International Journal of Fisheries and Aquatic Studies 2017; 5(6): 34-40

E-ISSN: 2347-5129
P-ISSN: 2394-0506
(ICV-Poland) Impact Value: 5.62
(GIF) Impact Factor: 0.549
IJFAS 2017; 5(6): 34-40

www.fisheriesjournal.com
Received: 07-09-2017
Accepted: 08-10-2017

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Variation of water column density in the Bay of Bengal aquatic ecosystem

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Abstract
Water column stratification is very important to investigate the ocean dynamics. For this study, the Bay of Bengal was divided into some sub-regions and division wise temperature and salinity data were taken to study the distribution of water column density comprehensively from Argo profiling floats for the period January 2009 to December 2013. To understand the processes affecting the sigma-t variability, we also examined static stability parameters for the same region. In winter, temperature profiles of regions 1, 2 and 3 were showed a distinct thermal inversion. It may occur due to maximum net heat loss. In spring, the basin averaged temperature profile were showed no thermal inversion. Salinity was increased sharply from 25m to 85m. During spring temperature remained same, but a decrease was observed in salinity (0.5 psu) and sigma-t (0.2 kg m-3). Considering all regions, salinity was increased sharply from 15m to 65m whereas salinity at 5m was 33.1 psu, during summer. During fall season, Along the southern bay from west (Region-7) to east (Region 9) a decrease in temperature (0.3 °C), salinity (0.3 psu) and sigma-t (0.1 kg m-3) occurred. In winter and spring, southern bay stability was stronger than northern. In summer and fall, northern bay stability was stronger than southern and also highest compared to other season. Ship cruise CTD data can be collected for further study.

Keywords: Bay of Bengal, water column, density, sigma-t, static stability

1. Introduction
The solar heating is the principal source of oceanic heat and oceanic circulation [1]. The absorption of solar radiation within the water column and the exchanges of heat and fresh water across the sea surface alter the stratification of the layer that may either stabilize or destabilize the water column. Upper layers of the ocean with nearly uniform hydrographic properties that may extend up to a depth of 25 to 200 m in the tropical regions [2]. During winter, the northern bay experiences strong temperature inversions in the surface layer [3]. Changes in the shallow thermo-clines seem to influence Sea Surface Temperature to a large extent in these areas [4]. A limited number of studies examined the formation and spatio-temporal variability of the water column in the overall context of basin-wide oceanography of the Bay of Bengal. The upper layer heat content known as cyclonic heat potential is the important energy required for intensification and movement of tropical cyclone for this basin [5]. So, the study of water column becomes more important as the rate of intensification of cyclones is sensitive to water column structure. Therefore, the main objectives of the study is to investigate spatial variability of the temperature, salinity and sigma-t and its seasonal cycle in the bay.

2. Materials and Methods
The data pertaining to temperature, salinity to understand the formation and variability of the water column density/sigma-t were obtained from Argo profiling floats in the Bay of Bengal for the period of January 2009 to December 2013. All Argo floats carry sensors to measure the temperature and salinity of the ocean as they vary with depth. The quality control procedures reduced the total number of profile and finally, 8058 numbers (nos) of profiles were used for this study (Table 1). Each profile was interpolated by using Cubic Spline Method within the interval of 1meter starting from the depth of 5 meters.

3. Results and Discussion

We first examined the vertical thermo-haline structure to understand the processes affecting the variability of water column density/sigma-t.

3.1 Seasonal distribution of vertical profiles of temperature, salinity and sigma-t

In order to understand the seasonal variability of the vertical thermo-haline structure, the study domain was divided into 10 sub-regions as Region-1 (21-15°N, 80-85°E), Region-2 (21-15°N, 85-89°E), Region-3 (21-15°N, 89-93°E), Region-4 (15-10°N, 80-85°E), Region-5 (15-10°N, 85-89°E), Region-6 (15-10°N, 89-93°E), Region-7 (10-05°N, 80-85°E), Region-8 (10-05°N, 85-89°E), Region-9 (10-05°N, 89-93°E), Region-10 (05-16°N, 93-98°E), and Regions are shown in Figure 1. In each of these sub-regions, the number of available Argo profiles are listed in Table 1.

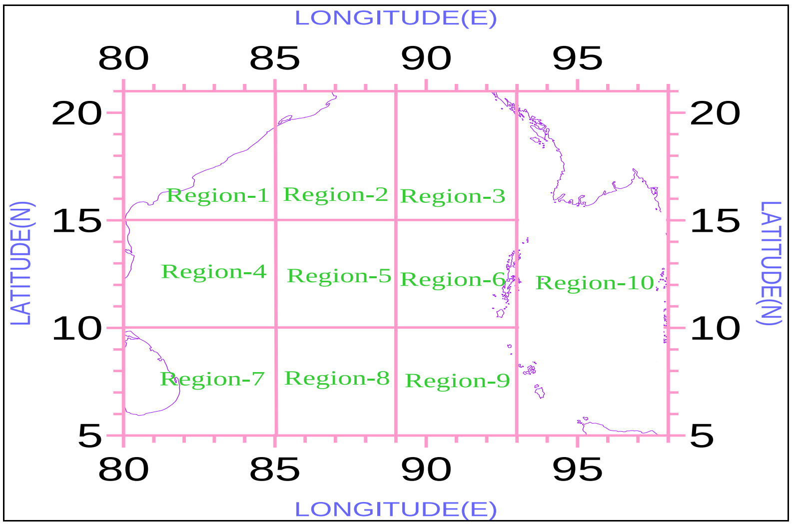


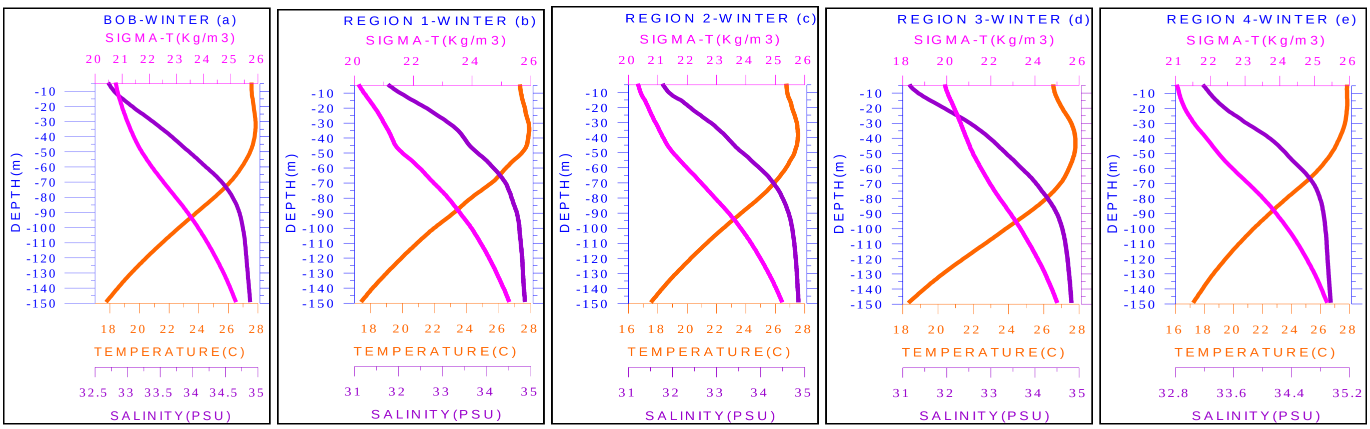
Fig 1: Location of sub- regions within the study domain in the Bay of Bengal.

Total 8058 number of Argo profile were available, which has been collected from different sub-region within different seasons (Table 1). Finally, all the profiles for a given region within different seasons are averaged to obtain seasonally averaged vertical profiles (Thermohaline structure) for each region which is also graphically presented (Figure 2 to 5).

Table 1: Sub-region wise number of Argo profiles during different season.

Season	Region1	Region2	Region3	Region4	Region5	Region6	Region7	Region8	Region9	Region10	TOTAL
Winter	134	808	455	315	583	526	133	221	247	16	**3438**
Spring	43	333	289	238	367	105	87	110	31	11	**1614**
Summer	23	183	663	377	454	238	117	214	53	28	**2350**
Fall	5	87	168	84	119	80	27	69	10	7	**656**
TOTAL	**205**	**1411**	**1575**	**1014**	**1523**	**949**	**364**	**614**	**341**	**62**	**8058**

3.2 Vertical profiles during winter



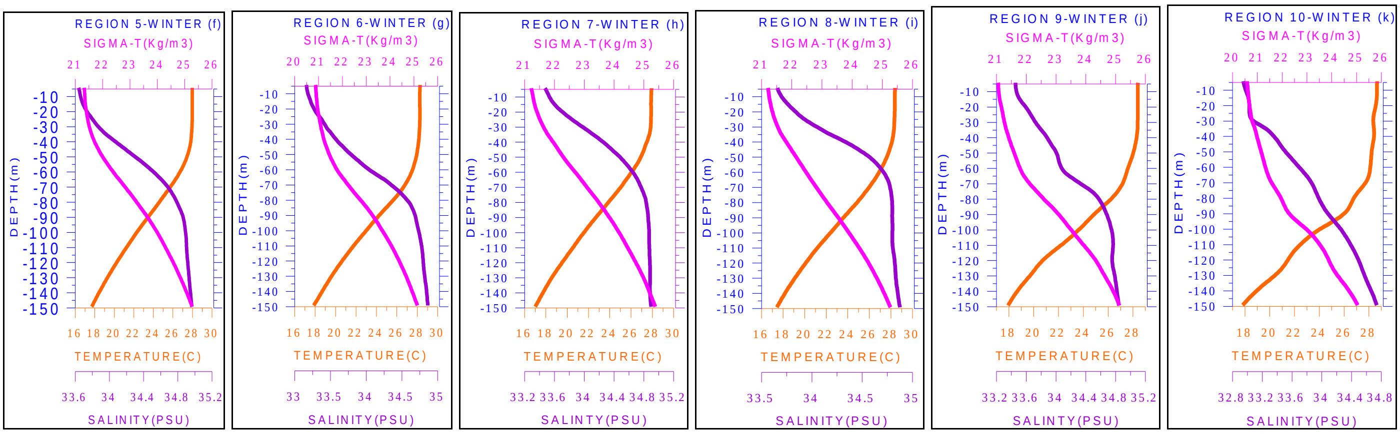


Fig 2: Sub-region wise vertical profiles of temperature, salinity and sigma-t during winter monsoon.

In winter a total 3438 noes of profiles were averaged and those temperature profiles showed distinct presence of thermal inversion (Figure 2.a). The Barrier Layer may therefore constitute a warm subsurface reservoir where increase of temperature occurs as compared to the surface [6]. Thadathil along with others in 1992 [7] have stated that the area of occurrence of inversion is limited to the coastal waters and exist up to 15°N (Figure 2). Salinity increased sharply from 15 m to 70 m depth whereas at 5 meters salinity was 32.75 psu. In regions 1, 2 and 3 temperature profile showed thermal inversion. Salinity increased sharply from 20 m to 70 m in Region-1, 15 m to 70 m in Region-2, 20 m to 75 m in Region-3, 25 m to 60 m in Region-4, 30 m to 70 m in Region-5, 30 m to 75 m in Region-6, 20m to 55 m in Region-7, 20 m to 50 m in Region-8, 65 m to 85 m in Region-9, 35 m to 70 m in Region-10.

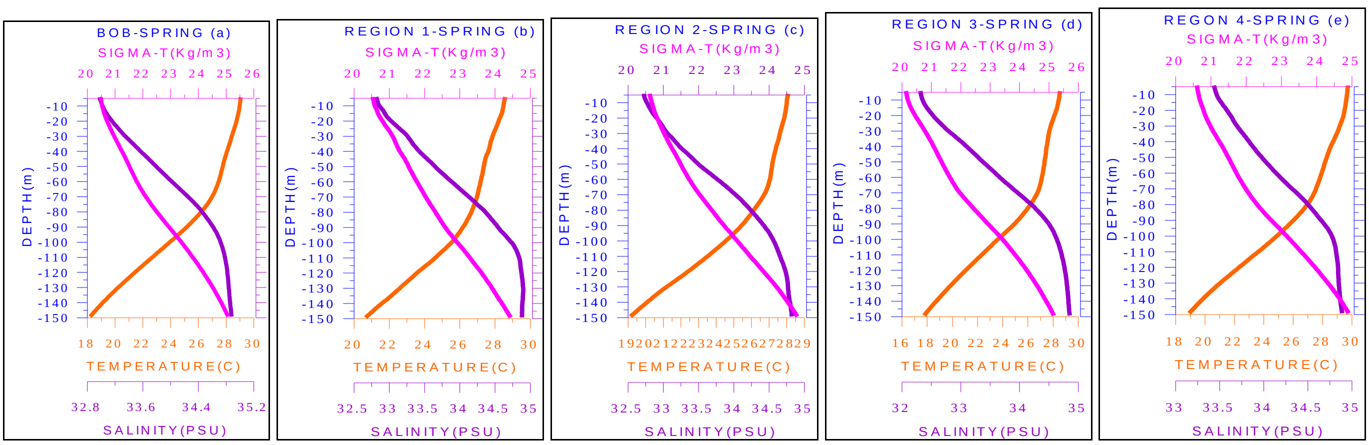
During winter, there was a zonal decrease in temperature (0.8 °C), salinity (0.6 psu) and sigma-t (0.2 kg m-3) from west (Region-1) to east (Region-3) along the northern bay. From west (Region-4) to east (Region 6) along the central bay a decrease was noticed in both temperature (1.5 °C) and sigma-t (0.2 kg m-3), while salinity remained same, whereas Region-5 showed the highest salinity and sigma-t. From west (Region-7) to east (Region 9) along the southern bay temperature increased (0.5 °C) and salinity remained same, but sigma-t decreased (0.2 kg m-3), whereas Region-8 showed the highest salinity and sigma-t.

There was a meridional increase during winter in temperature (0.6 °C), salinity (1.7 psu) and sigma-t (1.2 kg m-3) from north (Region 1) to south (Region 7) along the western bay. Also, from north (Region 2) to south (Region 8) along the central bay the temperature (1.7 °C), salinity (1.9 psu) and sigma-t (0.8 kg m-3) increased, whereas region-5 showed higher salinity and sigma-t like Region-8. Along the Eastern Bay also there was an increase from north (Region 3) to south (Region 9) in temperature (1.9 °C), salinity (2.3 psu) and sigma-t (1.1 kg m-3). The salinity profiles in Region-9 and Region-10 (Andaman Sea) showed comparatively greater fluctuation (Figure 2).

3.3 Vertical profiles during spring

In spring season, average temperature of total 1614 temperature profiles did not show any thermal inversion (Figure 3.a). Vinayachandran along with others in 2002 [8] observed the temperature inversion in the Bay of Bengal are few in April and August, but peak during November to March. Salinity increased sharply from 25 m to 85 m, whereas at 5 meters depth, salinity was 33 psu. Salinity increased sharply from 25 m to 100 m in Region-1, 35 m to 85 m in Region-2, 20 m to 80 m in Region-3, 25 m to 95 m in Region-4, 20 m to 95 m in Region-5, 25 m to 90 m in Region-6, 25 m to 60 m in Region-7, 30 m to 70 m in Region-8, 30 m to 70m in Region-9, 20m to 60m in Region-10.

During spring season, temperature remained same, but a decrease was observed in salinity (0.5 psu) and sigma-t (0.2 kg m-3). The Region-3 showed the lowest temperature, salinity and sigma-t from west (Region-1) to east (Region-3) along the northern Bay. Along the central bay, there was a decrease from west (Region-4) to east (Region 6) in temperature (0.4 °C), salinity (1.1 psu) and sigma-t (0.6 kg m-3), but region-5 showed higher salinity and sigma-t than region-6. Also, there was an increase in temperature (0.1 °C) but decrease in salinity (1.1 psu) and sigma-t (0.1 kg m-3) from west (Region-7) to east (Region 9) along the southern bay. However, the Region-8 showed the lowest temperature, salinity and sigma-t.



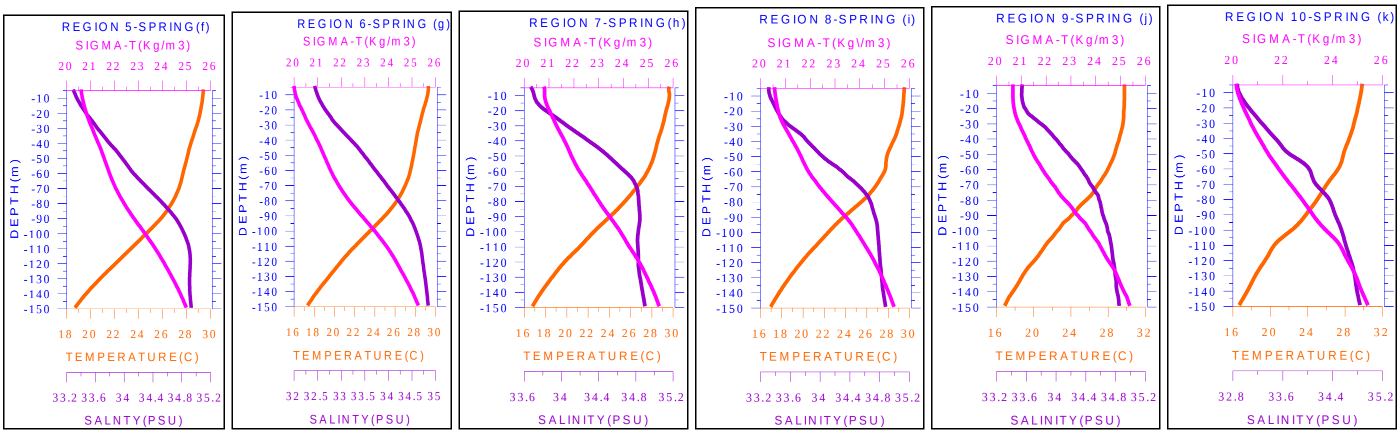


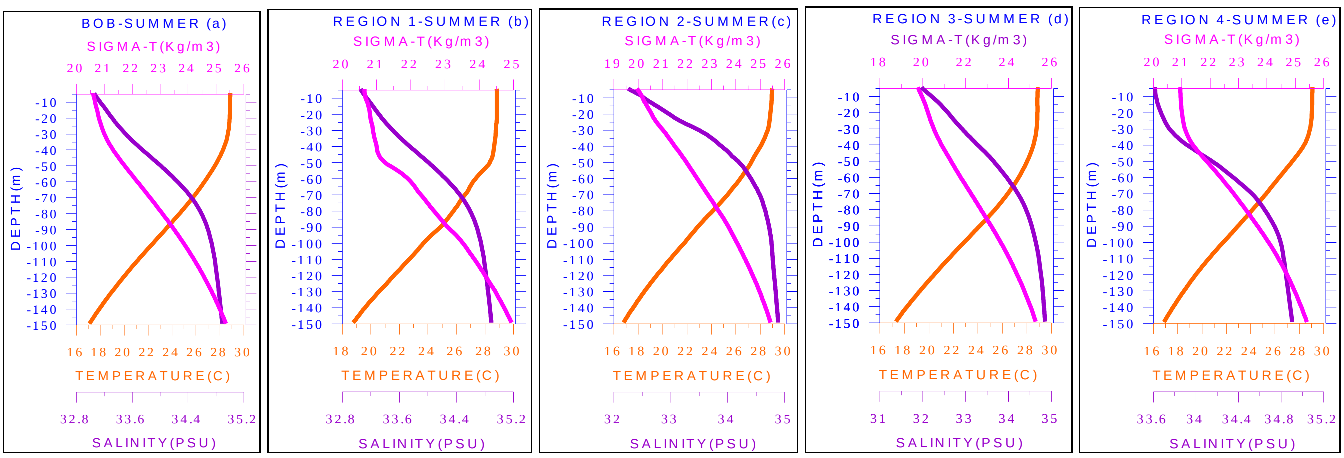
Fig 3: Sub-region wise vertical profiles of temperature, salinity and sigma-t during spring inter monsoon.

In spring there was a meridional increase (Region-1 to Region-7) in temperature (1.1 °C), salinity (0.9 psu) and sigma-t (0.2 kg m-3) with the highest temperature in Region-4 along the western bay. Along the Central Bay there was also an increase in both temperature (1.5 °C) and salinity (0.6 psu) from north (Region 2) to south (Region 8) but sigma-t remained same, whereas Region-5 showed similar sigma-t as like Region-2 and Region-8. Along the eastern bay, from north (region 3) to south (region 9), there was an increase in temperature (1.2 °C), salinity (1.3 psu) and sigma-t (0.5 kg m-3), whereas Region-6 showed lowest sigma-t (20 kg m-3). During spring in region-10 (Andaman Sea) the vertical profile of salinity showed comparatively higher variability (Figure 3).

3.4 Vertical profiles during summer

Total 2350 noes of profiles were available for summer monsoon which was averaged according to sub-regions. The averaged temperature profile haven't shown any thermal inversion (Figure 4.a). Considering all regions, salinity increased sharply from 15 m to 65 m whereas salinity at 5 m was 33.1 psu. A sharp increase of salinity was noticed vertically from 25 m to 70 m in Region-1, 5 m to 50 m in Region-2, 5 m to 60 m in Region-3, 40 m to 80 m in Region-4, 35 m to 60 m in Region-5, 60 m to 80 m in Region-6, 25m to 40 m in Region-7, 25 m to 60 m in Region-8, 40m to 80 m in Region-9, 30 m to 75 m in Region-10.

During summer temperature has shown an increase (0.8 °C) while a decrease was noticed in salinity (1.1 psu) and sigma-t (0.9 kg m-3). Along the northern bay temperature, salinity and sigma-t showed an increase from west (Region-1) to east (Region-3). In contrast, along the central Bay a decrease was noticed in temperature (0.6 °C), salinity (0.6 psu) and sigma-t (0.4kg m-3) from west (Region-4) to east (Region-6) but Region-5 was showed similar salinity and sigma-t like Region-4. Along southern bay a decrease in temperature (0.1 °C), salinity (0.6 psu) and sigma-t (0.4 kg m-3) was noticed from west (Region-7) to east (Region 9), whereas Region-8 was showed same salinity but higher sigma-t (21.5 kg m-3) than Region-7. Meridionallly, an increase in temperature (0.6 °C), salinity (1.7 psu) and sigma-t (1.2 kg m-3) was seen from north (Region 1) to south (Region 7) along the western bay.



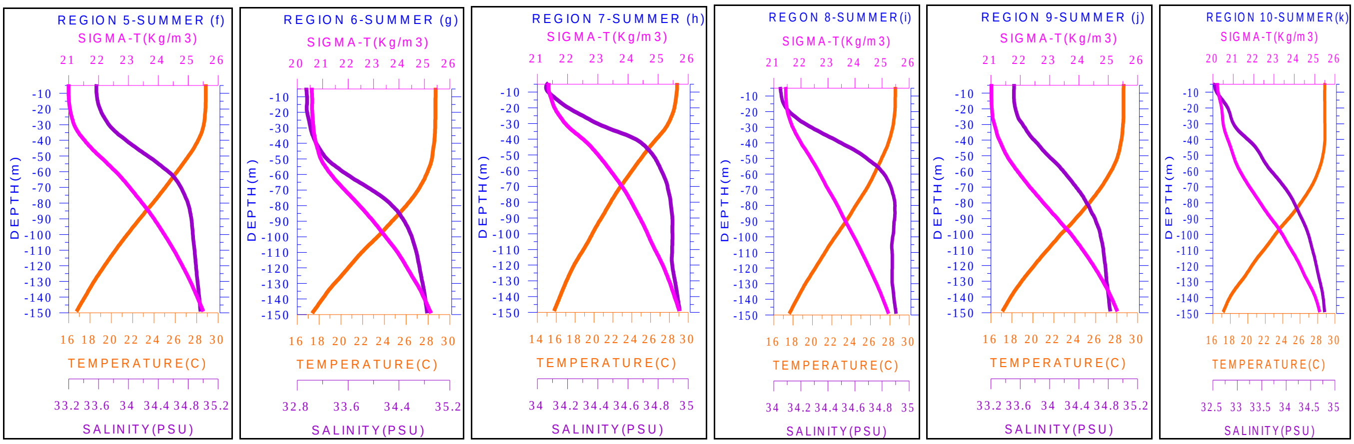


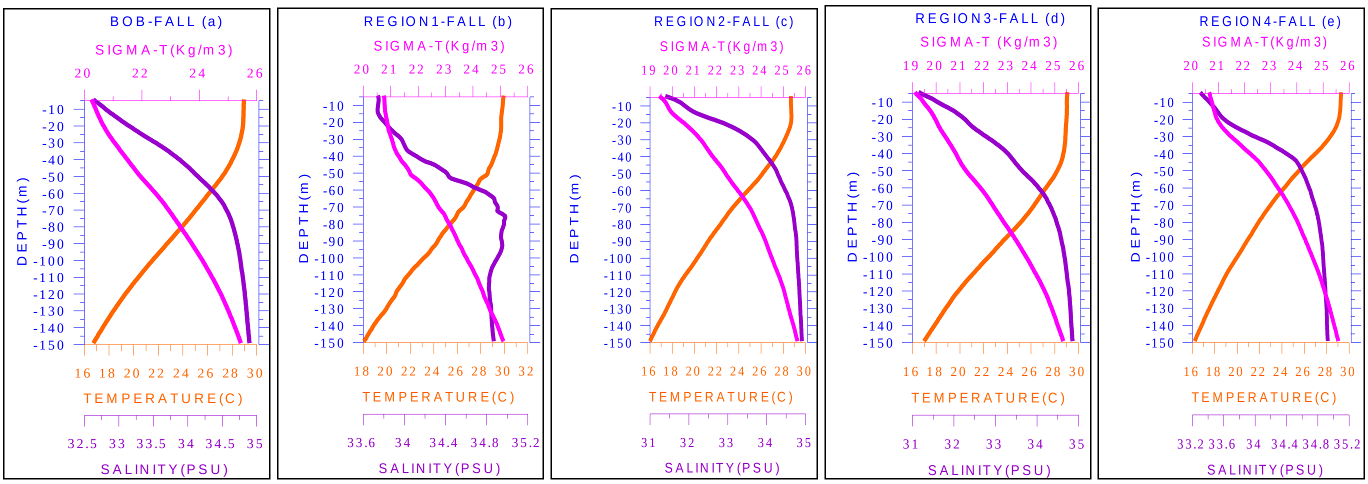
Fig 4: Sub-region wise vertical profiles of temperature, salinity and sigma-t during summer monsoon.

Along the central bay an increase in temperature (1.7 °C), salinity (1.9 psu) and sigma-t (0.8 kg m-3) was also discernible from north (Region-2) to south (Region-8). However, the Region-5 was showed higher salinity and sigma-t similar to Region-8. From north (Region-3) to south (Region-9) along the eastern bay, an increase was seen in temperature (1.9 °C), salinity (2.3 psu) and sigma-t (1.1 kg m-3) (Figure 4).

3.5 Vertical profiles during fall

A total number of 656 profiles were available during fall inter monsoon and those profiles were averaged according to the sub-regions. The averaged temperature profile hasn't shown any thermal inversion (Figure 5.a). Bishnu and others in 2011 [5] stated that the basin contains a dipole phase for the Heat Content, becoming warm in winter to spring season in the western Bay of Bengal and summer to fall season in the eastern Bay of Bengal. Salinity increased sharply from 5 m to 60 m whereas salinity at 5 m was 32.6 psu. Salinity increased sharply from 25 m to 60 m in Region-1, 10 m to 40 m in Region-2, 5 m to 55 m in Region-3, 20 m to 40 m in Region-4, 25 m to 50 m in Region-5, 30 m to 60 m in Region-6, 25 m to 40 m in Region-7, 20 m to 40 m in Region-8, 20 m to 70 m in Region-9, 35 m to 50 m in Region-10. Anomalously low temperatures at depths more than100 m are a consequence of below-average fall runoff and above-average late-winter cooling [9].

During fall, there was a general decrease of temperature (0.9 °C), salinity (2.6psu) and sigma-t (1.7 kg m-3) from west (Region-1) to east (Region-3) along the northern bay. Also, from west (Region-4) to east (Region 6) along the central bay a decrease in temperature (0.3 °C), salinity (0.9 psu) and sigma-t (0.6 kg m-3) occurred, while Region-5 showed the highest salinity and sigma-t. Along the southern bay from west (Region-7) to east (Region 9) a decrease in temperature (0.3 °C), salinity (0.3 psu) and sigma-t (0.1 kg m-3) occurred, whereas Region-8 showed the highest salinity (34 psu) and sigma-t (21.3 kg m-3). During boreal fall, a strong easterly anomaly arises near the Equator, which triggers an equatorial Kelvin wave response and generates upwelling in the eastern equatorial region [4].



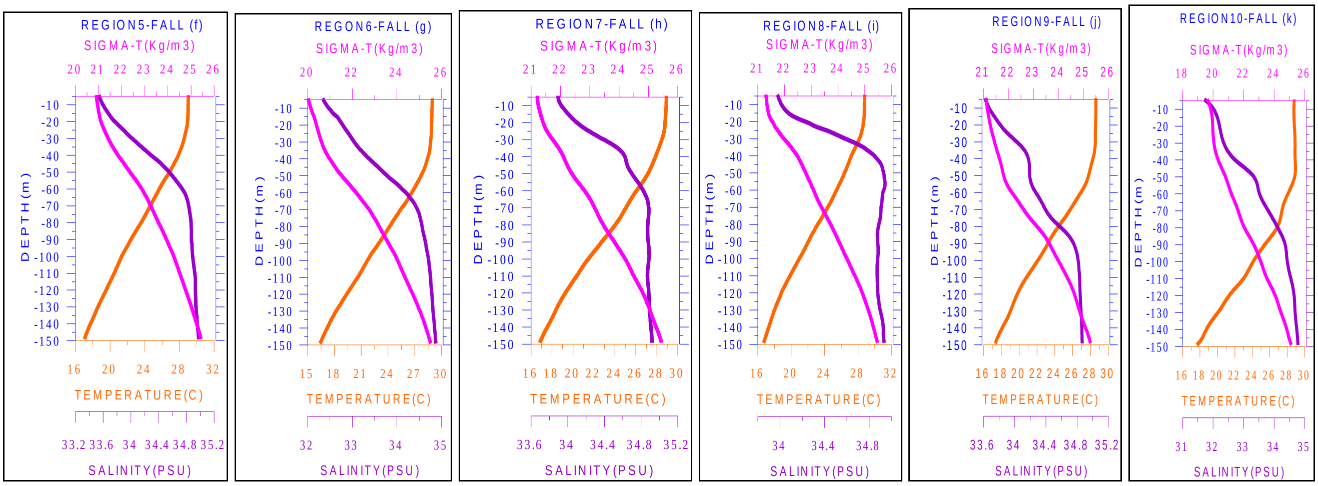


Fig 5: Sub-region wise vertical profiles of temperature, salinity and sigma-t during fall inter-monsoon.

Meridionally, during fall a decrease in temperature (1 °C) but increase in salinity (0.1psu) and sigma-t (0.4 kg m-3) was noticed from north (Region-1) to south (Region-7) along the western bay. Also, from north (Region-2) to south (Region-8) along the Central Bay temperature (0.1 °C), salinity (2.6 psu) and sigma-t (1.8 kg m-3) was increased, whereas Region-5 showed higher temperature, salinity and sigma-t than the Region-2. Along the eastern bay from north (Region-3) to south (Region-9) temperature (0.4 °C) was decreased, but salinity (2.4 psu) and sigma-t (2 kg m-3) was increased (Figure 5).

3.6 Seasonal Static Stability parameter

Seasonal Static Stability parameter (E, m-1) was defined during winter, spring, summer and fall season for region (21-15°N, 85-89°E) as northern bay, region (15-10°N , 85-89°E) as central bay and region (10-05°N, 85-89°E) as southern bay. Static Stability was analyzed to examine the stratification that could control Isotherm layer.

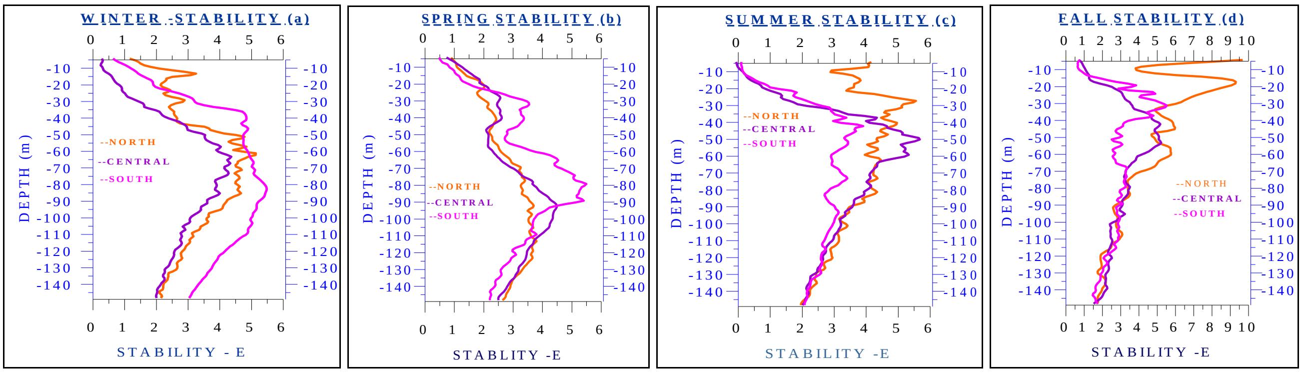


Fig 6: Seasonal Static Stability (E, m-1) parameter during (a) Winter (b) Spring (c) Summer and (d) Fall seasons in the Bay of Bengal.

In winter, southern bay stability was stronger than northern. In the upper 30 m, northern bay stability dominantly exceeded (5× 10-5 m-1) the southern bay, whereas the central bay showed the lowest. From upper 30 m to 100m, southern bay stability (5× 10-5 m-1) was stronger than northern (3× 10-5 m-1) but central bay (4× 10-5 m-1) showed the lowest value. The subsurface temperature maximum is stronger (more than 1.5^0C) at high latitudes, during the local winter season. A similar pattern of stability is seen in deeper than 100 m.

In spring, southern bay stability was stronger than northern. In the upper 25 m, central bay stability was exceeded (3× 10-5 m-1) the southern, whereas northern bay was showed intermediate value. From upper 25 m to 120m, southern bay stability (5× 10-5 m-1) was stronger than northern (3× 10-5 m-1) but the central bay (4 × 10-5 m-1) was showed intermediate value.

In summer, northern bay stability was stronger than southern and highest compared to other season. In the upper 45 m, northern bay stability was dominantly exceeded (5× 10-5 m-1) the southern, whereas central Bay was the lowest. From upper 45 m to 80m, central bay stability (5× 10-5 m-1) was stronger than northern (4× 10-5 m-1), but southern bay (3× 10-5 m-1) was seen the lowest value. In fall season, stability was showed similar pattern like summer. Stability was showed similar pattern in deeper than 100 m in almost all season (Figure 6).

5. Conclusions

Thermal inversion is a phenomenon that occurs most prominently in the northern Bay of Bengal during winter (Figure 5). High heat flux causes upper layer thermally stratified during spring and fall season that prohibits to exchange temperature towards deeper layer.

During winter, there was a zonal decrease in temperature (0.8 °C), salinity (0.6 psu) and sigma-t (0.2 kg m-3) from west (Region-1) to east (Region-3) along the northern bay. During spring temperature remained same, but a decrease was observed in salinity (0.5 psu) and sigma-t (0.2 kg m-3). The Region-3 showed the lowest temperature, salinity and sigma-t from west (Region-1) to east (Region-3) along the northern Bay. In spring there was a meridional increase (Region-1 to Region-7) in temperature (1.1 °C), salinity (0.9 psu) and sigma-t (0.2 kg m-3) with the highest temperature in Region-4 along the western bay.

It is important to lay down regional co-operation to set up immediate exploration and also to collect in-situ observation to analyze extensively the isotherm layer distribution, pycnocline variations etc for further study.

Acknowledgments

This research was possible due to the free availability of the Argo temperature and salinity profile data. We are also grateful to the core group members of Grapher software and MATLAB that were used to analyze the data.

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