

## CIRCULATION AND GEOSTROPHIC TRANSPORT IN THE BAY OF BENGAL

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### ABSTRACT

Utilising the hydrographic data collected during the early northeast monsoon of 1983 and southwest monsoon of 1984, the circulation of waters of the Bay of Bengal and the associated volume transport have been studied in the upper 1000 m. The circulation is primarily cyclonic surrounded by cyclonic and anticyclonic gyres during both the seasons. The volume transport across the zonal sections reveals net influx of  $64 \times 10^6 \text{ m}^3/\text{s}$  during northeast monsoon and  $1 \times 10^6 \text{ m}^3/\text{s}$  during southwest monsoon in the area of study.

### INTRODUCTION

The Bay of Bengal is subjected to seasonally reversing northeast and southwest monsoon wind forcings coupled with the freshwater discharge from various rivers opening out into the Bay, having its peak discharge during August-September. The circulation of the Bay has been studied earlier by many investigators (La Fond and La Fond, 1968; Varadachari et al., 1968; Duing, 1970; Wyrтки, 1971; Rao, 1977 and Rao and Sastry, 1981) based on the hydrographic data limited both in space and time. These studies revealed that the circulation is predominantly anticyclonic during pre-monsoon (March-May) and cyclonic during post-monsoon (October-November) periods (La Fond and La Fond, 1968). Duing (1970), based on the IIOE data, suggested that circulation in the Bay is anticyclonic throughout the year. Rao (1977) and Rao and Sastry (1981) mentioned that the circulation during northeast monsoon consists multiple-cellular gyres- cyclonic and anticyclonic- extending to deeper depths and further mentioned that the freshwater discharge may develop an estuarine type of circulation in the northern region of the Bay. Thus, it is clear that the circulation pattern in the Bay is complicated by winds, freshwater discharge etc.

In this paper, the geostrophic circulation and the associated volume transport in the Bay of Bengal between  $6^\circ\text{N}$  and the head of the Bay are discussed for the early northeast monsoon and southwest monsoon seasons.

### MATERIAL AND METHODS

Hydrographic data were collected in the Bay of Bengal during October-December, 1983 on board 'RV *Gaveshani*' and during July- October, 1983 on board 'ORV *Sagar Kanya*'. A number of hydrographic stations were occupied at  $1^\circ$  interval in longitude along eight zonal sections of  $2^\circ$  interval in latitude from the head of the Bay upto  $6^\circ\text{N}$  during 1983 survey and were re-occupied during 1984 survey. The study

area is about  $1.3 \times 10^6$  sq. km which forms 58% of the total area of the Bay with its southern limit along  $6^\circ\text{N}$ . The data at the stations, obtained through conventional hydrocast operations during 1983 survey and by continuous CTD profiler during 1984 survey, were subjected to routine data processing. Utilising these data sets, the dynamic topography charts have been constructed at various horizontal surfaces relative to 1000 db level surface. The volume transports in the upper 1000 m between the station pairs have also been computed and presented.

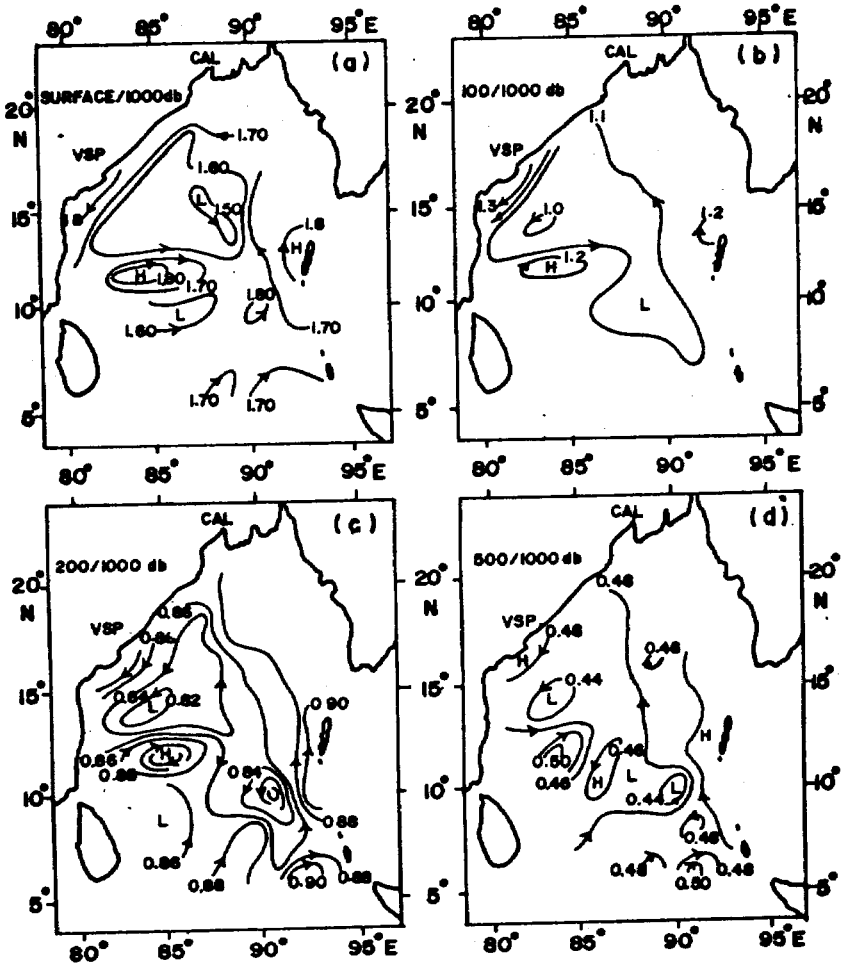


Fig. 1. Dynamic topography (dyn. m) at various depths relative to 1000 db surface during northeast monsoon.

## RESULTS AND DISCUSSION

### *Northeast monsoon*

The dynamic topography at sea surface (Fig. 1a) varied between 1.50 and 1.80 dyn.m with the region of dynamic 'valley' centered at 15°N and 89°E. A large cyclonic circulation gyre exists between 18°N and 12°N with southwestward flow along the western boundary and northward flow in the east, west of the Andaman Islands. The southwestward flow along the western boundary could be due to prevailing northeast winds and the baroclinic adjustment resulted from the shoreward density gradients caused by the low salinity waters. These low salinity waters are due to

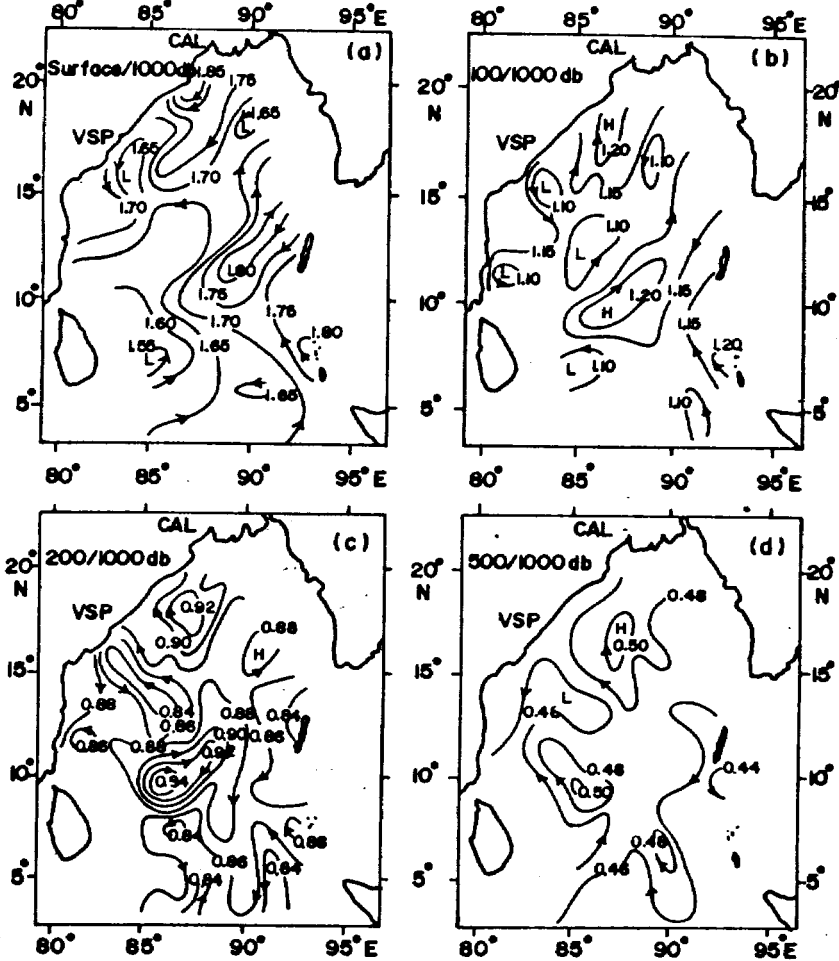


Fig. 2. Dynamic topography (dyn. m) at various depths relative to 1000 db surface during southeast monsoon.

mixing of freshwaters with the sea water. South of  $12^{\circ}\text{N}$ , anticyclonic and cyclonic eddies are noticed. In the southern Bay, the eastward flow turns northward in the eastern Bay. This eastward flow is the reminiscence of the monsoon drift current which has weakened into eddies. The northward flow in the eastern Bay is also seen in the mean surface circulation maps (Varadachari and Sharma, 1967) for October and November.

At 100 m, the dynamic topography varies between 1.0 and 1.2 dyn.m (Fig. 1b). The circulation on this surface resembles to that at the sea surface and the centre of the cyclonic gyre is shifted westward to  $14^{\circ}\text{N}$ ,  $83^{\circ}\text{E}$ . The cyclonic gyre extends southeastward upto west of the Nicobar Islands. The same features continue to 200 m depth (Fig. 1c). However, the strength of the circulation decreases considerably on this surface.

At 500 m (Fig. 1d), the cyclonic gyre is diffused completely. However, weak northwesterly flow from the southeastern Bay persists east of  $85^{\circ}\text{E}$ . The signatures of the anticyclonic and cyclonic eddies are present.

#### *Southwest monsoon*

The dynamic topography at sea surface (Fig. 2a) varies between 1.55 dyn.m in the southwest Bay and 1.85 dyn.m at the head of the Bay. The circulation is largely cyclonic. The eastward flowing monsoon drift current splits into two branches in the southwestern region of the Bay. One branch continues to flow eastward in the southern Bay and the other penetrates into the Bay as a significant northeastward flow upto the central regions. The former branch, turns northwestward in the southeastern region which also joins the later and enhances the inflow. An elliptical anticyclonic circulation cell, oriented in a southwest-northeast direction, prevails west of the Andaman Islands. North of  $16^{\circ}\text{N}$ , an anticyclonic circulation tapering southward prevails with cyclonic circulation cells on either side. The low salinity ( $<25 \times 10^{-3}$ ) waters from the head of the Bay appear to advect southward along the southwestward branch of this anticyclonic flow. In the eastern Bay, the flow is towards north from the Nicobar Islands upto the Andaman Islands. This northward flow is the result of the baroclinic adjustment due to prevailing low salinity ( $<34.5 \times 10^{-3}$ ) waters in the eastern Bay.

At 100 m (Fig. 2b), the circulation pattern reflects the sea surface pattern with comparatively weak flow as in the case of Northeast monsoon. On this surface, the dynamic topography varies from 1.10 dyn.m in the southwest to over 1.20 dyn.m at the head of the Bay and southcentral Bay.

At 200 m (Fig. 2c), the features of circulation are similar to that at 100 m with a decreasing strength of the flow. The anticyclonic circulation persists in the region north of  $16^{\circ}\text{N}$  and between  $8^{\circ}\text{N}$  and  $14^{\circ}\text{N}$ . The flow reverses southward, east of  $90^{\circ}\text{E}$  between  $15^{\circ}\text{N}$  and  $10^{\circ}\text{N}$  and westward, south of  $8^{\circ}\text{N}$ ,

At 500 m depth (Fig. 2d), the circulation is anticyclonic in the central Bay, but with a westward shift compared to that at 200 m depth. The flow is southerly and

nearly meridional in the eastern region. The anticyclonic circulation appearing in the upper levels in the north Bay still persists on this surface also.

The above features suggest that the geostrophic circulation penetrates to deeper depths with decreasing intensity of flow during both the periods studied.

### Volume transport

The vertically integrated volume transport in the upper 1000 m between station pairs across the zonal sections for both the seasons is shown in Fig. 3 along with the total transports (shown in ellipses) across respective sections. During the southwest monsoon, the transport is northward across 16°N, 10°N and 8°N and southwards across the rest of the latitudes. The northward transport is maximum (15.8 x 10<sup>6</sup> m<sup>3</sup>/s) across 8°N. The southward transport varied from 0.7 x 10<sup>6</sup> m<sup>3</sup>/s to 4.0 x 10<sup>6</sup> m<sup>3</sup>/s. The southward transport (2 x 10<sup>6</sup> m<sup>3</sup>/s) across 1930'N and 18N indicates the higher contribution of freshwater discharge in the northern Bay. During northeast monsoon, the transport is directed northward across all sections except across 16°N and 20°N. The magnitude of the northward transport varied from 4 x 10<sup>6</sup> m<sup>3</sup>/s to 19 x 10<sup>6</sup> m<sup>3</sup>/s.

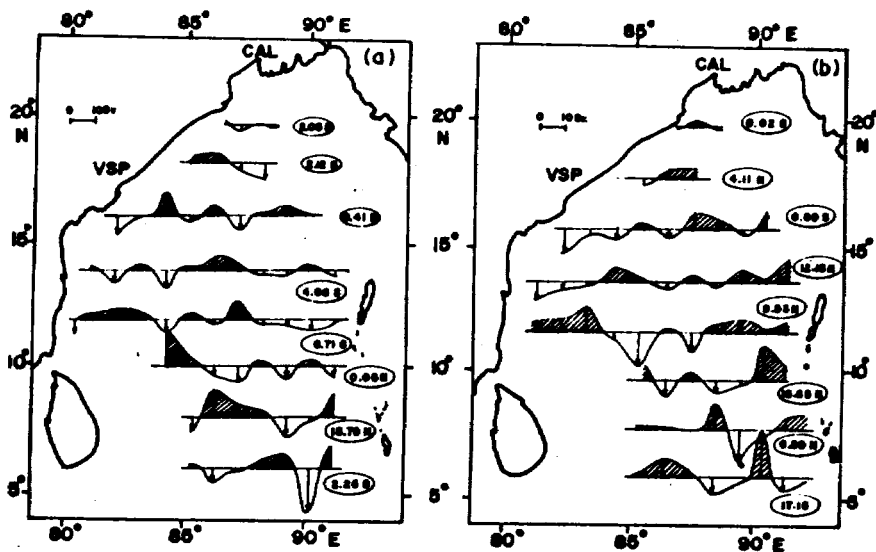


Fig. 3. Volume transport (10<sup>6</sup> m<sup>3</sup>/s) in the upper 1000m during (a) Southwest monsoon and (b) Northeast monsoon (Hatched portion denotes northward transport. The numbers in ellipses indicate total transport (N-northward & S-southward) across the latitudes.

The net transport within the volume bound by the sections shows an influx of 4.5 x 10<sup>6</sup> m<sup>3</sup>/s and 68 x 10<sup>6</sup> m<sup>3</sup>/s during southwest and northeast monsoons respectively. However, Varkey (1986) reported a net influx of 17 x 10<sup>6</sup> m<sup>3</sup>/s and outflux of 10 x 10<sup>6</sup> m<sup>3</sup>/s in the upper 1250 m across 6°N between 80°E and 95°E during south-

west and northeast monsoons respectively. The maximum transport occurs in the upper 100 m. The net transport in this 100 m water column shows an influx of  $18 \times 10^6 \text{ m}^3/\text{s}$  and  $16 \times 10^6 \text{ m}^3/\text{s}$  during southwest and northeast monsoons respectively.

Considering the equal length of the sections in both the seasons, it is noticed that the total transport is directed northward across  $18^\circ\text{N}$ ,  $12^\circ\text{N}$  and  $8^\circ\text{N}$  and southward across  $19^\circ30'\text{N}$  and  $20^\circ\text{N}$ . A reversal in the direction of transport occurs from one season to the other across the other sections. However, the net transport becomes  $1.0 \times 10^6 \text{ m}^3/\text{s}$  and  $64 \times 10^6 \text{ m}^3/\text{s}$  during southwest and northeast monsoons respectively, indicating a net influx into the Bay always, with maximum influx during northeast monsoon. This shows that with the decrease of the freshwater discharge from the rivers there is an increase of seawater influx to maintain the mass continuity.

Limiting the volume bound between  $6^\circ\text{N}$  and  $14^\circ\text{N}$  and from  $85^\circ\text{E}$  to  $92^\circ\text{E}$ , the net transport shows an influx of  $6.5 \times 10^6 \text{ m}^3/\text{s}$  and  $48 \times 10^6 \text{ m}^3/\text{s}$  during southwest and northeast monsoons respectively. To maintain the mass continuity, there should be a net outflux of water outside the volume bound. We envisage strong coastal currents along the western boundary of the Bay. The mean sea level studies (Shetye and Almeida, 1985) at Nagapattinam, Madras and Visakhapatnam along the physical, static western boundary of the Bay indicate a longshore current directed northward at these locations during southwest monsoon. They also noticed a rise in sea level at these locations during October-December (with its peak in November) which is consistent with southward directed longshore current. The net influx of water in the open-sea area might contribute to intensify of these longshore currents along the western boundary during both the seasons. The large amount of influx during northeast monsoon might also be due to the presence of eddies. Lack of observations in the southwestern and northeastern regions of the Bay hampers one to examine the water balance of the Bay in detail.

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