# Sonic Layer Depth estimated from XBT temperatures and climatological salinities

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## Abstract

Sonic layer depth (SLD) plays an important role in antisubmarine warfare in terms of identifying the shadow zones for submarine safe parking. SLD is estimated from sound velocity profiles (SVP) which is inturn is obtained from temperature and salinity (T/S) profiles. Given the limited availability of salinity data in comparison to temperature, SVPs need to be obtained from alternate methods. In the present work, to make use of voluminous temperature data sets from XBT, CTD and other source for estimating SLD, we propose a method of utilizing XBT measurements and World Ocean Atlas climatological salinities to compute SVP and then extract SLD. This approach is demonstrated by utilizing T/S data from Argo floats in the Arabian Sea (40° – 80° E and 0 – 30° N). SLD is estimated from SVP obtained from Argo T/S profiles first and again by replacing the Argo salinity with climatological salinity. It is found that in more than 90% of cases, SLD matched exactly, with the root mean square deviation ranging from 3 – 12 m with an average of 7 m.

**Keywords:** Argo, Arabian Sea, Sonic layer Depth, Climatological Salinity, XBT.

## 1. Introduction

Water is an efficient medium for the transmission of the sound. This characteristic resulted in development of submarine acoustic methods that are of tremendous value in navigation (Svedrup et al. 1961). The largest temporal fluctuations in sound velocity profile (SVP) occurs in the upper ocean, mainly on account of diurnal and seasonal variations of temperature and salinity (T/S) (Brekhovskikh and Lysanov 2003). Sound speed in the ocean increases with temperature, salinity and pressure and it varies significantly with time of day, season and depth. In typical situations, the stratified ocean may create shadow zones, depending on the variations of sound speed with depth. Spatial variations of sound speed cause acoustic rays to bend according to Snell’s law and sound is partially reflected as the sound speed varies sharply. A requirement for navy is the accurate determination of sound speed structure in the ocean which is used for determining sonic layer depth (SLD). SLD is estimated from SVP and is defined as the depth of maximum sound speed above the deep sound channel axis (Etter 1996; Udaya Bhaskar et al. 2008). SLD plays a vital role in antisubmarine warfare by identifying the shadow zone for submarine safe parking.

Among temperature, salinity and pressure, temperature acts as the primary controller of acoustic propagation in the ocean. Effect of salinity on sound speed is greatest in regions of high influx of fresh water and high evaporations. In general salinity data over oceanic region is sparse, compared to temperature alone profiles. Climatological temperature/salinity relations have been obtained to infer salinity from the temperature data (Thacker, 2006). Under the Indian XBT program, temperature data were collected in the Arabian Sea (AS). Numerous XBT operated in the AS by various countries are available via GTS. In this analysis, a new method is proposed to estimate SLD, to make use of the voluminous temperature profiles besides other XBT data. The Method proposes estimation of SLD using temperature from XBT and salinity from World Ocean Atlas 2001 (WOA01) climatology (Conkright et al. 2002) and is demonstrated by using Argo T/S profiles in the AS.

## 2. Data

The subsurface data used were T/S profiles from Argo floats in AS (Fig.1). Profiles spanning years 2002 – 2008, comprising of 14572 observations are used. Argo profiling floats provide T/S measurements from surface to about 2 km depth every 5/10 days (Argo Science Team 2001). The data were made available after real time quality control checks (Wong et al. 2006). In addition, data have been checked for outliers and spurious values. XBT data for the AS during the period 2002 – 2008 comprising of 2292 profiles were obtained from CORIOLIS centre in addition to those collected under the Indian XBT program (Fig. 1).

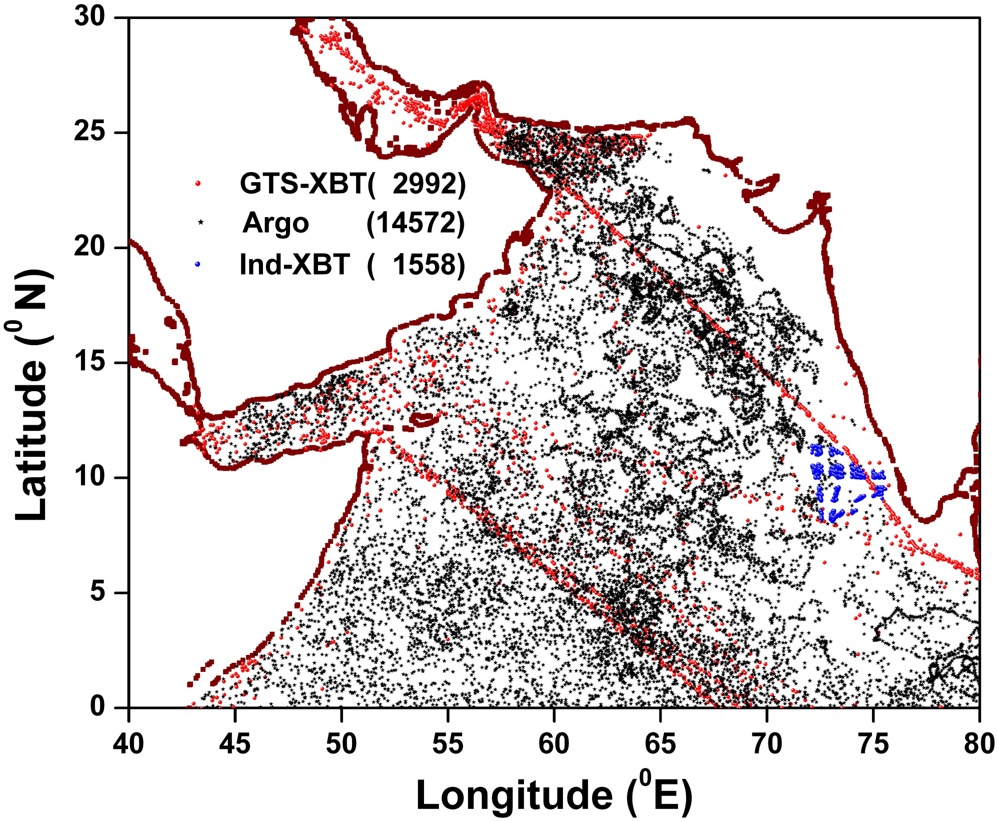

**Fig. 1:** Distribution of 14572 quality controlled Argo T/S profiles and XBT data in Arabian Sea. Black small point indicates Argo profiles, red and blue filled circles indicate XBT sections available during the period 2002 - 2008.

## 3 Methodologies

Since all the profiles are not of uniform depths, linear interpolation was used to obtain data at 1 m depth. Same is applied to climatological salinity profiles. Using these interpolated observations from Argo, SVPs were computed. SLD was estimated from SVP as near surface sound speed maximum (Udaya Bhaskar et al. 2008). SVPs were then recomputed by replacing Argo salinity profiles with WOA01 salinities and SLD was derived with similar definition. Hence forth SLD from Argo T/S and Argo temperature and WOA01 salinity are termed as $SLD_A$ and $SLD_C$ respectively. Kriging method is used to obtain $SLD_C$ and $SLD_A$ fileds at resolution of 1° X 1°. Kriging is a set of linear regression routines which minimize estimation variance from a predefined covariance model.

## 4. Results

### 4.1 Salinity difference between observation and climatology

Comparison was done between climatological salinities and Argo salinities in AS, to see how well they match with each other. Salinity profiles from the grid nearest to the Argo observation position and month are extracted from WOA01 climatology and compared.

Further Root mean square deviation (RMSD) between Argo salinity and climatological salinity is estimated.

Fig.2 presents the monthly RMSD between Argo and climatological salinities in the AS. From figure, it is observed that salinity variability in the upper layers is large compared to deeper layers. Deviations of less than 0.12 PSU are observed below 160 m in all the months except September and October. In the upper layers the errors are significantly high during November – February. Maximum deviation of 0.48 PSU was observed during December. These large errors can be attributed to lack of good number of observation during winter period. Macdonald et al (2001) pointed out that number of observations generally decreases during winter due to bad weather. The high RMSD between observed and climatological salinity during winter can be attributed to lack of good amount of observations that went in to the preparation of climatology.

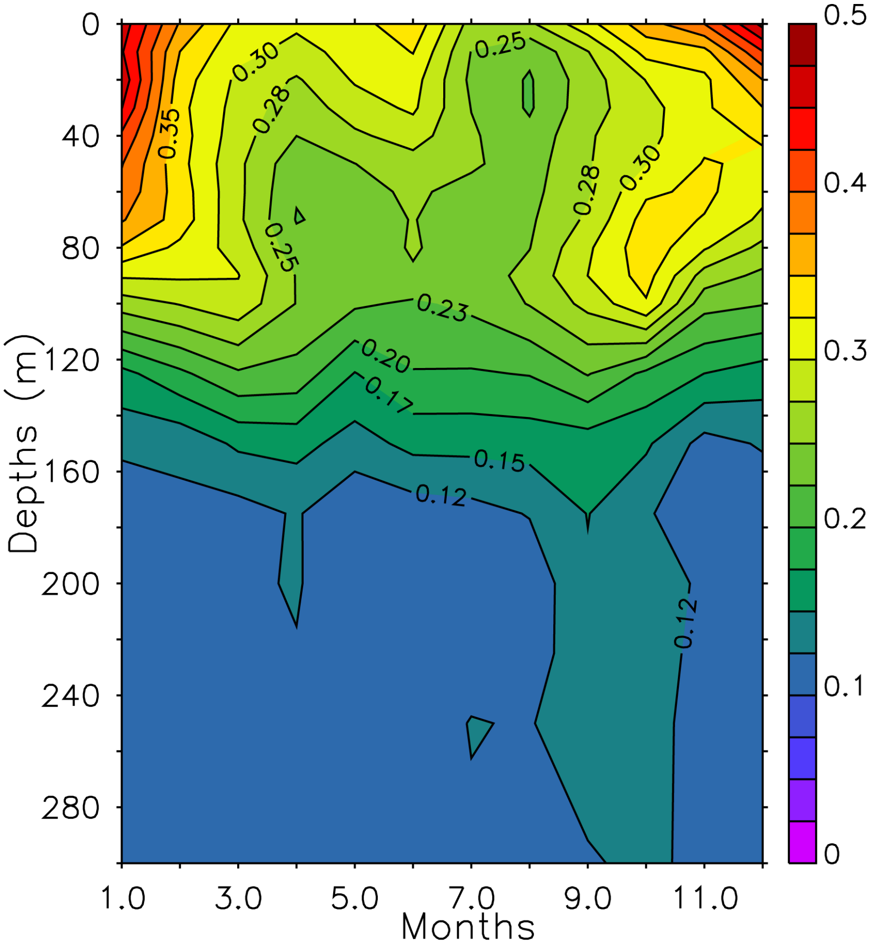

**Fig. 2:** Monthly root mean square deviation (psu) between Argo and corresponding WOA01 salinities at standard depths in the Arabian Sea.

| **Month** | **No. of Observations** | **Frequency of exact match (%)** | **RMSD (m)** | **SD Ratio** |
|---|---|---|---|---|
| January | 717 | 90 | 11 | 0.44 |
| February | 655 | 88 | 10 | 0.43 |
| March | 720 | 93 | 6 | 0.36 |
| April | 728 | 93 | 3 | 0.27 |
| May | 833 | 93 | 4 | 0.19 |
| June | 907 | 94 | 6 | 0.25 |
| July | 918 | 87 | 8 | 0.26 |
| August | 953 | 93 | 10 | 0.32 |
| September | 942 | 94 | 7 | 0.31 |
| October | 900 | 94 | 6 | 0.39 |
| November | 896 | 90 | 11 | 0.45 |
| December | 847 | 89 | 12 | 0.51 |

**Table1:** Monthly statistics of % frequency of exact match, RMSD (m) and SD ratio between $SLD_A$ and $SLD_C$, for the period 2002 – 2008 in Arabian Sea.

### 4.2 Statistical comparison of $SLD_A$ with $SLD_C$

$SLD_A$ is compared with $SLD_C$ to see how well they match with each other in the AS. Statistical parameters like RMSD, standard deviation ratio are estimated to examine the robustness of the method. For each T/S profile the difference between $SLD_A$ and $SLD_C$ is estimated. Fig. 3 presents the percentage frequency histograms of differences between $SLD_A$ and $SLD_C$ for each month. It is observed that $SLD_A$ and $SLD_C$ matched exactly, in most cases. Further, to estimate the error involved in the estimation, RMSD between $SLD_A$ and $SLD_C$ was computed. Table 1 summarises month wise, number of observations, % frequency of exact match between $SLD_A$ and $SLD_C$, their RMSD and standard deviation (SD) ratio.

From the table 1, we observe that RMSD between $SLD_A$ and $SLD_C$ is found to vary between 3 – 12 m with an average value of 7 m. The RMSD is observed to be small (high) for the pre-summer (winter) monsoon months. On an average, $SLD_A$ and $SLD_C$ exactly matched in 91.5% of profiles. Since temperature is the primary controller, we observe a high percentage of exact match owing to small differences between climatological (WOA01) and actual salinities (Argo) (Fig.2). It is also observed that SD ratio varied between 0 and 0.4 for all month except for winter month of November – February. Highest S.D ration 0f 0.51 is observed in December with lowest of 0.19 recorded in May.

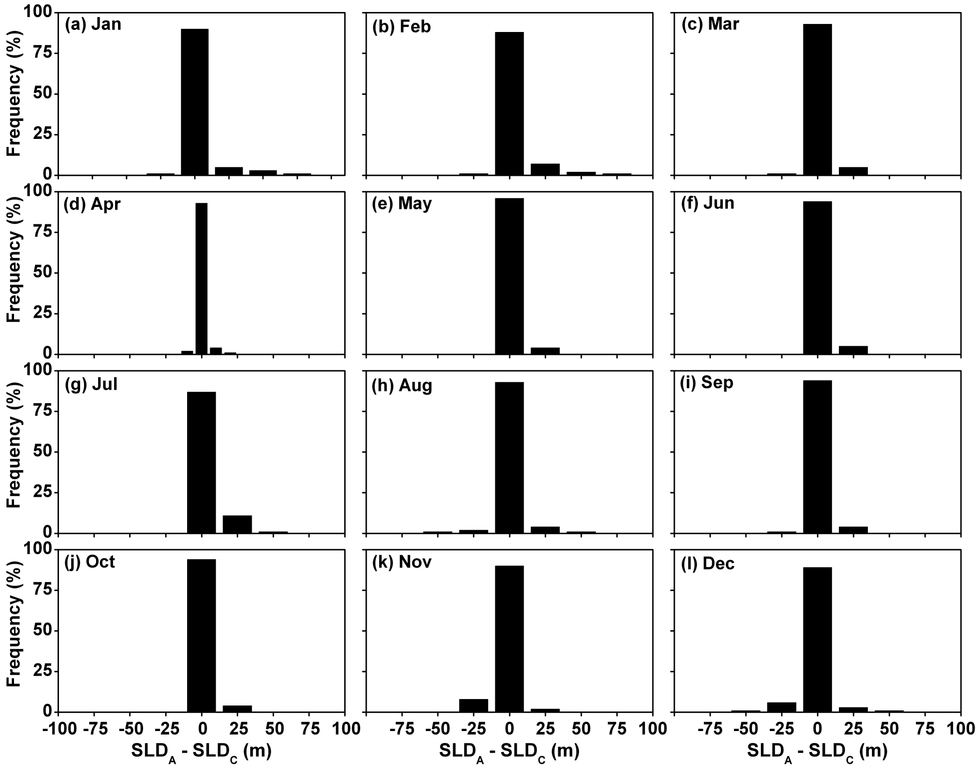

**Fig. 3:** Percentage frequency histograms of differences in SLD$_A$ and SLD$_C$ for different months [(a) January to (l) December].

4.3 Skill score

SLD$_A$ and SLD$_C$ are further evaluated based on more comprehensive statistical metrics. For this purpose monthly mean objectively analysed SLD$_A$ and SLD$_C$ observations are used for fair comparison. The statistical metrics employed here for comparing SLD$_A$ and SLD$_C$ are mean error (ME), correlation coefficient (R) and non-dimensional skill score (SS). The same is applied as follows. Let $X_i$ (i=1,2,…n) be the set of n reference SLD$_A$ values, and let $Y_i$(i=1,2,…n) be the set of corresponding values of SLD$_C$. Also let $\overline{X}$ ($\overline{Y}$) and $\sigma_X$ ($\sigma_Y$) be the mean and standard deviations of the reference values, respectively. Following Murphy (1995) and Wilks (1995), the preceding statistical measures are given as:

$$ME = \overline{Y} - \overline{X} \tag{1}$$

$$R = \frac{1}{n}\sum_{i=1}^{n}\left(X_i - \overline{X}\right)\left(Y_i - \overline{Y}\right) / \left(\sigma_X \sigma_Y\right) \tag{2}$$

$$SS = R^2 - \Big[\underbrace{R - (\sigma_Y / \sigma_X)}_{B_{cond}}\Big]^2 - \Big[\underbrace{(\overline{Y} - \overline{X}) / \sigma_X}_{B_{uncond}}\Big]^2 \tag{3}$$

In the time series comparisons, n is equal to 12, i.e., we have monthly mean $SLD_A$ and $SLD_C$ time series at a given grid point over the seasonal cycle (January through December). ME is obtained by subtracting values of $SLD_A$ from $SLD_C$. It simply represents climatological mean difference with respect to $SLD_A$. R value is a measure of the degree of linear association between time series.

The SS in Eq.(3) is the fraction of variance explained by two non-dimensional biases which are not taken into account in the R formulation. Note that $R^2$ is equal to SS only when $B_{cond}$ and $B_{uncond}$ are zero. These two biases are never negative. SS is 1.0 for perfect agreement and is negative for $B_{cond} + B_{uncond} > R^2$.

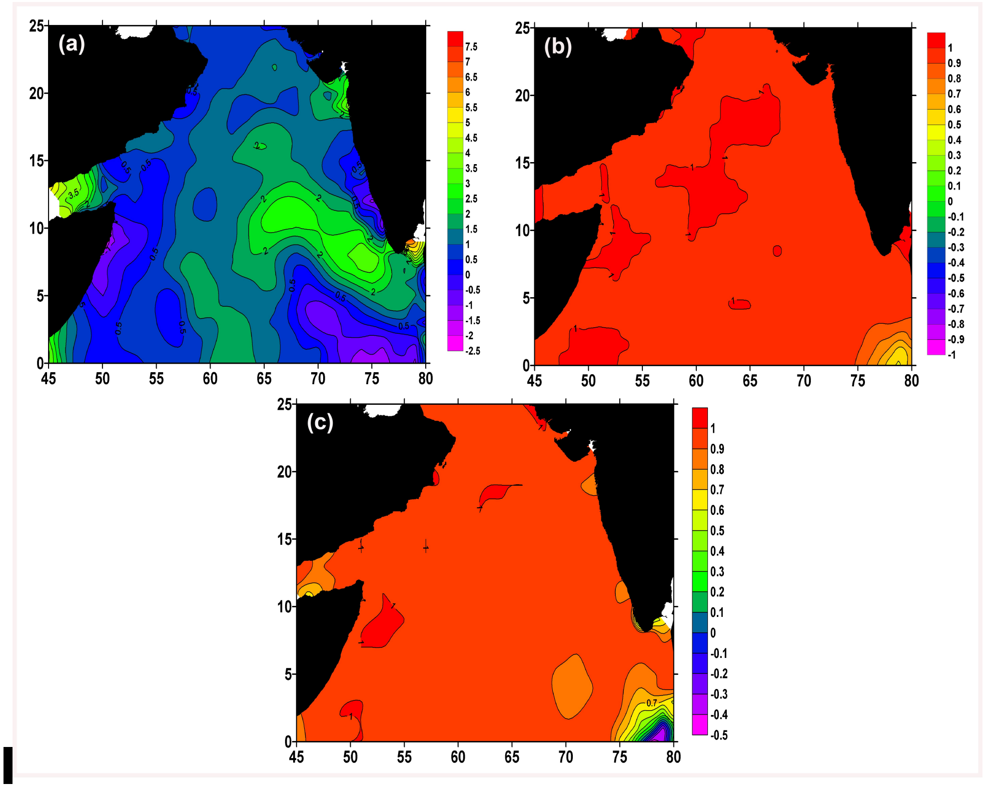

**Fig. 4:** (a) Climatological annual mean bias between $SLD_A$ and $SLD_C$ in meters. (b) Linear correlation coefficient between $SLD_A$ and $SLD_C$ (c) Skill score between $SLD_A$ and $SLD_C$. Monthly mean time series at each grid point over the seasonal cycle is used to compute statistical values.

Fig. 4 provides spatial fields of ME, R and SS for Arabian Sea, all of which were calculated over the seasonal cycle. In comparison to $SLD_A$, climatological mean bias for $SLD_C$ is small with in ± 3 m over most of the region (Fig.4a). Seasonal cycle from both $SLD_C$ and $SLD_A$ agree with each other well. This is evident from correlation values close to 1 almost all over the region (Fig.4b). The perfect skill value of 1 is also evident between $SLD_A$ and $SLD_C$ almost every where (Fig.4c) except in the eastern equatorial region where the SS is negative, which need to further explored. This indicates that the use of climatological salinity in place of observed salinity yields almost identical results in this particular ocean domain. Thus the proposed method is found to be robust and climatological salinity can be used along with temperature from XBT profiles alone in order to estimate SLD reasonably well.

## 5. Summary and Conclusion

In this study a new method is proposed for estimating sonic layer depth utilizing enormous amount of temperature profiles. Argo salinity differed from WOA01 salinity in the upper 160 m which contributed to higher error in estimated SLD. Monthly RMSD between $SLD_A$ and $SLD_C$ is found to vary between 3 – 12 m with average of 7 m. $SLD_A$ and $SLD_C$ matched in more than 90% profiles. $SLD_C$ and $SLD_A$ are further evaluated based statistical metrics like skill score, mean error and correlation. A mean bias of ± 3 m is observed between $SLD_A$ and $SLD_C$. Perfect skill score value of 1 is observed between $SLD_A$ and $SLD_C$ almost every where indicating that, the use of climatological salinity in place of observed salinity yields almost identical results in this particular ocean domain.

Hence climatological salinities can be used along with XBT for estimating SLD in the absence of CTD salinities to a major extent in AS. As robustness of the proposed method depends mainly on high quality salinity climatology, updating climatology with more and more CTDs from sources like Argo, ships, scientific cruises enable this suggested method to be more usable.

## Acknowledgements

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