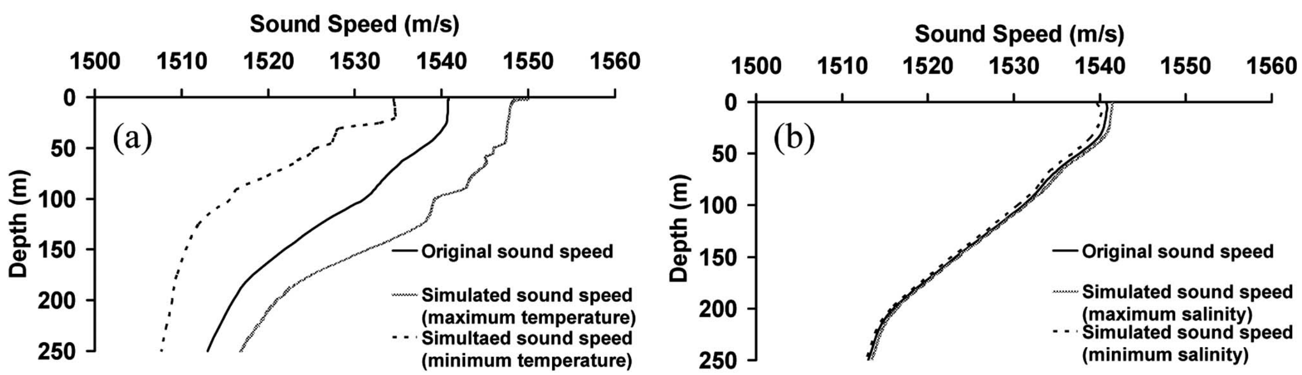

Fig. (2). Effect of (**a**) subsurface temperature and (**b**) subsurface salinity on sound speed profiles.

We have compared the annual standard deviation (SD) of both T/S values obtained from WHOI using all the hourly observations. The SD of salinity values varies from 0.26 to 2.94 psu with a maximum value at 250 m (Fig. **3**). Though SD in salinity is high, the sound speed computed from these values do not show the significant effect of salinity in sound speed estimations (Fig. **2b**). On the other hand, the SD of temperature is reflected in these estimations (Fig. **2a**).

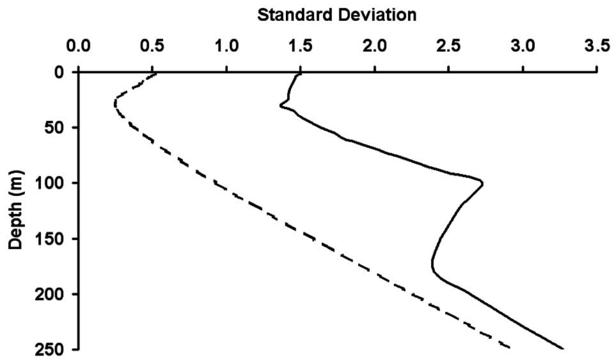

Fig. (3). Annual SD of WHOI hourly observations of temperature (dashed line) and salinity (solid line).

3.3. Replacement of Measured Salinity Values with Climatological Salinity

As shown in previous section, changes in the sound speed due to the annual variations in salinity are minimal. On the other hand, the influence of temperature changes is very significant. Since the temperature measurements from XBT measurements are relatively more compared with the T/S measurements from the conductivity–temperature-depth (CTD) profiles, it is worth attempting the errors involved if measured salinity values are replaced with Levitus climatological salinities. For this purpose, the measured salinity values from the WHOI mooring measurements are replaced with the Levitus climatological values corresponding to the grid and month of mooring location. The sound speeds thus obtained by using the measured T/S values and those obtained by using the WHOI mooring buoy temperature measurements and the climatological salinity values are shown in Fig. (**4**) for alternate months. The two profiles almost coincide with each other with an annual average RMSE (root mean square error) of 0.25 m/s indicating that the errors involved in the estimation of sound speed using the measured temperature and the climatological salinities are negligible. Even the slight variations that are present at the surface are within 0.4 m/s. Hence, XBT temperature profiles together with climatological salinities can be conveniently used to estimate the SSPs. Ali *et al.* [23] also have shown that climatological salinity values can be conveniently used along with the measured temperature values for the computation of dynamic height. However, this analysis is not meant for demeaning the CTD measurements of T/S profiles; but to show the utilisation of relatively more number of XBT temperature profiles in absence of CTD observations, keeping in mind the limitations of XBT measurements [17-21].

On the other hand, the sound speed obtained by using the WHOI T/S profiles significantly differ from the climatology (Fig. **4**) in which both T/S values are used from the climatological profiles corresponding to the grid and month of the mooring. This study indicates that for any strategic planning we should have at least the temperature measurements. Climatological T/S profiles are only useful to have a broad guideline. The annual RMS error in sound speed at different depths using the original WHOI and climatological salinity values is shown in Fig. (**5**). The RMS errors are around 0.30 m/s for the first 100 m and reduce gradually to 0.10 m/s at 25 m depth.

However, the present analysis is carried out at one location and it is worth attempting these results at other locations. Since the measurements similar to the WHOI mooring are not available at other places, we analysed Levitus climatological profiles on a seasonal basis. In Fig. (**6**), we present the climatological distribution of sound speed, temperature and salinity at 0, 50 and 100 m depths for four seasons.

3.4. Winter Season

The sound speed at surface and at 50 m varies from 1530 to 1536 m/s and values are almost same at both these depths excepting near the head Bay of Bengal (BOB) where it is more at 50 m than that at surface. For the same latitudes, sound speed is more in the Arabian Sea (AS) than that in BOB at surface. At 100 m the sound speed has slightly reduced compared with the previous two depths varying from 1522 to 1532 m/s. The sound speed almost followed the temperature distribution both spatially and vertically. Although in the BOB salinity has increased at 100 m compared with surface and 50 m, the sound speed decreased at 100 m following temperature. This result also indicates that the sound speed is mainly dependent on temperature rather than on salinity.

3.5. Pre-Monsoon Season

As the temperature increased during the summer season the sound speed also increased. The sound speed during this season varies from 1532 to 1538 m/s at surface, from 1530 to 1536 m/s at 50 m and from 1522 to 1532 m/s at 100 m . Though salinity during this season is almost similar to that during the winter season, the sound speed increased following the temperature pattern reemphasizing the dominant effect of temperature on sound speed. During this season also, sound speed follows the temperature pattern. The change in temperature from surface to 50 m is less compared with that at 100 m as in the previous season.

3.6. Southwest Monsoon Season

The main peculiarity of this season is high winds, the effect of which is seen particularly near the Somali and Arabian coasts. Strong winds near the region blowing almost parallel to the coast result in upwelling due to which the temperature reduces that in turn reduced the sound speed. The sound speed increased from west to east near this region following the temperature pattern. However, the sound speed and the temperature patterns are not similar at surface. The high surface temperatures, particularly, near the head bay and in the southern part of the study are not reflected in the sound speed patterns whereas at other depths the two patterns are similar. The effect of Somali and AS coastal upwelling is clearly evident at all these depths.

3.7. Post-Monsoon Season

The effect of Somali upwelling apparently persisted at 50 m depth. As in the case of other seasons, the sound speed decreases with depth in this season also following almost temperature patterns excepting at the surface near head BOB as in the case of the previous season.

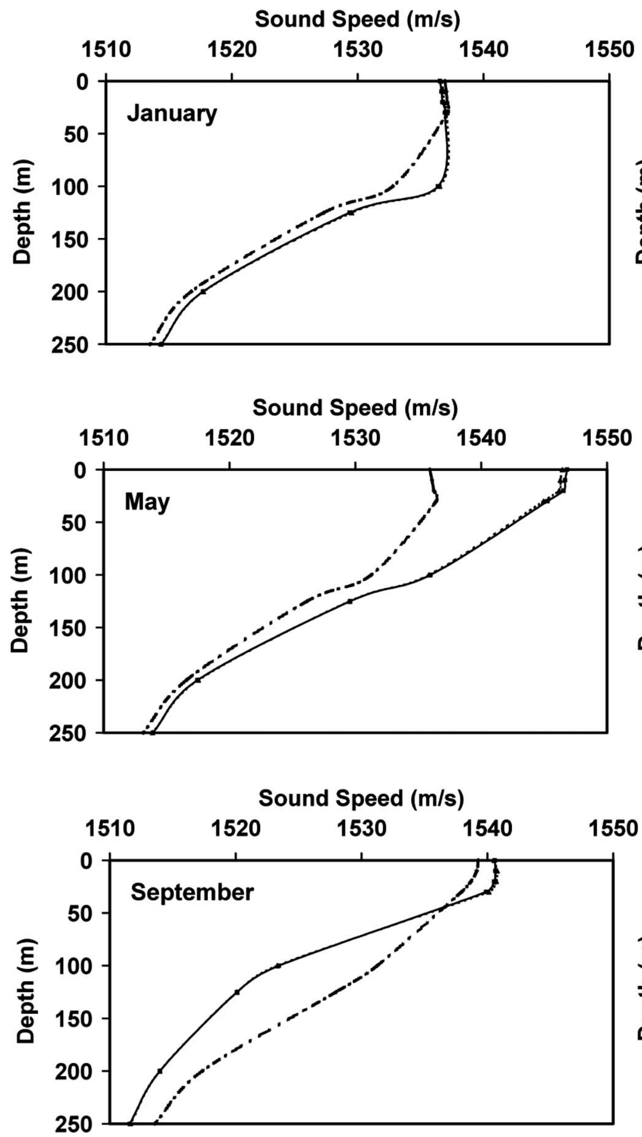

Fig. (4). Sound speed profiles estimated using (a) climatological temperatures and salinities (—), (b) Woods Hole Oceanographic Institution's mooring temperature salinity profiles (—•—) and Woods Hole Oceanographic Institution's mooring temperature and Levitus climatology salinities (---).

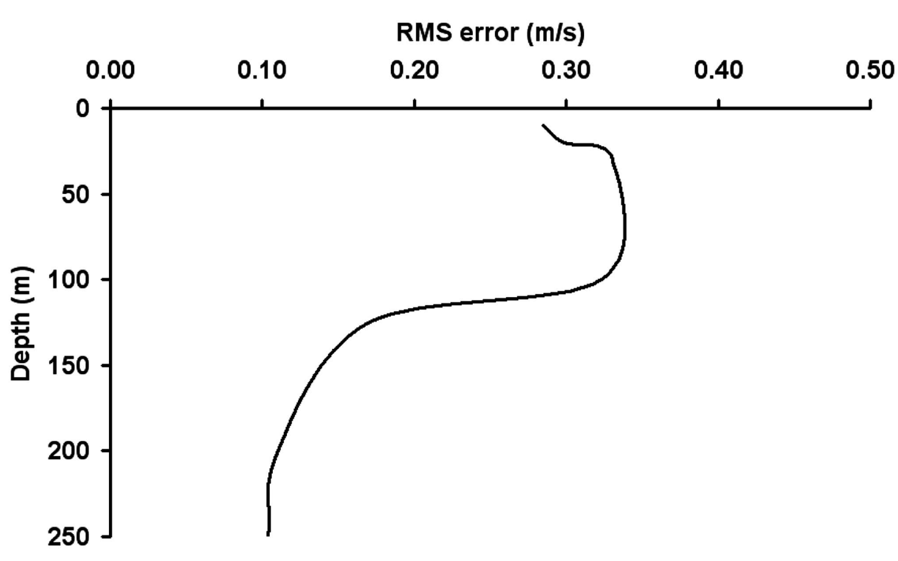

Fig. (5). Root mean square errors between sound speeds estimated using WHOI and climatological salinity values.

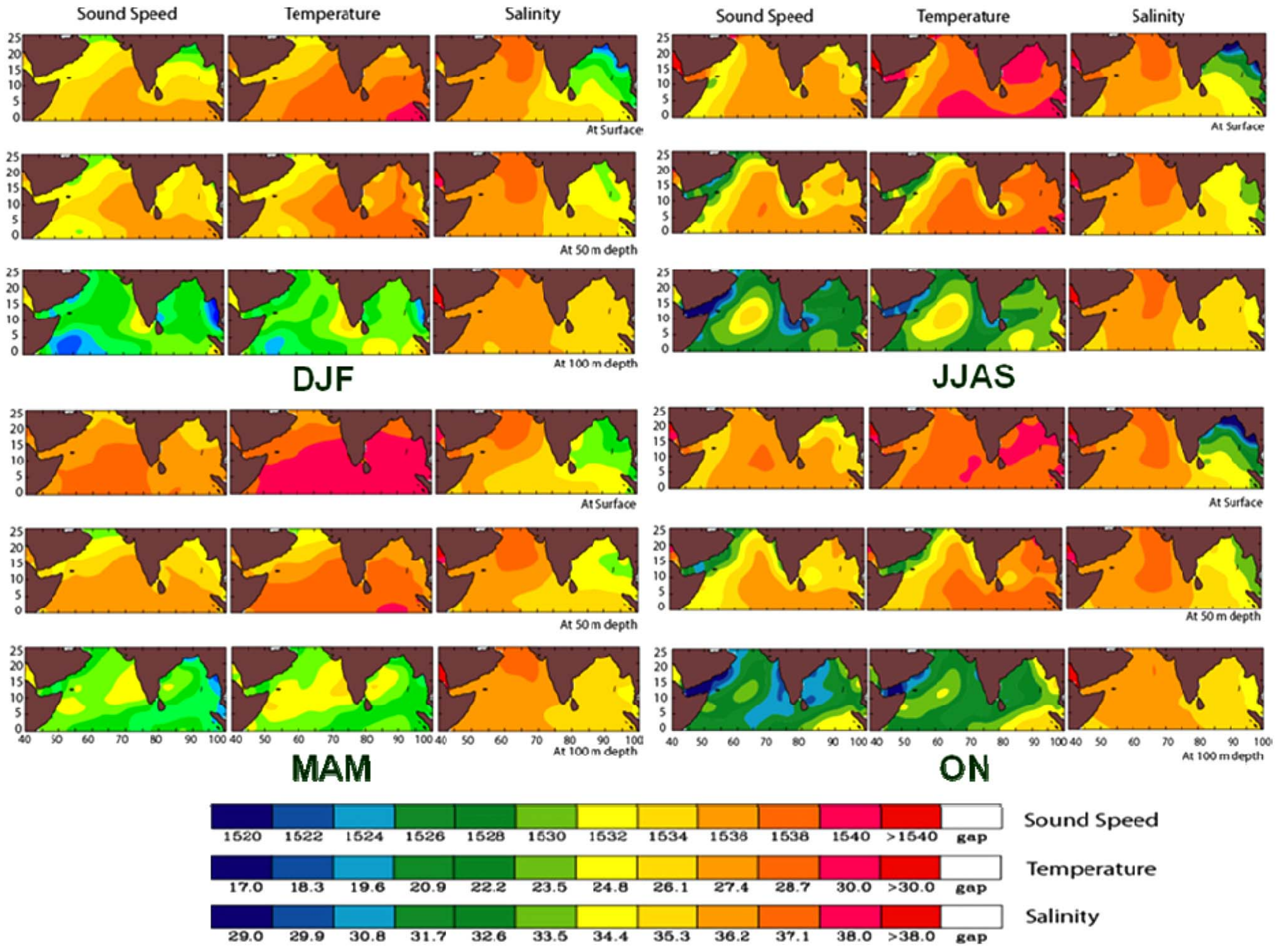

Fig. (6). Spatial variation of climatological sound speed, temperature and salinity at surface, 50m and 100m depths for December-February (DJF), March-May (MAM) and June-September (JJAS).

4. SUMMARY AND CONCLUSIONS

Temperature and salinity profiles have both spatial and temporal variation. To study the relative importance of these profiles on SSPs an exercise has been carried out with WHOI mooring hourly observations. Annual average SSP has been compared with the SSPs obtained by using maximum and minimum temperatures at each depth in the entire year. Average salinity is used along with these two temperature profiles. The difference between these two profiles using maximum and minimum temperatures with average salinities varies from 9 m/s at 250 m to 26 m/s at 140 m depth. On the contrary, the difference between the two profiles obtained by considering the maximum and minimum salinities at each depth with average temperatures is negligible. These two profiles are almost equal to the annual average SSP obtained by using measured T/S profiles.

This important finding can be used to estimate SSPs from relatively more number of temperature profiles from XBT along with climatological salinities. To further this, salinities from the WHOI mooring have been replaced with climatological salinities of the month and spatial grid in which the mooring observations fall. The difference between the two observations thus obtained is negligible. However, the SSPs obtained by using both T/S from climatology significantly differ from the measured profiles. Spatial distribution of seasonal climatological sound speed profiles at 0, 50 and 100 m depths closely follow the distribution of temperature rather than with that of salinity at all depths for all the seasons. Thus, it can be concluded that (i) temperature change plays a major role in controlling the SSPs in the ocean and that of salinity is negligible, (2) climatological salinities can be conveniently used to estimate SSPs in absence of actual measurements and (3) for any strategic planning we should have at least temperature measurements; climatological profiles are useful only as a broad guideline.

REFERENCES

[1] W. Wilson, "Equation for the speed of sound in Sea Water," *J. Acous. Soc. Am.*, vol. 32, no. 10, pp.1357, 1990.

[2] V.A. Del Grosso, "New equation for the speed of sound in natural waters (with comparisons to other equations)," *J. Acoust. Soc. Am.*, vol. 56, no. 4, pp. 1084-1091, 1974.

[3] K. V. Mackenzie, "Nine-term equation for the sound speed in the oceans," *J. Acoust. Soc. Am.*, vol. 70, no. 3, pp. 807-812, 1981.

[4] A.B. Coppens, "Simple equations for the speed of sound in Neptunian waters," *J. Acoust. Soc. Am.*, vol. 69, no. 3, pp. 862-863, 1981.

[5] G.S.K. Wong, and S. Zhu, "Speed of sound in seawater as a function of salinity, temperature and pressure," *J. Acoust. Soc. Am.*, vol. 97, no. 3, pp. 1732-1736, 1995.

[6] H. Medwin, and C. S. Clay, "*Fundamentals of Acoustical Oceanography*," Academic Press: London, pp. 712,1998.

[7] C.C. Leroy, S. P. Robinson, and M. J. Goldsmith, "A new equation for the accurate calculation of sound speed in all oceans", J. Acoustical . Society of Am.erica, vol. 124 (5), pp. 2774-2782, 2008.

[8] C.T. Chen, and F. J. Millero, “Speed of sound in seawater at high pressures,” *J. Acoust. Soc. Am.*, vol. 62, no. 5, pp.1129-1135, 1977.

[9] B.A. Taft, and W. S. Kessler, “Variation of zonal currents in the central tropical Pacific during 1970 to 1987: sea level and dynamic height measurements,” *J. Geophys. Res.*, vol. 96, pp.12599-12618, 1991.

[10] J.R. Donguy, G. Meyers, “Observation of geostrophic transport variability in the western tropical Indian Ocean,” *Deep-Sea Res.*, vol. 42, pp.1007-1028, 1995.

[11] V.S.N. Murty, M.S.S. Sarma, B.P. Lambata, V.V. Gopalakrishna, S. M. Pednekar, A. S. Rao, A. J. Luis, A. R. Kaka, and L. V. G. Rao, “Seasonal variability of upper-layer geostrophic transport in the tropical Indian Ocean during 1992-1996 along TOGA-I XBT lines,” *Deep-Sea Res.*, vol. 147, pp.1569-1582, 2000.

[12] J.P. Rebert, J. R. Donguy, G. Eldin, and K. Wyrtki, “Relations between sea-level, thermocline depth, heat content and dynamic height in tropical Pacific,” *J. Geophy. Res.*, vol. 90, no. (C6), pp.11719-11725, 1985.

[13] D. Roemmich, and B. Cornuelle, “Observing the fluctuations of gyre-scale ocean circulation: a study of the sub-tropical south Pacific,” *J. Phys. Oceanogr*., vol. 20, pp. 1178-1187, 1990.

[14] G. Reverdin, P. Rual, Y. du Penhoat, and Y. Gouriou, “Vertical structure of the seasonal cycle in the central equatorial Atlantic Ocean: XBT sections from 1980 to 1988,” *J. Phys. Oceanogr.*, vol. 21, pp. 277-291, 1991.

[15] M. M. Ali, V. V. Gopalakrishna, N. Araligidad, G. V. Reddy, and G. Salgoanker, “Determination of dynamic heights in the Bay of Bengal from XBT profiles and climatological salinities,” *J. Mar. Res.*, vol. 63, no. 4, pp.671-682, 2005.

[16] S. Levitus, Y. P. Boyer, “*World Ocean Atlas 1994,* Temperature, NOAA Atlas, NESDIS, 4, US Department of Commerce, Washington, DC, vol. 4, pp. 117, 1994.

[17] P. Thadathil, A.K. Ghosh and P.M. Muraleedharan, “An evaluation of XBT depth equations for the Indian Ocean”, Deep-Sea Res. I, vol. 45, pp. 819-827, 1998.

[18] P. Thadathil, A. K. Saran, V. V. Gopalakrishna, P. Vethamony, and Nilesh Araligidad, “XBT fall rate in waters of extreme temperature: a case study in the Antarctic Ocean”, J. Atmos. Oceanic Technol, ., vol. 19, 391-396, 2002.

[19] S. Kizu, H. Yoritaka and K. Hanawa, “A New Fall-Rate Equation for T-5 Expendable Bathythermograph (XBT) by TSK”, Journal of Oceanography, vol. 61, pp. 115-121, 2005.

[20] F. Reseghetti, , M. Borghini and G. M. R. Manzella, “Factors affecting the quality of XBT data – results of analyses on profiles from the Western Mediterranean Sea”, Ocean Sci., vol. 3, 59–75, 2007.

[21] F. Machín, M. Emelianov, P. Rodriguez, E. Garcia-ladona, J. Menendez and J. Salat , “XBT profilers for operational purposes: application and validation in real exercises”, Scientia Marina, vol. 72 (4), pp. 779-799, 2008.

[22] D.L. Rudnick,, R. A. Weller, C. C. Eriksen, T. Dickey, J. Marra, and C. Langdon, “One-year moored observations of the Arabian Sea,” *EOS Trans., AGU*, vol. 78, no. 117, 120-121, 1997.

[23] J. I. Antonov, R. A. Locarnini, T. P. Boyer, H. E. Garcia, and A. V. Mishonov, “*World Ocean Atlas 2005*, *Salinity*. S. Levitus, Ed., NOAA Atlas NESDIS 62, U.S. Gov. Printing Office, Washington, D.C., Vol. 2, pp. 182, 2006.

[24] R. A. Locarnini, A. V. Mishonov, J. I. Antonov, T. P. Boyer, and H. E. Garcia, “*WorldOcean Atlas 2005,” Temperature.* S. Levitus, Ed. NOAA Atlas NESDIS 61, U.S. Gov. Printing Office, Washington, D.C., Vol. 1, pp. 182, 2006.

[25] C. C. Leroy and F. Parthiot, “Depth-pressure relationships in the oceans and seas,” *J. Acoust. Soc. Am.* vol. 103, pp. 1346-1352, 1998.

Received: February 28, 2011 Revised: June 06, 2011 Accepted: June 07, 2011