T-S variability and volume transport in the central Bay of Bengal during southwest monsoon*

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The variability of temperature and salinity along 11°N and 12°N sections in the Bay of Bengal during southwest monsoon months (July-September) was found to be large in the upper 200 m west of 83°E and east of 90°E, and up to upper 400 m in the central parts between 84° and 89°E. Coastal upwelling off Madras appears to be intense during August with a strong (40 cm sec⁻¹) northward flow close to the coast. The associated northward transport in the upper 100 m (between 81° and 82°E) increased by $2.5 \times 10^6$ m³ sec⁻¹ from July to August. At the location of penetration of Arabian Sea High Salinity Watermass ($T = 25°C$, $S = 35.2 \times 10^{-3}$, $\Delta_{oc} = 400 \text{cl} \text{t}$) doming of isolines of T, S and $\sigma_t$ (sigma-t) towards sea surface was noticed between 86° and 89°E only during August. The flow in this region was directed towards north with a volume transport of $5.5 \times 10^6$ m³ sec⁻¹ in the upper 100 m.

Studies on the influence of the southwest monsoon on the variability of water characteristics and circulation of the Bay of Bengal are few, mainly due to the paucity of data. Based on the one-time observations in the Bay of Bengal, the water characteristics, current structure, circulation and volume transport have been studied. In the present study, utilizing the CTD data collected under the Indian TOGA (Tropical Ocean and Global Atmosphere) program along two adjacent latitudinal sections in the central Bay of Bengal, an attempt is made to understand the T-S variability and volume transport in the central Bay of Bengal during SW monsoon (July and August).

Materials and Methods

CTD data (Seabird, USA, temperature sensor accuracy: ± 0.002°C, salinity accuracy: ± 0.002 PSU and depth accuracy: 0.02% of full scale) were collected in the upper 2000 m onboard ORV Sagar Kanya along Madras-Port Blair section (~12°N) during August 1991 and onboard RV Gaveshani along 11°N section during July 1993 (Fig. 1). The CTD data collected along 12°N section during September 1984 were also used (wherever necessary) in the present study to understand T-S variability during SW monsoon season (July through September) irrespective of the timings of data collection. The meridional currents and volume transport across the zonal sections in the upper 1000 m have been computed following Pond & Pickard. Maps of vertical distribution of temperature (T), salinity (S), sigma-t ($\sigma_t$) and currents along the sections for July and August were prepared.

Results and Discussion

Watermass structure

The variability of water characteristics along 12°N and 11°N latitudinal sections is examined through T-S diagrams. Figure 2 represents the typical T-S diagrams presented at three locations—82°E (western), 88°E (central) and 91°E (eastern). At the western loca-
tion (Fig. 2a) the surface salinity was $33.8 \times 10^{-3}$ during July-August and $34.2 \times 10^{-3}$ in September. Below the surface, salinity and temperature increased steadily at a given depth in the upper 100 m from July to August. However decrease in temperature and increase in salinity was noticeable in the upper 75 m from August to September. Higher differences in temperature and salinity were noticed at 75 m depth (marked in Fig. 2).

At the central location (Fig. 2b) the T-S variability was large in the upper 100 m from July to September while marginal variability was noticed between 100 m and 400 m depth. The T-S structure reveals the presence of high salinity ($35.18-35.30 \times 10^{-3}$) watermass located at about 90-100 m along 440 cL/t in August and 400 cL/t in September (Fig. 2b). The core temperatures of this watermass is 1°C higher in August ($T = 25°C$) compared to that of September ($24°C$). These thermohaline indices indicate the penetration of warm, high saline Arabian Sea High Salinity Watermass (ASHSW)\(^1\). This watermass is advected into the Bay through the Indian Monsoon Current (IMC) during SW monsoon season\(^5-8\). The changes in the temperature and salinity of this watermass and hence its occurrence at different isanosteric levels and depths are due to its proximity to the sea surface where the surface wind forcing is strong with positive wind stress curl\(^{12,13}\) acting over the central Bay of Bengal.

In the T-S diagram for the eastern (91°E) location (Fig. 2c) greater variability was seen in the upper 200 m, with cold, high saline waters during July; warm, less saline waters during August and relatively warm and saline waters in September at 75 m depth. The reduction in salinity by September in upper 100 m is due to the flow of low saline waters from the northeast Bay.

The T-S variability is further examined through vertical sections of temperature, salinity, sigma-t, current structure and volume transport along 11°N and 12°N sections.

**Thermal structure**

Figure 3 represents the thermal structures in July and August in the upper 500 m. The sea surface temperature (SST) in general varied between 28.4° and 29.4°C with a decreasing trend towards east. Downward sloping of thermocline towards east from 86°E was noticed in July. However during August doming of isotherms (28° to 24°C) in the upper thermocline between 86° and 89°E was conspicuous. On the western side of the sections upward rising of thermocline from 100 m depth was noticed between 83°E and coast-
tional region (13°-11°N) of Tamil Nadu. During August, this upward tilt of isotherms continued up to the continental shelf (where data is available). This indicates the presence of coastal upwelling process off Tamil Nadu during SW monsoon. Earlier Gopalakrishna & Sastry\(^2\) reported intense upwelling process off Madras coast during August. The positive upwelling index\(^1\) (indicator of offshore Ekman transport) during July-August also supports coastal upwelling. The observed minimum (negative) values of sea level\(^7\) at Madras during SW monsoon indicates a northward flow which is the manifestation of upwelling process. The variations in the sea level\(^7\) and the upwelling index\(^1\) at Nagapattinam coast during SW monsoon, also supports upwelling process\(^1\) and its impact can be seen at 81°E along 11°N section. The vertical velocity field\(^12,13\) derived from the climatological\(^1\) and observed (during SW monsoon of 1984) surface wind data over the Bay of Bengal for July and August further substantiates the upwelling process west of 85°E between 10° and 13°N. The above observations confirm that the upwelling process off Madras coast is a permanent hydrographic feature during SW monsoon.

**Salinity structure**

During July, a layer of low salinity (< 34 x 10\(^{-3}\)) water gradually decreasing towards east occupied top 50 m column (Fig. 4a). However, during August (Fig. 4b) salinities in the upper 50 m column decreased considerably to 32.8 x 10\(^{-3}\) particularly in the eastern parts due to flow of low salinity waters and increase in local precipitation by August\(^5\). Between 85° and 89°E relatively high saline waters (> 34 x 10\(^{-3}\)) were noticed at the surface separating the low waters (< 33.4 x 10\(^{-3}\)) on both sides. On the western side of the sections the isohalines (> 33.8 x 10\(^{-3}\)) exhibited an upward tilt in the region of coastal upwelling (as discussed in the section on thermal structure). On the

![Fig. 3—Vertical distribution of temperature (a) along 11°N (July), (b) along Madras-Port Blair route (August)](image)

![Fig. 4—Vertical distribution of salinity (a) along 11°N (July), (b) along Madras-Port Blair route (August)](image)
eastern side of the sections, the isohalines exhibited downward slope east of 89°E with a decrease in salinity to $2.8 \times 10^{-3}$ August. It is interesting to note a small high salinity ($> 35.0 \times 10^{-3}$) cell at 88°E around 100 m depth during July (Fig. 4a) and a broad high salinity ($> 35.2 \times 10^{-3}$) cell with an upward tilt towards east from 86° to 88°E in the depth interval 75-100 m during August (Fig. 4b). This high salinity cell represents the presence of ASHISW being advected into the Bay of Bengal during SW monsoon through the Indian monsoon current. The isohalines above the high salinity core exhibit doming resulting in a salinity front-like structure at the sea surface between 87° and 88°E. This doming of isohalines and the isothersms result from the divergence associated with the positive wind stress curl$^{12-13}$ over the central Bay of Bengal. The salinity front is conspicuous with large cross-frontal salinity differences at 85°E and 89°E during August. The vertical mixing between this high salinity ($> 35.0 \times 10^{-3}$) watermass and the ambient ($33.4 \times 10^{-3}$ as in July) surface waters could give rise to relatively higher surface salinities (about $34.0 \times 10^{-3}$) between 87° and 88°E.

Current structure

A broad northward flow with higher velocity (40 cm sec$^{-1}$) at 89.5°E was noticed between 88° and 92°E during July (Fig. 5a), while the northward flow was strong (49 cm sec$^{-1}$) and confined to 87°-90°E during August (Fig. 5b). This northward flow represents the Indian monsoon current and its magnitude is in agreement with that reported earlier$^9$ for the SW monsoon of 1984. The surface currents$^7$ of this region also indicate northward flow with similar magnitude in July and August. The current pattern west of this broad northerly flow shows alternating flows (north/south) of width (100 km) equal to the spacing between the hydrographic stations and shows noise in the flow field. This noise, however, cannot be eliminated in the geostrophic computations. A northerly flow was present off Madras coast which appears to strengthen by August. Similarly, a relatively strong (30 cm sec$^{-1}$) southward flow occurs in the eastern parts of the section during August.

Surface dynamic heights and volume transport

The alternating flows of geostrophic currents can also be visualized from the variations in the slope of the dynamic heights at the sea surface computed relative to 1000 db (Fig. 6a). Compared to July, the dynamic heights in August were higher throughout the section except at 92°E. These higher dynamic heights are resulted from deep isothermal layer of temperature 28°C, followed by deep thermocline and the presence of relatively less saline waters. During July the steady increase in the surface dynamic height towards east between 88° and 92°E is resulted from the deepening of thermocline (Fig. 3a) and the occurrence of lower salinity waters over a deeper water column (Fig. 4a). Similar slope was noticed between 87° and 89°E during August. The maximum variation of dynamic heights between 87° and 89°E from July to Aug-

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**Fig. 5** - Vertical distribution of relative velocity (cm sec$^{-1}$) in the upper 1000 m
Just is resulted from the penetration of ASHSW at sub-surface depths and its uplift towards surface causing the shoaling of the isothermal (28°C) layer, characterized by relatively saline waters. The dip in the dynamic height at 87°E in August may indicate the centre of the large cyclonic gyre that occupies the central Bay of Bengal during SW monsoon. The doming of isolines of T, S and σt towards surface with penetration of ASHSW at sub-surface depths may also be due to this cyclonic gyre. West of 87°E, the variation of dynamic height in August is a mirror image to that in July.

The geostrophic volume transport in the upper 100 m water column representing the upper thermocline reveals different patterns of transport (Fig. 6b) from July to August. During July a broad northward transport (influx) was present east of 88°E, with higher influx (4 × 10^6 m^3 sec^-1) between 89° and 90°E and weak influx (1 × 10^6 m^3 sec^-1) between 81° and 82°E. During August, the volume transport between 81° and 82°E shows an influx of about 4 × 10^6 m^3 sec^-1 and similar magnitude of influx was also noticed between 88° and 89°E. A comparison of the upper thermocline transport shows an increase of influx by 2.5 × 10^6 m^3 sec^-1 between 81° and 82°E and also between 88° and 89°E from July to August. Moreover, within the month of August while there is an influx at the western end, outflux (southward transport) prevailed at the eastern end. In the region of ASHSW penetration, the transport in the upper thermocline showed an influx of 5.0 × 10^6 m^3 sec^-1 between 88° and 90°E during July and an influx of 5.6 × 10^6 m^3 sec^-1 between 87° and 89°E during August. This influx associated with ASHSW is consistent with that reported by Murty during SW monsoon.

The integrated volume transport in the upper 1000 m during July (Fig. 6c) showed highest influx (17 × 10^6 m^3 sec^-1) between 88° and 90°E, lesser influx (∼5 × 10^6 m^3 sec^-1) between 82° and 84°E and higher outflux (6 × 10^6 m^3 sec^-1) between 81° and 82°E. The total volume transport across the section amounts to an influx of 18 × 10^6 m^3 sec^-1 during July. The magnitude of this influx during July is in good agreement with that estimated (16.6 × 10^6 m^3 sec^-1) in the upper 1250 m across 6°N section during southwest monsoon (June-August). During August, broad alternating transports, occurring over a distance of 300 km, were noticed. While there was a large influx (14 × 10^6 m^3 sec^-1) at the western end, slightly lesser outflux (9 × 10^6 m^3 sec^-1) took place at the eastern end. The total transport across the section during August showed an influx of about 7 × 10^6 m^3 sec^-1 which is comparatively less from July. However, when the total transports across these sections and that reported earlier across 12°N section (80°S-92°E) in the upper 1000 m during September, 1984 are compared, one would notice a drastic reduction in the influx in the central Bay from July to September. This can be visualized easily from the layerwise total transport across the sections (Fig. 7). The large differences in the magnitudes of total transport in the upper 1000 m across the sections from July through September (Fig. 7) suggest the presence of large intraseasonal variability in the total transport or possibly the dominance of outflux across the central Bay at the end of SW monsoon. It is interesting to notice that the influx associated with the transport of ASHSW in the upper thermocline is nearly the same during the months of SW monsoon (July through September). Further, the westward shift in the occurrence of this ASHSW from July to August at 11°N and 12°N sections (though these sections occupied in different years) indicates the presence of cyclonic flow of the large cyclonic gyre with its centre at 87°E (Fig. 6a) in the central Bay of Bengal, which is in confirmation with the earlier studies during SW monsoon. Further,
from the similar magnitude of the observed salinity maximum and its depth of occurrence in August in the central parts (Fig. 2b) and in September at the western part (Fig. 2a), the presence of large cyclonic gyre through which the high salinity watermass is advected towards western Bay can clearly be inferred.

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