Characteristics of Bay of Bengal Water mass in South Eastern Arabian Sea during 2001-2002

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Present study consists characteristics of intruded Bay of Bengal Water mass (BBW) in the South Eastern Arabian Sea (SEAS) during November 2001 – May 2002 by utilizing Simple Ocean Data Assimilation (SODA) model outputs (Temperature, Salinity and Currents). During November 2001 the southward flowing East India Coastal Current (EICC) along with Winter Monsoon Current (WMC) brings BBW to Arabian Sea traversing around Sri Lanka coast and feeds the poleward flowing West India Coastal Current (WICC). Even though EICC reversed its direction by January, the WMC along with the WICC transported the BBW further north into Arabian Sea. Maximum northward limit of the BBW was 16°N during January-February which is the peak phase of WICC. When the WICC reversed its direction by March the BBW started depleting and by May no trace of BBW was seen in SEAS. Thickness of the water mass were computed for the entire study region and also vertical integrated volume transport were computed along transects (77.5°E, 8.25°N, 10.25°N, 12.75°N and 15.25°N) perpendicular to the coast. Thickness of the water mass was found to vary from 10 to 60 m during the entire study period. It was shallow during November and March-April while it was deep during peak phase of WICC (January-February). Maximum volume transport of 0.8 Sv towards west along 77.5°E was observed during February. During the period of study total volume transport was seen to be less towards the Northern transects.

[Keywords: Bay of Bengal, Water mass thickness, East India, Coastal Current, West India, Coastal Current, Winter Monsoon Current]

Introduction

Arabian Sea and the Bay of Bengal are both tropical basins located in similar latitudes but separated by the landmass of Indian peninsula. Both the basins are forced by seasonally reversing monsoon winds-southwesterly during June to September and northeasterly during November till February. In response to this forcing, the surface circulation also undergoes seasonal reversal. Annually, the Arabian Sea loses fresh water through intense evaporation (~1 m yr⁻¹) while the Bay of Bengal receives immense quantities of fresh water by way of heavy precipitation (~2 m yr⁻¹) as well as by run off from peninsular rivers (1.625 x 10⁻¹² m³ yr⁻¹). This creates a hydrological imbalance. Seasonally reversing circulation plays an important role in exchanging the water masses between the Arabian Sea and the Bay of Bengal. In contrast, during winter (November – February), both the westward flowing Winter Monsoon Current (WMC) between equator and 10°N and the southward flowing East India Coastal Current (EICC) brings warm and low-salinity waters into the Arabian Sea from the Bay of Bengal. Pankajakshan and Ramaraju (1987) examined the possible driving mechanism using the theory of McCreary et al., 1986 for the intrusion of Bay of Bengal waters into South-Eastern Arabian Sea (SEAS). They suggested that, in spite of a weak equatorward wind stress, the meridional salinity gradient that occurs in the Eastern Arabian Sea after the withdrawal of the Southwest monsoon is capable of forcing a northward current along the west coast of India. Recent theories suggest that remote forcing, especially from the Bay of Bengal, plays an important role in the dynamics of the southwest coast of India. Remotely forced Kelvin and Rossby waves generates the Laccadive High. LH (Laccadive Low, LL), which is a large pattern of anti-cyclonic circulation (cyclonic) observed in the
east of Laccadive Islands (centered around 10°N, 70°E) during the northeast monsoon\textsuperscript{12,13} (Southwest monsoon). The currents associated with these waves also bring low-saline waters from the northern Bay of Bengal into the SEAS during November–January\textsuperscript{14,15}. It is identified that Bay of Bengal Water mass (BBW) is characterized by temperature 25-29° C, salinity 28-35 PSU, sigma-t 21-22\textsuperscript{16}. Though there exists documentation on the inflow of Bay of Bengal waters into SEAS, there is no information available on the time evolution characteristics of this waters in SEAS. Present study highlights the thickness of this low saline BBW and associated volume transport into the SEAS during northeast monsoon of 2001-2002.

**Materials and Methods**

To study spatial and temporal variability of BBW; information on temperature, salinity and currents over 4 spatial domains (longitude, latitude, depth and time) are required. But in situ data on these domains is very sparse. Hence, monthly mean temperature, salinity and currents derived from a model reanalysis product, Simple Ocean Data Assimilation\textsuperscript{17} (SODA) analysis is utilized for the present study. Usually anomalous events like ElNino and IOD will tend to produce some ambiguous circulation features. Hence 2001- 2002 was chosen which is void of any anomalous events. Recent decade is fed with enormous qualitative and quantitative in situ as well as satellite observations, during which the SODA data is more reliable. Hence, the period chosen is the first normal/non anomalous tenure during the recent decade. By utilizing the temperature, salinity data T-S analysis is carried out to identify the BBW. From the BBW characteristics the shallowest and deepest

![Fig. 1–T-S diagram for the profiles in the SEAS region (70-77°E, 8-15°N) during October 2001 to May 2002](image-url)
depths of BBW are computed and from the difference of these two, thickness of BBW is computed. Further vertical integrated volume transport of BBW along the transects 77.5°E, 8.25°N, 10.25°N, 12.75°N and 15.25°N (transects are shown in Fig. 2) are computed from the coast and averaged over the transects. In vertical, depth is considered up to which BBW can be traced.

Results and Discussion

Water mass is defined by its temperature and salinity taken as conservative parameters only altered by mixing. T-S diagram is one method of its kind to identify water masses. In this study, T-S profiles in the upper 230m are utilized. T-S analysis carried out (Fig. 1) in the SEAS (70-77°E, 8-15°N) depict the intrusion and retreat of BBW into SEAS during post monsoon followed by winter monsoon and pre-monsoon. During October, no points are seen over 21-22 sigma-t curve (Fig. 1) which shows the absence of BBW in the region. With the commencement of winter monsoon (November), some points are seen over the <21 to 22 sigma-t curve which indicate BBW is started intruding. During the progress of the winter monsoon (December-January), even though temperature of the water mass is more or less same, the salinity further decreased. This decreased the density of water mass less than 21 (19.8-21). The points which are falling below 21 sigma-t are called modified BBW. During February, the slope of the T-S curve increased which means that the temperature of the water mass is increased. This decreases the density further and hence sigma-t is less than 19. With the retreat of monsoon (March - May), the slope of the T-S curve still increases and number of points over 21-22 sigma-t curve are decreased. This is due to the fact that BBW has been modified by pre-monsoon heating.

The thickness of BBW is computed during October 2001 to May 2002 utilizing the BBW criteria (Fig. 2). But for the present study the modified BBW is not considered. Minimum thickness of BBW (0-10 m)

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Fig. 2–Thickness of BBW (m) during October 2001 to May 2002 overlaid by currents (Transects shown are along which volume transport is computed)
in the central Bay of Bengal during October is observed when EICC is equatorward (Fig. 2). No trace of this water mass is seen in the SEAS (evident from T-S diagram also) since the currents along the west coast are not favoring for the transport. When current along the west coast reversed to poleward which is well known as West India Coastal Current (WICC) during November, along with equatorward EICC transports BBW into SEAS. Model studies show that these currents are associated with a downwelling Kelvin wave triggered along the east coast of India with the collapse of summer monsoon10,11. During this month, the northward limit is upto 10°N with a thickness of 30 m. During December, when EICC and WICC strengthened along with the westward Winter Monsoon Current (WMC) south of Sri Lanka the northward limit of this water mass extended more upto 12°N with increased thickness (40-50 m). While during January eventhough the EICC changed its direction and started flowing poleward upto 16°N (weak southward flow noticed north of 16°N), the northward limit of this water mass in SEAS is upto 16°N with maximum thickness (50-60 m). This can be attributed to the strong poleward flowing WICC. North of 8°N the water mass is very much confined to the coast and south of it spreads offshore which can be clearly linked to the prevailing circulation pattern. In February the EICC completely flow towards north. It is seen that WMC along with WICC transport the BBW further southward with reduced thickness. This water mass spread offshore upto 65°E south of 6°N – equator by the westward flowing WMC. As the monsoon is retreating the WICC and even WMC also weakens. This depletes the BBW layer in the SEAS during March 2002. During the transition period, the WICC changes direction and starts flowing southward which causes the BBW in SEAS to retreat and it is present only along the coast upto ~9.5°N. South of southern tip of India to 2°N, the BBW thickness also found to be decreased. By May 2002, well developed equatorward WICC is formed and no trace of BBW is seen in the SEAS. This can be due to the fact that the BBW is modified by the pre-monsoon heating. Moreover, these results are compared with climatology (Fig. not shown). Since, the study period chosen is normal year; the observed patterns are similar to climatology with high magnitudes.

To quantify the transport of BBW into SEAS, vertical integrated volume transport is computed along the transects perpendicular to the coast along 77.5°E, 8.25°N, 10.25°N, 12.75°N and 15.25°N (Fig. 3). Along 77.5°E, transport is found to increase from October to December and then decreased. From January to February, it increases and then continuously decreases. The contribution of zonal transport in westward direction is more when compared to meridional for the total transport. Peak of volume transport (0.8 Sv) is observed during February in the westward direction. Along 77.5°E, transport is found to increase from October to December and then decreased. From January to February, it increases and then continuously decreases. The contribution of zonal transport in westward direction is more when compared to meridional for the total transport. Peak of volume transport (0.8 Sv) is observed during February in the westward direction. Along southwest coast of India, meridional transport is more and in the northward direction. In zonal direction, the transport is almost along west. Maximum volume transport is observed during December – January and decreased from February onwards. Maximum volume transport is observed along 12.75°N with a value of 0.45 Sv and minimum along 15.25°N with 0.2 Sv.

**Conclusion**

In summary, the waters of the tropical basins of the Arabian Sea and the Bay of Bengal though subjected to similar atmospheric forcing and situated
in same latitudes, experiences large hydrological imbalances on an annual scale. Primary reason for this is the intense evaporation in the Arabian Sea which loses fresh water on an annual scale, while reverse is the case in the Bay of Bengal which receives immense quantities of fresh water due to precipitation and river run off. In winter the southward flowing EICC carry the low salinity Bay of Bengal waters from the northern Bay to the southern part of the Peninsular India and feeds the northward flowing WICC in the Arabian Sea along with WMC. This intrusion of the Bay of Bengal waters into the Arabian Sea is seen upto 16°N during peak phase of WICC i.e., January-February. Thickness of the water mass is found to vary from 10 to 60 m during the entire study period. It is shallow during November and March-April while it is deep during peak phase of WICC (January-February). Results are analogous to climatology with high magnitudes. Maximum volume transport of 0.8 Sv towards west along 77.5°E is observed during February. Thus the present study, infers the seasonal variability of this exchange both qualitatively and quantitatively. This inter-basin mass exchange between Bay of Bengal and Arabian Sea plays vital role in altering the physical and biological properties of both the basins as well as determining the surface heat content of the warm pool zone in the SEAS\textsuperscript{19,20,21,8,22}.

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