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Hydrography and circulation in the northwestern Bay of Bengal during the retreat of southwest monsoon

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Abstract. The distribution of temperature and salinity in the upper 500 m of the northwestern Bay of Bengal, adjoining the east coast of India, during the retreat of southwest monsoon (September) of 1983 is presented. This study reveals coastal upwelling (limited to the upper 40 m) induced by the local winds. Waters of higher surface salinity near the coast characterize the upwelling. The freshwater influx near the head of the Bay diluted the surface salinity to as low as $26{\cdot}0 \times 10^{-3}$. The surface circulation was weak and led to a net transport of $2{\cdot}0 \times 10^{6}\,\mathrm{m^{3}{\cdot}s^{-1}}$ directed towards northeast.

Keywords. Hydrography; upwelling; freshwater influx; northwestern Bay of Bengal; retreat of southwest monsoon.

1. Introduction

The Indian summer monsoon, generally known as the southwest monsoon (SWM), prevails over the north Indian Ocean during June–September with its peak intensity in July–August. The retreat of SWM, in general, begins from mid-September from the northwestern Indian region and from the northwestern Bay of Bengal by mid-October (Ramasastry *et al* 1984). During the period of SWM, the Bay of Bengal is subjected to strong wind forcing and receives huge quantity of freshwater from the surrounding rivers. While there are some studies on the effect of wind forcing and freshwater discharge on the hydrographic characteristics and the circulation of the waters of the Bay of Bengal during peak SWM (Gopalakrishna and Sastry 1985; Shetye *et al* 1985; Babu 1987; Shetye and Shenoi 1988; Suryanarayana 1988; Sasamal 1989; Murty 1990; Suryanarayana *et al* 1991), no work has been carried out, particularly in the northwestern Bay of Bengal during the retreat of SWM. In this paper, we present the hydrography and circulation in the upper 500 m of the northwestern Bay of Bengal during the retreat of SWM of 1983.

2. Data and methodology

The present study is based on the hydrographic data collected through conventional hydrocast operations on board R V Gaveshani during 7–18 September 1983 along four sections normal to the east coast of India in the northwestern Bay of Bengal (figure 1). Water samples were analysed for conductivity on Guildline Autosal (model 8400A) and the salinity was obtained using practical salinity scale algorithms. (Anon

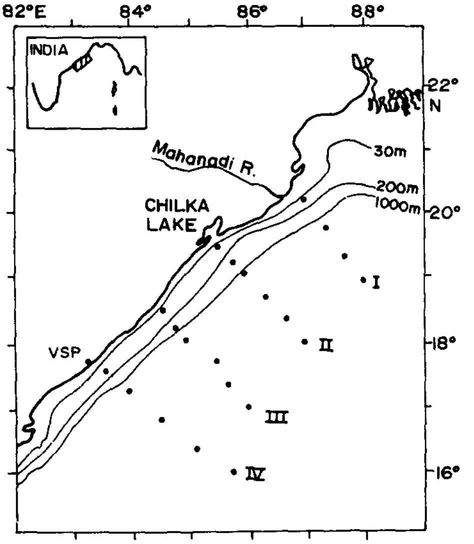

Figure 1. Station location map.

1981). The data were processed following La Fond (1951). The dynamic heights at the stations, the relative currents between station pairs and the geostrophic volume transport (Sverdrup *et al* 1942) across each of the sections were computed with reference to 500 db level surface. This reference level surface was chosen as the variation in density was considerably small at 500 m depth. Moreover, Murty (1990) noticed that the surface circulation pattern during SWM in the Bay of Bengal does not exhibit appreciable variation qualitatively with the change of reference level surface from a shallow reference level to a deep one. For stations having depths less than 500 m, the dynamic heights were obtained through extrapolation methods as suggested by Sverdrup *et al* (1942) and Nowlin and McLellan (1967). The alongshore (τ_y) and cross-shore (τ_x) components of the wind stress were computed from the observed wind data at the stations. The Brunt-Vaisala frequency was computed at the stations following Pond and Pickard (1983) to examine the stability of the water column.

3. Results

3.1 *Temperature*

At the sea surface (figure 2a), temperature varied between 28·5°C and 29·5°C with a uniform temperature of 29°C over a large area. At 30 m (figure 2b), cold (<26°C) water appeared near the coast and temperature increased to 29·5°C towards north and offshore. A cell of cold (26°C) water was noticed in the south. At 50 m (figure 2c), the cold (23°C) water cell centered at 17°N and 84°30′E was conspicuous and the temperature increased towards the coast from its centre. Temperature decreased from the north to south along the coast. At 100 m (figure 2d), the cold water cell was persistent with its core temperature at 17°C. At this depth, temperature increased towards north with a variation from 17°C to 20°C. Sections I to IV (figure 3a–d) showed an isothermal layer near the surface. Temperature of this isothermal layer of

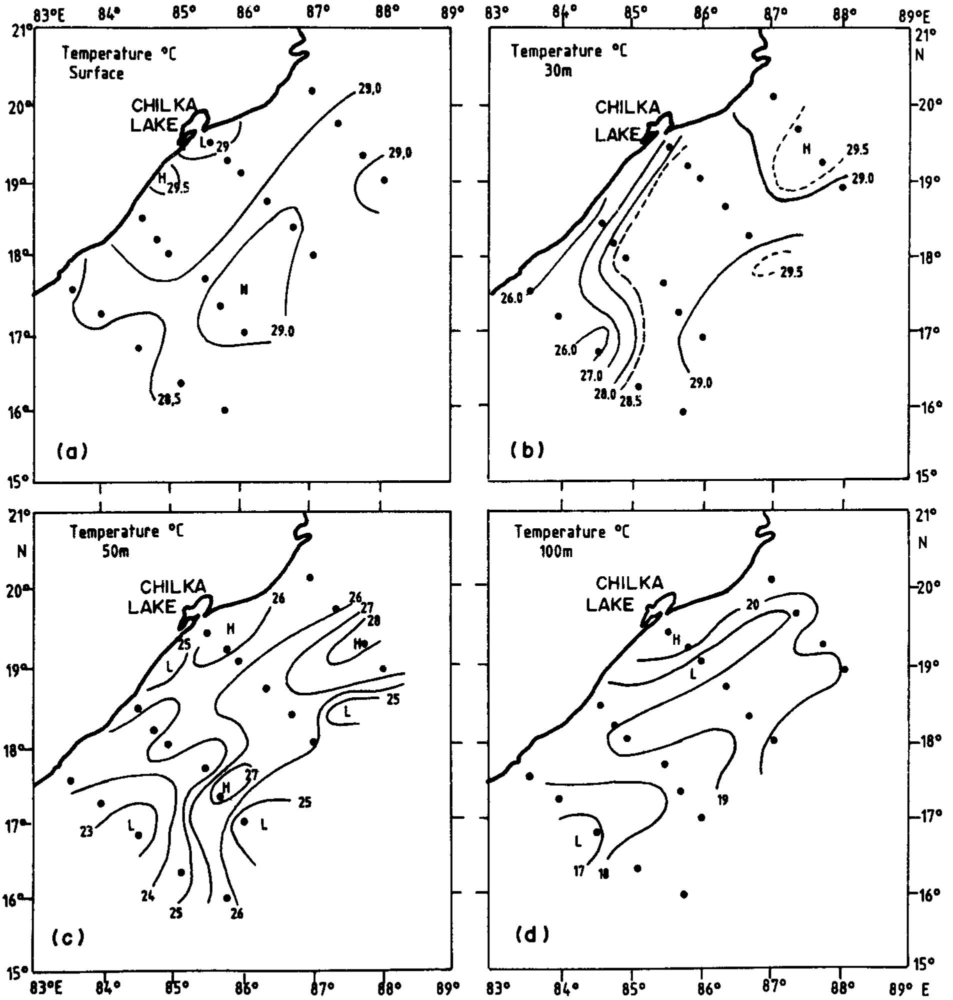

Figure 2. Horizontal distribution of temperature (°C) at (a) surface, (b) 30 m, (c) 50 m and (d) 100 m.

thickness 30 m was 29°C along sections I to III and about 28·5°C along section IV. Near the coast the isotherms rose upward above 40 m depth and inclined downward between 40 and 150 m along sections II to IV.

3.2 *Salinity*

At the surface (figure 4a), the salinity was low ($< 26{\cdot}0 \times 10^{-3}$) in the north and increased to $33{\cdot}5 \times 10^{-3}$ nearer the coast in the south. These low salinity waters were due to the effect of freshwater influx from the head of the Bay. At 30 m (figure 4b), relatively saline ($> 34{\cdot}4 \times 10^{-3}$) waters prevailed near the coast with the isohalines oriented parallel to the coast and salinity decreased away from the coast. At 50 m (figure 4c), salinity was around $34{\cdot}5 \times 10^{-3}$ near the coast and about $34{\cdot}7 \times 10^{-3}$ at the farthest. At 100 m (figure 4d), salinity was around $34{\cdot}9 \times 10^{-3}$.

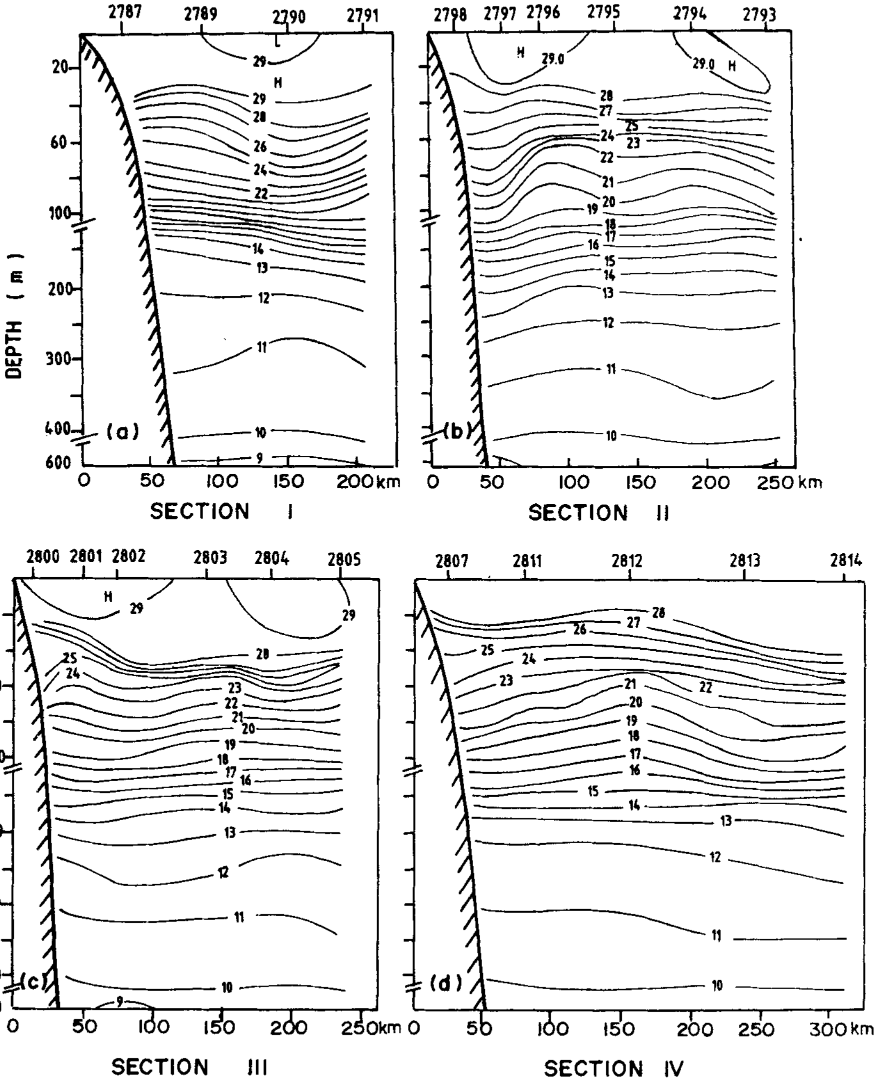

Figure 3. Vertical distribution of temperature (°C) along (a) section I, (b) section II, (c) section III and (d) section IV.

Along the sections (figures 5a–d), the distribution of salinity showed parcels of low salinity in the upper 20 m with their salinity increasing from 26·0 × 10^{-3} along section I to 33·5 × 10^{-3} along section IV. Downward sloping of isohalines, similar to that seen in isotherms, was noticed in sections II to IV. A broad subsurface maximum in salinity was present along all sections. The salinity in this maximum increased from south to north but was always in the proximity of 35·0 × 10^{-3}.

3.3 *Circulation and volume transport*

The dynamic topography at the sea surface relative to 500 db surface indicates a weak flow with a cyclonic cell centered at 17°N and 84°30'E (figure 6a). North of this, the

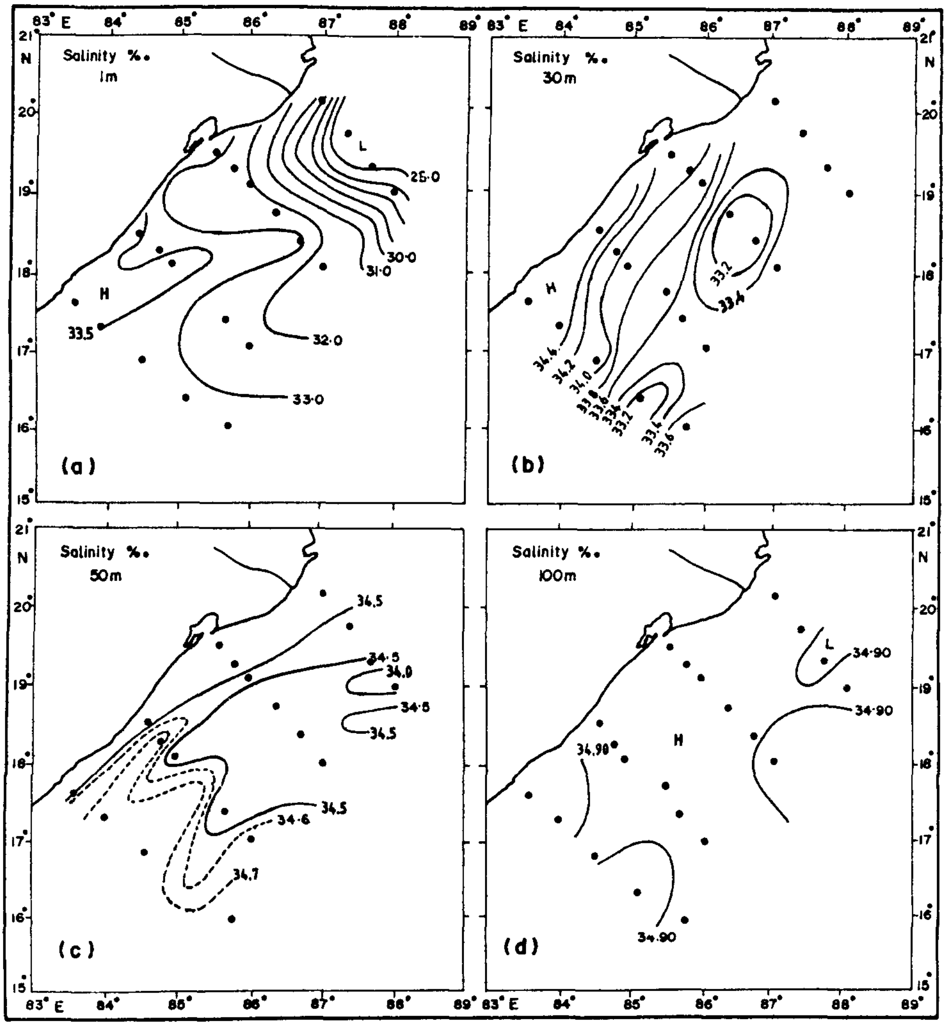

Figure 4. Horizontal distribution of salinity ($\times 10^{-3}$) at (**a**) surface, (**b**) 30 m, (**c**) 50 m and (**d**) 100 m.

flow is anticyclonic. At 100 m (figure 6b), the flow near the coast is opposite to that at the surface. The computed net volume transport in the study area is about $2{\cdot}0 \times 10^6\,\mathrm{m^3 \cdot s^{-1}}$ directed towards northeast.

4. Discussion

Recent studies (Gopalakrishna and Sastry 1985; Suryanarayana *et al* 1991) of the northwestern Bay of Bengal during the peak SWM (August) show downward tilt of isopleths near the coast in the upper water column in association with an equatorward flow. The observed distribution of temperature and salinity in the study area during the retreat of SWM (September) indicates the upward tilt of isopleths above 40 m and downward tilt below 40 m on approaching the coast. This upward rise of the

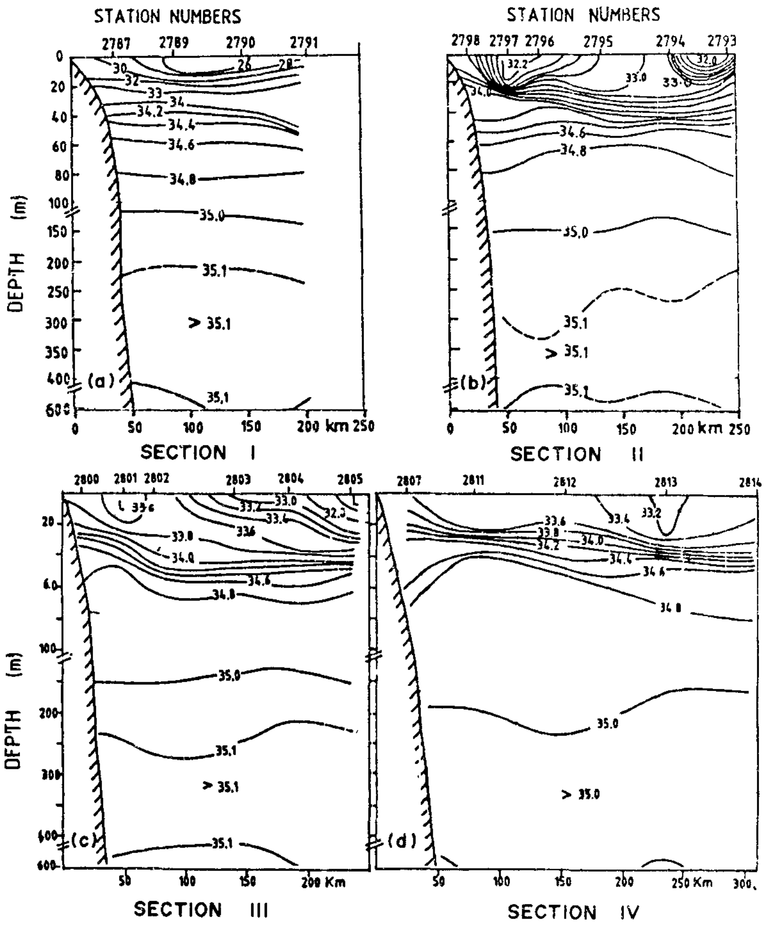

Figure 5. Vertical distribution of salinity ($\times 10^{-3}$) along (**a**) section I, (**b**) section II, (**c**) section III and (**d**) section IV.

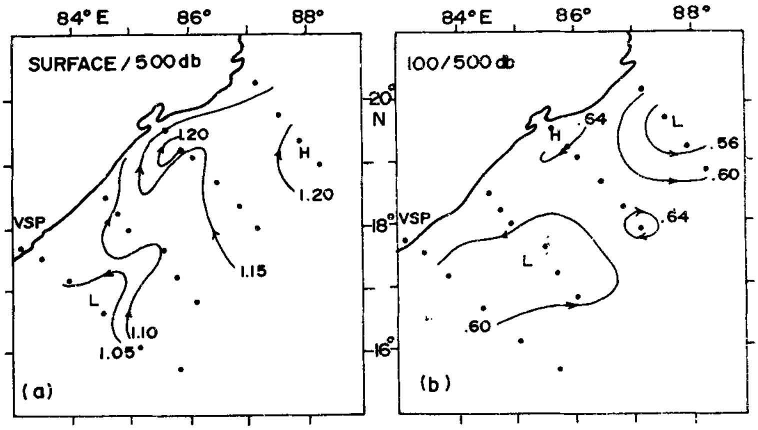

Figure 6. Dynamic topography (dyn. m.) relative to 500 db level surface (**a**) 0/500 db and (**b**) 100/500 db.

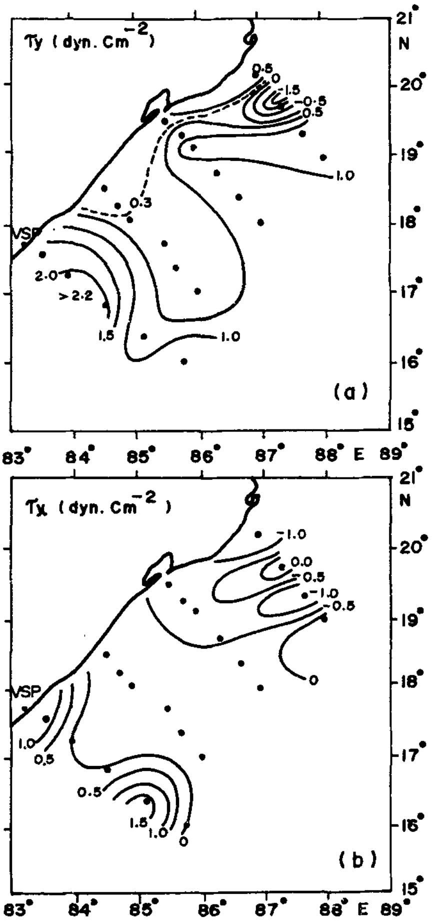

Figure 7. Distribution of wind stress (dyn·cm^{-2}) components (**a**) alongshore (τ_y) and (**b**) cross-shore (τ_x).

isopleths draws attention and is suggestive of the abrupt response of the upper layers of the northwestern Bay of Bengal to the local winds during the retreat of SWM. While southeasterly winds blow over the northwestern Bay of Bengal (Prasad *et al* 1990) during the peak SWM, the general southwesterly winds of the SWM prevail over this region during the retreat of SWM. The winds during the observational period were from west/southwest with speeds between 5 and 13 m·s^{-1}. These winds are conducive to upwelling near the coast. The alongshore stress has higher magnitudes compared to the cross-shore wind stress (figure 7a, b). These stress values are slightly higher than those obtained from the mean climatic winds (Shetye *et al* 1985). The alongshore stress (figure 7a) is positive and directed northeastward. Its magnitude increases towards offshore and a maximum positive stress occurs in the south. We expect that this northeastward wind stress drives an offshore Ekman transport thereby leading to the process of upwelling. This is supported by the presence of cold, saline waters (figure 2a, b and figure 4a, b) and the thinner (< 20 m) surface isothermal layer (figure 8) near the coast. The distribution of upwelling index (Suryanarayana 1988) at Visakhapatnam and Gopalpur (south of Chilka Lake) also

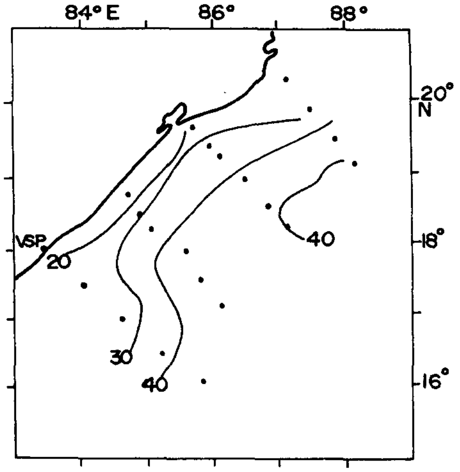

Figure 8. Topography of thickness (m) of surface isothermal layer.

reveals the Ekman process of upwelling during September. The observed higher near-surface salinity nearer the coast is an indicator of the Ekman process of upwelling. The zone of upwelling confines to about 50–75 km from the coast (figure 3b–d). The southward decrease of temperature at 50 m and 100 m along the coast is probably related to the increased values of τ_y there. However, the shoreward increase in temperature at these depths corresponds to the downward tilt of the isopleths. It may be mentioned that the downward tilt of the isopleths in the study area is rather weak compared to the similar feature observed off the west coast of India during SWM (Antony 1990). This downward tilt in the isopleths near the coast below 40 m (figure 3b–d and figure 5b–d) and the upward tilt above 40 m give rise to spreading of the isopleths centered at around 40 m. This spreading is related to the presence of current shear near the coast in the upper 100 m (figure 6a, b). The stability of waters near the coast is high (higher values of Brunt-Vaisala frequency) at 30 m and low below this depth corresponding to upwelling and spreading respectively. This indicates that the upwelling is limited to the upper 40 m. The Brunt-Vaisala frequency reaches maximum values in the north (section I) at 15 m due to shallow halocline resulting from the influence of freshwater influx from the head of the Bay and indicates higher stability in this region. Under the influence of offshore Ekman transport, low salinity waters are present in the offshore region in south.

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