

Current structure and volume transport across 12°N in the Bay of Bengal

V S N Murty, A Suryanarayana & D P Rao

National Institute of Oceanography, Dona Paula, Goa 403 004, India

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Geostrophic currents and the associated volume transport across 12°N in the Bay of Bengal during early southwest monsoon (April), southwest monsoon (September) and early northeast monsoon (November) show flow reversal near the east coast of India from April to September. Current structure in November is similar to that in September with a shift in the current bands. Transport in the upper 1000 m between the stations exhibits a reversal west of 83°E from April to September and east of 85°E from September to November. Total geostrophic transport in the upper 1000 m shows an outflux (southward transport) of $3 \times 10^6 \text{ m}^3 \cdot \text{sec}^{-1}$ in April and less outflux ($< 1 \times 10^6 \text{ m}^3 \cdot \text{sec}^{-1}$) in September and a large influx of about $6 \times 10^6 \text{ m}^3 \cdot \text{sec}^{-1}$ in November. Total geostrophic transport in the upper 100 m is comparable in magnitude to that of Ekman transport across 12°N. Total transport (sum of geostrophic and Ekman transports) in the upper 1000 m is comparable in magnitude and direction to the steady Sverdrup volume transport across 12°N in April and November. In September, while the total transport indicates outflux of about $3.2 \times 10^6 \text{ m}^3 \cdot \text{sec}^{-1}$, the Sverdrup transport shows influx of about $5 \times 10^6 \text{ m}^3 \cdot \text{sec}^{-1}$.

Based on data collected during the International Indian Ocean Expedition (IIOE) and some other cruises in the Bay of Bengal, the computed net geostrophic volume transport¹ in the upper 1250 m across 6°N shows an influx (northward transport) of $17 \times 10^6 \text{ m}^3 \cdot \text{sec}^{-1}$ during June-August and an outflux of $12 \times 10^6 \text{ m}^3 \cdot \text{sec}^{-1}$ during December-February. Later, using the comprehensive hydrographic data collected onboard *RV Gaveshani* and *ORV Sagar Kanya* during October-December (early northeast monsoon, NEM) of 1983 and July-October (southwest monsoon, SWM) of 1984, the net geostrophic volume transports in the upper 1000 m across various zonal sections from 4°N to 20°N have been presented². While studying the wind driven circulation by applying the Sverdrup model³ for the Bay of Bengal, Babu⁴ has presented the monthly maps of steady state Sverdrup transport. The variability of meridional Ekman volume transport in the Bay of Bengal is not addressed so far, though Levitus⁵ presents the latitudinal averages for the entire Indian Ocean. In this paper, variability of current structure and meridional geostrophic, Ekman and steady Sverdrup volume transport across 12°N in the Bay of Bengal during 3 seasons - premonsoon (PRM) or early SWM (April), SWM (September) and early NEM (November) are discussed in relation to the circulation.

Materials and Methods

As a part of the institutional project work hydrographic data were collected along 12°N (Fig. 1) with stations located at 80°30'E and from 81°E to 92°E (with 1 degree interval of longitude) in April 1987, September 1984 and November 1983 during the surveys in the Bay of Bengal from 4°N to 20°N on board *RV Gaveshani* and *ORV Sagar Kanya* in 3 seasons - early SWM (March-June) of 1987, SWM (July-October) of 1984 and early NEM (October-December) of 1983, and the same data were utilised in the present study. Necessary corrections were applied⁶ to the temperature readings of the reversing thermometers and the depths at which the Nansen bottles were reversed had been estimated⁶. Water samples were analysed for conductivity using Autosol (Model 8400A Guildline make) and then salinity was obtained from practical salinity scale algorithms⁷. Likewise, temperature and salinity data obtained from CTD were corrected with that of obtained through reversing thermometers and Rosette samplers respectively attached to CTD by fitting linear regression lines^{8,9} for temperature and salinity. T-S diagrams for the stations were plotted to examine the variability in the T-S structure with the season. Dynamic method¹⁰ was employed to compute the geostrophic currents and volume transport (V_g) between the stations by choosing 1000 db

as the reference level. Meridional Ekman volume transport (V_{EK}) along 12°N in April, September and November was estimated¹¹ from the climatological zonal component of wind stress (τ_x) read from the time-latitude sections⁴ presented for 3 longitudinal ($80^\circ\text{--}85^\circ\text{E}$; $85^\circ\text{--}90^\circ\text{E}$; $90^\circ\text{--}92^\circ\text{E}$) grids.

Results and Discussion

Figures 1 and 2 represent the large scale surface circulation during early SWM, SWM and early NEM seasons and vertical current structure along 12°N in April, September and November respectively. A strong flow prevails near the Indian coast in all the 3

seasons with a change in its direction from north in April (Fig. 1a) to south in September (Fig. 1b) and November (Fig. 1c). The strength of this current exhibits a decrease from $90\text{ cm}\cdot\text{sec}^{-1}$ in April (Fig. 2a) to $50\text{ cm}\cdot\text{sec}^{-1}$ in September (Fig. 2b) and November (Fig. 2c). In September the core ($50\text{ cm}\cdot\text{sec}^{-1}$) of the southward current lies at subsurface depths (50-100 m). In April, the strong ($90\text{ cm}\cdot\text{sec}^{-1}$) northward current in the western bay and the southward currents in the central bay constitute the large scale anticyclonic gyre during early SWM season (Fig. 1a). Vertical current shear (change of flow direction with depth) occurs around 200 m between 81° and 89°E .

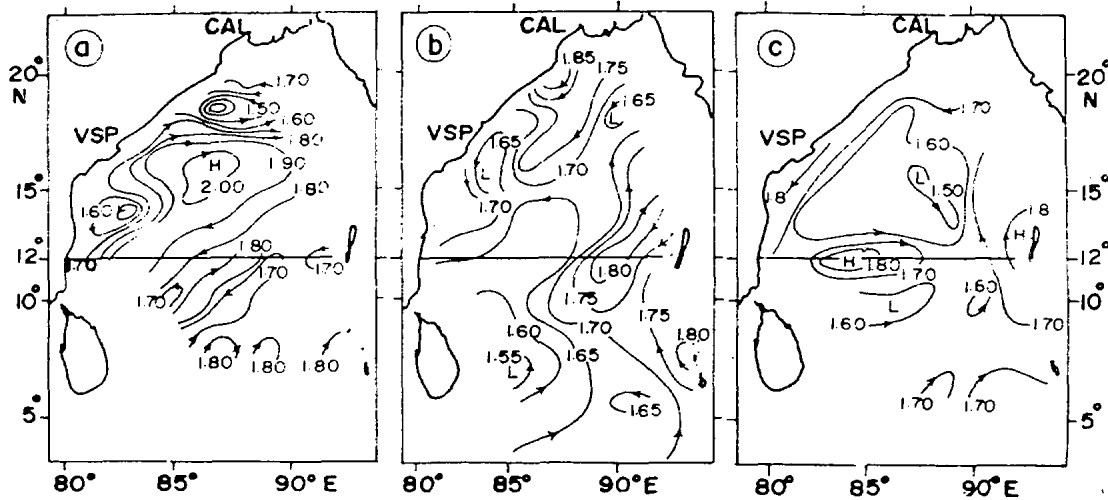


Fig. 1—Area of study, 12°N section (—) and surface circulation relative to 1000 db surface in the Bay of Bengal during (a) early SWM, (b) SWM and (c) early NEM (Contour numbers indicate dynamic heights (dyn.m). Please note the change in contour interval)

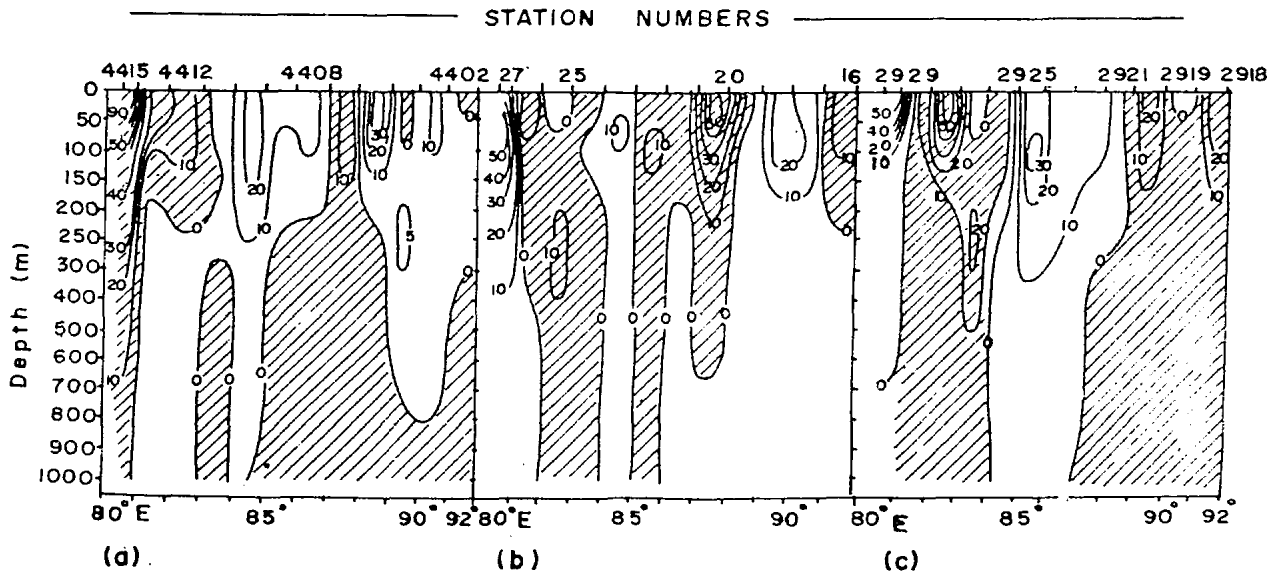


Fig. 2—Vertical current structure ($\text{cm}\cdot\text{sec}^{-1}$) across 12°N during (a) April, (b) September and (c) November (Hatched area indicates northward current)

East of 88°E, a broad southward current is characterised by a double core (30 cm.sec⁻¹ and 10 cm.sec⁻¹) in the upper 150 m. In September, the northward current (50 cm.sec⁻¹) between 85° and 89°E is associated with flows of large cyclonic gyre (Fig.1b) during SWM^{9,12}. The weak northward current (10 cm.sec⁻¹) in the far eastern bay is the continuation of northerly flow west of the Nicobar Islands. This flow has been mentioned as the northward flowing eastern boundary current¹² in the Bay of Bengal which gets its support from the Indian Ocean monsoon drift current during SWM. In October, northward and southward currents prevail in the central bay between 81° and 89°E in association with the anticyclonic eddy centered at 12°N (Fig. 1c). The northward current (10-20 cm.sec⁻¹) between 89° and 91°E indicates the flow of the northbound eastern boundary current west of the Andaman Islands¹³ during early NEM.

Figure 3 represents vertically integrated meridional geostrophic volume transport in the upper 1000 m between the stations of the section for April, September and November. The transports west of 84°E exhibit a reversal from April (Fig.3a) to September (Fig.3b) and more or less the same pattern prevails in the region east of 84°E. While there is no change in the pattern of transport in the region west of 85°E from September to November (Fig.3c), there exists a reversal in the direction of transport between 89° and 92°E. Near the Indian coast, a large northward transport of $11 \times 10^6 \text{ m}^3.\text{sec}^{-1}$ prevails in April and southward transport of $4-6 \times 10^6 \text{ m}^3.\text{sec}^{-1}$ in September and November. The northward transport (about $11 \times 10^6 \text{ m}^3.\text{sec}^{-1}$) between 89° and 92°E in November corresponds to the transport associated with the northward flowing eastern boundary current. The total geostrophic transport (Table 1) across the section (cumulated westward from 92°E) indicates an outflux (southward transport) of $3.3 \times 10^6 \text{ m}^3.\text{sec}^{-1}$ in April, an insignificant outflux in September and a large influx (northward transport) of $6 \times 10^6 \text{ m}^3.\text{sec}^{-1}$ in November into the northern bay.

The meridional Ekman volume transports (V_{EK}) along 12°N exhibits a change in direction within the 3 longitudinal grids during April. While transport in each grid is directed southward in September, it is directed northward in November. Total Ekman transport (Table 1) across the section, obtained by westward integration⁵ from the eastern boundary (92°E) in line with the Sverdrup transport, indicates less influx ($0.09 \times 10^6 \text{ m}^3.\text{sec}^{-1}$) in April, relatively higher outflux ($2.45 \times 10^6 \text{ m}^3.\text{sec}^{-1}$) in September and influx ($1.03 \times 10^6 \text{ m}^3.\text{sec}^{-1}$) in November. In April, the winds are weak and variable¹⁴ at this latitude and hence less Ekman transport. In September, consistent strong southwesterlies¹⁴ prevail over the central bay. Under their influence the zonal component of wind stress is directed eastward which in turn gives rise to southward Ekman transport. In November, the wind field shows the presence of northeasterlies¹⁴ confining to small region of the western bay and predominance of easterlies towards the eastern bay. These winds give rise to westward zonal wind stress leading to northward Ekman transport.

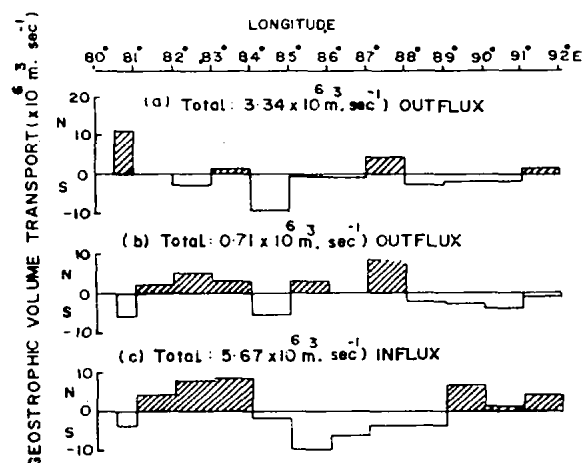


Fig. 3—Geostrophic volume transport ($\times 10^6 \text{ m}^3.\text{sec}^{-1}$) across 12°N during (a) April, (b) September, and (c) November (Hatched area indicates northward transport)

Table 1—Estimates of meridional geostrophic (V_g), Ekman (V_{EK}) and Sverdrup (V_{SV}) volume transports ($\times 10^6 \text{ m}^3.\text{sec}^{-1}$) across 12°N during 3 seasons

Seasons	V_{g1000}	V_{EK}	V_{SV}	V_{g100}	V_{Total} ($V_{g10000} + V_{EK}$)
Early SWM (April)	-3.34	0.09	-1.24	-0.62	-3.25
SWM (September)	-0.71	-2.45	5.06	2.17	-3.16
Early NEM (November)	5.61	1.03	5.57	1.76	6.64

(-ve indicates southward transport)

The meridional steady Sverdrup transport (V_{SV}) (Table 1) across 12°N shows an outflux ($1.2 \times 10^6 \text{ m}^3.\text{sec}^{-1}$) in April and influx of 5.1×10^6 and $5.6 \times 10^6 \text{ m}^3.\text{sec}^{-1}$ in September and November respectively. Continuity requires that there should be a north flowing western boundary current in April and south flowing western boundary current in September and November and the presence of these western boundary currents are indicated in the recent studies^{12,15,16} of the Bay of Bengal. However, the studies¹⁷ on the wind driven circulation in the Norwegian-Green Land Sea, reveal that the return flow need not take place at the western boundary.

The northward (southward) Ekman transport across 12°N gives rise to mass convergence (divergence) further north since the northern bay is nearly closed by the land boundary and leads to either downwelling (upwelling) or rise (fall) in the sea level. The observed Ekman influx in April and November is weak and may not support a strong downwelling north of 12°N . However, the Ekman outflux in September may lead to mass divergence and hence upwelling north of 12°N . From the classical simple dynamics, one would expect that consequent to the downwelling (upwelling) the meridional geostrophic transport in the interior of the ocean (away from the boundaries) would be directed equatorward (poleward). For this purpose a comparison is made between the Ekman transport and the total geostrophic transport in the upper 100 m with an assumption that the Ekman dynamics are predominant within this water column. Interestingly, it is noticed that the computed meridional geostrophic transport in the upper 100 m (Table 1) is in near balance (within the error limits) with the Ekman fluxes in April and September. Similarly in September, the geostrophic influx ($2.2 \times 10^6 \text{ m}^3.\text{sec}^{-1}$) is balanced by Ekman outflux ($2.5 \times 10^6 \text{ m}^3.\text{sec}^{-1}$). From the table, it is obvious that the geostrophic transport in the water column 100-1000 m is nearly the same with an outflux of $2.8 \times 10^6 \text{ m}^3.\text{sec}^{-1}$ for April and September. In November, both the geostrophic and Ekman transports show influx. As mentioned above, the circulation during this month is characterised by anticyclonic eddy centered at 12°N which in turn effects the geostrophic transport.

Since the Sverdrup transport comprises the geostrophic and Ekman transports, it is worth comparing the Sverdrup transport with the total transport (sum of geostrophic and Ekman transports; V_{total}) in the upper 1000 m across the section. In April and November, the total transport (Table 1) and the Sverdrup transport agree

reasonably well both in the direction and magnitude. During these months, the contribution of Ekman transport to the total transport is considerably less. Thus during the period of weak winds the interior geostrophic transport in the upper 1000 m is equal to the Sverdrup transport in the interior of the Bay of Bengal. This suggests that the circulation during these periods is primarily thermohaline driven. Moreover, as pointed out above, from the observation that fresh water influx during these periods is either minimum or confined to the shelf regions¹⁸ of the Bay of Bengal, it can be reasoned that the circulation in the Bay of Bengal during April and November is influenced by the waters of southern or equatorial bay having different thermohaline characteristics from the northern bay. Though this is indicative in the earlier works¹³⁻¹⁹, further studies are needed for its substantiation. During September, the total transport is opposite to the Sverdrup transport. While the total transport shows outflux ($3.2 \times 10^6 \text{ m}^3.\text{sec}^{-1}$), the Sverdrup transport shows influx ($5 \times 10^6 \text{ m}^3.\text{sec}^{-1}$). During this period, the contribution of southward Ekman transport to the total transport is very significant (Table 1) in contrast to that in April and November. This implies that during SWM the circulation is mainly governed by the Sverdrup dynamics in the interior of the bay.

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References

- 1 Varkey M J, *Salt balance and mixing in the Bay of Bengal*, Ph.D. thesis, Kerala University, 1986.
- 2 Rao D P & Murty V S N, Volume transport and circulation in the Bay of Bengal. Presented at the *First Convention of Indian Society of Physical Sciences of the Ocean*, held at NIO during 13-15 December, 1989.
- 3 Sverdrup H U, *Proc Natl Acad Sci (USA)*, 33 (1947) 318.
- 4 Babu M T, *Hydrography and circulation in the Bay of Bengal during post-monsoon season*, M.Sc. thesis, Bombay University, 1987.
- 5 Levitus S, *J Phys Oceanogr*, 18 (1988) 271.
- 6 LaFond E C, *Processing oceanographic data* (US Hydrographic Office, Washington DC), 1951, pp.114.
- 7 Anon, *UNESCO technical papers in Marine Sciences*, Report Nos.36 & 37 (1981).
- 8 Murty V S N, Sarma Y V B, Babu M T, Suryanarayana A, Santanam K, Rao D P & Sastry J S, *Report on the physical oceanographic characteristics of the Bay of Bengal during southwest monsoon*, Tech. Report, TR-NIO/8-90 (National Institute of Oceanography, Goa, India), 1990, p.41.
- 9 Murty V S N, *Some aspects of large scale circulation in the Bay of Bengal during southwest monsoon*, Ph.D. thesis, Andhra University, 1990.

- 10 Sverdrup H U, Johnson M W & Fleming R H, *The oceans: their physics, chemistry and general biology* (Prentice Hall Inc, New York), 1942, pp.1087.
- 11 Pond S & Pickard G, *Introductory dynamical oceanography* (Pergamon Press, Oxford), 1983, pp.329.
- 12 Murty V S N, Sarma Y V B, Rao D P & Murty CS, *J Mar Res*, 50 (1992) 207.
- 13 Suryanarayana A, Murty V S N & Rao D P, *Deep-Sea Res.* (in press).
- 14 Hastenrath S & Lamb P J, *Climatic atlas of the Indian Ocean, I: Surface climate and atmospheric circulation* (Univ. Wisconsin Press, Wisconsin), 1979.
- 15 Legeckis R, *J Geophys Res*, 92 C12 (1987) 12974.
- 16 Babu M T, An equatorward western boundary current in the Bay of Bengal. Presented at the *First Convention of the Indian Society of Physical Sciences of the Ocean* held at NIO, Goa during 13-15 December, 1989.
- 17 Aagaard K, *Deep-Sea Res*, 17 (1970) 281.
- 18 Suryanarayana A, Murty V S N, Sarma Y V B, Babu M T, Rao D P & Sastry J S, in *Oceanography of the Indian Ocean*, edited by B N Desai (Oxford & IBH Publ, New Delhi), 1992, 553.
- 19 La Fond E C & La Fond K G, *Bull Natl Inst Sci India*, 1 (1968) 169.