Late Summer Intrusion of Arabian Sea Waters into the Bay of Bengal: Observations in 2015

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Abstract: ***Intrusion of Arabian Sea (AS) waters into the Bay of Bengal (BoB) during August 2015 is examined using Conductivity Temperature Depth (CTD) observations made during R/V Roger Revelle research cruise (4-15 August 2015). Consistent with earlier studies Southwest Monsoon Current (SMC) flows eastward around Sri Lanka (SL) serving as an open ocean link connecting AS and BoB during summer monsoon. We have noted that SMC is strong during early August with a speed of 0.8 – 1.2 m/s and reduces up to 0.6 – 0.7 m/s at the end of the month. CTD observations in southern BoB clearly indicate the presence of AS waters (ASW) at a depth of 80– 110m (34.8 – 35.2 psu) and provide evidence for the intrusion of ASW into the BoB during summer. Further, our analysis indicates the presence ofour salinity extreme layers in the upper 250 m with a thickness around 10 – 20 m east of SL and points out the importance of subsurface mixing associated with Temperature-Salinity properties of the water column.***

Keywords: Arabian Sea, Bay of Bengal, Summer Monsoon Current, Water Exchange

1. Introduction

Arabian Sea (AS) and the Bay of Bengal (BoB) are the two counterparts of the Northern Indian Ocean, which are having unique characteristics and located in the same latitude. Both basins are influenced by Asian Monsoon and the surface circulation characterized with seasonally reversing currents as a response to the seasonal winds in the region (Schott and McCreary, 2001). Seasonal freshwater influx (precipitation and river runoff) and evaporation forced the changes in salinity level and the variations observed suggests that AS (BoB) is consisted with high (low) salinity waters. Thus, relatively higher evaporation over AS and freshwater flux into the BoB creates a hydrological imbalance between these two basins (Kumar *et al.*, 2004). Hence it is important to understand the processes which contribute to maintain the hydrological balance between these two unique basins.

The seasonally reversing of circulation plays an important role in controlling the imbalance between AS and the BoB which maintains long-term average salinities (Jensen, 2001). Earlier studies based on observations (Shetye *et al.*, 1991, Schott *et al.*, 1994, Vinayachandran and Yamagata, 1998, Gopalakrishna *et al.*, 2005) and model simulations (Jenson, 2001, 2003; Yuhong and Yan, 2012; Vos *et al.*, 2014) pointed out that during summer (June - September) the eastward flowing Southwest Monsoon Current (SMC) brings high saline AS waters into the BoB, while during winter (December - February) the westward flowing Northeast Monsoon Current (NMC) carries low saline BoB waters into the AS. Jensen (2001) using passive tracers as a tool in a model of the Indian Ocean revealed that NMC carries BoB waters into the AS about four (4) months starting in December and SMC advects water from AS into the BoB around (4) months starting from June. Rao et al., (2013) suggested that southward flowing of East Indian Coastal Current (EICC) along with NMC carries BoB waters into the AS traversing around Sri Lanka coast and feeds the poloward flowing West Indian Coastal Current (WICC) during winter monsoon based on Simple Ocean Data Assimilation (SODA) model results. Vinayachandran et al., 1999 have pointed out that the intrusion of SMC into the BoB with a mean seasonal (May - September) transport around 10 Sv with integrated results of expendable bathythermograph (XBT) observations and ocean general circulation model (OGCM). Thus the water exchange between these two basins is an important mechanism to maintain the hydrological balance in the region.

Water masses found in different regions of the world oceans emphasize the uniqueness due to their conservative properties (potential temperature and salinity) and provide evidences of the typical formation region. Hence the water types can be identified using temperature-salinity (T-S) diagrams as a tool (Worthington, 1981).Indian Ocean has a very complex upper water mass structure due to its relatively smaller size, unique geographical conditions, monsoonal influence and freshwater influx (Emery, 2001).Emery (2001) suggested that the upper waters (0 – 500 m) of the Indian Ocean is consisted of Bay of Bengal Water (BBW) (25 - 29°C, 28 – 35 psu), Arabian Sea Water (ASW) (24 – 30°C, 35.5 – 36.8 psu), Indian Equatorial Water (IEW) (8 – 23°C, 34.6 – 35 psu), Indonesian Upper Water (IUW) (8 – 23°C, 34.4 – 35 psu) and South Indian Central Water (SISW) (8 – 25°C, 34.6 – 35.8 psu). Thus unique T-S properties and salinity extremes at a location is cosidered as one of the best ways to detect specific water masses in a region. The observations collected in August 2015 during *R/V Roger Revelle* cruise in the BoB provided the opportunity to examine the presence of ASW in the BoB.

The objective of this study is to explain the water exchange between AS and BoB during August 2015 utilizing *R/V Roger Revelle* CTD observations together with data from National Oceanographic Data Center (NODC) CTD, Ocean Surface Currents Analysis Real-time (OSCAR) and Surface

Velocity Program (SVP) drifter data. The paper is organized as follows. In section 2, data and methodology used in the study are described. Results and discussion are presented in section 3, which is followed by a conclusionin section 4.

2. Data and Methodology

The primary observations of this study were made from the CTD (conductivity, temperature, depth) data collected during the cruise of *R/V Roger Revelle* from 04th August to 15th August 2015 (Figure 1).

CTD data were averaged over 0.5 m bins and the data were linearly interpolated to 1m intervals to facilitate the analysis. Further, CTD profiles in 2° - 22° N and 60°-100°E from National Oceanographic Data Center (NODC) collected during August 1990 to 2016 (Figure 1) were used to identify the watermass characteristics in the AS and BoB. To identify the temperature-salinity (T-S) characteristics in the upper waters (0 – 500 m)of AS and the BoB, CTD data were categorized into four different regions as AS01 (12°-22° N, 60°-80° E), AS02 (2°-12° N, 60°-80° E), BoB01 (12°-22° N, 80°-100° E) and BoB02 (2°-12° N, 80°-100° E) (Figure 1).

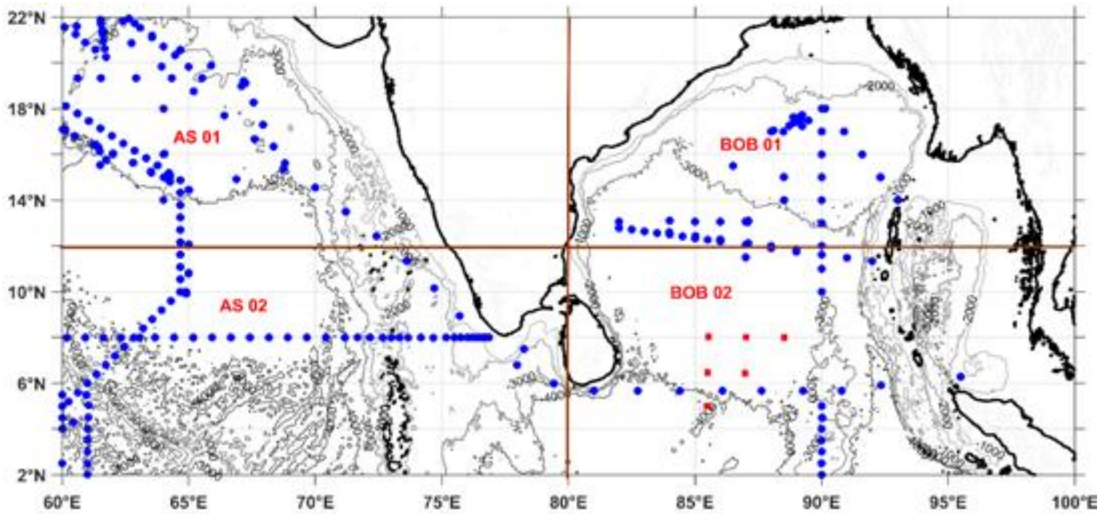

Figure 1: NODC (blue circles) and *RV Roger Revelle* (red squares) CTD locations available during the August from 1990 – 2016 in the region. Contour lines represent the bathymetry of the region

Assuming that the upper-layer of the tropical oceans could undergo significant temperature changes in its diurnal cycle, we have estimated mixed-layer depth (MLD) as the depth where the density changed is equivalent to $0.2\,°C$ temperature criterion from a reference depth of 10 m (de Boyer Montegut et al., 2004). Top of Thermocline Depth (TTD) is calculated as the depth where temperature is $0.2\,°C$ lower than the SST at 10 m reference depth. Thus in our calculation of MLD and TTD is based on a fixed threshold on temperature profiles. BLT is defined as the difference of TTD and MLD. $BLT = TTD - MLD$ (Sprintall and Tomczak, 1992). Further, in order to represent the depth of the thermocline (TCL) (halocline: HCL) we have considered the position of maximum gradient of temperature (salinity) with depth, $^{dT}/_{dz} \approx maximum$ $(^{dS}/_{dz} \approx maximum)$.

Surface currents from OSCAR (August 2015), and the data acquired from satellite tracked SVP drifters during 2013 – 2014 have been utilized to study the surface circulation during August in the region. The OSCAR data is available at Physical Oceanography Active Archive Data Center (PODAAC) with 1/3º x 1/3º spatial resolution. The drifter observations have been collected under the Air-sea Interaction in the Bay of Bengal (ASIRI) program by National Aquatic Resources Research and Development Agency (NARA) of Sri Lanka in collaboration with Scripps Institution of Oceanography (SIO).

3. Results and Discussion

In northern Indian Ocean, surface currents flow eastward/westward during the southwest/northeastmonsoon as a response to the seasonal (monsoon) winds in the region. Vinayachandran et al., (1999) pointed out that the existence of a strong flow into the BoB during southwest moonsoon, which is identified as the intrusion of the SMC. The analysis of SVP drifter data during 2013 – 2014, indicated that the current along the western boundary of the BoB flows to the AS around Sri Lanka during northeast monsoon (Nov-Dec, Figure 2). The direction of thesurface currents change towards the east during southwest monsoon and turn to north-eastward with the progression of southwest monsoon suggesting the monsoonal impact on the surface circulation in the region. Surface currentsexamined utilizing OSCAR data reveals that during August 2015 the currents flow from AS into the BoB around southern coast of Sri Lanka.

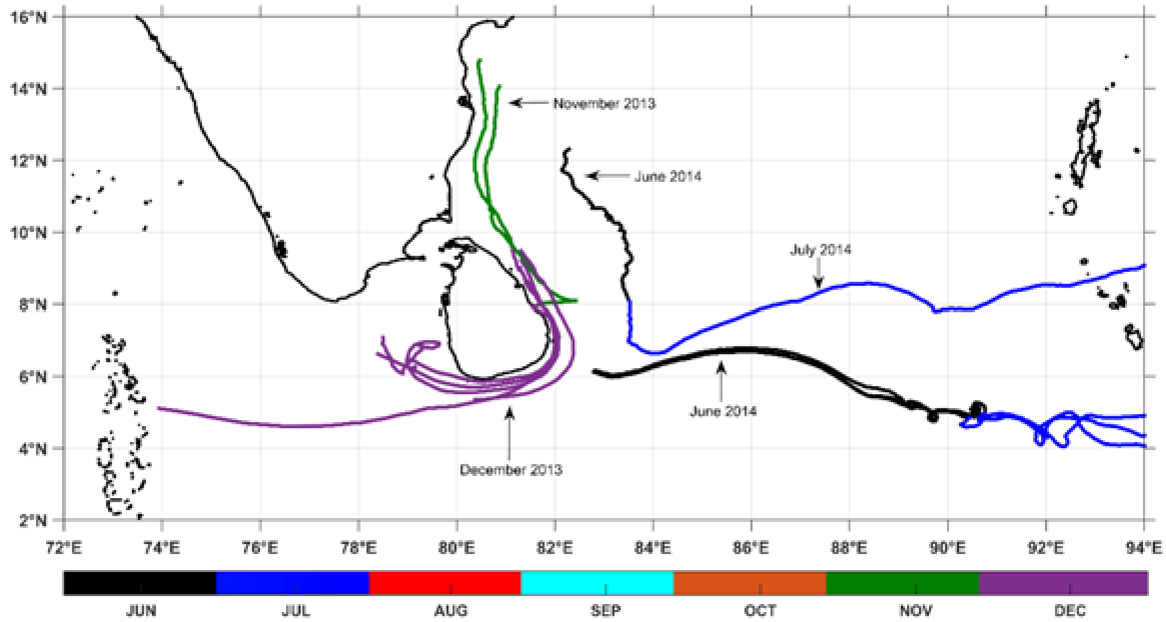

Figure 2: Surface currents computed from SVP drifters during 2013 -2014

The SMC is relatively strong around Sri Lanka during early Augustwith a speed around0.8 – 1.2 m/s and decreases the flowing speed (0.6 – 0.7 m/s)with time (late August) (Figure 3).

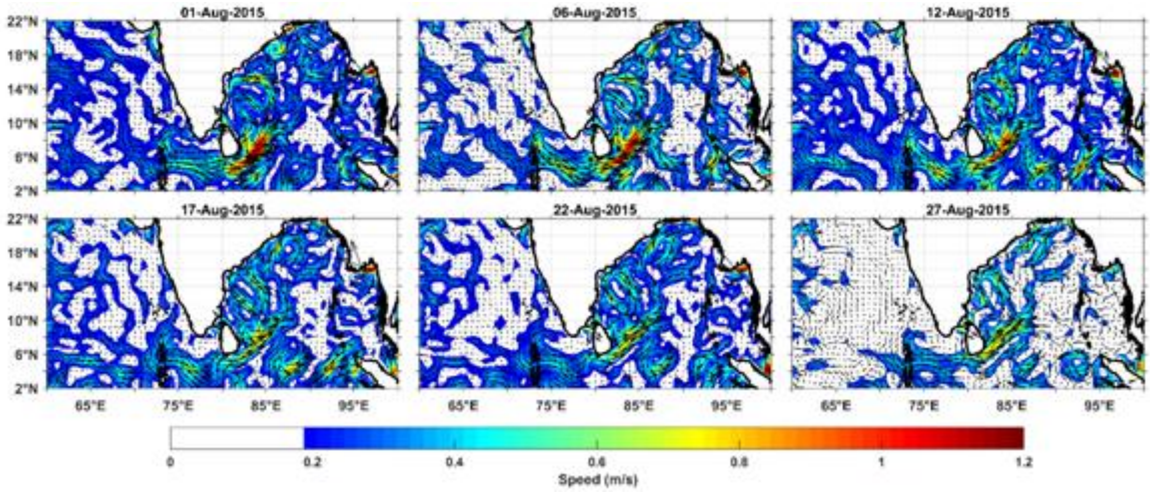

Figure 3: Surface currents during August 2015 from OSCAR data. Arrows represents the flow direction and color represents the magnitude of the speed (m/s). Current speed between 0 – 0.2 m/s is set to white for the clear identification of water exchange between AS and BoB

The noted changes in the SMC clearly pointed out the formation of Sri Lanka Dome during the southwest monsoon in east of Sri Lanka. Schott et al., (1994) suggested that the watermass flowing during southwest monsoon around Sri Lanka is shallow and mostly confined to the upper 200 m based on the observations from south of Sri Lanka. Thus it provides evidence for the water flow from southeastern AS into the southern BoB during summer.

Temperature-salinity (T-S) diagrams are widely used to detect specific water masses in the world's oceans based on the region specific conservative properties (potential temperature and salinity). The water masses can be tracked down to their source regions using these unique T-S characteristics. Due to the differences in hydrological conditions, upper waters (0 – 500 m) in both AS and BoB are identical. Emery (2001) pointed out that upper waters in BoB (BBW) is identical with 25 – 29°C, 28 – 35 psu T-S properties while upper waters in AS (ASW) is identical with 24 – 30°C, 35.5 – 36.8 psu. Prior to the analysis ofthe water massesusing CTD data acquired during *R/V Roger Revelle*, water mass characteristics in the BoB are examined using NODC CTD profiles available during August for the period of 1990-2016. The CTD profiles were geographically sorted into four sections as northern AS (AS01), southern AS (AS02), northern BoB (BoB01), and southern BoB (BoB02) (Figure 1). It is noted from the mean T-S characteristics that the upper waters of AS01 region indicate the presence of three water layers including two salinity extreme layers, ~36.3 psu at a depth around 33-82 m and ~35.9 psu at a depth around 130-195 m (Figure 4a). AS02 region indicates a salinity extreme layer of ~36.1 psu in the upper 50 m of the water column (Figure 4b). The approximate depths of the water layers have been estimated from the density profiles calculated from the vertical distribution of mean temperature and salinity in each region. Watermass characteristics observed at the upper layerin AS01 and AS02is similar to that of ASW defined byEmery (2001).

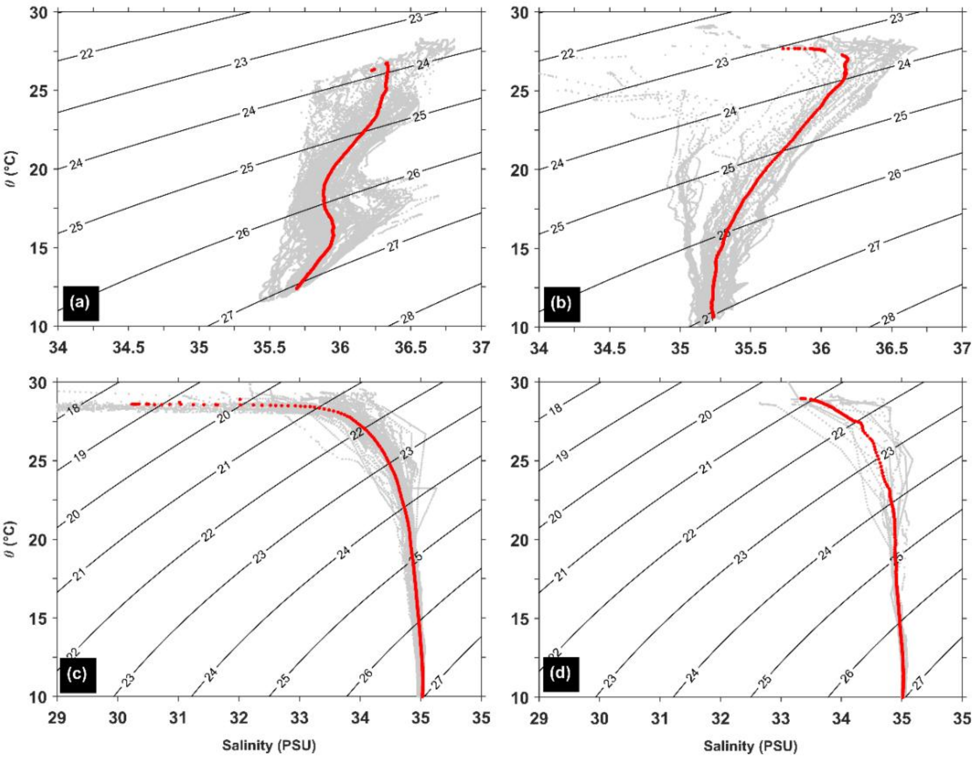

Figure 4: Temperature-Salinity diagrams (a) Arabian Sea 01 (0 – 500 m), (b) Arabian Sea 02 (0 – 500 m), (c) Bay of Bengal 01 (0 – 500 m), and (d) Bay of Bengal 02 (0 – 500 m) estimated from NODC CTD data during August for the period of1990 to 2016. Gray color represents all the available CTD profiles in each region and red color represents the mean. Contour lines represent potential density (kg/m^3)

The mean T-S curve in the BoB is relatively differ to that observed in the AS. In the BoB01 region salinity varies in between30.25– 34.5 psuin the upper 500 m of the water columnand T-S curve shows characteristically homogeneous beyond (~100 m) to deeper (Figure 4c).It is noted thatin thenorthern BoB, salinity varies around 27.5 – 35 psu compared to that noted in thesouthern BoB, salinity around33 – 35.5 psu in the upper water layers. This clearly emphasize the impact of freshwater influx to the BoB from Indian rivers such as Brahmaputra and Gangees, which have been well discussed in previous studies. Further, it isnoted that in the BoB02 region the salinity variesaround33.34 – 34.62 psu and the T-S curve remains nearly constant with salinity (Figure 4d), similar to that noted atBoB01.We have examined the water mass charactristics in the BoB up to 1000 m depth from the surface and did not observe any specific diffrences in comparison to that noted at upper water column (Figure not shown). Due to the sparse historical CTD observations available in southern BoB (BoB02)during August (Figure 4d), there is no solid evidence for presence of ASW in the BoB. Hence we examine the water mass characteristics in the BoB in more detail utilizing CTD observations collectded during August 2015.

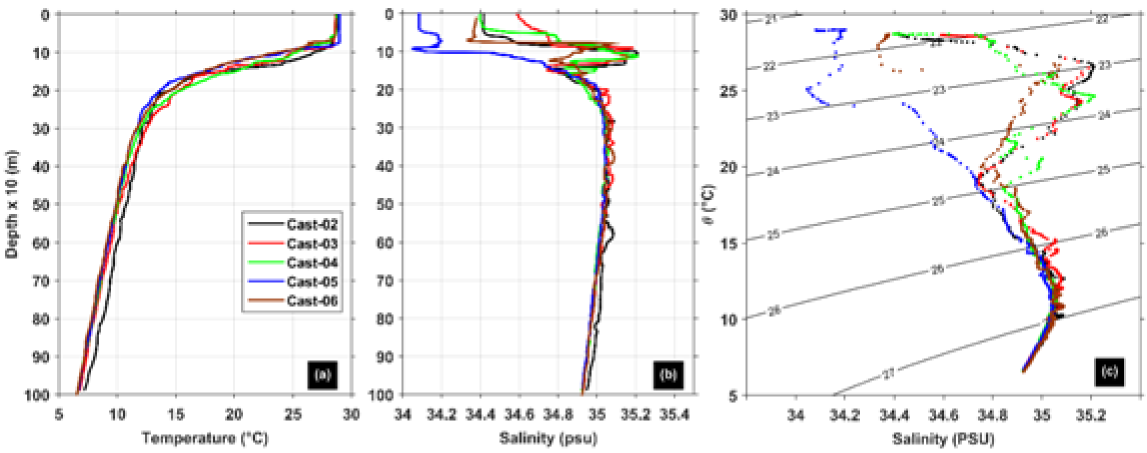

Figure 5: Temperature and Salinity characteristics (a) temperature profiles, (b) salinity profiles, and (c) T-S diagram estimated from *RV Roger Revelle* CTD data during August 2015. Color represents the individual CTD profiles

Figure 5 illustrates the T-S properties observed in the southern BoB up to 1000 m depth from the surface and the estimated upper ocean characteristics are presented in the Table 1.

Table 1: Upper ocean stratification observed at the CTD locations during August 2015 in BoB.

Cast	Lon (°E)	Lat (°N)	MLD±13 (m)	ILD±7.4 (m)	BLT±9.8 (m)	TD±29 (m)	HD±20 (m)
2	85.484	5.009	74.58	85.68	11.1	135	95
3	85.497	6.465	85.63	87.07	1.44	133	88
4	85.531	8.022	52.01	74.58	22.56	122	51
5	87.017	8.009	83.01	83.87	0.85	84	102
6	88.530	8.000	70.80	70.26	-0.54	72	76

The estimated average MLD, TTD and BLT varies around 51±9.6m, 66±12.4 m and 15±17 m respectively. Thus it highlights the presence of relatively deeper mixed-layer and relatively thicker barrier-layer during late summer (August) in the BoB. The estimated thermocline depth varies around 120±20m whilehalocline depth around 82±21m and points out the influence from freshwater influx during late summer. It is noted that the temperature profiles at each location follow a similar pattern with minor variations (Figure 5a) while the noted change in salinity is obvious with depth (upper 200 m) (Figure 5b).Thus the noted differences in salinity profiles further highlights the possible impacts from intrusion of ASW with the SMC during summer in the BoB. It is evident in the results that the presence oftwo salinity extreme conditions at depths around80 – 110m (~ 34.9 – 35.2 psu) and 150 – 220 m (~ 35.1psu) (Figure 5c). T-S properties (23– 27°C, 34.9 – 35.2psu) and potential density (23 -24 kg/m^3) observed at 80– 110m depth in southern BoB resembles to the surface waters observed in AS02 region (Figures 4d and 5c) and well agrees with the ASW mass defined in Emery (2001). The evidence noted in surface currents further point outs the watermass exchangebetween AS and BoB through SMC (Figure 3) and confirms the intrusion of AS waters into the BoB during August. Further, the noted increment in salinity around ~ 100 m depth at the sampling locations could be due to the intrusion of high saline AS waters during late summer (Figure 5b).

Further, we have deployed continuous CTD casts (48) with 30 minute time interval at 6.42° N, 85.21° E on 11th August 2015in order to study the diurnal migration of thermoclineand the results are presented in Figure 6.

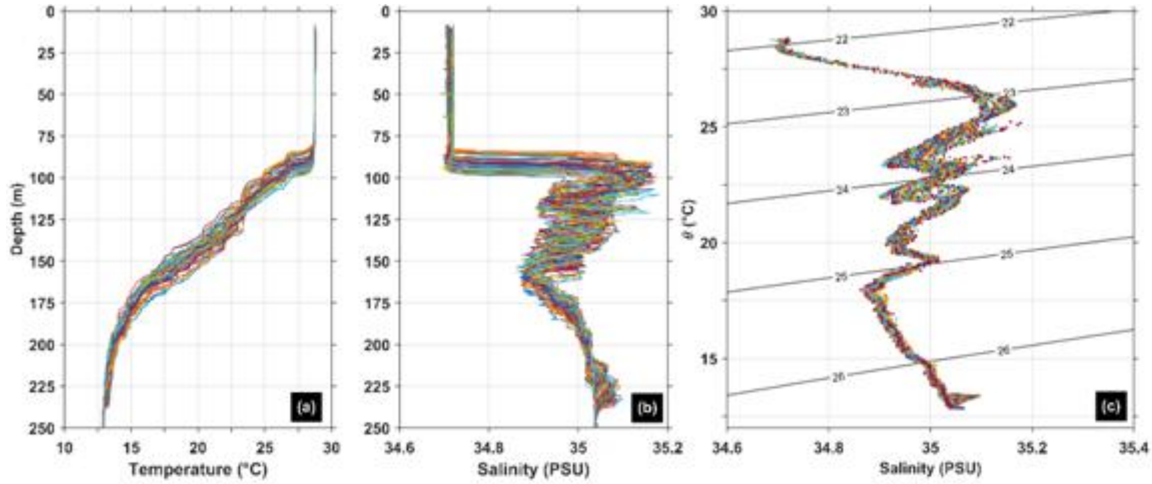

Figure 6: Temperature and Salinity characteristics (a) temperature profiles, (b) salinity profiles, and (c) T-S diagram estimated from *RV Roger Revelle* CTD data (48 casts) during 11 August 2015 at 6.42° N, 85.21° E. Color represents the individual CTD profiles. Measurements were taken from surface to a depth of 250 m

The sampling location was located east of Sri Lanka, just outside the Exclusive Economic Zone (EEZ). The analysis reveals a change of MLD at a rate of 0.12±3.8m/hr, a change of TTD at a rate of 0.12±3.7m/hr and change of thermocline depth at a rate of 0.09±3.0 m/hr. Change of temperature with depth remains relatively small (Figure 6a) compared to that of salinity (Figure 6b).However, a thicker barrier-layer is not evident in the results and the BLT remains around zero at the sampling location. The pronounce increase insalinity evident in the results between 80 – 170m depth layer (Figure 6b) emphasize the possibility of high salinity water intrusion into the region.The T-S properties observed at the location also provide the evidence for intrusion of high salinity waters from AS into the BoB (Figure 6c).Emery, (2001) suggetsed that in a specific region a high resolution inspection will reveal a great variety of smaller water mass classifications. Figure 6c illustrates a similar results in upper 250 m water column east of Sri Lanka with four salinity extreme layers between 100 – 150 m with a thickness varies around10 – 20 m in each layer. The variations observed in the T-S curves (Figure 6c) emphasize the importance of subsurface mixing, which can influence to the T-S properties.

4. Conclusion

Due to the hydrological imbalance between the AS and the BoB, water mass exchange between the two basins is important to maintain the meanhydrological conditions. The seasonal circulation associated with SMC and NMC plays an important role in maintaining the salt balance in both basins.

During summer monsoon, currents flow eastward carrying high salinity waters from AS into the BoB and serve as an open ocean link south of Sri Lanka that connects AS and BoB. CTD observations in the southern BoB during August 2015 clearly indicated the presence of ASW at a depth around ~80 – 110m and provide the evidence for the intrusion of AS waters into the BoB during summer. The surface currents analysis depicts the flow of SMC is eastward and the observed T-S properties confirms the availability of AS water mass in southern BoB during late summer. Mixing within the subsurface layers is obvious in upper 250 m in the southern BoB and emphasize the complexity of upper water mass structure. Thus, higher resolution systematic observations will provide a better understanding about the dynamics in the region.

5. Acknowledgement

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