Seasonality of Stratification Along the Offshore Area of the Northern Bay of Bengal

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Abstract

One of the vital factors for understanding and investigating ocean dynamics is the stratification of the water column. Argo profiling floats for the period of January 2011 to September 2017 and World Ocean Data (WOD) for the same region were taken to comprehensively study temperature-salinity distribution from which to calculate the sigma-t (density). The average density increased sharply from around 20 m to 180 m depth. It is obvious that the northern Bay of Bengal (BoB) is much cooler than the southern bay. Additionally, the southern BoB is denser than the northern BoB. The strong seasonal cycle of temperature and salinity was noticed which eventually controls the comparatively fresher water in the north and saltier water to the south. Furthermore, the static stability parameter of the water column was used to understand the processes affecting the stratification. The more the water is stable, the more the stratification of water is observed. Vertical stability was undulated in the upper 200 m and between 300-500 m depth. It was also found to be varied with strong south-west monsoon and north-east monsoon. Summer monsoon showed much stable than the winter monsoon because of the river runoff. Perhaps, the less dense water floating in the surface in summer could create the layer much stratified by inhibiting the subsurface nutrient to come upward and the opposite pattern was seen in winter monsoon. In spring and fall, southern BoB stability was stronger than northern. The study revealed that both of the available open-source datasets are very useful and precise to each other.

Keywords: Stratification, sigma-t, Argo, Stability Parameter, Northern Bay of Bengal

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Introduction

Water column stratification in the global ocean occurs mostly due to differences in densities between two layers. Stratification of seas is forced not only by solar heating at the surface but also by coastal freshwater run-off or by an excess of precipitation over evaporation (Longhurst 2007) and also by Sea Surface Temperature (SST), Sea Surface Salinity (SSS) to some extent. BoB being in the tropical region and severely affected by precipitation and river runoff, studying water stratification in this bay is highly challenging considering the fact that fewer studies are performed in the northern part of the bay. Development of fronts between stratified and non-stratified regions of the shelf are contributed by multiple processes; most important, perhaps, is vertical shear within the tidal streams, together with the effect of baroclinic eddies of semidiurnal frequency. The oceans occupy three-fourths of the earth's surface and are a vast reservoir of living and nonliving resources. They, directly and indirectly, provide foods and livelihoods to millions of people of the coastal states and elsewhere. Developing countries earn considerable revenue through the exploitation and marketing of marine living resources and other biological resources which might be affected and altered by the process of seasonal variation in stratification. One of the largest bays in the world, the Bay of Bengal (BoB) with a semi-enclosed basin with waters flowing straight out of the Himalayas through the Bengal region. The bay is roughly triangular (Vinayachandran, Murty, and Ramesh Babu 2002). It is bordered by India, Myanmar, Sri Lanka, Indonesia. Countries dependent on BoB straddle both South Asia and Southeast Asia. The BoB occupies an area of 2,172,000 square kilometres (Hussain et al. 2017)

Biological productivity in the northern BoB is one of the highest among all the oceans (Arun Kumar, Babu, and Shukla 2015; Gauns et al. 2005). Despite being in the monsoon belt, BoB comes under the influence of semi-annual seasonality due to the differential heating and cooling of the land and sea. In winter monsoon (November to February), winds are weakly (~5 m/s) blowing from the northeast. Cool and dry continental air is brought to the BoB by this wind. In contrast, during the summer monsoon (June to September), strong (~10 m/s) southwest winds bring humid maritime air into the BoB (Ramage 1971). The winds are still north-easterly during the winter monsoon when the current along the western boundary reverses and flows northward. This is called East Indian Coastal Current (EICC), which peaks during March-April (spring inter-monsoon) when the winds are weak and possess anti-cyclonic curls (Shetye et al. 1991). The excessive river runoff (1.625 X 1012 m^3y^{-1}) into the BoB (Subramanian 1993) and rainfall leads to a positive water balance (P–E=0. 8m y^{-1}) (Balachandran et al. 2008). Runoff from the Indian rivers to the BoB play a critical role in the process of monsoon intensification by creating and sustaining low salinity layer on the top of the BoB (Rajamani et al. 2006). The massive freshwater influxes result in strong vertical stratification, which impedes the vertical transfer of nutrients to the surface, leading to low biological production. Based on the monsoon (arrival and retrieval) and its associated environmental characteristics, the northern Indian Ocean experiences variations in seasonality. The four seasons addressed are as follows:

Spring inter-monsoon (March to May): The water column becomes more stabilised by thermal stratification. Hot weather prevails with occasional violent local storms accompanied by violent winds, torrential rain, etc.

Summer monsoon (June to August): Characterised by south-westerly winds and resultant heavy rainfall, the bulk of annual rainfall in India is received during these months.

Fall inter-monsoon (September-October): Intensity of rainfall becomes much less. Low-pressure zones are developed, which sometimes intensify into cyclonic storms. Generally, a season of transition.

Winter monsoon (November to February): A period when the sea surface loses heat to the atmosphere, consequently, the surface water becomes colder, bringing heavy rain, particularly in the northern regions of the BoB. (Babu et al. 2003; Murty et al. 1992)

BoB appears to be variable and also quite complex. The more the water would be stratified, the less the water would mix and less mixed water column would be less productive (less production of marine living resources) due to less nutrient upwelling from deeper water. Therefore, study of water column stratification is very important for the nation's economic growth. The area selected for this study is located in the BoB having geographic coordinates 85º to 95ºE longitude and from 18ºN to 21ºN latitude. As a basin situated in the monsoon regime, it is influenced by several oceanic processes with seasonal variability.

Objectives

The prime objective of this study is to characterise the distribution of water column stratification of the northern BoB, however, other important goals of this study are:

- To know the seasonal variability of the stratification in Northern Bay of Bengal
- To determine the seasonality of the density of the Northern Bay of Bengal
- To compare the open-source data to the Argo profiling data in the Northern BoB

Materials and Methods

Study area

Bathymetry of the study area indicates that inside the black dashed line (Fig. 1), there are lower depth area, shelf-slope region, and depth increases rapidly after the shelf until 18°N. All the Argo profiling floats and in-situ measurements data from the World Ocean Database (WOD) were considered in the box. Because of the shallower depth, the Argo floats were not available from 20°N to the coast of Bangladesh. So, WOD datasets were only used in that case.

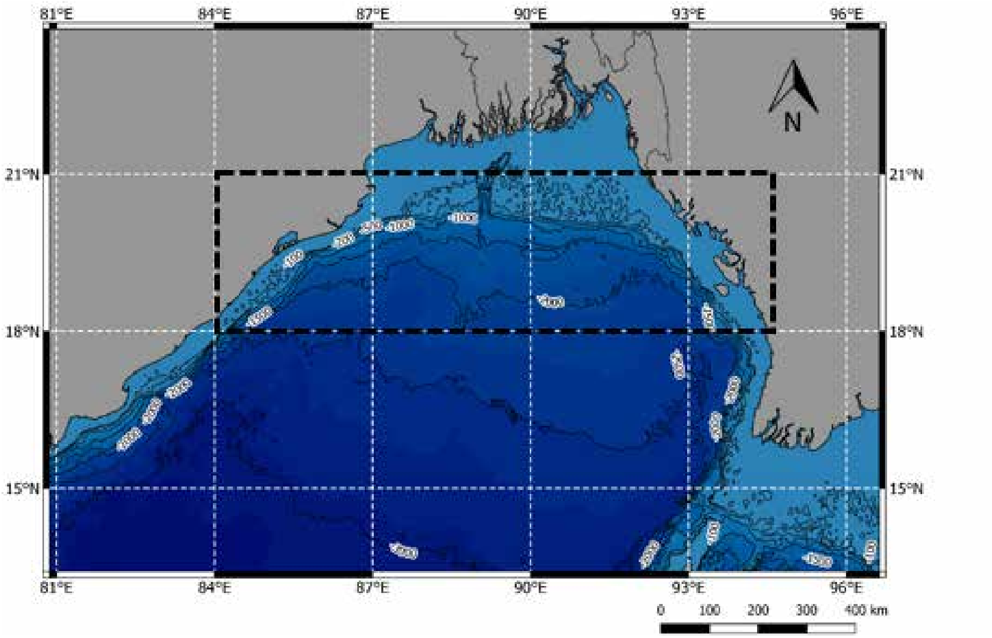


Figure 1 Bathymetry of the northern BoB. The black dashed line is the area (18–21°N, 85°E–95°E) of this study.

Data Sources and Analyses

Temperature and salinity data for the present study were obtained from USGODAE website (https://www.usgodae.org/cgi-bin/argo_select.pl) of Argo profiling floats in BoB within the domain 18–21°N, 85°E–95°E from the period January 2011 to September 2017. The spatial distribution of the number of Argo-derived temperature-salinity profiles was taken in the delay mode. Note that, north of 21°N latitude, there are no Argo profiles and in BoB the number of profiles was extremely low. Another data source for this study would be, World Ocean Database (WOD), which builds on this record and includes updates and new data. The 40 standard depth levels used in previous versions of WOD are all among the 137 standard depth levels used in WOD13, to provide continuity. Open-source software package Ocean Data View (ODV) is used to read the WOD native format and display the data. Ocean Data View 4.5.7 has been updated to read the amended format. All the Argo profiles were in NetCDF format (.nc) and in the discrete grid. Therefore, the ODV software was used to visualise by interpolating with the built-in DIVA method. GEBCO 2014 bathymetry data was used to produce the location map by using QGIS software.

Visual observation of temperature, salinity, and density profiles in BOB indicated that temperature-based techniques have been used most frequently, owing to the ease of reliability. For regions with weaker haloclines, both the temperature and density-based techniques produce nearly equivalent results (Brainerd and Gregg 1995). However, density-based methods have more reliability for regions where upper ocean salinity changes are high and precipitation can stabilise the water column stratification (Brainerd and Gregg 1995; Lukas and Lindstrom 1991; S Levitus, (173), and 1982, n.d.).

In the present study, the water column stratification is defined as the density sharply increase from surface value and it's denoted by "E". Stability in the Ocean, just like in the atmosphere, there are three possible scenarios: $E > 0$, stable, $E = 0$, neutral, and $E < 0$, unstable water column. The temperature and salinity also further used to calculate the density for the computation of the static stability parameter as follow:

$$E = -1/\rho\ (\delta\rho/\delta z)$$

Where E is the static stability parameter (m^{-1}), ρ is the density (kgm^{-3}) of the water and z is the depth (m) (Pond and Pickard 1983). The density of seawater was calculated using the equation of state for seawater developed by Pond and Pickard (1983) from Argo and WOD temperature and salinity, while depth was calculated from pressure using in an equation by inputting latitude and pressure at the location. The temperature/salinity/density at 5 m depth is considered as surface or initial temperature/salinity/density.

Results

Sigma-t Distribution Profiles

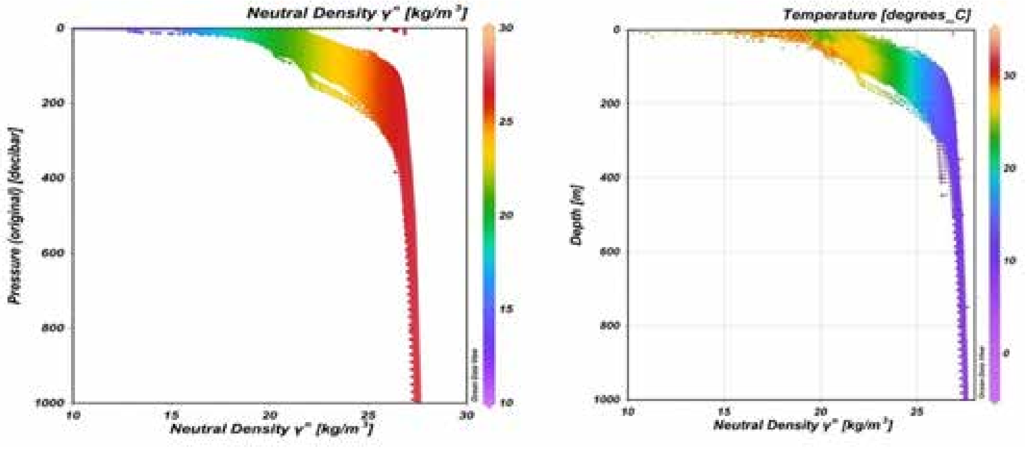


Figure 2 Vertical sigma-t profiles from Argo data (left) and WOD data (right) from 2011 to 2017.

During the seven years' study, all profiles were averaged without any seasonality and the averaged Vertical Sigma-t profile (VS-t) showed the presence of a typical profile with a large pycnocline in Fig. 2. Sigma-t increased sharply from 10 m to 180 m depth. Over the whole period of study of all seasons, the highest value of sigma-t was around 28 kg m-3 beyond the depth of around 200 m while the lowest was approximately 12 kg m^{-3} near to the surface that can be seen in Fig. 2 (right). Surface Sigma-t (SS-t) distribution within the area 90ºE to 94ºE and 18ºN-20ºN is comparatively lower (14-16 kg m^{-3}) than the other part of the bay.

Surface Sigma-t Distribution (SS-t)

It was clear that the highest value of SS-t was around 20 kgm^{-3} and the lowest is 12 kgm-3 that can be seen in Fig. 3 (right). SS-t distribution within the area 90ºE, 91ºE and 94ºE and 18ºN-20ºN is comparatively lower (14-16 kgm^{-3}) than the other part of the bay. Comparatively higher values of SS-t of around 18 kgm^{-3} are found along the 91ºE, 92ºE and 93ºE longitude line. There are no Argo data after 20ºN to the northern part of the bay while the WOD has more data beyond the north of 20ºN latitude. The WOD data captures a similar pattern of Argo data for all SS-t distribution that can be seen in Fig. 3 (left). However, it is obvious that the northern BoB is much dense than the southern bay. During

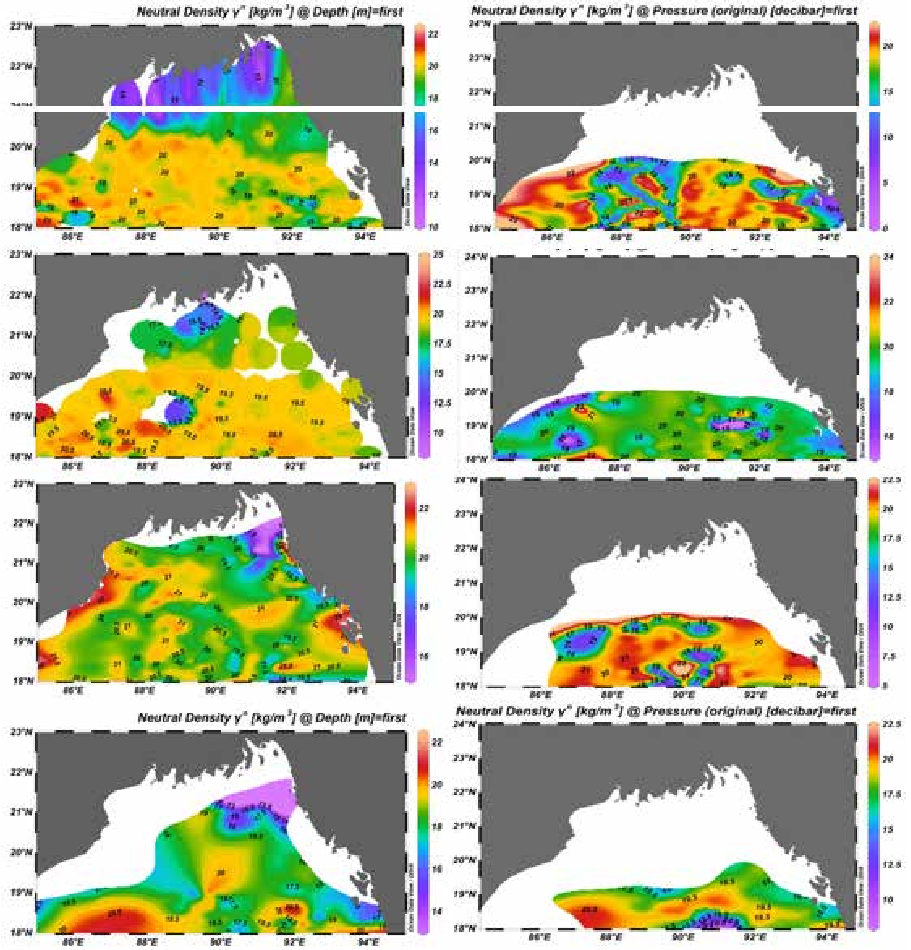


Figure 3 Surface sigma-t distribution from WOD data (left) and Argo data (right), Summer, Spring inter-monsoon, Winter monsoon, Fall inter-monsoon respectively (top to bottom).

all seasons, the density varies by 3-4 kgm^{-3} from northern to the southern bay. Although, both datasets have revealed almost the similar pattern of SS-t, whereas the maximum values of WOD and Argo SS-t are 20 kgm^{-3} and 20 kgm^{-3} respectively.

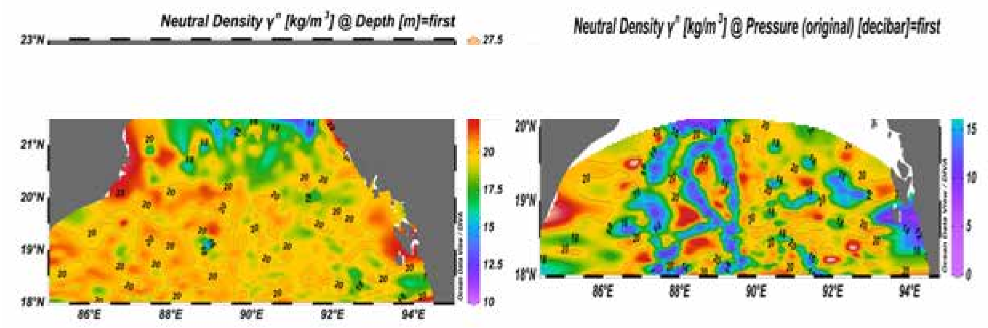


Figure 4 All seasons averaged surface sigma-t distribution from WOD data (left) and Argo data (right).

The above images illustrated the overall pattern of the surface density (SS-t) over the entire period of averaged values. Both of the datasets showed a similar density structure in the area of 18ºN -21ºN where the SS-t values ranged from 14-22 kgm^{-3} (Fig-4). In the western BoB, the higher density observed while the northernmost and eastern bay is comparatively lower dense. The fresher water was found very close to the Bangladeshi coast.

Latitude Average Vertical Sigma-t Structure (LAVS-t)

During all monsoons, the highest value of latitude averaged vertical sigma-t structure (LAVS-t) near-surface is 21 kgm^{-3} and the lowest value is 19kgm^{-3} that can be seen in Fig. 5 (upper). The first unbroken contours 20.5 kgm^{-3} is seen along approximately 40 metres' depth whereas contours are drawn 0.5 kgm^{-3} intervals in this figure. LAVS-t contour line 20.5 kgm^{-3} to contour line 26 kgm^{-3} is distributed with a sharp change of density within the depth 40-160 metres that depth range can be defined as pycnocline.

After the depth of about 160 metres, density started to change slowly. If we look at both in upper and lower Fig. 5 around 91ºE longitudes, downward or down-welling tendency (with comparatively deeper 25 kgm^{-3} contour line) can be seen there. Except that longitude line others area shows somehow horizontal pattern contour line with few concaves up or upwelling tendency. The WOD data captures the closely similar pattern of Argo data for the all-season LAVS-t distribution that can be seen in Fig. 5 (lower). Although both datasets have revealed almost the similar pattern of LAVS-t, whereas the minimum surface values of WOD and Argo data are 19.5 kgm^{-3} and 19 kgm^{-3} respectively.

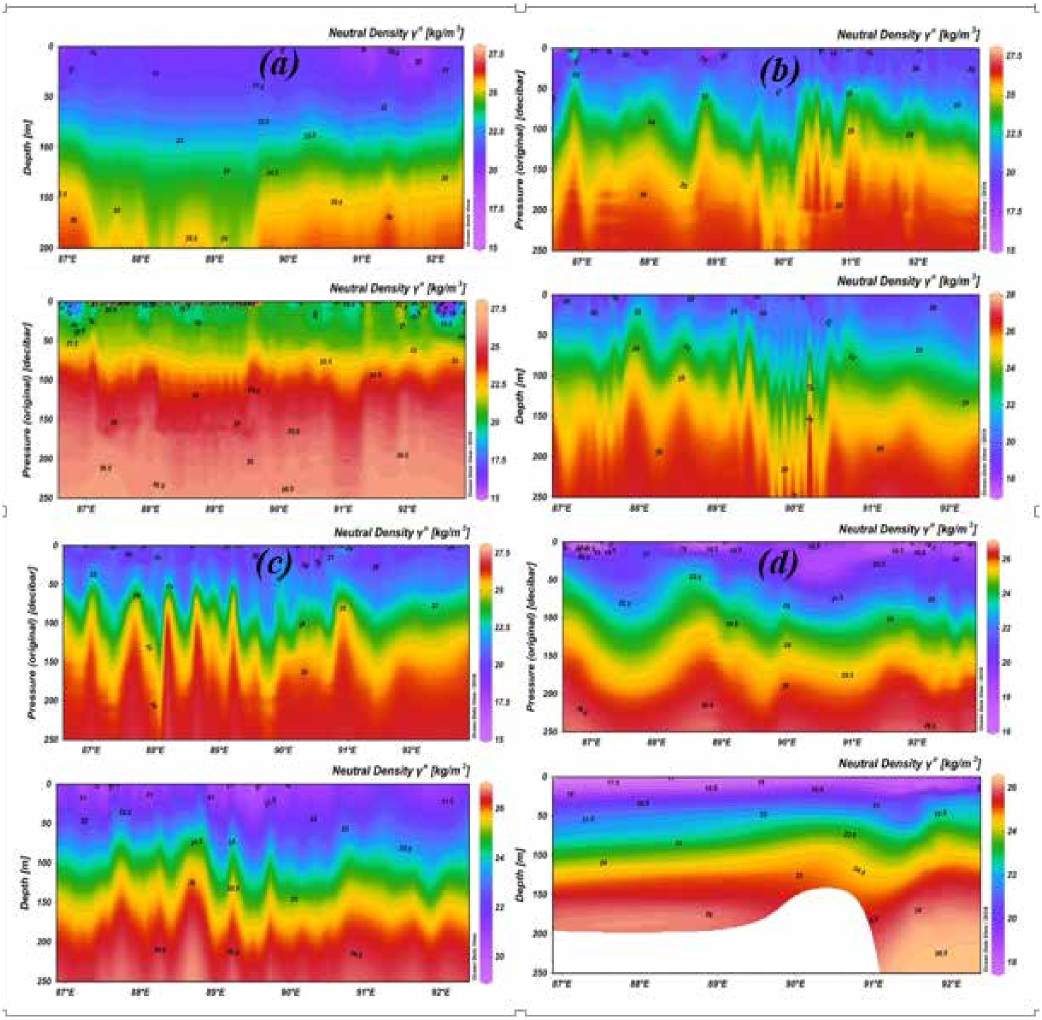


Figure 5 Latitude average section plot for sigma-t of WOD (upper) and Argo (lower): (a) Winter monsoon, (b) Summer monsoon, (c) Spring inter-monsoon (d) Fall inter-monsoon.

Stability Distribution Profiles

Throughout the whole period of study, all profiles were averaged without any seasonality and the averaged Vertical Stability-Rp (VS-Rp) profile showed the changing tendency of stability from both Argo data and WOD data (see Fig. 6). Most of the data showed zero Rp whereas within the 200 m depth and between 200-400 m depth Rp ratio fluctuates intensively. After the depth of 400 m Stability, the ratio is almost constantly zero. The WOD data captures a similar pattern of Argo data for the study VS-Rp distribution that can be seen in Fig. 6.

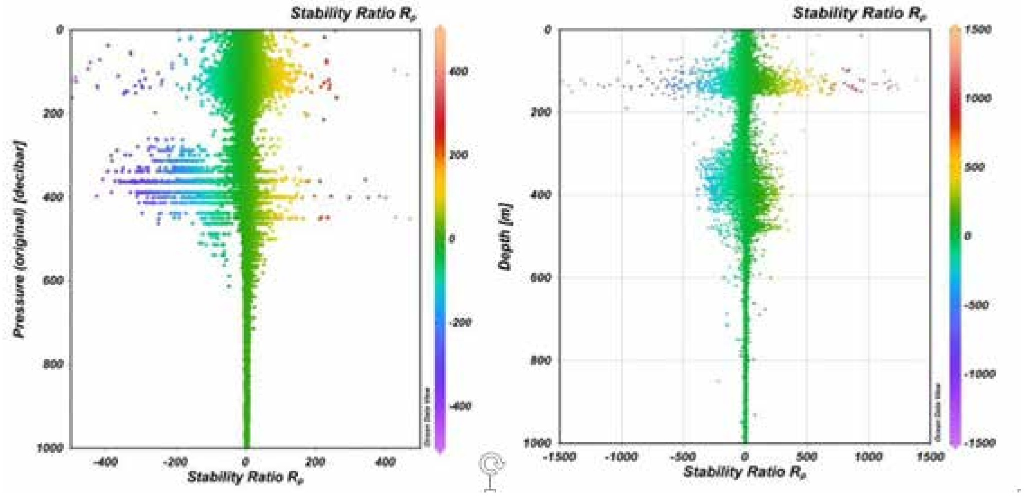


Figure 6 Vertical stability Ratio-Rp from Argo (left) and WOD (right) from 2011 to 2017

Surface Stability-Ratio Distribution

All through the seven years' study of all seasons, the highest value of stability is 40 and the lowest value is -10 that can be seen in Fig. 7 (right). Stability ratio distribution within the study area indicates a stable situation. There are no Argo data after 20ºN to the northern part of the bay while the WOD has more data beyond the north of 20ºN latitude. The WOD data captures a similar pattern of Argo data for them all season's stability distribution that can be seen in Fig. 7. However, it is noticeable that the northern BoB is much stable than the southern bay. Although, both datasets have revealed almost the similar pattern of stability, whereas the maximum values of WOD and Argo vary by 5 Rp.

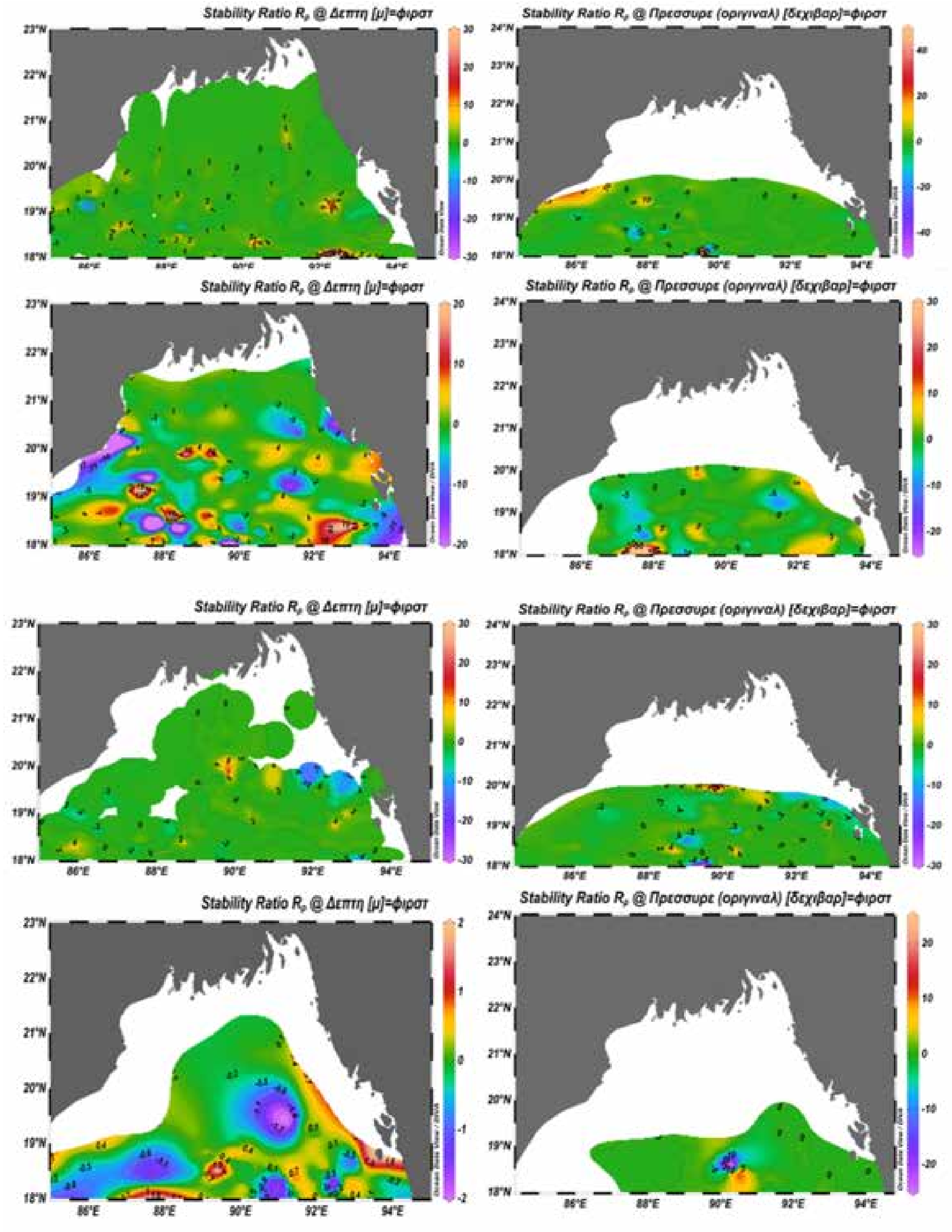


Figure7 Surface sigma-t distribution from WOD (left) and Argo (right), Winter monsoon, Spring inter-monsoon, Summer monsoon, Fall inter-monsoon respectively (top to bottom)

Latitude Average Vertical Stability Ratio-Rp structure (LAVS)

For the period of the study of all seasons, the highest value of latitude averaged vertical stability structure (LAVS) near-surface is 0 that can be seen in the Fig. 8 and

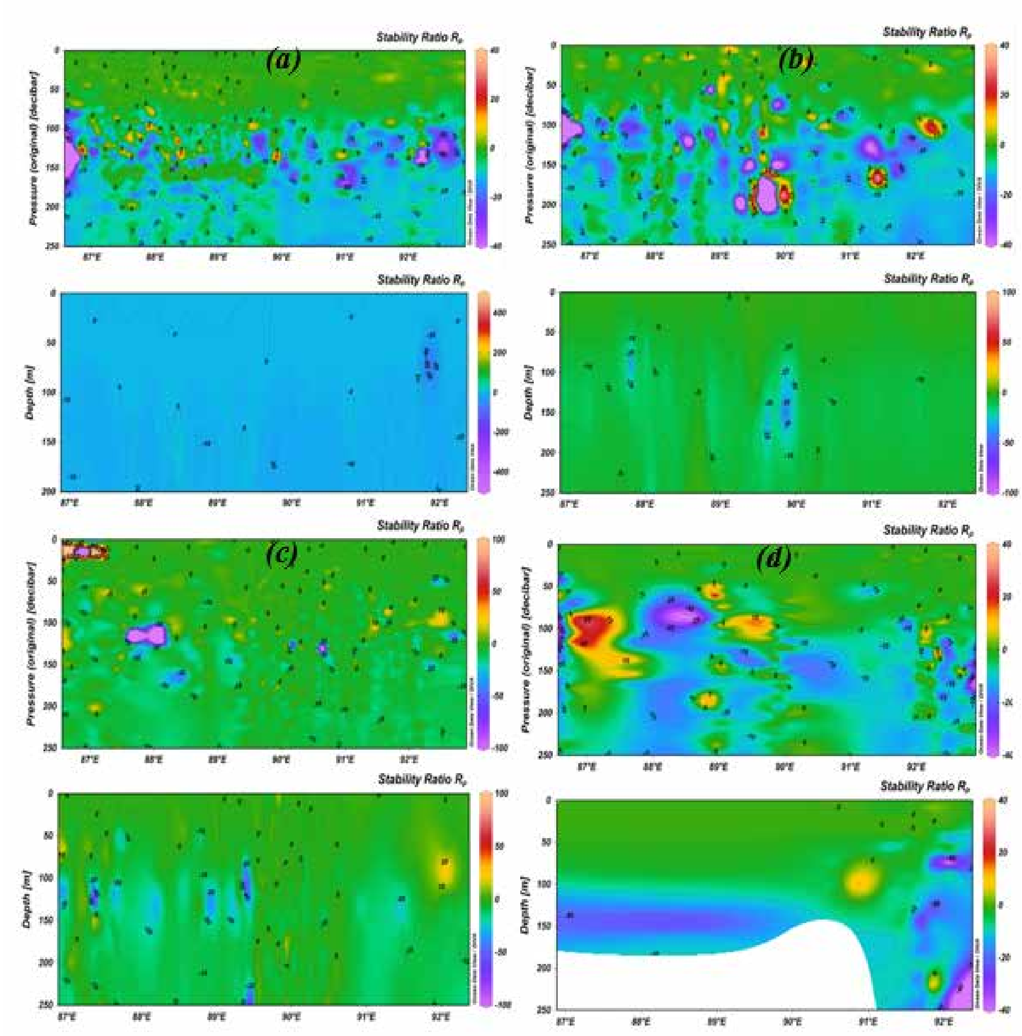
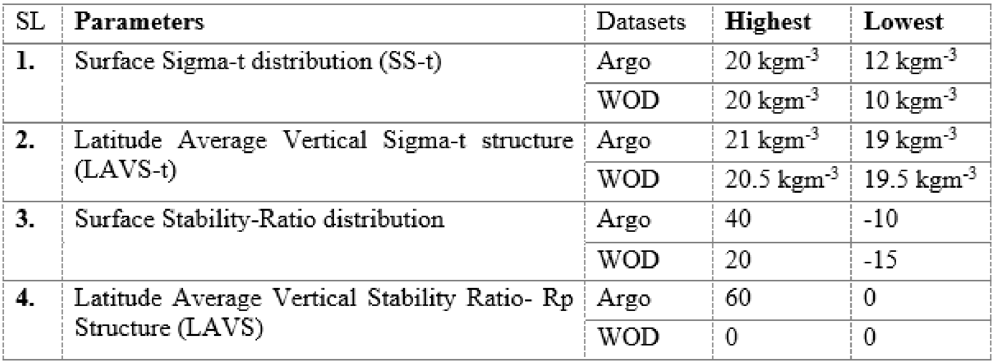


Figure 8 Latitude average vertical sigma-t structure for WOD (upper) and Argo (lower): (a) Winter, (b) Spring, (c) Summer, and (d) Fall.

means that water is stable near-surface. LAVS is distributed with a sharp change of stability within the depth 100-150 m that depth range can be defined as instability of water column. After the depth of about 150 m, water becomes more stable. The WOD data captures the closely similar pattern of Argo data for all seasons combined distribution except the instability extended more area in Fig. 8.

Table 1 Summary of all parameters with different sources of datasets



SL	**Parameters**	Datasets	**Highest**	**Lowest**
1.	Surface Sigma-t distribution (SS-t)	Argo	20 kgm^{-3}	12 kgm^{-3}
		WOD	20 kgm^{-3}	10 kgm^{-3}
2.	Latitude Average Vertical Sigma-t structure (LAVS-t)	Argo	21 kgm^{-3}	19 kgm^{-3}
		WOD	20.5 kgm^{-3}	19.5 kgm^{-3}
3.	Surface Stability-Ratio distribution	Argo	40	-10
		WOD	20	-15
4.	Latitude Average Vertical Stability Ratio- Rp Structure (LAVS)	Argo	60	0
		WOD	0	0

Discussion

The BoB is traditionally considered to be a less productive bay. We have tried to find out the reasons for this in the northern bay during summer (June-August). Large rainfall and river water decrease salinity discharge along with the upper layers of the bay during summer, and SS-t was also warmer. This leads to a strongly stratified surface layer. The weaker winds over the BoB are unable to erode the strongly stratified surface layer, thereby restricting the turbulent wind-driven vertical mixing to a shallow depth of <20 m (Prasanna Kumar et al. 2002). During the spring inter-monsoon (March-May), strong stratification depleted nitrate concentration in the water column (60 m water column had <0.01µM) (Jyothibabu et al. 2006). During this period, dissolved oxygen concentrations in the surface waters (upper 50 m) of the Bay of Bengal were higher than in other seasons (Jyothibabu et al. 2008). During winter (November-February), there was a spatial decrease in temperature (4 °C), salinity (11 psu) and sigma-t (6 kg m$^{-3)}$ from south to north along the northern bay. The special difference of SS-t between WOD and Argo data was 21-22 kg m^{-3} (Fig. 3). During the fall, there was a general decrease of sigma-t (7.5 kg m^{-3}) from south to north along the northern bay (Fig. 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 equator meridional (Chowdhury et al. 2017). Vertical and surface seasonal static stability parameter (E, m^{-1}) was defined during winter, spring, summer and fall season for WOD and Argo data focusing the differences between them. Static stability was analysed to examine the stratification that could control the isotherm layer. In winter, southern bay stability was stronger than northern because of the temperature gradient from the south to north. In the upper 30 m, northern bay stability dominantly exceeded (5× 10-5 m^{-1}) the southern bay (Fig. 7). From upper 30 m to 100 m, southern bay stability (5× 10-5 m^{-1}) was stronger than northern (3× 10-5 m^{-1}) due to the subsurface temperature maximum which was stronger (more than 1.5°C) at high latitudes during the local winter season. A similar pattern of stability was seen in deeper than 100 m. The north-east winter monsoon was collapsed just after the winter which causes the southern bay stability stronger than northern bay in spring. In the upper 25 m, the northern bay was showed intermediate value which could be the reduced amount of freshwater present in the spring. In summer, northern bay stability was stronger than southern and highest compared to another season. In the upper 45 m, northern bay stability was dominantly exceeded (5× 10-5 m^{-1}) the southern. 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 as the lowest value. This phenomenon was mainly because of the huge amount of freshwater from the river runoff as well as rainfall which normally less dense and floated in the surface of the northern bay waters. Thus, this surface freshwater became much stratified during the summer. In the fall season, stability was showed a similar pattern like summer. Stability was showed a similar pattern in deeper than 100 m in almost all seasons (Fig. 8) (Chowdhury et al. 2017) because the deep water was not much affected by the surface stratified layer due to the temperature and salinity derived stratification.

Conclusion

The present study focuses on the seasonal variability of stratification in the northern BoB. The energy required for mixing from Argo observations and WOD is analysed to understand the as seasonal variability of upper-ocean stratification from 2011 to 2017. Water column stratification is a phenomenon that occurs most prominently in the northern Bay of Bengal during inter-season. Higher heat flux could be one of the reasons for thermal stratification in the upper layer, especially during spring and fall season, followed the exchange of temperature with the deeper layer. During winter there was a spatial decrease in temperature, salinity and (6 kgm^{-3}) from south to north along the northern bay. Static stability was analysed to examine the stratification that could control the Isotherm layer. The southern bay was strongly stable than its northern counterpart during winter. Also, in the spring season, stability showed a similar pattern like winter. Conversely, in summer, northern bay stability was stronger than southern. Similarly, in the fall season, stability showed a similar pattern like summer. It is important to lay down spatial and temporal co-operation to set up immediate exploration and also to collect in-situ observation to analyse extensively the water column stratification and its seasonal variations etc. for further elaborate study.

Acknowledgement

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