An Alternate and a Better Approach to Estimate Geostrophic Velocities in the Bay of Bengal in the Absence of Salinity Profiles

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Abstract

Conventionally, Geostrophic Currents (GCs) are estimated from hydrographic transects using vertical temperature and salinity profiles, which are relatively sparse in the Bay of Bengal (BoB) compared to the temperature profiles alone from Expendable Bathythermograph (XBT). Hence, here we propose a different and better approach to compute GCs with reference to 700 m depth using temperature from XBT and salinity from climatological records with an accuracy of less than 8.12 cm/s (root mean square error) at the surface, which is proved to be better than the Temperature-Salinity (T/S) relationship with rmse of 9.624 cm/s. The RMSE error of 8.12 cm/s at the surface is 44% of the mean value. To demonstrate the present approach, we combined the temperatures from XBT and climatological salinities and computed the GCs along the Chennai-Port Blair section (covering 11° N-13° N; 80° E-90° E) from October 2006 to October 2012. This method is more suitable to use available temperature profiles from historical data to estimate the climatology and changes in GCs in various temporal scales along a selected transect in the ocean. This approach can also be used to validate GCs estimated from satellite and numerical models with certain limitations.

Keywords: Bay of Bengal, Geostrophic Currents, RMSE, T/S relationship, XBT, Climatological salinities.

1. INTRODUCTION

Estimation of GCs across a hydrographic transect is a standard procedure (Zervakis et al.,2003; Antony et al.,1993) provided temperature, salinity and pressure/depth measurements are available. Though eXpendable Bathythermograph (XBT)
technology has certain advantages, particularly, in terms of cost and logistics, the major drawback is the lack of salinity observations without which dynamic height or Geostrophic Currents (GCs) cannot be computed. Since the combined temperature and salinity data over an oceanic region from conductivity, temperature and depth and hydrographic observations (hereafter CTD) are always sparse compared to temperature profiles alone from XBT, climatological temperature/salinity relationship have been obtained to infer salinity from the temperature data (Taft and W.S.Kessler, 1991; Donguy and Meyers, 1995; Murty et al., 2000; Rebert et al., 1985; Roemmich and Cornuelle, 1990; Reverdin et al., 1991). Lagerloef (1994) obtained empirical relationships between vertically integrated temperature profiles and empirical dynamic height modes. These were then applied to XBT data to estimate dynamic heights. Ali et al. (2005) suggested a different approach to estimate dynamic height using climatological salinity from World Ocean Atlas (WOA-09; hereafter LB salinities) and temperature from XBT with respect to different reference levels. They reported that the errors involved in dynamic height computations by replacing the measured salinities with climatological salinities are 3.8%, 2.7% and 2.6% with respect to the reference levels of 200, 700 and 1000 decibars. Similarly, Ali et al. (2011) reported that errors are within the acceptable limits if sound speed profiles are estimated utilizing the LB salinities and XBT temperature profiles.

During 1992 - 2012 under the Indian XBT program quite a number of temperature profiles were collected along a few shipping lanes in the Bay of Bengal (BoB). To make use of these voluminous temperature profiles we use the approach of Ali et al. (2005) to compute GCs. The approach replaces the CTD salinities with LB salinities and the estimations are compared with estimations using CTD salinities (in both the cases CTD temperatures are considered). We selected BoB for two reasons: one is the availability of more number of CTD and XBT observations in this region compared to Arabian Sea and secondly the BoB being more challenging because of the freshwater discharge that affects salinity and thermohaline stratification (Murty et al., 1993,1992; Sastry et al.,1985; Ramesh Babu et al.,2000). While Ali et al. (2005) estimated the dynamic heights using XBT temperatures and LB salinities; we have gone one step further in estimating GCs as these estimates are obtained from the first order derivatives.

2. DATA AND APPROACH

We have used available CTD data along the selected meridional and zonal sections during 1992-2005 (Figure 1.)
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Figure 1: Study area and the locations of the stations (red dots represent the CTD stations and the black dots represent the XBT stations).

All CTD sections have more or less one degree spacing between any two selected stations. The data collection, processing and quality control procedures adopted are given in Abhishek et al., (2012). Ali et al. (2005) computed dynamic height from XBT observations, using LB salinities (https://www.nodc.noaa.gov/OC5/WOA09/pr_woa09.html), corresponding to the grid and month of the XBT observations. Earlier studies (Benny and Keisuke, 2000; Goni and Baringer, 2002) have used Temperature-Salinity (T/S) relationship to supplement XBT temperature observations with salinities. We also obtained monthly climatological T/S relationship at 1ºx1º resolution at the standard 16 depths. Altogether we obtained 192 T/S (16 depths for each profile for 12 months) relationships over 625 grid points in BoB spanning 75º E to 100º E and 5º N to 25º N by using regression technique. The slope and intercept obtained in this regression analysis is used to compute salinities from temperature alone. Thus, we have three types of salinities; (1) from CTD observations (2) from those obtained from the T/S relationship and (3) from climatology (LB salinities). GCs were computed using the temperature from CTD observations and these three
salinities separately. Considering salinity from CTD observations as a standard, we estimated the statistical parameters between (1) CTD salinities and LB salinities (2) CTD salinities and salinities from T/S relationship at different depths. Since our ultimate aim is to demonstrate the use of XBT profiles, we selected the CTD profiles only up to 700 m depth as most of XBT data are available up to this depth. The statistical parameters for different depths from all available sections in the BoB (176 stations) are given in Table 1.

Table 1: Statistical comparison of salinities obtained by the two methods and the CTD observations at different depths

<table>
<thead>
<tr>
<th>Depth</th>
<th>RMSE (CTD-LB)</th>
<th>RMSE (CTD-T/S)</th>
<th>R² (CTD-LB)</th>
<th>R² (CTD-T/S)</th>
<th>SI (CTD-LB)</th>
<th>SI (CTD-T/S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.579</td>
<td>2.432</td>
<td>0.6691</td>
<td>0.0790</td>
<td>0.0175</td>
<td>0.0733</td>
</tr>
<tr>
<td>10</td>
<td>0.554</td>
<td>1.897</td>
<td>0.6939</td>
<td>0.1354</td>
<td>0.0167</td>
<td>0.0571</td>
</tr>
<tr>
<td>20</td>
<td>0.435</td>
<td>1.491</td>
<td>0.5041</td>
<td>0.0630</td>
<td>0.0130</td>
<td>0.0447</td>
</tr>
<tr>
<td>30</td>
<td>0.392</td>
<td>0.685</td>
<td>0.3832</td>
<td>0.1156</td>
<td>0.0117</td>
<td>0.0204</td>
</tr>
<tr>
<td>50</td>
<td>0.475</td>
<td>0.546</td>
<td>0.3238</td>
<td>0.3170</td>
<td>0.0140</td>
<td>0.0161</td>
</tr>
<tr>
<td>75</td>
<td>0.361</td>
<td>0.368</td>
<td>0.3295</td>
<td>0.3215</td>
<td>0.0105</td>
<td>0.0107</td>
</tr>
<tr>
<td>100</td>
<td>0.24</td>
<td>0.29</td>
<td>0.1560</td>
<td>0.0392</td>
<td>0.0069</td>
<td>0.0083</td>
</tr>
<tr>
<td>125</td>
<td>0.15</td>
<td>0.211</td>
<td>0.1076</td>
<td>0.0071</td>
<td>0.0043</td>
<td>0.0060</td>
</tr>
<tr>
<td>150</td>
<td>0.098</td>
<td>0.114</td>
<td>0.0506</td>
<td>0.0576</td>
<td>0.0028</td>
<td>0.0033</td>
</tr>
<tr>
<td>200</td>
<td>0.059</td>
<td>0.062</td>
<td>0.0847</td>
<td>0.0001</td>
<td>0.0017</td>
<td>0.0018</td>
</tr>
<tr>
<td>250</td>
<td>0.052</td>
<td>0.056</td>
<td>0.0534</td>
<td>0.0144</td>
<td>0.0015</td>
<td>0.0016</td>
</tr>
<tr>
<td>300</td>
<td>0.048</td>
<td>0.055</td>
<td>0.0625</td>
<td>0.0001</td>
<td>0.0014</td>
<td>0.0016</td>
</tr>
<tr>
<td>400</td>
<td>0.05</td>
<td>0.054</td>
<td>0.0000</td>
<td>0.0009</td>
<td>0.0014</td>
<td>0.0015</td>
</tr>
<tr>
<td>500</td>
<td>0.05</td>
<td>0.051</td>
<td>0.0190</td>
<td>0.0077</td>
<td>0.0014</td>
<td>0.0015</td>
</tr>
<tr>
<td>600</td>
<td>0.045</td>
<td>0.05</td>
<td>0.0166</td>
<td>0.0038</td>
<td>0.0013</td>
<td>0.0014</td>
</tr>
<tr>
<td>700</td>
<td>0.046</td>
<td>0.055</td>
<td>0.0445</td>
<td>0.0038</td>
<td>0.0013</td>
<td>0.0016</td>
</tr>
</tbody>
</table>
The root mean square error (RMSE) between CTD and LB salinity varies from 0.579 Practical Salinity Units (PSU) at the surface to 0.046 PSU at 700 m depth and the scatter index (SI: defined as RMSE normalized to the mean CTD salinity) varies from 0.0175 to 0.0013. On the other hand, the RMSE (SI) of CTD salinity and that obtained from T/S relationship varies from 2.432 (0.073) PSU at the surface to 0.055 (0.0016) PSU at 700 m depth. Both the RMSE and SI between CTD salinities and climatological salinities are better compared to CTD salinities and those obtained from T/S relationship. Similarly, the coefficient of determination ($R^2$) values (significant at 95% confidence) is also better from the estimations made with LB salinities. Hence, we used LB salinities to obtain the GCs from XBT data instead of using the T/S relationship and replaced the CTD salinities with the LB salinity profiles corresponding to the month and location of the CTD salinity data. Since a few meridional and zonal sections are slightly slant, we computed the distance, $D$ in km, between the two stations, (lat1, lon1) and (lat2, lon2), using the equation (1) and the GC (in cm/s) using equation (2), following Pond and Pickard (1983), and Stewart (2008). The GCs were computed at the standard depths with respect to the 700 m level.

$$D = \text{ACOS} (\text{SIN} (\text{lat1}) \ast \text{SIN} (\text{lat2}) + \text{COS} (\text{lat1}) \ast \text{COS} (\text{lat2}) \ast \text{COS} (\text{lon2-lon1})) \ast r \quad (1)$$

$$GC = \frac{g \text{ d} \zeta}{f \text{ D}} \quad (2)$$

where $r$ is the radius of the earth (6371 km), $g$ is the earth's gravity and $d\zeta$ is the difference in dynamic height between any two adjacent stations.

Finally, to demonstrate the use of XBT temperature and LB salinities, we combined the temperatures from XBT and LB salinities and computed the GCs along the Chennai-Port Blair section (covering 11° N-13° N; 80° E-90° E) from October 2006 to October 2012, as an example.

3. RESULTS AND DISCUSSIONS
The GCs at different depths computed using temperature, salinity measurements from CTD observations, those estimated from temperature measurements from CTD and LB salinities and the difference between the two estimations along a zonal section (81.5° E - 90° E along 12° N) during August 1991 is shown in Figure 2.
The GCs obtained in the same manner along a meridional section (4°E - 17°N along 90°E) during August 1995 is shown in Figure 3. For the zonal section the magnitudes of GCs showing negative (positive) values indicate the southward (northward) flow of current. They vary from -35 to 40 cm/s. The entire section along 11°N (Figure 2a) has shown southward flowing currents with magnitudes varying between 0-20 cm/s in the upper 100 m except a narrow band of 30 cm/s northward current concentrated at 81.5°E and a strong band of 40 cm/s also noticed at 88°E. There is a strong current of 20 cm/s at 83°E that extended up to 250 m depth. Except the northward current at 81.5°E and the southward current at 83°E, that extended up to 250 m, rest are limited to only 100 m. Similar patterns with a slight change in magnitude are present in the GCs estimated with LB salinities (Figure 2b). The difference between the two estimates vary between 15 cm/s southward to 10 cm/s northward around 88°E-90°E. This difference is significant only up to 50 m (Figure 2c), from which it is evident that the GCs estimated using LB salinities are more accurate below 50 m. The anomalies are prominent only up to 50 m even at 81.5°E (83°E), where northward (southward) flow is present up to 250 m. The surface GCs using CTD temperature and salinity profiles, using CTD temperature and LB salinity profiles and the difference between the two along the zonal section (81.5°E - 90°E along 12°N) during August 1991, is shown in the Figure 3. The difference between the GCs estimated from CTD temperature and
salinities and CTD temperature and LB salinity is very less. Similarly GCs along the meridional section (4° N - 17° N along 90° E) during August 1995 are shown in Figures 3a, 3b and 3c. In this section, the magnitudes of GCs showing negative (positive) values indicate the westward (eastward) flow. Magnitude of currents along this section are significant only from 5° N to 8° N (Figure 3a). Very strong eastward flow of 60 to 70 cm/s is seen in the upper ocean near 6° N that extended up to 250 m beyond which the magnitude of currents are insignificant. However, westward currents of about 50 cm/s are notices near 7° N, which has extended up to 75 m. These currents vary from -20 to 20 cm/s in magnitude. The entire section along 11° N (Figure 3a) has shown southward flowing currents varying between 0-20 cm/s in the upper 100 m besides a narrow band of strong (30 cm/s) northward flowing current centred at 89° E.

![Figure 3(a-c): GCs with respect to 700 m depth: (a) using CTD temperature and salinity profiles, (b) using CTD temperature and LB salinity profiles and (c) the difference between the two estimations along meridional section (4° N – 17° N along 90° E) during August 1995.](image)

The RMSE between GCs with CTD salinity and LB salinities as well as GCs with CTD salinity and salinity from T/S relationship at different depths with reference to 700 m level for all the 176 stations is shown in Figure. 4. The RMSE difference between the two estimations is ~1.5 cm/s at the surface is quite significant. This difference reduces gradually and is negligible at about 75 m, which is the average mixed layer depth of the study region. It is not very clear why T/S relationship should
coincide with LB climatology at this depth, though. The RMSE of GCs from CTD-LB salinity are less (RMSE=8.12 cm/s at 0 m to 0.644 at 600 m) compared to those from CTD-T/S relationship (RMSE=9.62 cm/s at 0 m to 0.922 at 600 m).

**Figure 4:** RMSE of the GCs (cm/s) estimated using CTD temperature and salinity and CTD temperature and LB salinity (blue) and CTD temperature and salinity and CTD temperature and T/S relationship salinity (red) at the standard depths for all stations.

Since CTD temperature profiles are known to be accurate, we compare the profiles from these two instruments where CTD and XBT profiles are present at the same
location. Generally the distance between any two adjacent stations for XBT/CTD measurements is 1° (~100 km) and the time difference varies from 3.5 to 4 hours in taking the measurements, depending on the ship speed. However, the time and space between 2 adjacent stations varies depending on the requirements as well. The profiles from CTD and XBT compared at different locations are shown in Figure 5. Both CTD (red) and XBT (black) profiles match very well throughout. The RMSE at these locations vary from 0.109°C to 0.198°C which is negligible. The $R^2$ values between the two observations are 0.99 at all the depths.

![Figure 5: Comparison of temperature profiles from CTD and simultaneous XBT observations at a few selected locations in the BoB during October 2008.](image)

Thus, the XBT temperature profiles can be conveniently used in the GC estimations. Hence, to demonstrate the present approach, we combined the temperatures from XBT and LB salinities and computed the GCs along the Chennai-Port Blair section (covering 11° N-13° N; 80° E-90° E) from October 2006 to October 2012, as an example. The GCs at surface and 50 m depth are shown in Figure 6. The currents at these two depths are almost same. The southward currents are stronger over 82°E - 85°E during pre-monsoon and monsoon months of 2007, 2008, 2010, 2011 with some spatial variability. The strong southward movement is observed during June 2008 both at surface and 50 m depth over 84°E to 85°E. These strong southward transport have both intraseasonal and seasonal variations (Sarma et al., 1999; Suryanarayana et al., 1993). The eastern part of the section (86°E- 90°E) shows northward current without any seasonal changes. Nevertheless, the temporal variability of these currents is less. The spatial and temporal variability is observed in the southward currents (from Figure 6). However, it is also evident that these changes are more or less confined to western BoB.
Figure 6: GCs with respect to 700 m along the Madras-Port Blair transect (covering 11°N-13°N; 82°E-90°E) during October 2006-October 2012 estimated using XBT temperature and LB salinity profiles at surface (left panel) and at 50 m (right panel).

We have also compared the currents computed with the CTD (temperature and salinity) and CTD temperature and LB salinity, with the daily Sea Level Anomalies (SLA) data (Figure 7) from Aviso (ftp.aviso.altimetry.fr), along 4°N – 17°N at 90°E during the observation period of the section (24-29, August 1995). These estimates are closely following the altimeter observations. Thus, this approach is proved to be more accurate than using the salinity from T/S relationship.
4. CONCLUSIONS

Bay of Bengal (BoB) is more dynamical in nature due to complex air-sea interactions and frequent cyclonic activity. Presence of permanent warm (cold) core eddies with high (low) subsurface heat content, and highly stratified upper ocean due to inflow of fresh water from surrounding mainland into the bay, makes estimation of geostrophic velocities (GCs) very challenging in BoB. Further, the complex nature of winds, seasonal changes in heat fluxes in the upper ocean due to cloud cover, precipitation and depressions makes subsurface more dynamical in BoB. Since XBT profiles having temperature alone are relatively more in BoB than CTD profiles having temperature and salinity, we proposed an approach to compute GCs using XBT temperature profiles and climatology salinity profiles. The errors involved in GC estimations using XBT temperature and LB salinities are less that involved in using T/S relationship. The RMSE between the GCs computed using this data and CTD data is less than 8.12 cm/s in the surface that further decreased to 0.644 at 600 m. The RMSE error of 8.12 cm/s at surface is 44% of the mean value. Since the difference of CTD temperature profiles and XBT profiles are negligible and also because the error involved in the estimation of GCs using LB salinities is within the acceptable limits,
we conclude that XBT temperature profiles can be conveniently used along with LB salinities to estimate GCs in absence of CTD observations. However, more detailed analysis is required to accurately estimate the intraseasonal to seasonal changes in GCs in this part of the ocean. Though there are satellite altimeter observations, numerical and dynamical models available to fulfil this task, these methods have both spatial and temporal limitations. On the other hand, the present approach can be used to validate GCs from available satellite data and numerical models with certain limitations. Also, this approach is handy in utilising available temperature profiles in the pre-satellite era to compute the GCs, such that to estimate the historical and climatology of GCs along a selected section in the ocean. Thus, we used and validated this approach to estimate the GCs in BoB in the present work.

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