Barrier Layer Thickness of Central Bay of Bengal during the post monsoon season, 2013

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Abstract

Barrier Layer (BL) lies between bottom of the Mixed Layer (ML) and the Isothermal Layer (IL). It is a unique phenomenon in oceanic areas with excess fresh water input. A seasonally and spatially distributed BL exists in Bay of Bengal. Conductivity Temperature Depth (CTD) profiles, collected during October, 2013 by R/V Fridtjof Nansen, were used to describe the behavior of the Barrier Layer Thickness (BLT) at the Central Bay of Bengal. Sea Surface Salinity (SSS) map showed a high and a low saline water cells with the salinity range of 34-34.6 and 33.2- 33.8 PSU respectively. BLT had varied from 10 to 60 m. Spatial distribution of BLT exhibits strong positive correlation with distribution of IL (R = 0.837), but not with ML (R = -0.443) and SSS (0.198). Distribution of the BLT showed a meridional gradient, as the thickness at Northern and Southern survey area are 10-30 and 30-60 m respectively.

Keywords: Barrier Layer Thickness, Mixed Layer, Isothermal Layer.

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Introduction

Ocean is vertically stratified, thus physical properties of the water column, including temperature and salinity vary with depth. Temperature decreases, while salinity increases with depth. Pond and Pickard (1983) categorized the ocean water column into uniform upper zone (50 to 200 m), strong temperature gradient or rapidly decreasing temperature zone (200 to 1000 m), and weak temperature gradient zone (>1000 m) respectively named as Mixed Layer and thermocline and a deep zone (Fig. 1). Thermocline is the depth, at which the temperature gradient is at maximum (Pond and Pickard, 1983). Similar to temperature layers, salinity too has a uniform upper layer, followed by halocline and deeper water weak salinity gradient. Thus, density has a uniform surface layer, as of temperature and salinity, followed by pycnocline and deepwater with uniform density. The upper zone or surface layer with uniform density is named as the surface Mixed Layer (ML), while the surface layer with uniform temperature is called isothermal layer (IL) (Tomczak and Godfrey, 1994; Chu and Chenwu, 2011). The layer between IL and ML is defined as the Barrier Layer (BL), and its thickness is named as the Barrier Layer Thickness (BLT). It has a strong salinity stratification and weak (or neutral) temperature stratification (Chu and Chenwu, 2011). BL get its name because it acts as a barrier to turbulent entrainment of cold thermocline water into the surface Mixed Layer (Cronin and McPhaden, 2002).

In seas, where freshwater input exceeds evaporation, the base of the Mixed Layer is often controlled by salinity and the Mixed Layer can be significantly shallower than would be expected from the temperature stratified isothermal layer (Cronin and McPhaden, 2002). Bay of Bengal receives about 1.5×10^{12} m^3 y^{-1} of fresh water from the major rivers; Irrawaddy, Brahmaputra, Ganga and Godavari, while rainfall exceeds evaporation by ~ 2 m y^{-1} (Shetye *et al.*, 1996). This freshwater influx into the Bay of Bengal maintains the BL, which has a thickness of 25 m during the summer monsoon (Sprintall and Tomczak, 1992). Seasonal, inter and intra seasonal climatology of the BLT is widely studied in all the major oceans. The BL formation and its variability have been extensively studied for the Western equatorial Pacific using the observations from Tropical Ocean Global Atmosphere - Coupled Ocean Atmospheric Research Experiment (Sprintall and Tomczak, 1992). According to Pankajakshan *et al.*,(2007), BL in BoB is a more stable and sustained feature than that in the Western equatorial Pacific (Sprintall and Tomczak, 1992).

BL have strong consequences on air-sea interactions as it thermodynamically insulates the deep cold ocean from the surface layer interacting with the atmosphere (Chu and Chenwu, 2011).

BLT depends on both IL and ML depth. The variability of IL depth or upward/downward movement of the thermocline is mainly controlled by Ekman pumping, long waves (Kelvin and Rossby waves) propagation (Pankajakshan *et al.*, 2007) and upper ocean processes such as surface heat fluxes, advection and mixing (Lindstorm *et al.,* 1987).

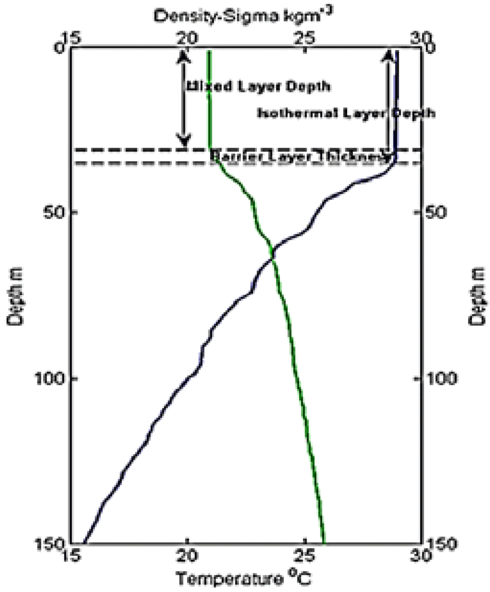

Fig. 1. Temperature and density profiles at 8.5 °N/ 85.31°E, during 2013 post monsoon period

ML depth is controlled by transfer of turbulent fluxes of heat, mass (freshwater) and momentum across the air-sea interface and the horizontal advection in the surface layer. Wind stress deepens ML, thus destroys the BL, while fresh water flux and its redistribution by horizontal advection (Ekman and geostrophic currents) in the surface layer builds the BL (Pankajakshan *et al.*, 2007). The dynamically opposing these seasonal external forces exert varying impact on the formation and establishment of IL, ML and BL.

A wide range of methods are used to calculate ILD, MLD or thermocline depth. However, most of these methods can be grouped into three major categories; difference, gradient and curvature method. All these methods are subjected to their own precisions, but generally final result may vary widely. The difference criterion requires the deviation of temperature (or density, ρ) from its near surface value (i.e. reference level) is to be smaller than a certain fixed value. The gradient criterion requires $\partial T/\partial z$ (or $\partial \rho/\partial z$) to be smaller than a certain fixed value and the curvature criterion requires $\partial^2 T/\partial z^2$ (or $\partial^2\rho/\partial z^2$) to be maximum at the base of mixed layer (Chu and Chenwu, 2011).

Materials and Methods

Oceanographic data was collected as a part of the fish resources survey, conducted at the end of the Southwest and continued during the IInd Inter Monsoon (fall monsoon) of 2013 at central Bay of Bengal (BoB) between 6.5-10.5°N and 85-88.5°E (Fig. 2). The survey was conducted by National Aquatic Resources Research and Development Agency (NARA), Sri Lanka jointly with Institute of Marine Research, Norway under a Sri Lanka – Norway bilateral collaborative program, coordinated by Food and Agriculture Organization (FAO). The expedition was conducted from October 22nd to November 2nd, 2013 using R/V Dr. Fridtjof Nansen. A Sea-Bird CTD 19 plus was used to obtain 39 profiles (cast) up to the depth of ~1000 m. In total, five latitudinal sections (Sections I to V) were occupied at one degree interval from 10.5°N to 6.5°N. The 3rd (8.5°N) and 1st (10.5°N) sections had 5 locations each, while other locations had 6 locations at 0.5° interval (Fig. 2). Each cast is labeled as 1-6 towards east.

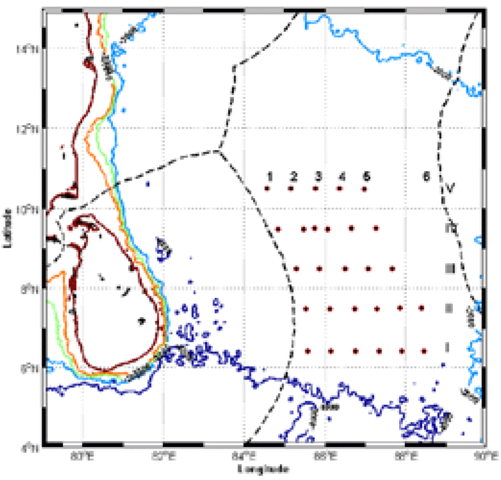

Fig. 2. CTD locations

(Solid line indicates the bathymetry of the area and dashed line indicates the maritime boundaries. Each cast section is labeled bottom to top as I-V and each cast is symbolized as 1-6.)

Density is calculated from salinity and temperature using Gibbs Sea Water (GSW), a MATLAB supported tool box. All the raw salinity, temperature and density data were quality controlled by filtering, aligning and bin averaging processes. Bin size was set to 1 m. Sea Surface Height (SSH) anomalies data were generated from Archiving, Validation and Interpretation of Satellite Oceanographic Data (AVISO) (http://www.marine.copernicus.eu).

In this difference criterion, value of deviation is 0.01 - 1.0 ^{0}C (or 0.01 -0.03 kgm^{-3}) and the reference level is 0 to 10 m (Thomson and Fine, 2003). In this study ILD was calculated as the depth, where the temperature is less than 0.5°C from the surface temperature and the MLD was determined as the depth, where density (sigma) is higher than 0.01 kgm^{-3} from the surface density value. The different layer depths are calculated in accordance with;

$$ILD = z(T = T_S - \Delta T) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Equation\ 1$$
$$MLD = z(\rho = \rho_S + \Delta\rho) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Equation\ 2$$
$$BLT = ILD - MLD \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Equation\ 3$$

Where z =depth, T =Temperature at IL, T_S= Sea surface temperature, ΔT = Temperature difference = 0.5 ^{0}C (Uddin *et al.*, 2014), ρ =Density at ML, ρ_s =Sea surface density, $\Delta\rho$ = Density difference = 0.01 kgm^{-3} (Wijesekera and Gregg, 1996).

Results

Vertical profiles of temperature and salinity of Section I_1, III_5&V_3 in Fig. 3 shows spatial distribution of ILD at study site. The SST and SSS show typical distribution during the transition period from IInd Inter Monsoon to Northeast Monsoon. Distinct water masses with varying temperature and salinity distributed at the study area. Sea Surface Temperature (SST) was ranged from 28.5 to 28.9 °C, with an average of 28.7 ^{0}C indicating a warm sea surface during the survey period (Fig. 4). Highest temperatures (28.9 ^{0}C) were recorded at the Northwestern and Southeastern corners of survey area. Another high temperature (28.8 ^{0}C) water cell is located at the center (8.2-8.75 N and 86.4-86.6E), and it is surrounded by surface water of 28.6 ^{0}C.

SSS varied from 33.4 to 34.4 PSU on the study area, where the lowest salinity was recorded at the Northern and Southwestern side of the study area (Fig. 5). Highest recorded SSS is 34.6 at the Southern part of the sampling area. A high saline (34.4 ppt) water cell can be seen at the center (8 - 8.5 N and 86-86.5°E) of the study area. The high temperature (28.8^{0}C) and saline (34.4 PSU) water cell coincides at the center of the sampling area, indicating an existence of warm high saline water mass at the centre of the study area. Arabian Sea water signature. Advection of summer monsoon current in to BoB during post summer monsoon time, which carries warm, saltier water from Arabian Sea, could be described as the reason for the existence of such high saline, warm water mass.

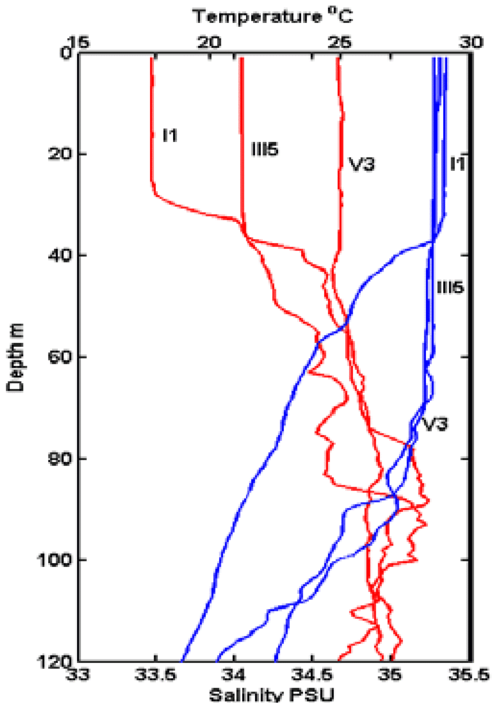

Fig. 3. Temperature (blue line) and salinity (red line) profiles of I_3 (10.5N/ 85.77 °E), III_2 (8.5N /85.17 °E) &V_3 (6.5N/84.57 °E)

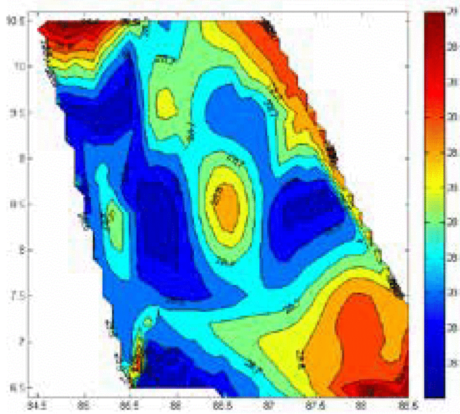

Fig. 4. Temperature distribution at 5 m of the sampling area

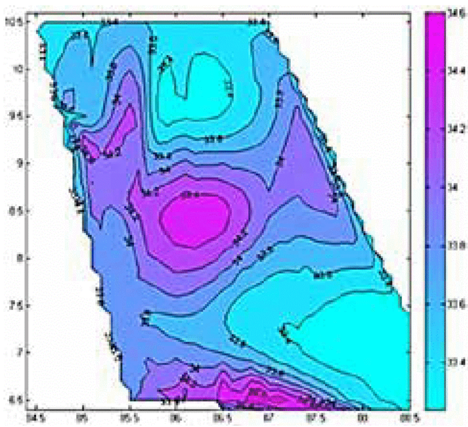

Fig. 5. Salinity distribution at 5 m of the sampling area

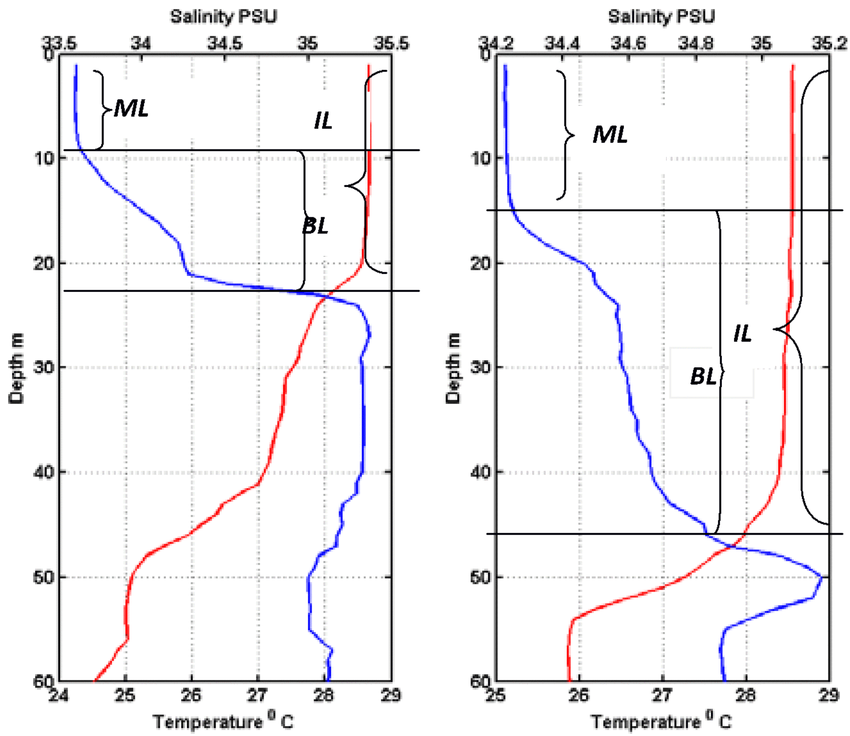

Fig. 6. Temperature (red) and Salinity (blue) profiles at I_3 (Left) and IV_5 (Right) depicting mixed layer, isothermal and Barrier Layer depth

Fig. 6 shows different layer depths at cast I_3 and IV_5. The Mixed Layer depth at cast I_3 and IV_5 are 10 and 15 m respectively, while the isothermal layers are 20 m at the former and 42 m at the later. This results in a thin (10 m) Barrier Layer at cast of I_3, while a thick Barrier Layer (27 m) at cast IV_5.

Fig. 7 shows different layer's thickness at the study site. The IL depth and BL thickness shows tendency to increase with the decreasing latitude towards equator. The thickness of the Mixed Layer at the study area varied between 5 to 37 m with an average depth of 20 m. The recorded lowest MLD value (5m) was recorded at high saline warm water cell, followed by a ~10m at the Southern part of the study area. IL varies from 25 to 75 m, the maximum depth is recorded at the lower half of the study area, and however it again shows a slight tendency to shallow towards equator. Overall the BL thickness, differences between the ILD and MLD, increases towards the Southern Bay of Bengal (Fig. 7c). The BLT is strongly correlated to the deepening of IL [$r = 0.837$ ($p>0.05$)] and weakly correlated shoaling of mixed layer. However, the correlation between MLD and BL thickness is poor [r = -0.443 (p>0.05)]. In general, SSS and BL thickness are expected to have strong correlation, however the analysis does not show any correlation [r = 0.198 (p>0.05)]. Similarly the correlation between BL thickness and SST is poor [r= -0.0750 (p>0.05)].

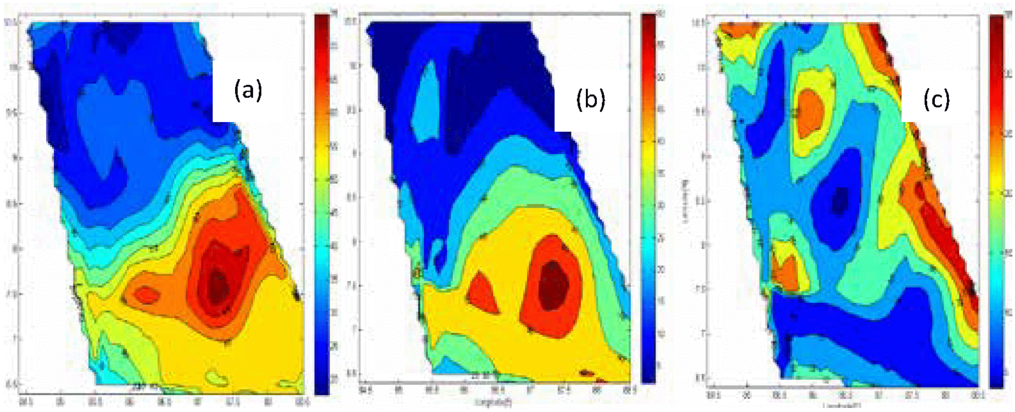

Fig. 7. Distribution of (a) mixed (b) isothermal (c) Barrier Layer thickness

Discussion

BLT showed a distinct distribution pattern at the central BoB, the study area (Fig. 7). It shows a tendency to increase along the longitudinal axis towards equator, giving its maximum value (60 m) at the Southern sector of the study area (7.5°N and 87.5°E). It corresponds with the study of Pankajakshan *et al.*, 2007, who recorded similar BL thickness of 60-70 m thick BL, during the same period at the northeast and central BoB. According to Uddin *et al.*, 2014, ILD does not show specific distribution, but MLD has a significant deepening (30-55 m) over the central BoB, during September and October than other months. However, this study records a deeper ILD at the study reaching up to 75 m , while thinner MLD, varying between 5-35 m (Fig. 5 and 6) also. ILD shows an increasing pattern along the meridional axis but MLD does not show such a distinct pattern. The lowest MLD was recorded at the warm and saline water cell in center BoB. This high saline water mass could be an advection of summer monsoon current in to BoB which carries high saline water of Arabian Sea (AS). Generally, during the summer monsoon period, high saline water at AS transports towards the BoB by the advection of Summer Monsoon Current (Shetye *et al.*, 1996). This high saline water mass can replace the low saline water masses in BoB (Benshila *et al.,* 2014), thus could increase the MLD of the area but such an increasing was not recorded during this survey.

Pankjakshan *et al.*, 2007 in his paper described that distribution of the BLT can be explained based on the surface forcing of wind, current and fresh water induced buoyancy. Published literature based on the BLT has suggested a positive correlation with SSS (Pankajakshan *et al.*, 2007). But in this study, the calculated correlation between SSS and BLD was 0.198 ($p>0.05$), expressed the low enforcement of SSS over the BLT. It means there are other factors which governs the deepening of BLT than the SSS. Girishkumar *et al.,* (2013) stated that observed intra-seasonal variability in BLT is mainly controlled by the vertical movement of ILD in the presence of a shallow mixed layer. Calculated correlation between ILD and BLT is significantly positive as 0.8374 ($p>0.05$), proving the observations of Girishkumar *et al.,*(2013). Wind field is the other factor which carries surface waters by Ekman drift (Pankajakshan *et al.*, 2007). Also Weller *et al.,* (2002) reported that wind mixing is the primary driving force of mixed-layer deepening during the summer monsoon (June–September) while convective deepening driven by surface buoyancy flux is more important during the winter monsoon (December–February). The study reveals that the recorded BLD is very much similar to previous studies by various authors as Pankajakshan *et al.*, 2007; however MLD and ILD are varying widely from previous studies like Uddin *et al.,* (2014). All these available literatures have done for entire BoB, thus could not be able to resolve spatial variability of MLD or ILD in a small area as done in this study.

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References

Benshila, R., Durand, F., Masson, S., Bourdallé-Badie, R., de Boyer Montégut, C., Papa, F. and Madec, G. (2014). The upper Bay of Bengal salinity structure in a high-resolution model. *Ocean Modelling* **(74):** pp 36-52.

Chu, P.C. and Chenwu, F. (2011). Determination of Ocean Mixed Layer Depth from Profile Data. Proceedings of 15th Symp Int Obs Ass Sys Atmos, Ocn Lnd Sfc, AMS: pp 1001-1008.

Cronin, M. F. and McPhaden, M. J. (2002). Barrier Layer formation during westerly wind bursts. *Journal of Geophysical Research* **107(C12):** pp 1-19.

Emery, W.J.(2003). Water types and water masses. In: Encyclopedia Atmospheric Sciences, ed. Holton, J.R., Curry, J.A., Pyle, J. A. pp 1556-1567. Elsevier science, USA.

Girishkumar, M.S., Ravichandran, M. and Mcphaden, M.J. (2013). Temperature inversions and their influence on the Mixed Layer heat budget during the winters of 2006–2007 and 2007–2008 in the Bay of Bengal. *Journal of Geophysical Research* **118:** pp 1-12.

Jayu, N. and Prasanna, K. (2006). Seasonal variability of the Mixed Layer in the central Bay of Bengal and associated changes in nutrients and chlorophyll. *Deep Sea Research* **53:** pp1-42.

Lindstrom, E., Lukas, R., Fine, R., Firing, E., Godfrey, S., Meyers, G. and Tsuchiya, M.(1987). The Western Equatorial Pacific ocean circulation study. *Journal of Geophysical Research* **101(C6):** pp 533-537.

Pankajakshan, T., Muraleedharan, P.M., Rao, R.R., Somayajulu, Y.K., Reddy, G.V. and Revichandran, C. (2007). Observed seasonal variability of Barrier Layer in the Bay of Bengal. *Journal of Geophysical Research* **112:** pp1-18.

Pond, S. and Pickard, J.L. (1983). Introductory Dynamical Oceanography. 2nd edn, pp 08-153. Pergamon Press, Oxford.

Shetye, S.R., Gouveia, A.D., Shankar, D., Shenoi, S.S.C., Vinayachandran, P.N., Sundar, D., Michael, G.S. and Nampoothiri, G. (1996). Hydrography and circulation in the Western Bay of Bengal during the northeast monsoon. *Journal of Geophysical Research* **101(C6):** pp 14011 – 14025.

Sprintall, J. and Tomczak, M. (1992). Evidence of the Barrier Layer in the surface layer of the tropics. *Journal of Geophysical Research* **97(C5):** pp 7305– 7316.

Stewart, R.H. (2008) Introduction to Physical Oceanography, Texas: Texas A&M University. [Available at http://oceanworld.tamu.edu/resources/ocng_textbook/PDF_files/book.pdf]

Stommel, H. and Fewrov, K. N. (1967). Small scale structure in temperature and salinity near Timor and Mindanao. *Tellus* **19:** pp 306-325.

Thomson, R.E. and Fine, I.V. (2003). Estimating Mixed Layer Depth from Oceanic Profile Data. *Journal of Atmospheric and Oceanic Technology* **20:** pp 319-329.

Tomczak, M. and Godfrey, J.S. (1994) Regional Oceanography: an introduction, pdf version 1.2, Delhi: Daya publishers. [Available at http://www.geo.unibremen.de/~apau/proper3/library/tomczak_godfrey_1994.pdf]

Uddin, M.M. Chowdhury, Z.R. Ahammed, S. and Basak, S.C. (2014). Seasonal variability of Mixed Layer Depth (MLD) in Bay of Bengal. *Indian journal of Geo-Marine Sciences* **43(3):** pp 400-407.

Vinayachandran, P.N. Murthy, V.S.N. and Ramesh Babu, R. (2002). Observations of Barrier Layer formation in the Bay of Bengal during summer monsoon. *Journal of Geophysical Research* **107(C12):** pp 191-197.

Weller, R. A., Fischer, D.L., Eriksen, C.C., Dickey, T.D., Marra, J.,Cox, C. and Leben, R. (2002). Moored observations of upper-ocean response to the monsoons in the Arabian Sea during 1994-1995. Deep sea research. Part II: Topical studies in oceanography, **49(12)**: pp 2195-2230.

Wijesekera, R. H. and Gregg, M.C. (1996). Surface layer response to weak winds, westerly bursts, and rain squalls in the Western Pacific warm pool *Journal of Geophysical Research* **101(C12):** pp 977–997.