

Hydrographic features of the western Bay of Bengal in the upper 500 m under the influence of NE and SW monsoons

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Abstract - The distribution of temperature, salinity, density and geostrophic currents in the upper 500 m of the western Bay of Bengal within 500 km adjoining the east coast of India for NE and SW monsoons have been studied. These distributions show considerable variation in space from season to season. The variations are mainly influenced by the seasonal winds and fresh water discharge from major rivers located all along the periphery of the Bay. The salinity fronts as demarcated by 33.0 ‰ isohaline separating the shelf and open sea waters are clearly visible. The near surface flow is mainly southwesterly during NE monsoon while during SW monsoon, it is characterised by cyclonic and anticyclonic gyres. North of 15°N, the influence of fresh water on the flow is dominant within 100 km from the coast. Beyond 100 km, the flow is influenced by the wind forcing. The geostrophic current speeds range from 20 cm s⁻¹ to 90 cm s⁻¹ during NE monsoon and from 10 cm s⁻¹ to 60 cm s⁻¹ during SW monsoon. The meridional volume transport exhibits wide variation within the season both in magnitude and direction. However, the net transport is found to be $12 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ directed towards south during NE monsoon and $13 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ directed towards north during SW monsoon.

INTRODUCTION

The Bay of Bengal circulation is influenced by the combined effect of the seasonally reversing winds, freshwater influx, the narrow shelf topography and the winter cooling at the head of the Bay. The inflow from the monsoon drift current during southwest monsoon also influence the Bay circulation.

Earlier studies on circulation and property distribution of the western Bay of Bengal (SEWELL, 1929; LA FOND, 1954 and 1958; RAMASASTRY and BALARAMA MURTY, 1957; VARADACHARI, 1961) are very much limited to some specific regions. The studies of DUING (1970), WYRTKI (1971), COLBORN (1975), MURTY and VARADACHARI (1968) and RAO (1977) have confined to the open areas and could not document the spatial and temporal variations comprehensively along the western boundary adjoining the east coast of India. In this paper, we present a comprehensive picture of the thermohaline characteristics and geostrophic circulation in the upper 500 m in the western Bay of Bengal during the northeast monsoon (NEM) and southwest monsoon (SWM). The effects of wind and freshwater discharge are also discussed.

MATERIALS AND METHODS

Hydrographic data were collected in the Bay of Bengal through conventional hydrocast during November-December, 1983 (NEM) onboard RV Gaveshani and through a CTD profiler during July- August, 1984 (SWM) onboard ORV Sagar Kanya. Data at 57 stations during NEM and 87 stations during SWM occupied within a distance of about 500 km from the coast (Fig.1) have been used in the present study. For NEM, the hydrographic stations form six zonal sections (I-D to VI-D) and four sections normal (VII-D to X-D) to the east coast of India. Similarly for SWM, the stations form twelve normal (I-J to XII-J) sections. The hydrographic and CTD data were processed through

standard methods following LA FOND (1951) and ANON (1981) and detailed in SURYANARAYANA(1988) and MURTY *et al.* (1990).

Geostrophic computations were carried out with reference to 500 db surface. For geostrophic currents at shallow stations, the method suggested by Fomin (1964) was adopted.

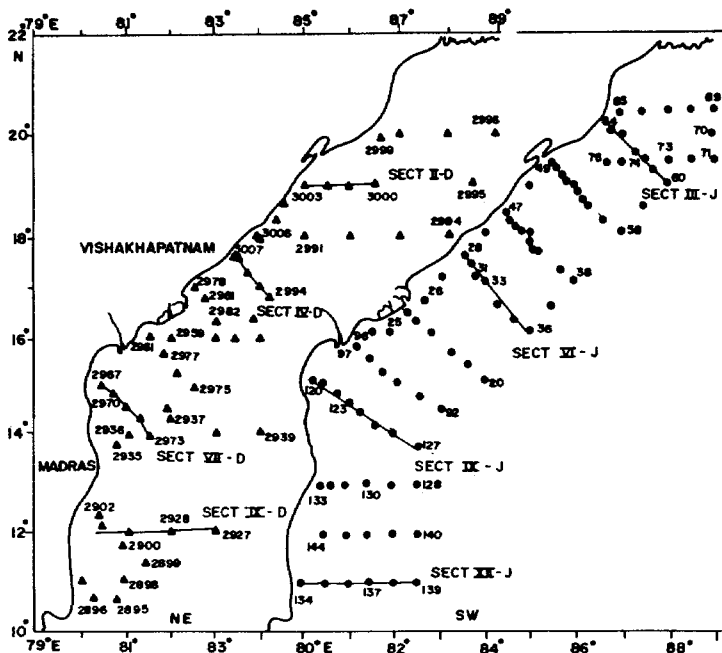


Fig. 1. Station location map during (a) NE and (b) SW monsoon seasons.

RESULTS

Salinity

The spatial distribution of salinity at different levels during the two seasons are shown in Fig.2. At sea surface (Fig.2a) during NEM, the salinity is low all along the coast as shown by 33.0 ‰ isohaline running almost parallel to the coast. Between this isohaline and the coast, the salinity decreases to less than 27.0 ‰ in two isolated pockets. In contrast, during SWM the 33.0 ‰ isohaline lies midway across the coast. In the south, salinities gradually increase to as much as 34.5 ‰. In the northern Bay the salinity is as low as 16 ‰. The present data does not extend to the coastline where one would naturally expect much freshwater ahead. The freshwater spreads southwards along the coast as can be seen from the structure of isohalines. At 100 m (Fig.2b), the salinity shows considerable increase during both the seasons. Over most of the shelf the salinity varies between 34.6 and 34.9 ‰ except at an isolated pocket where the influence of freshwater discharge from the rivers is seen. The isohalines at this depth are also parallel to the coast. At 200 m (Fig.2c), the salinity is more or less uniform during both the seasons. One noticeable feature is that the salinity distribution during

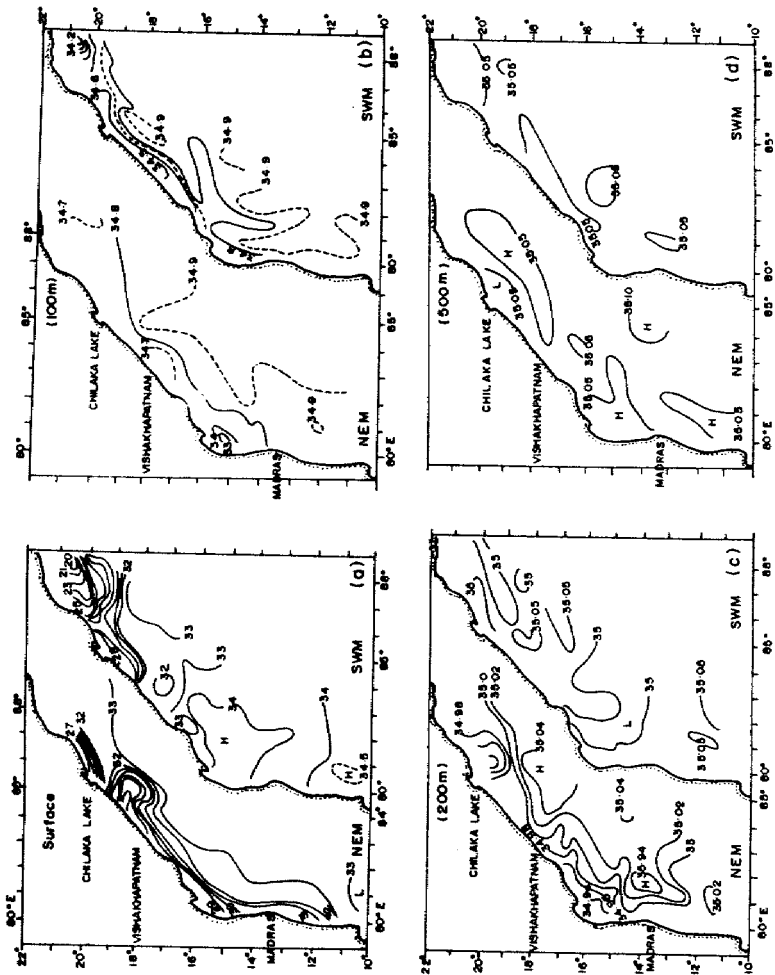


Fig. 2. Spatial distribution of salinity (%) during NE and SW monsoon seasons.

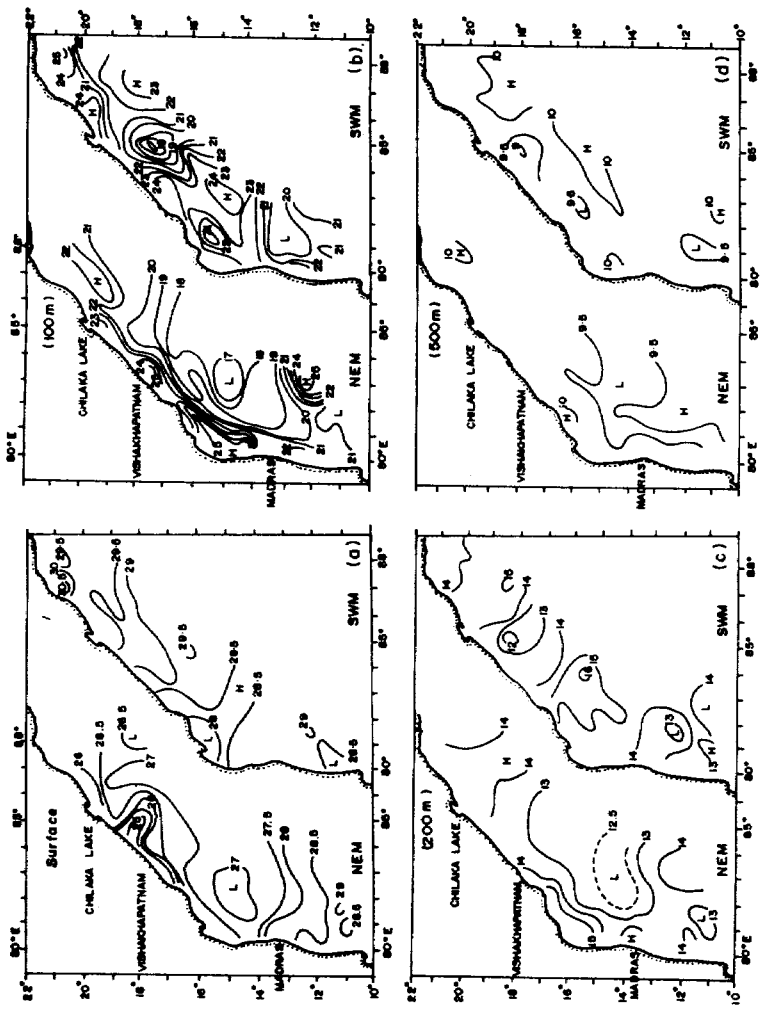


Fig. 3. Spatial distribution of temperature (°C) during NE and SW monsoon seasons.

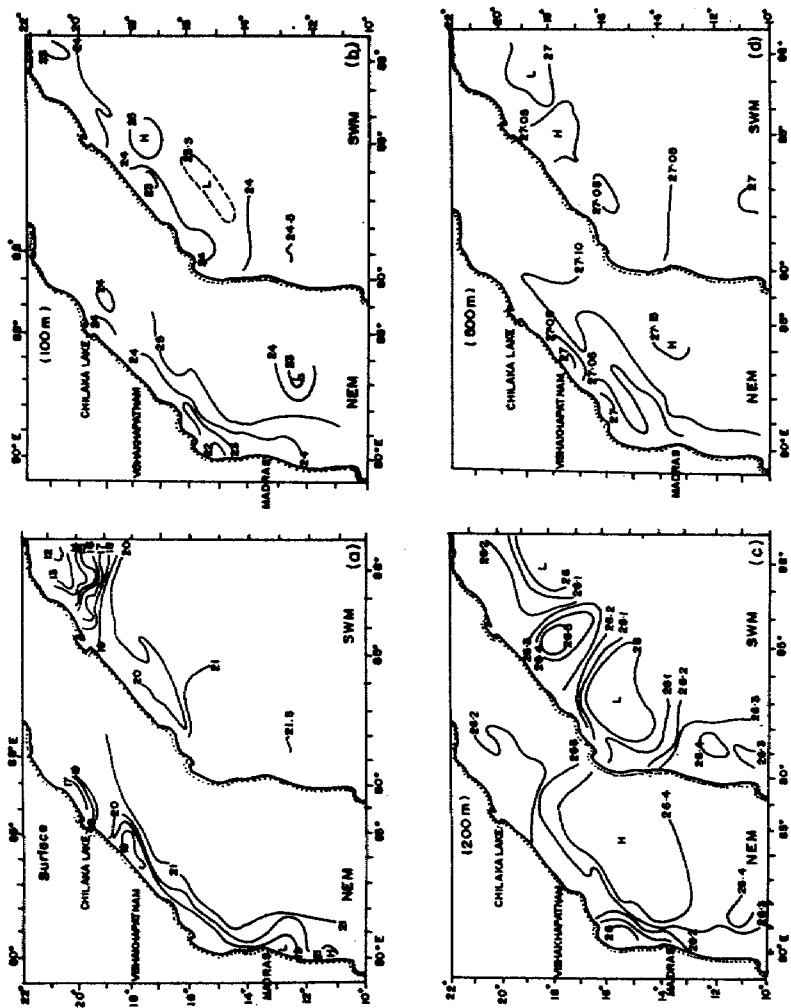


Fig. 4. Spatial distribution of density (σ_t) during NE and SW monsoon seasons.

NEM appears to be more organised with isohalines parallel to the coast, whereas, during SWM such feature is not observed. At 500 m (Fig.2d), the salinity varies between 35.05 to 35.10 ‰.

Temperature

The distribution of temperature at surface (Fig.3a) shows remarkable difference during NEM and SWM. During NEM, the surface temperature is about 25.8°C at 20°N and gradually increases to 28.5°C towards south. During SWM, in contrast, the temperature decreases from north to south. The temperature at the head of the Bay exceeds 30°C while south of 18°N, it varies between 28.0 and 29.0°C. Thus, the overall temperature gradient changes its sign with the change of the season. Closer to the coast, the low temperature cells correspond to the low salinity pockets (Fig.2a). At 100 m (Fig.3b), during NEM the isotherms run parallel to the coast. A broad cold water cell (<17°C) appears between 13 and 16°N. During SWM, the temperature pattern on this surface is complex with warm (25°C) and cold (18°C) water cells. At 200 m (Fig.3c), the temperature varies between 12.0 and 16.0°C during both the seasons. At 500 m (Fig.3d), the temperature variation is narrow and ranges from 9 to 10°C.

Density

Surface sigma-t varies between 17 and 21.0 during NEM and between 12.0 and 21.5 during SWM (Fig.4a). Similar to the salinity pattern, the isopycnals run parallel to the coast during the NEM. The surface density during SWM shows the influence of freshwater upto 16 N along the coast demarcated by isopycnal 20.0 sigma-t. The range of sigma-t at 100 m is higher (> 3.0) during NEM than that during SWM (2.0). Below 100 m, the range in sigma-t is about 0.5 during both the seasons inferring that the variation of density below 100 m is very less. Pockets of high (low) sigma-t coincide with the cold (warm) water cells below 100 m (Figs.4b, 4c and 4d).

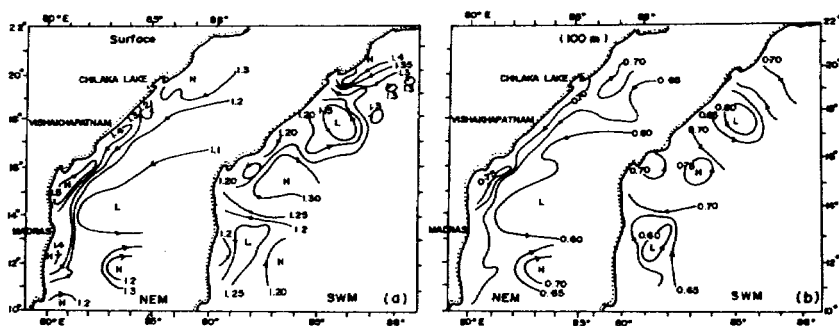


Fig. 5. Dynamic topography (dyn.m) charts during NE and SW monsoon seasons.

Circulation

The dynamic topography charts for the sea surface, 100 m and 200 m with reference to 500 db during the two seasons are presented in Fig.5. During the NEM, the surface circulation is characterised by a large cyclonic cell between 19 and 13°N in the offshore regions (Fig.5a), coupled with a strong southward directed coastal current along the

Central east coast of India. North of 18°N , the circulation is anticyclonic. A small anticyclonic cell is present at $12^{\circ}\text{N}/84^{\circ}\text{E}$. The surface circulation during SWM is characterised by alternate cyclonic and anticyclonic gyres all along the region. The strong southward directed flow seen during the NEM is absent during SWM. The range of dynamic topography is about 15 dyn.cm at 100 m . The circulation at 100 m is almost the same as that of surface during both the periods (Fig.5b). However, during SWM, the prevailing anticyclonic cell north of 19°N is absent at 100 m . The flow pattern at 200 m has not been presented since the dynamic height difference is very nominal (about 3 dyn.cm).

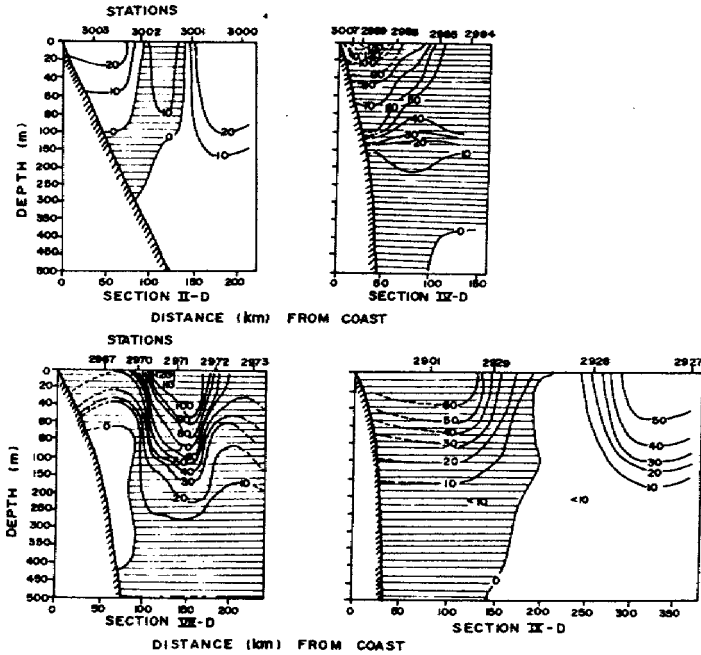


Fig. 6. Vertical current structures along sections II-D, IV-D, VII-D and IX-D during NE monsoon (Hatched area indicates southerly flow).

Current structure

The vertical currents during the NEM across selected sections are shown in Fig.6. Along 19°N (section II-D), the flow is northerly with speeds upto 20 cm s^{-1} at the surface within 100 km from the coast. A weak southerly flow ($<10 \text{ cm s}^{-1}$) is present between 100 and 150 km . Beyond 150 km , the flow is northerly with speeds of 20 cm s^{-1} . Along section IV-D, off Visakhapatnam, the currents are southward with a core speed of 140 cm s^{-1} in the upper 400 m . The core of the current lies close to the coast, about 50 km offshore. Along VII-D, between 15° and 14°N , a wide southerly current is present in the upper 400 m with a core speed of 120 cm s^{-1} . This core lies at a distance of 100 km from the coast. A subsurface northward flowing undercurrent with speeds of 5 cm s^{-1} is noticed close to the coast in the depth interval of $60\text{--}400 \text{ m}$ on the continental slope. Across section XI-D (along 12°N), a broad southerly current with

a core speed of 60 cm s^{-1} is observed upto 200 km from the coast. Beyond 200 km, offshore, the flow is northerly with speeds of 50 cm s^{-1} .

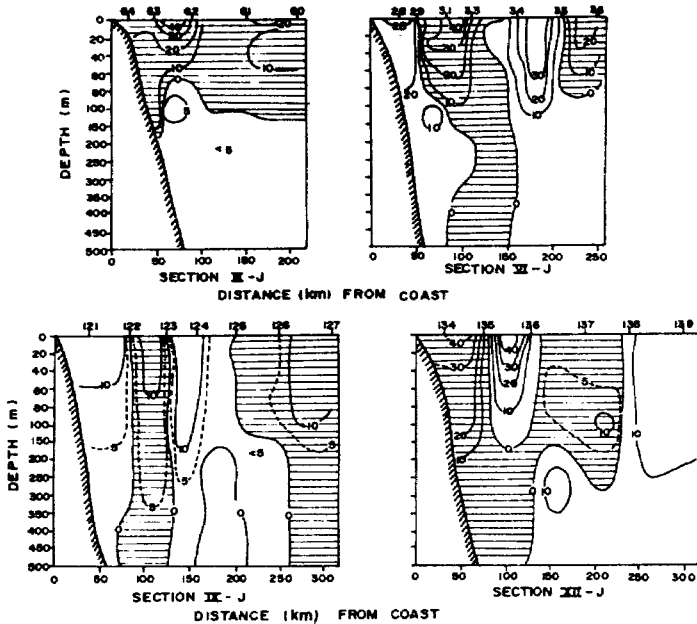


Fig. 7. Vertical current structures along sections III-J, VI-J, IX-J and XII-J during SW monsoon (Hatched area indicates southerly flow).

The geostrophic currents across selected sections during SWM are shown in Fig.7. Across section III-J, the flow is southerly in the upper 100 m. It is northerly below 100 m. The northerly flow attains a higher velocity of 10 cm s^{-1} on the shelf, 90 km offshore. Overlying this core, the southerly current also attains higher speeds of 25 cm s^{-1} at sea surface. Across section VI-J, the flows are alternatingly north and south. Nearer the coast, the flow is northerly in the entire 500 m column. Across section XI- J, similar pattern of alternatingly north/south flows are present in the entire water column. The flow is northerly (10 cm s^{-1}) nearer the coast. Across XII-J (12°N), the flow is broadly southerly with strong (40 cm s^{-1}) northward flow enbeded between 70 and 150 km offshore.

DISCUSSION

It is known that Bay of Bengal is under the influence of the reversing monsoon systems, freshwater discharge during the SWM extending upto December and the equatorial current system. Till recently, the response of the Bay to the above forcing parameters has not been well documented. The salinity, temperature and circulation in the western Bay clearly bring out the influence of wind and freshwater discharge through Ganges at the head of the Bay. The influence of freshwater is reflected by the strong salinity gradients in the northwestern Bay. While in the southern Bay the salinity shows a gradual increase indicating that the spreading of freshwater is limited to

northwestern region only. In contrast, during NEM eventhough the overall surface salinity has increased the spreading of freshwater extends all along the inshore region of the coast. The northeasterly wind field during NEM aids the flow in such a way that the freshwater is closer to the coast. The prevailing sea surface temperature gradient towards north during NEM is due to the cold, dry northeasterly winds aiding evaporative cooling and sensible heat loss from the sea surface in the north Bay. During SWM, the winds over the southern peninsula are nearly normal to the coast and the associated drift in the nearshore region causes the disorganised flow as evidenced (Fig.5a). The low salinity at the head of the Bay and the associated horizontal and vertical gradient of salinity may develop a thermohaline circulation superimposed upon the basic wind-driven circulation.

The freshwater entering the marine environment appears as a band of low (<33 ‰) saline water close to the coast. Occasionally, this is seen in the form of a lens in the vicinity of the river mouths (Fig.2). The quantum of freshwater and its impact on the salinity of the coastal and open ocean waters are to a certain extent controlled by these pools of relatively freshwater occupying the vertical column of 40-50 m. The band of shelf water diluted by the freshwater forms a complex frontal zone as the relatively less saline waters over ride the ambient saline and nearly homogeneous waters. The dynamics maintaining this frontal structure could closely be compared to that of a partially mixed estuary but for the difference in the alongshore heterogeneity within the nearshore zone where lateral or horizontal mixing processes would be maximum or of priority. The presence of saline fronts could be identified by 33.0 ‰ isohaline separating the less saline waters of the shelf from the saline open ocean waters. These low salinity waters could be seen as a band along the coast during NEM whereas it is limited to north of 16°N during SWM. The width as well as the vertical extent of this band vary along the coast with the season. North of 17°N, the width of this band varies from 150 to 250 km with its vertical extent from 20 to 40 m during SWM. Between 17 and 14°N, the width varies from 100 to 200 km with a vertical extent from 60 to 100 m during NEM.

The influence of freshwater is seen off the river mouths between 17 and 16°N over a distance of 100 km from the coast. Beyond 100 km, the influence of southwesterly winds giving rise to northeastward flow is evident (Fig.5). The effect of wind forcing is also noticed along sections VII-J and VIII-J (between 17 and 15°N) from the upward rising of the isopleths upto the surface from offshore towards the coast. Between 16 and 14°N, the influence of windforcing is felt upto the coast as seen in the upward rise of the isopleths of salinity and temperature, leading to the process of upwelling near the coast from about 80 m depth. South of 14°N, the prevailing westerly winds in the nearshore region give rise to southward Ekman transport which in turn leads to the process of sinking along the coast (SURYANARAYANA, 1988).

Studies by SURYANARAYANA (1988) showed that the computed total transports across each section in the upper 500 m exhibit variations both in magnitude and direction for NEM and SWM. The transports are affected by the presence of the cyclonic and anticyclonic eddies in the study area. However, the net transport is about $13 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ and directed southward during NEM, whereas it is about $12 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ and directed northward during SWM.

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