

‘Thermohaline Front’ off the east coast of India and its generating mechanism

PV Hareesh Kumar¹, Basil Mathew¹, MR Ramesh Kumar², A Raghunadha Rao¹, PSV Jagadeesh¹,
KG Radhakrishnan¹, TN Shyni¹

¹Naval Physical & Oceanography Laboratory, Kochi 682 021, India

²National Institute of Oceanography, Goa

Abstract

Physical oceanography measurements reveal a strong salinity (0.18 psu.km^{-1}) and temperature ($0.07^\circ\text{C.km}^{-1}$) front off the east coast of India in December 1997. T-S diagrams suggest lateral mixing between the fresh water at the coast and the ambient warmer, saltier water. This front seems to be the result of southward advection of fresh and cool water, formed in the northern Bay of Bengal during the monsoon, by the East Indian Coastal Current, as suggested by the large scale salinity structure in the SODA re-analysis and the anti-cyclonic gyre in the northwestern Bay of Bengal during winter. The data further reveals an offshore front in January, which appears to be the result of a meso-scale re-circulation around an eddy, bringing cold and freshwater from the northern Bay of Bengal further away from the shore. Our cruise data hence illustrates that very strong salinity fronts can appear in the Bay of Bengal after the monsoon, as a result of intense coastal circulation and stirring by eddies.

Key words: Bay of Bengal, Ocean front, East India Coastal Current, ElNino-Dipole year, Anti-cyclonic eddy, Thermal inversion

Corresponding authors Email id: hari2745@gmail.com

1. Introduction

The Bay of Bengal (BoB) receives large quantities of freshwater (Martin et al, 1981; UNESCO, 1988; Subramanian, 1993; Sengupta et al, 2006) and silt (Subramanian, 1993) from various rivers, especially during the monsoon seasons. This freshwater influx not only causes considerable dilution in the surface layers of the northern Bay (Martin et al, 1981), but also plays a strong role in its hydrological characteristics. Shenoi et al (2002) noticed that the massive freshwater discharge from precipitation and river runoff during the summer monsoon season increases the near surface stratification in the BoB thereby inhibiting the vertical mixing. The dominance of a cyclonic gyre in the northern BoB after the summer monsoon season (Wu et al, 2007) causes a southward current along the western boundary and a northward current along the eastern boundary of the bay, resulting in the southward extension of the freshwater plume.

Broadly, the surface layer circulation in the BoB (Shankar et al, 1996; Mc Creary et al, 1996; Shetye et al., 1991; Schott and McCreary, 2001; Shenoi, 2010) consists of an anti-cyclonic gyre between February and April with a poleward East Indian Coastal Current (EICC). By May, the anti-cyclonic gyre begins to breakup and a cyclonic circulation develops in the northern BoB and starts expanding southward. This cyclonic circulation continues till October-December. During early winter, there is a cyclonic gyre in the interior Bay, which is coupled to the then southward EICC. In a nutshell, along the coastal boundaries of the western BoB, the EICC flows poleward during the summer monsoon season and equatorward during early winter (Shankar et al, 1996; Mc Creary et al, 1996; Shetye et al., 1991; Schott and McCreary, 2001; Shenoi, 2010). Probably, the southward EICC transports the low salinity water that originates in the northern BoB due to river runoff to the southwest coast of India (Shetye et al, 1996).

Studies (Shankar et al, 1996; Mc Creary et al, 1996) have suggested that the local winds are the prime forcing of the northward EICC during the summer monsoon season (June-September). During winter, the remote forcing also contributes significantly to the southward EICC (including Ekman pumping in the interior Bay, and coastal Kelvin waves forced by equatorial winds and northern BoB alongshore winds) (Shankar, 2000; McCreary et al, 1996; Rao et al, 2010; Hareesh Kumar et al, 2013). Durand et al (2009) observed that the circulation in the western BoB is a combination of several independent re-circulating eddies that hug the east coast of India, with EICC on its western arm. These eddies (Chelton et al, 2011) contribute to the discontinuity of the EICC along its path. Durand et al (2009) observed that the EICC was anomalously poleward during the fall

1997 Indian Ocean Dipole (IOD) event. Therefore, the re-circulating gyres observed along the path of EICC may be viewed independently for different years.

The huge freshwater inflow from the Ganges-Brahmaputra Rivers results in the formation of a front in the northern BoB, which is present throughout the year (Belkin, 2009). As the front observed in this region is of meso-scale nature, the monthly climatology fields of temperature and salinity cannot resolve this feature. In the present study, we investigate how the various aspects discussed above combine to produce an intense salinity front utilizing the hydrographic data collected during December 97 - January 98. Interestingly, the year 1997-98, was a very anomalous year, as the occurrence of IOD and the strongest El Nino of the century coincided (Saji et al, 1999; Webster et al, 1999).

2. Data

To investigate the characteristics of an oceanic front observed off the east coast of India during winter, two cruises were conducted along two transects (TR1 and TR2) during December 1997 and January 1998 (Fig. 1). Along these tracks, temperature and salinity data were collected using CTD systems (accuracy $\pm 0.05^{\circ}\text{C}$, 0.01 psu). In December, the stations were occupied at every 10 nautical miles (NM) while in January, the separation between the consecutive stations were 10 NM near the coast and 15 NM beyond 1000 m depth contour. As the *in situ* hydrographic data are limited to describe the front, the data sets are supplemented with sea surface temperature (SST) from AVHRR (9 km resolution) and sea surface salinity (SSS) from SODA (0.5°x0.5° degree grid resolution, Version 2.2.4) for the period July 1997 to January 1998 (Carton and Giese, 2008). The efficiency of using satellite altimetry information for the study of frontal dynamics and eddy formation has been demonstrated in several studies (Sokolov and Rintoul, 2000; Rintoul and Trull, 2001; Ducet and Le Traon, 2000). To highlight the presence of the anti-cyclonic eddy in the study region, the multi-mission gridded sea level anomaly (SLA) data (<http://www.aviso.oceanobs.com>) corresponding to the observational period is utilized.

3. Results

The vertical sections from nearshore to offshore along TR1 (Fig. 2) indicate that the temperature and salinity near the coast is 26.9°C, 28.8 psu in December (at 17.92°N, 83.9°E) and 26.4°C and 29.8 psu in January (at 17.94°N, 83.83°E). The temperature and salinity increases by 1.2°C and 5 psu respectively up to 17.69°N, 84.11°E in December and by 1.3°C and 3.5 psu up to

17.84°N, 83.93°E in January. This suggests that the water near the coast is both cooler and fresher compared to the offshore waters. The changes in salinity and temperature result in a density variation across the front ($\sim 3.41 \text{ kg.m}^{-3}$ in December and 2.24 kg.m^{-3} in January), with shelf water being less dense than open ocean water.

In January, the temperature profiles show thermal inversion up to $\sim 1.5^\circ\text{C}$ (1.3°C in December) near the coast (17.94°N, 83.83°E) and 1.3°C (0.3°C in December) farther offshore (17.29°N, 84.42°E). The inversion is noticed up to a maximum depth of 55m farther offshore. As the increase in temperature is compensated by the increase in salinity (up to ~ 4.9 psu near the coast), these inversion layers are highly stable, which is evident from the density distribution.

The abrupt change in temperature and salinity in the vertical and lateral, especially between the shelf and slope (between 50 and 1500m isobaths), is an indicative of a “coastal front”. This coastal front separates the on-shelf water from the off-shelf oceanic water. The offshore limit of the coastal front, defined as the region up to which large horizontal gradients in temperature and salinity exist, is 84.11°E in December. In January, two frontal zones appear in the study region, one near the coast and another in the offshore. In January, the near shore frontal zone shifts closer to the coast, i.e. to 83.93°E, resulting in an increase in the lateral gradient across the front between December ($0.03^\circ\text{C.km}^{-1}$, 0.14 psu.km^{-1}) and January ($0.07^\circ\text{C.km}^{-1}$ and 0.19 psu.km^{-1}). The reduction in the temperature and salinity gradient along TR2 ($0.024^\circ\text{C.km}^{-1}$ and 0.11 psu.km^{-1} in December) is due to the increase in salinity in the coastal regions towards south (Fig. 2). In January, the “offshore front” is observed about 63 km away from the coast. However, the present data length is not sufficient to demarcate the eastern limit of this offshore front. With the available data, the variability in temperature, salinity and density across this front is 1.4°C , 1.4 psu , 0.6 kg.m^{-3} , with its eastern side having comparatively cold and fresh water.

The coastal and offshore fronts are separated by a zone of warm (28° to 28.3°C) and relatively high salinity water (33.75 psu), where the lateral and vertical stratification is very weak. In this region, referred to as transition zone, the water column is having nearly uniform temperature or thermal inversion up to 55-60 m in December and 75-80 m in January. As a result of strong near-surface stratification near the coast (Fig. 2), the thickness of the surface homogeneous layer based on density gradient (MLD) is much shallower than based on temperature (ILD, a drop of 1°C from SST). Here, because of thermal inversion, the ILD extends up to the bottom. In the transition zone, both ILD and MLD match well ($\sim 55\text{-}60\text{m}$ in December and $\sim 75\text{-}80\text{m}$ in January). The width of

transition zone reduces from ~30 NM in December to ~11 NM in January. Along TR2 also, similar features are observed, but with a reduced magnitude, as this transect is located slightly south of TR1.

The T-S diagrams during December (Fig. 3a) indicate gradual variation in the sigma-t values within the coastal frontal zone (from 18 to 21.5), suggesting mixing between the coastal and offshore water. In the transition zone (violet dots in Fig. 3a), only one watermass centered at 21.5 is noticed in the surface layers. By January (Fig. 3b), the watermass in the frontal zone becomes very distinct (centered at sigma-t of 19), whereas in the transition zone, many changes are not observed in the watermass characteristics compared to December. The characteristic of this watermass within the transition zone is the same as that present at the subsurface levels in the frontal zone and does not show significant variation between December and January. On the other hand, the lateral advection brings cooler and freshwater in a shallow layer (Fig. 2), which forms the “frontal zone” water and expands or contracts depending on the near surface currents. This results in strong thermal and salinity gradient between the nearshore region and the transition zone thereby forming a “front” in this region.

4. Discussion

The hydrographic data collected from the northwestern BoB during December 97-January 98 shows the existence of two fronts, one close to the coast and one further offshore. In order to describe the large scale patterns in the BoB and to investigate their possible influence on the frontal formation, we have utilized SSS from SODA, SST from AVHRR and SLA from satellite altimetry.

a. Monthly variation of SST, SSS

In July, a low salinity plume (<29 psu) is formed in the northern BoB, that reaches its peak in September (Fig. 4a). The plume extends along the coastal regions of the northeastern and northwestern BoB. Along the east coast of India, the southward limit of the plume is 15°N and persists until October. From November, the low salinity plume in the western BoB weakens and is replaced by comparatively high salinity waters. During this period, an anti-cyclonic eddy forms in the northeastern BoB (Fig. 5a) and the cyclonic eddy shifts southwestward. In the coastal regions along TR1, there is an increase of ~3 psu in the surface salinity between December 97 (~28 psu) and January 98 (~31 psu) and the increase is less than 1 psu in the offshore region. Even during early winter, remnants of the low salinity plumes of summer monsoon origin exist very close to the northeast of India.

In the surface layers of the northern BoB, progressive warming (till October) is replaced by winter cooling from November 97 (Fig. 4b). Between October 97 and January 98, the surface layers cool by 8°C (~30°C in October to ~22°C in January). The cold water (<27°C) stretches up to a distance of more than 800 km from the head of the Bay towards the central BoB. Few other studies (Subramanian, 1993; Varkey et al, 1996; Suryanarayana et al, 1992) also reported the spreading of this cold water up to a distance of more than 1000 km from the mouth of the BoB and their influence on the hydrological characteristics in the BoB. The cooling is also evident in the coastal regions along the observational tracks, but with a reduced magnitude (3.5°C). As the cold and freshwater floats over the existing more saline, warmer subsurface waters (Fig. 2, and Fig. 4), thermal inversion occurs in this region (~1.3°C). Shetye et al (1996) also reported thermal inversion in the western BoB during winter. This feature is unique to the northern BoB during winter, compared to the other parts of the Indian Ocean. During this period, a band of warm water (~27.5°C) sandwiched between cold water (~27°C) on either side is formed on the western BoB (Fig. 5b). Same feature is evident in the vertical sections (Fig. 2) of temperature, whereas the salinity section indicates comparatively saline water in the warm regions and fresh water in the cold water region. Interestingly, the observed coastal front occurs in the region between the warm water and the near shore cold water.

Figure 5 also indicates an anti-cyclonic eddy, centered at 18°N and 86°E, where a pool of warm water (27°C) is surrounding the cold water. The weekly snap shots of the sea level anomaly (Fig. 5a) between 3 December 97 and 7 January 98 also show an anti-cyclonic eddy (AC) beyond the continental slope of the northwestern BoB. At the latitude where AC is observed, a negative sea-level coexists with positive sea-level anomaly to its east. Note that the magnitude of negative sea level is much less (-5 cm) compared to the positive values (>10 cm). The AC grows and elongates southwestward parallel to the continental slope but slightly away and in January, the western arm of the eddy is observed closer to the slope. The southwestward drift of cyclones and anti-cyclones was proved theoretically by Cushman-Roison et al (1990).

In December, the stations on the eastern side of the TR1 lie on the western periphery of the AC. However, in January, as the AC shifts southwestward, the stations occupy the core of the eddy while the stations at the middle of TR1 lie at the western periphery of AC. Durand et al (2009) reported the trapping of EICC near the coast and the offshore current flowing in the direction opposite to that of the nearshore currents. Moreover, they also reported EICC as a discontinuous flow with few re-circulating loops along its path. The present study also shows opposite flows along the cross-shelf transect, with southwestward geostrophic currents on the eastern arm and

northeastward currents on the western arm of the AC (Fig. 5a). The curling of the currents around the AC brings fresh and cold water (Fig. 5b) from the northern BoB into the western BoB and creates the offshore front in January.

In the western BoB, formation of a band of warm water between two cold water regions is observed. In the coastal regions of northwestern BoB, thermal inversion and increase in salinity with depth during winter results in warm, high salinity waters at subsurface levels. Moreover, in the coastal regions of the northeast coast of India, surface temperature is slightly less and remnants of the low salinity waters plumes of summer monsoon season are still evident in the surface layers. T-S diagrams support lateral mixing between the fresh water at the coast and the ambient warmer, saltier water.

The year 1997-98 was a strong ElNino-Dipole year. Durand et al (2009) reported that the EICC was anomalously poleward during the fall 1997 IOD event. Moreover, there was a substantial depression in the sea level in the eastern basin compared to the mean value in the west; it exceeds 30 cm between November 97 and May 98 (Webster et al, 1999). Recent study by Sreenivas et al (2011) reported inter-annual variability in the BoB sea level anomaly associated with the ENSO and IOD event. However, the extent to which these systems influence the dynamics of the Indian Ocean system is yet to be resolved. Therefore, the features observed in the western BoB in this study may be viewed independently.

5. Summary and Conclusion

Physical oceanography observations were made off the northeast coast of India during December 97 - January 98. The present observations provide some insight into the variability of the upper-ocean along the pathway of EICC. The physical oceanography measurements indicate a front in the western Bay of Bengal, which is characterized by cold and fresh water in the nearshore region and warm and saltier water in the continental slope. Across the coastal front, maximum horizontal gradient in temperature ($>0.07^{\circ}\text{C.km}^{-1}$) and salinity (0.19 psu.km^{-1}) is observed in January. During this period, thermal inversions are noticed, with subsurface water up to 1.4°C warmer than the surface near the coast (0.3°C further offshore). The inversion is noticed up to a depth of 30 m near the coast and 45 m in the offshore. Within the inversion layer, increase in temperature is compensated by the increase in salinity making the inversion highly stable. In January, a band of warm water ($\sim 27.5^{\circ}\text{C}$) sandwiched between cold water ($\sim 27^{\circ}\text{C}$) on either side is formed on the western BoB. The T-S diagrams indicate lateral mixing between the fresh water at the coast and the

ambient warmer, saltier water. The coastal front seems to be the result of southward advection of the fresh and cool water formed during the monsoon in the northern BoB by the southward EICC and the formation of AC during winter. In January, another front appears further offshore, with warm and saline water on the western side and fresh and cold water on the eastern side. The offshore front appears to be the result of an anti-cyclonic circulation curling around an eddy, and bringing cold and freshwater from the northern Bay of Bengal in the offshore of the cruise location in January. This is supported by the surface salinity structure in the SODA re-analysis data.

The major limitation of the study is that the *in situ* data is available only along two transects covered during 1997-98, which was a very anomalous year of strong ElNino and Dipole. The SODA data used to supplement the *in situ* data is based on data assimilation and hence it may contain some error. In spite of these facts, however, the occurrence of strong fronts along the west coast of India and of stirring by eddies is a fact.

Acknowledgements

Authors are thankful to Shri. S. Ananthanarayanan, Director, NPOL for motivation and encouragement to carry out this study. The courteous efforts of Commanding Officer, officers and crew of INS Sagardhwani in smoothly conducting the mission are gratefully acknowledged.

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Figure Captions

Fig. 1. Station location map (Station spacing: 10 nautical miles (NM) during December; 10 NM near the coast and 15 NM in the deep water during January. TR1 and TR2 are the two transects along which observations were taken). Plus sign represents stations in December 1997 and circles represent stations in January 1998. The average slope between 50 and 1500m isobaths is $\sim 42 \text{ m.km}^{-1}$ and the slope reduces to 32 m.km^{-1} along TR2. The respective values between 100 and 1500m isobaths are 72 m.km^{-1} and 64 m.km^{-1} .

Fig. 2. Vertical sections of temperature (T), salinity (T) and density (ρ) during December 1997 and January 1998 along the two tracks TR1 and TR2. Contour intervals: Temperature: 0.25°C , Salinity: 0.25 PSU; Density 0.25 Kg/m^3 . Continuous maroon line indicates the mixed layer (based on density gradient) and dashed line indicates isothermal layer (based on temperature).

Fig. 3 T-S characteristics in the frontal zone (blue dots) and transition region (violet dots) during (a) December 1997 and (b) January 1998.

Fig. 4 Distribution of (a) Sea surface salinity (SSS) overlaid by surface currents from SODA data (b) sea surface temperature (SST) from AVHRR in the Bay of Bengal for typical months between July 1997 and January 1998. The contour interval for SST is 0.5°C and SSS is 0.5 psu.

Fig. 5 Distribution of (a) Sea level anomaly (SLA) overlaid by geostrophic currents (b) Sea surface temperature (SST) from AVHRR in the Bay of Bengal for typical days between December 97 and January 98. Black dots indicate the station locations during December 1997 and January 1998. The contour interval for SST is 0.5°C and for SLA it is 5 cm.

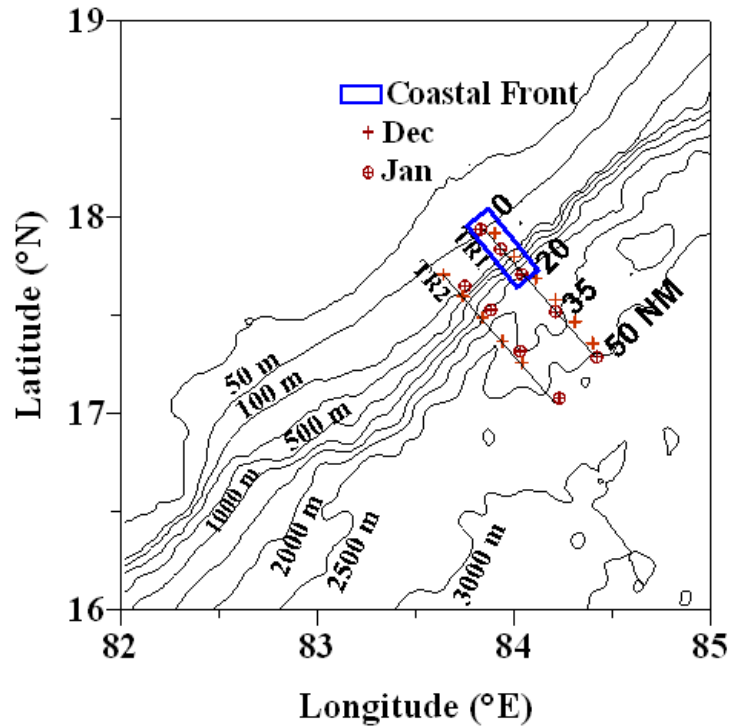


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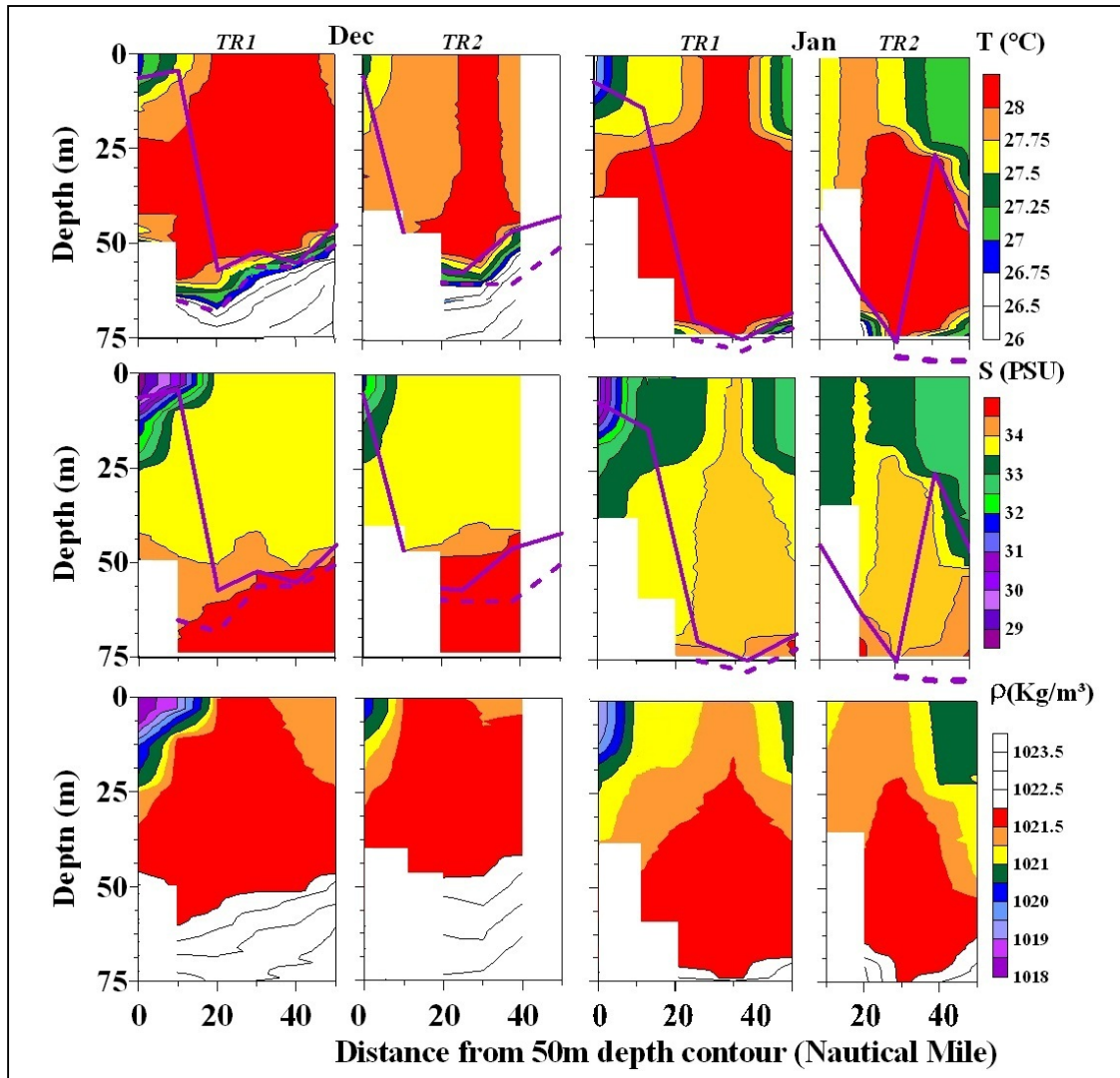


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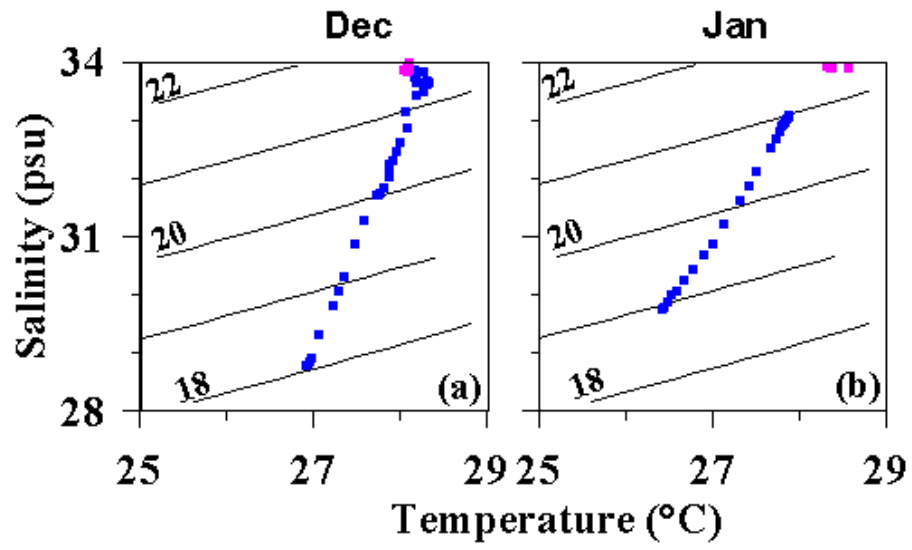


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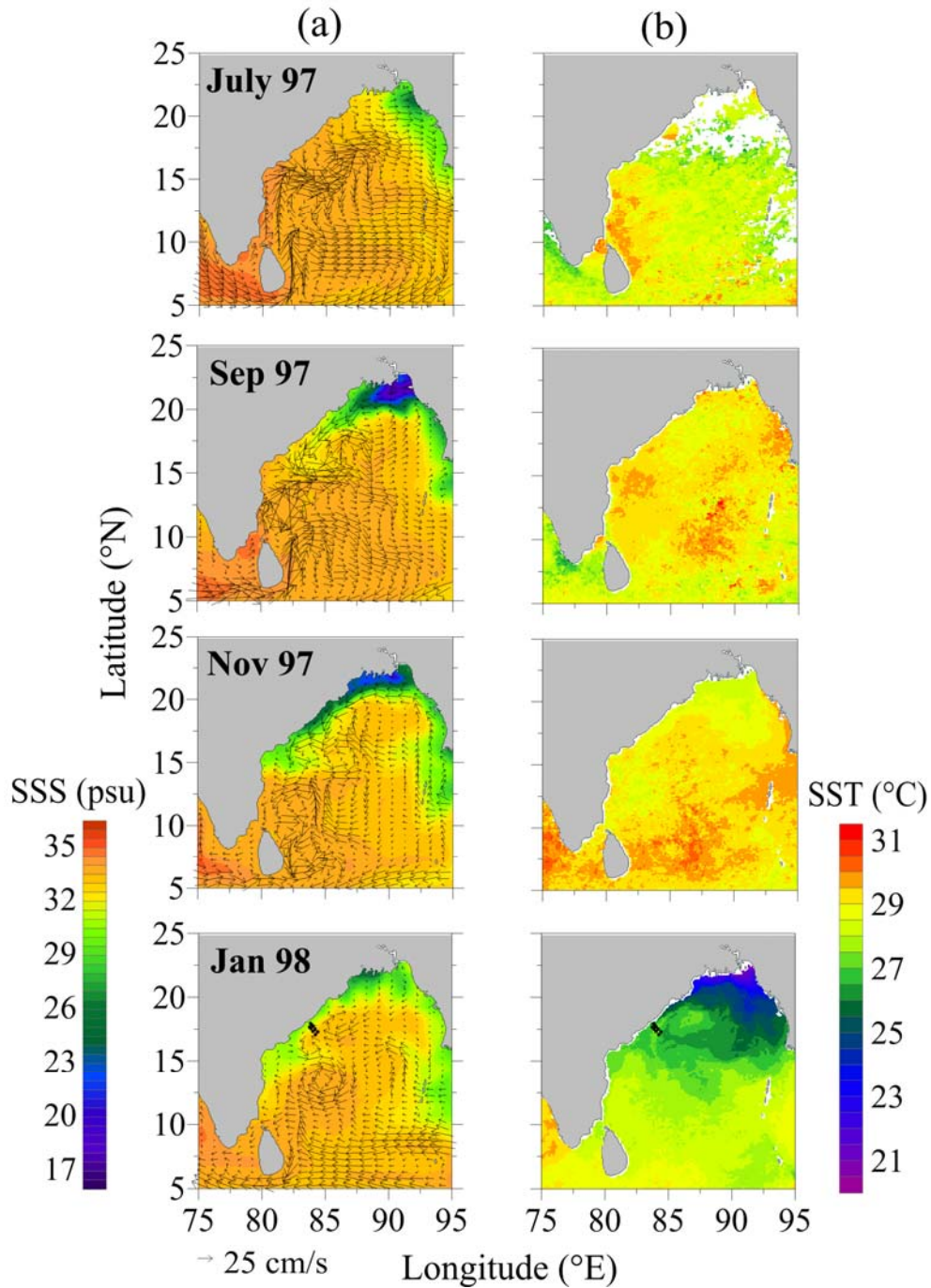


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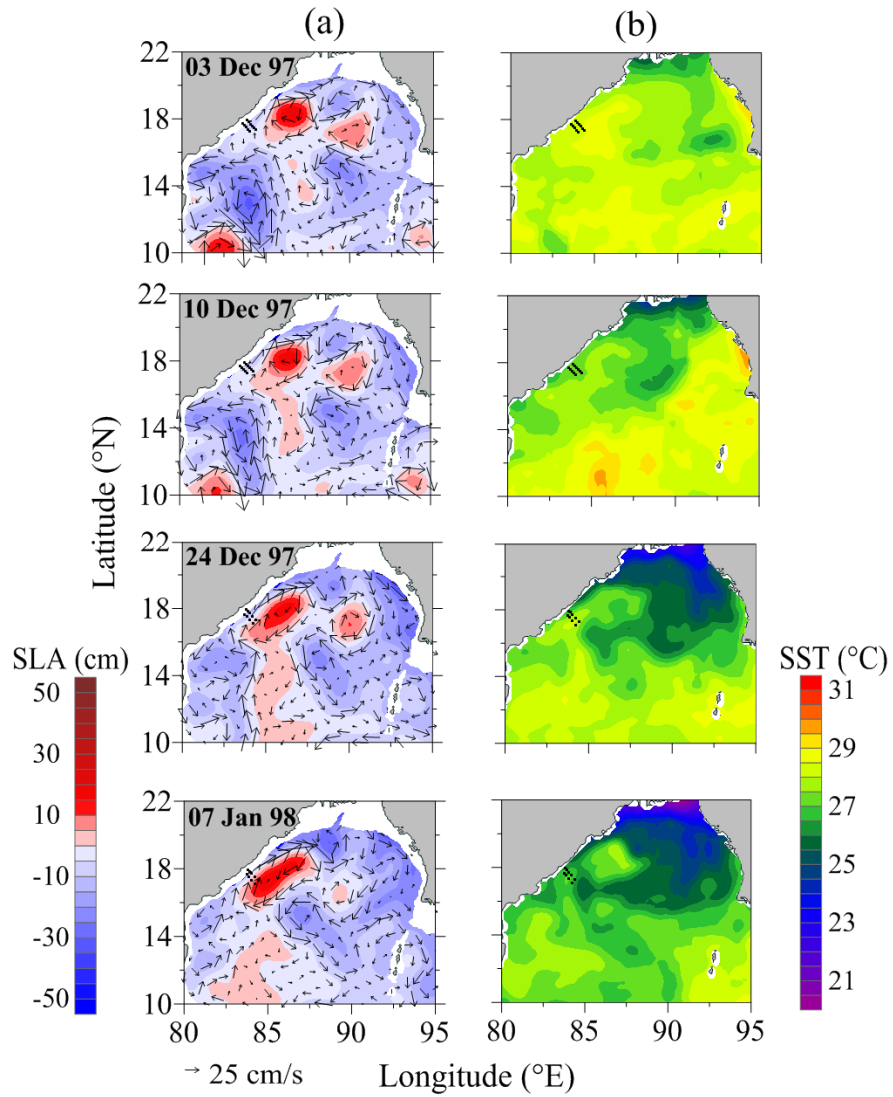


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