

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

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Received 21 December 1994; revised 5 October 1995

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 ( $40 \text{ cm} \cdot \text{sec}^{-1}$ ) northward flow close to the coast. The associated northward transport in the upper 100 m (between 81° and 82°E) increased by  $2.5 \times 10^6 \text{ m}^3 \cdot \text{sec}^{-1}$  from July to August. At the location of penetration of Arabian Sea High Salinity Watermass ( $T = 25^\circ\text{C}$ ,  $S = 35.2 \times 10^{-3}$ ,  $\Delta_{s,t} = 400 \text{ cl/t}$ ) 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  $5.5 \times 10^6 \text{ m}^3 \text{ sec}^{-1}$  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<sup>1-10</sup>. 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:  $\pm 0.002^\circ\text{C}$ , salinity accuracy:  $\pm 0.002 \text{ PSU}$  and depth accuracy: 0.02% of full scale) were collected in the upper 2000 m onboard *ORV Sagar Kanya* along Madras-Port Blair section ( $\sim 12^\circ\text{N}$ ) during August 1991 and onboard *R V 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<sup>11</sup>. 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-

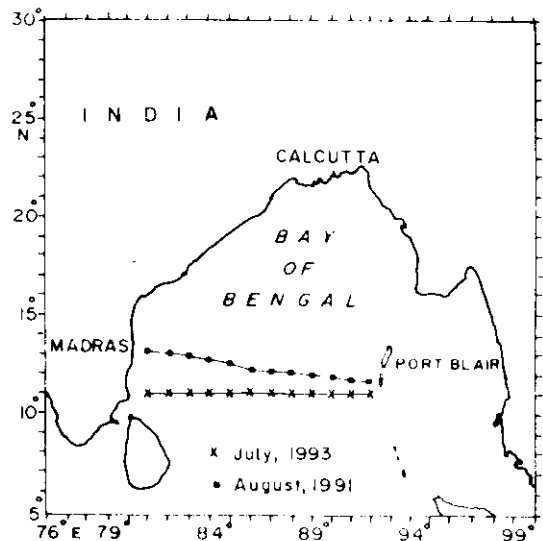


Fig. 1 Location of CTD sections along (a) 11°N and (b) Madras-Port Blair

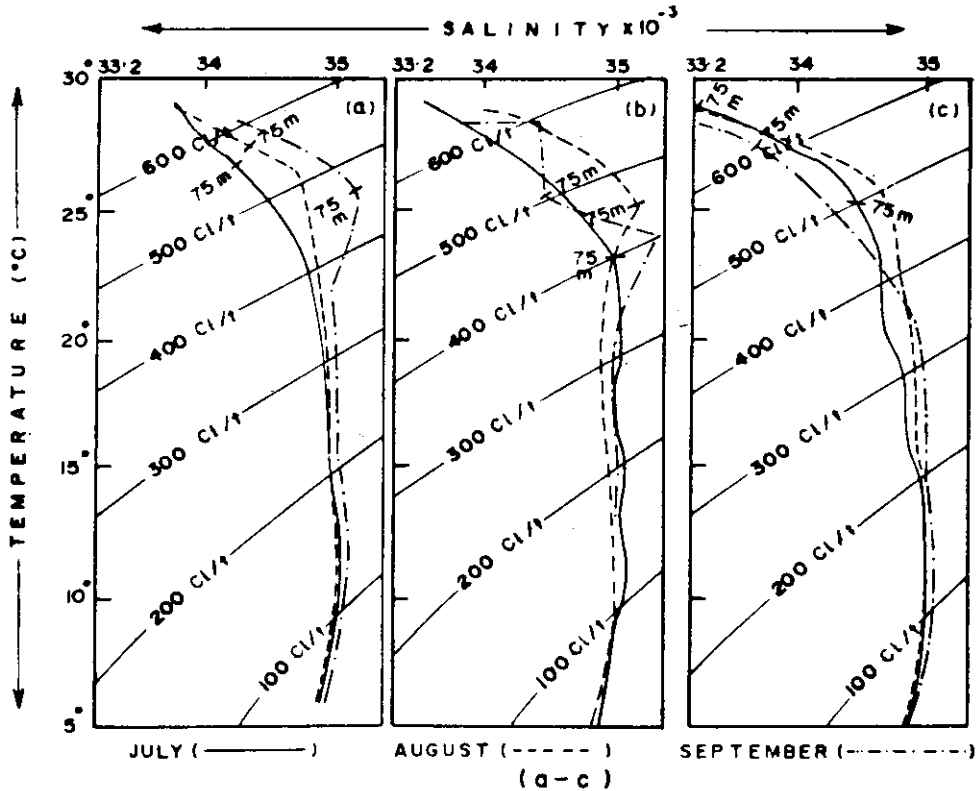


Fig. 2 – T-S diagrams at selected locations (a) 82°E, (b) 88°E, (c) 91°E

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 ( $T=25^\circ\text{C}$ ) compared to that of September ( $24^\circ\text{C}$ ). These thermohaline indices indicate the penetration of warm, high saline Arabian Sea High Salinity Watermass (ASHSW)<sup>1</sup>. This watermass is advected into the Bay through the Indian Monsoon Current (IMC) during SW monsoon season<sup>5,8</sup>. 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<sup>12,13</sup> 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  $28.4^\circ$  and  $29.4^\circ\text{C}$  with a decreasing trend towards east. Downward sloping of thermocline towards east from  $86^\circ\text{E}$  was noticed in July. However during August doming of isotherms ( $28^\circ$  to  $24^\circ\text{C}$ ) in the upper thermocline between  $86^\circ$  and  $89^\circ\text{E}$  was conspicuous. On the western side of the sections upward rising of thermocline from 100 m depth was noticed between  $83^\circ\text{E}$  and coas-

tal region ( $13^{\circ}$ - $11^{\circ}$ 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<sup>2</sup> reported intense upwelling process off Madras coast during August. The positive upwelling index<sup>14</sup> (indicator of offshore Ekman transport) during July-August also supports coastal upwelling. The observed minimum (negative) values of sea level<sup>7</sup> at Madras during SW monsoon indicates a northward flow which is the manifestation of upwelling process. The variations in the sea level<sup>7</sup> and the upwelling index<sup>14</sup> at Nagapatnam coast during SW monsoon, also supports upwelling process<sup>14</sup> and its impact can be seen at  $81^{\circ}$ E along  $11^{\circ}$ N section. The vertical velocity field<sup>12,13</sup> derived from the climatological<sup>15</sup> 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  $85^{\circ}$ E between  $10^{\circ}$  and  $13^{\circ}$ 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 ( $< 34 \times 10^{-3}$ ) 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  $32.8 \times 10^{-3}$  particularly in the eastern parts due to flow of low salinity waters and increase in local precipitation by August<sup>16</sup>. Between  $85^{\circ}$  and  $89^{\circ}$ E relatively high saline waters ( $> 34 \times 10^{-3}$ ) were noticed at the surface separating the low waters ( $< 33.4 \times 10^{-3}$ ) on both sides. On the western side of the sections the isohalines ( $> 33.8 \times 10^{-3}$ ) exhibited an upward tilt in the region of coastal upwelling (as discussed in the section on thermal structure). On the

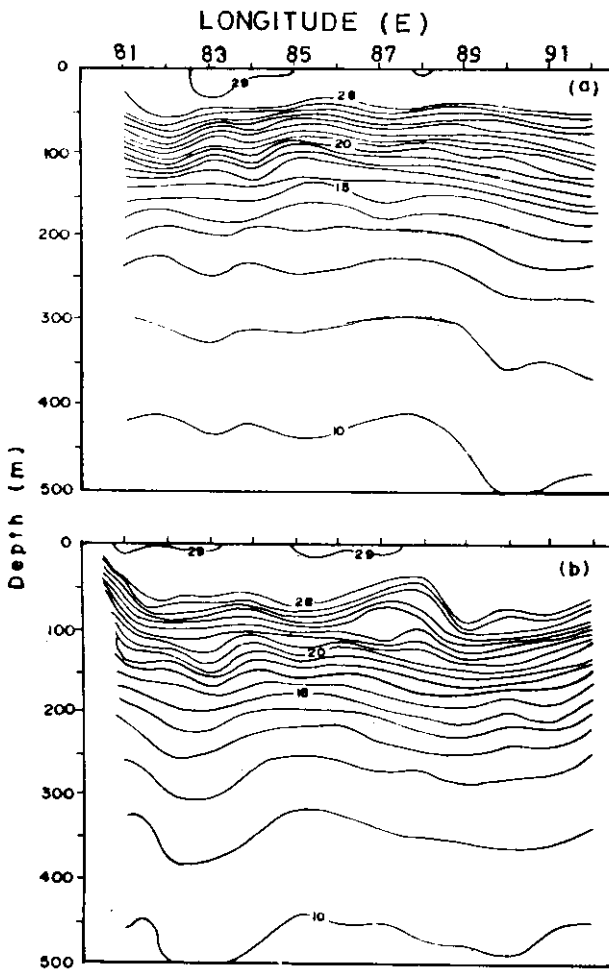


Fig. 3—Vertical distribution of temperature (a) along  $11^{\circ}$ N (July), (b) along Madras-Port Blair route (August)

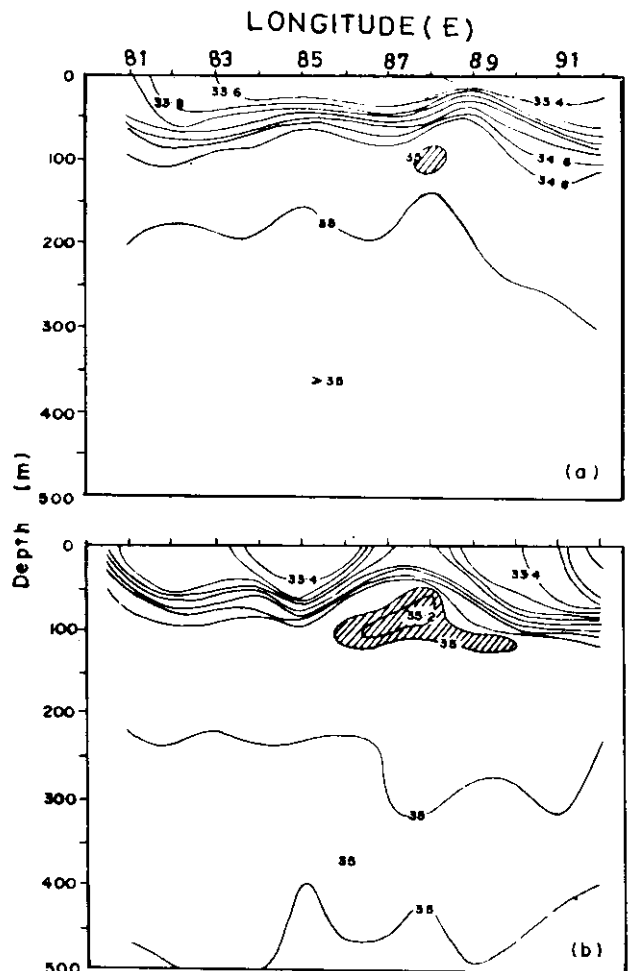


Fig. 4—Vertical distribution of salinity (a) along  $11^{\circ}$ N (July), (b) along Madras-Port Blair route (August)

eastern side of the sections, the isohalines exhibited downward slope east of 89°E with a decrease in salinity to  $32.8 \times 10^{-3}$  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 ASHSW 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 isotherms result from the divergence associated with the positive wind stress curl<sup>12,13</sup> 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 ( $> 35 \times 10^{-3}$ ) 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.

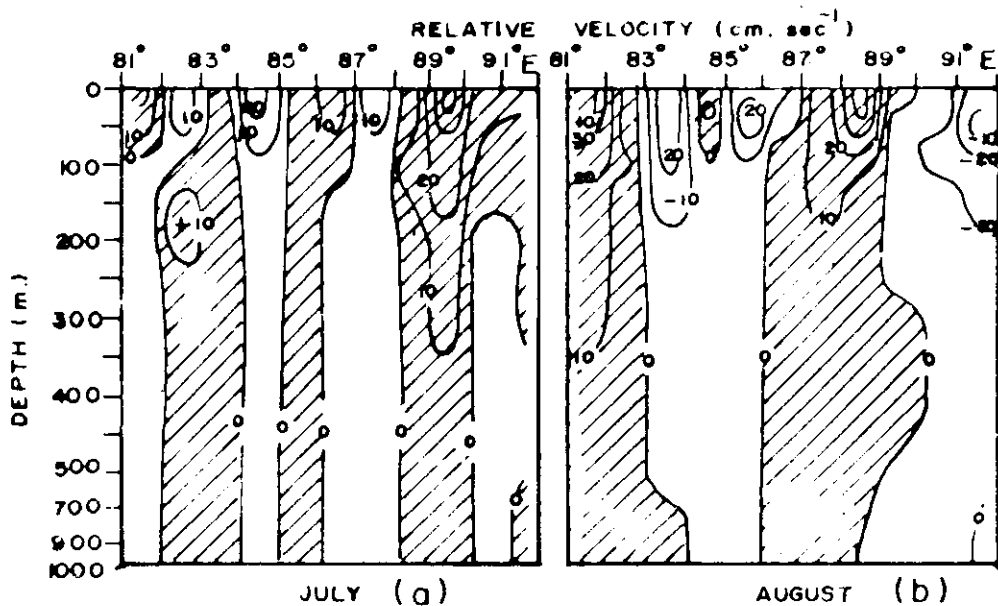
**Current structure**

A broad northward flow with higher velocity ( $40 \text{ cm}\cdot\text{sec}^{-1}$ ) at 89.5°E was noticed between 88° and 92°E during July (Fig. 5a), while the northward flow was strong ( $49 \text{ cm}\cdot\text{sec}^{-1}$ ) and confined to 87°-90°E during August (Fig. 5b). This northward flow represents the Indian monsoon current and its magnitude is in agr-

ement with that reported earlier<sup>8,9</sup> for the SW monsoon of 1984. The surface currents<sup>17</sup> 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, can not be eliminated in the geostrophic computations. A northerly flow was present off Madras coast which appears to strengthen by August. Similarly, a relatively strong ( $30 \text{ cm}\cdot\text{sec}^{-1}$ ) 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-



Hatched region indicate northward transport

Fig. 5—Vertical distribution of relative velocity ( $\text{cm}\cdot\text{sec}^{-1}$ ) in the upper 1000 m

ust is resulted from the penetration of ASHSW at sub-surface depths and its uplift towards surface causing the shoaling of the isothermal ( $28^{\circ}\text{C}$ ) layer, characterized by relatively saline waters. The dip in the dynamic height at  $87^{\circ}\text{E}$  in August may indicate the centre of the large cyclonic gyre<sup>8</sup> that occupies the central Bay of Bengal during SW monsoon. The doming of isolines of  $T$ ,  $S$  and  $\sigma_t$  towards surface with penetration of ASHSW at sub-surface depths may also be due to this cyclonic gyre. West of  $87^{\circ}\text{E}$ , 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  $88^{\circ}\text{E}$ , with higher influx ( $4 \times 10^6 \text{ m}^3 \cdot \text{sec}^{-1}$ ) between  $89^{\circ}$  and  $90^{\circ}\text{E}$  and weak influx ( $1 \times 10^6 \text{ m}^3 \cdot \text{sec}^{-1}$ ) between  $81^{\circ}$  and  $82^{\circ}\text{E}$ . During August, the volume transport between  $81^{\circ}$  and  $82^{\circ}\text{E}$  shows an influx of about  $4 \times 10^6 \text{ m}^3 \cdot \text{sec}^{-1}$  and similar magnitude of influx was also noticed bet-

ween  $88^{\circ}$  and  $89^{\circ}\text{E}$ . A comparison of the upper thermocline transport shows an increase of influx by  $2.5 \times 10^6 \text{ m}^3 \cdot \text{sec}^{-1}$  between  $81^{\circ}$  and  $82^{\circ}\text{E}$  and also between  $88^{\circ}$  and  $89^{\circ}\text{E}$  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  $5.0 \times 10^6 \text{ m}^3 \cdot \text{sec}^{-1}$  between  $88^{\circ}$  and  $90^{\circ}\text{E}$  during July and an influx of  $5.6 \times 10^6 \text{ m}^3 \cdot \text{sec}^{-1}$  between  $87^{\circ}$  and  $89^{\circ}\text{E}$  during August. This influx associated with ASHSW is consistent with that reported by Murty<sup>5</sup> during SW monsoon.

The integrated volume transport in the upper 1000 m during July (Fig. 6c) showed highest influx ( $17 \times 10^6 \text{ m}^3 \cdot \text{sec}^{-1}$ ) between  $88^{\circ}$  and  $90^{\circ}\text{E}$ , lesser influx ( $\sim 5 \times 10^6 \text{ m}^3 \cdot \text{sec}^{-1}$ ) between  $82^{\circ}$  and  $84^{\circ}\text{E}$  and higher outflux ( $6 \times 10^6 \text{ m}^3 \cdot \text{sec}^{-1}$ ) between  $81^{\circ}$  and  $82^{\circ}\text{E}$ . The total volume transport across the section amounts to an influx of  $18 \times 10^6 \text{ m}^3 \cdot \text{sec}^{-1}$  during July. The magnitude of this influx during July is in good agreement with that estimated ( $16.6 \times 10^6 \text{ m}^3 \cdot \text{sec}^{-1}$ ) influx in the upper 1250 m across  $6^{\circ}\text{N}$  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 ( $14 \times 10^6 \text{ m}^3 \cdot \text{sec}^{-1}$ ) at the western end, slightly lesser outflux ( $9 \times 10^6 \text{ m}^3 \cdot \text{sec}^{-1}$ ) took place at the eastern end. The total transport across the section during August showed an influx of about  $7 \times 10^6 \text{ m}^3 \cdot \text{sec}^{-1}$  which is comparatively less from July. However, when the total transports across these sections and that reported<sup>9</sup> earlier across  $12^{\circ}\text{N}$  section ( $80^{\circ}30' - 92^{\circ}\text{E}$ ) 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 intra-seasonal 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  $11^{\circ}\text{N}$  and  $12^{\circ}\text{N}$  sections (though these sections occupied in different years) indicates the presence of cyclonic flow of the large cyclonic gyre with its centre at  $87^{\circ}\text{E}$  (Fig. 6a) in the central Bay of Bengal, which is in confirmation with the earlier studies<sup>8,9</sup> during SW monsoon. Further,

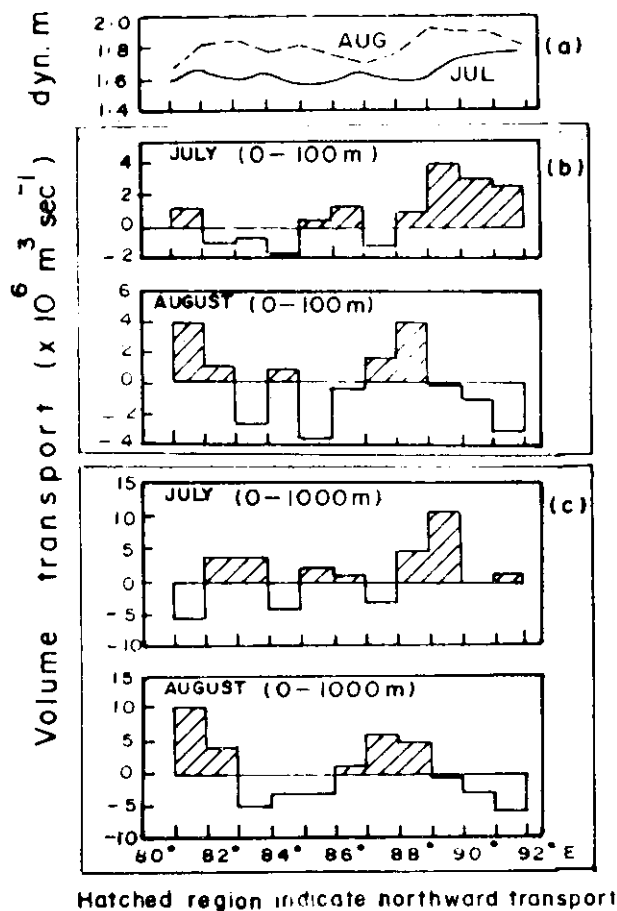


Fig. 6—Variation of (a) surface dynamic heights (dyn.m) relative to 1000 db level, (b) volume transport in the upper 100 m and (c) volume transport in the upper 1000 m

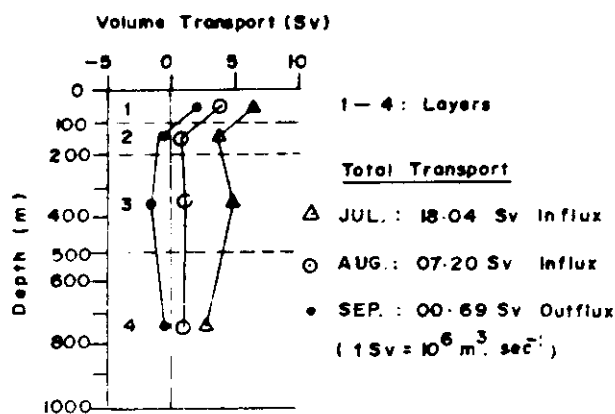


Fig. 7—Total volume transport across the section

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 water mass is advected towards western Bay can clearly be inferred.

#### Acknowledgement

The TOGA XBT project is funded by the Department of Science and Technology, New Delhi. Co-operation extended by the co-participants on-board the research vessel is highly appreciated.

#### References

- 1 Sastry J S, Rao D P, Murty V S N, Sarma Y V B, Suryanarayana & Babu M T, *Mahasagar—Bull Natn Inst Oceanogr*, 18 (1985) 153.
- 2 Gopalakrishna V V & Sastry J S, *Indian J Mar Sci*, 14 (1985) 62.
- 3 Somayajulu Y K, Ramanamurty T V R, Prasannakumar S & Sastry J S, *Indian J Mar Sci*, 16 (1987) 207.
- 4 Varkey M J, *Salt balance and mixing in the Bay of Bengal*, Ph.D. thesis, Kerala University, India, 1986.
- 5 Murty V S N, *Some aspects of large scale circulation in the Bay of Bengal during southwest monsoon*, Ph.D. thesis, Andhra University, India, 1990.
- 6 Murty V S N, Sarma Y V B, Suryanarayana A, Babu M T, Santanam K, Panakal Rao D & Sastry J S, *Report on the physical oceanographic characteristics of the Bay of Bengal during southwest monsoon*, Technical Report, No. NIO/TR-8/90 (National Institute of Oceanography, Goa, India), 1990, p. 57.
- 7 Shetye S R, Shenoi S S C, Gouveia A D, Michael G S, Sundar D & Nampoothiri G, *Cont Shelf Res*, 11 (1991) 1397.
- 8 Murty V S N, Sarma Y V B, Rao D P & Murty C S, *J Mar Res*, 50 (1992) 207.
- 9 Murty V S N, Suryanarayana A & Rao D P, *Indian J Mar Sci*, 22 (1993) 12.
- 10 Shetye S R, Gouveia A D, Shenoi S S C, Sundar D, Michael G S & Nampoothiri G, *J Geophys Res*, 98 C1 (1993) 945.
- 11 Pond S & Pickard G L, *Introductory dynamical oceanography*, (Pergamon Press, Oxford) 1983, pp. 329.
- 12 Babu M T, *Hydrography and circulation of the waters of Bay of Bengal during postmonsoon season*, M.Sc. thesis, Bombay University, India, 1987.
- 13 Babu M T, Heblekar A K & Murty C S, *Indian J Mar Sci*, 18 (1989) 223.
- 14 Suryanarayana A & Rao D P, in *Physical processes in the Indian seas*, edited by G Narayana Swamy, V Kesava Das & M K Anthony, (ISPO, NIO, Goa, India) 1992, 125.
- 15 Hastenrath S & Lamb P J, *Climatic atlas of the Indian Ocean*, Part 1, *Surface and atmospheric circulation*, (University Wisconsin Press, Madison) 1979.
- 16 Varkey M J & Sastry J S, *Physical processes in the Indian seas*, edited by G Narayana Swamy, V Kesava Das & M K Anthony, (ISPO, NIO, Goa, India) 1992, 43.
- 17 Cutler A N & Swallow J C, *Surface currents of the Indian Ocean (to 25°S, 100°E)*, Rep No. 187, (Inst Oceanogr Sci, Wormley, England) 1984.