

Upwelling and associated hydrography along the west Coast of India during southwest monsoon, 1999

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Abstract

During May 1999 twenty-five hydrographic stations were carried out covering the waters of the west coast of India from 8°N to 13°N as a part of Marine Research - Living Resources (MR-LR) programme. The inference on upwelling and related hydrography is discussed. Analysis of wind field and hydrography indicated active upwelling along the southwest coast of India. The sea surface temperature near the coast were lower by 1.7°C (off Kanyakumari), 1.4°C (off Cochin) and 1.2°C (off Mangalore) from the farthest stations, indicating the presence of upwelled water near the coast. Well defined thermal, saline and density fronts were visible. Relatively high offshore transport was observed off Kanyakumari. Signatures of coastal under current were prominent which deepens, as moving towards north.

Analysis of hydrographic characteristics reveals the presence of cool upwelled water by May itself. Strong signals of upwelling were observed off Kanyakumari, relatively less off Cochin and weak off Mangalore indicating the propagation of this seasonal phenomenon towards north with time.

1. Introduction

Upwelling and its importance in oceanic regime on the redistribution of nutrients and increased productivity have been well recognized. Primarily, the process of upwelling governs the transfer of nutrients across the mass discontinuity layer from the nutrient rich subsurface layer. The index of coastal upwelling is the presence of cooler and denser water containing less dissolved oxygen and more phosphate than usually found at a given depth. Concentrations of oxygen and phosphate cannot be reliable indices of upwelling because their concentrations are liable to rapid modifications by biochemical processes. This phenomenon causes a profound increase in productivity of a region by increasing the nutrient content in the euphotic zone.

Darbyshire (1967) studied the hydrography of Kerala coast during the whole year from 8°N to 12°N latitude indicating the presence of cold water (<22°C) over the entire shelf but denies the role of wind induced upwelling for this phenomenon. Banse (1968) points out that upwelling off the Southwest coast of India starts with the onset of the Southwest monsoon. Sharma (1978) studied the vertical distribution of density (σ_t) for different months and according to him upwelling in this region commences in the deeper layers of about 90 m in March and the upwelled water reaches the surface by May.

Shetye et al. (1990) studied the hydrography and circulation off the West Coast of India during the South-

west monsoon 1987. They observed the occurrence of upwelling with the nearshore surface temperature being about 2.5°C lower than farther offshore station. A shallow (~75-100 m deep) equatorward surface current above poleward undercurrent along the entire shelf is also reported. This condition existed up to 15°N but the intensity of upwelling, and the signatures of the surface current and the undercurrent grew weaker progressively from south to north, and ceased to be noticeable at about 20°N.

Period and direction of upwelling along the west coast of India have been a matter of controversy between authors. In this paper we describe an upwelling study made in early May 1999, along the SW coast of India from 8°N to 13°N. The purposes of the study are to delineate the coastal upwelling characteristics and to ascertain the hypothesis that the upwelled water is present at the surface by the month of May. Also hydrographic condition of the area in context of upwelling is analysed.

2. Data and Methodology

The present study is based on the data collected onboard FORV *Sagar Sampada* from May 7th to June 1st 1999, as part of the Marine Research - Living Resources (MR-LR) Programme along the south west coast of India (Fig. 1). Twenty five stations were covered, of which at 6 stations, 24-hr observation was done. A Sea Bird (Electronics Ltd, USA) CTD was used

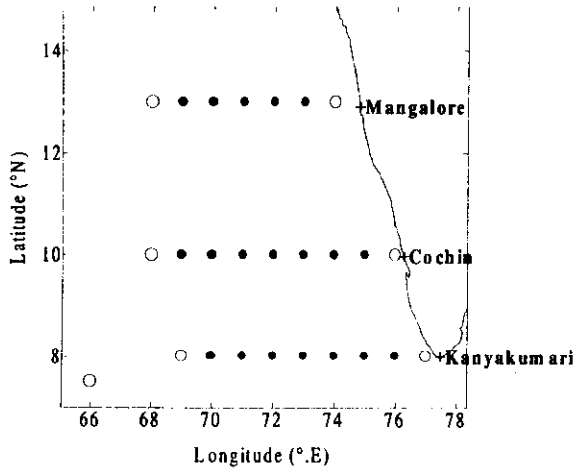


Fig. 1. Station locations.

to collect temperature, salinity, density and dissolved oxygen profiles from 25 stations to a maximum depth of 1500 m. The salinity values obtained from the CTD System were calibrated against the values obtained from the Autosal. Similarly dissolved oxygen values were calibrated against manual determination at selected depths.

The hydrographic data were processed by following standard procedures (LaFond 1951). Dynamic computations were carried out with reference to 1000 db surface. For shallow stations, the method suggested by Fomin (1964) was adopted. Surface meteorological data were collected at 3 hr interval along the track. The climatological mean wind stress and its longshore and offshore components computed by Shetye et al. (1984) along the west coast of India are used. Monthly surface wind stress curl were obtained from the atlas of Rao (1995). Wind stress was computed using the aerodynamic formula from the data collected during the cruise. The magnitude of the offshore component of the Ekman Transport is considered as an indicator of the amount of water upwelled through the bottom of the Ekman layer replacing those driven offshore. This is termed as upwelling index (Bakun 1973). It is given by Γ/f , where ' Γ ' is the alongshore component of the wind stress, ' f ' is the coriolis parameter. The upwelling indices were computed at all stations and averaged along each leg.

Mixed Layer Depth (MLD) is taken as the depth at which a negative temperature gradient exceeds 0.1°C per 10 m and persists over depth intervals of 30 m. In the present study 1°C drop from SST value is taken as MLD. Thermal structure of the oceans indicates sharp gradients in temperature between an upper isothermal layer and a lower stratified column, known as thermocline, where average value decrease in temperature is 5°C per 100 m (Defant, 1961). This discontinuity layer acts as a barrier to the vertical movements of

waters. The depth of occurrence of the thermocline was taken as the depth where the temperature falls by 1°C from the surface and 15°C isotherm was considered as the bottom of the thermocline (Kesavadas, 1992).

3. Results and Discussion

3.1 Wind Field

In summer (May) 1999, winds were predominantly northerly. The magnitude of the winds was on an average 5 ms^{-1} . Wind steadiness over the southwest coast during May-June is high ($>85\%$) (Hasternath and Lamb, 1979). As the prevailing winds being northerly to northeasterly and with the offshore transport of the surface water, the conditions are favorable for upwelling. The climatological mean alongshore component of wind during southwest monsoon season appears to decrease from Kanyakumari (8°N) to Cochin (10°N) and then increases up to Bhatkal (14°N) and again decreases towards north (Muraleedharan, 1995). The *in situ* wind measurements show positive (northerly) wind stress in the area. During the observational period the alongshore component of the winds was generally greater than cross-shore components. The north-south variation of alongshore components was less with maximum observed around 8°N and gradual decrease towards north. Monthly observation of

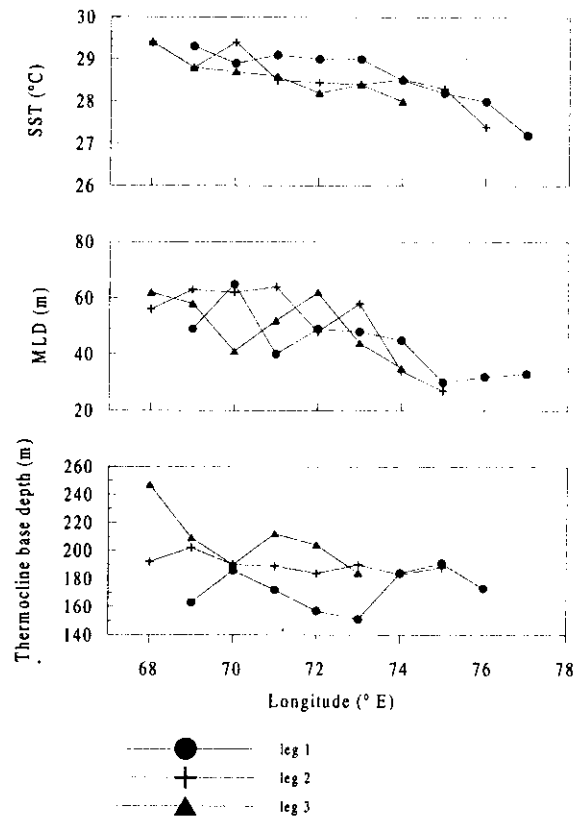


Fig. 2. Distribution of SST, MLD and base of thermocline.

climatological wind stress curl, the forcing function for oceanic motion, was observed to be positive along the south west of India. The positive wind stress curl is conducive to upwelling in the northern hemisphere (Hasternath and Lamb, 1979).

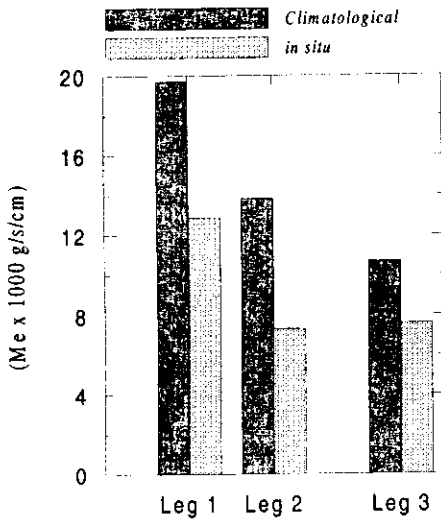


Fig. 3. In situ and climatological offshore Ekman transport.

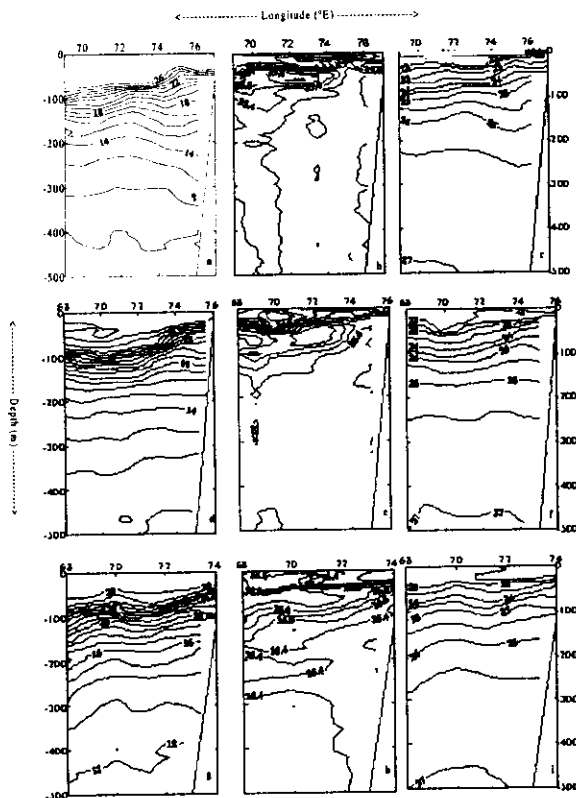


Fig. 4. Distribution of temperature (a,d,g), salinity (b,e,h) and density (c,f,i), (i) top panel, off Kanyakumari, (ii) central panel, off Cochin and (iii) bottom panel, off Mangalore.

3.2 MLD, Thermocline & SST

The mixed layer depth (MLD) in the study area varies between 30 m and 60 m depth (Fig. 2a). MLD is observed to increase towards north. MLD is shallower nearshore and deeper offshore. The base of the thermocline varies between 150 and 240 m depth in the study area (Fig. 2b). The rise in thermocline towards coast could be attributed to active upwelling in this area. Thermocline base is observed to be deeper in the offshore regions. This is mainly due to the strong on-shore monsoon winds, which should have given rise to thick isothermal layer. Thermocline base was lowest at leg 1 (off Kanyakumari) which is observed to have minimum MLD. At leg 2 (off Cochin) it is almost constant varying around 190 m. At leg 3 (off Mangalore), base of the thermocline is comparatively higher. This deepening of thermocline from north to south indicate the phenomenon of upwelling is significant at leg 1 (off Kanyakumari) and leg 2 (off Cochin) and is on its initial phase at leg 3 (off Mangalore). Sea surface temperature (SST) decreased towards coast (Fig. 2c). Minimum SST are noticed at leg 1 and leg 2, very near to the coast ($\sim 27.5^{\circ}\text{C}$) indicating the presence of colder upwelled water.

3.3 Upwelling Index

The distribution pattern of Upwelling Index (UI) indicates offshore transport in the surface Ekman layer. The longshore component along the west coast remains positive, higher in leg 1. Fig. 3 shows the in situ and climatological offshore Ekman transport during May from 8°N to 13°N . The transport is maximum off Kanya Kumari, the southern part of the peninsula, climatological data supports this observation.

3.4 Hydrographic field

The vertical thermal structure along leg 1, off Kanyakumari (8°N) exhibits fine upsloping of isotherms towards the coast producing colder surface water (Fig. 4a). This phenomenon extends upto 140 m depth, below which the trend is reversed and the isotherms were deepening towards the coast indicating the presence of an undercurrent. Surface temperature near the coast were almost 1.7°C lower than the farthest offshore station indicating active upwelling and presence of cold sub-surface water. Surface salinities near the coast were almost 0.7 psu higher than the offshore values (Fig. 4b). Isopycnals showed almost close resemblance to temperature profile. Upsloping of isopycnals from 120 m depth indicated the presence of denser water along the shelf and lighter water offshore (Fig. 4c). Both isotherms and isopycnals deepen towards the coast below the sub-thermocline region.

Vertical distribution of temperature at leg 2, off Cochin also indicates intense upwelling phenomenon (Fig. 4d). Shoaling of isotherms towards coast is prominent and this starts approximately around 200 m depth. This is much deeper considering the shoaling of isotherms observed off Kanyakumari (leg 1) indicating the deepening of undercurrent towards north. SST near the coast is 1.4°C lower than the farthest offshore station. The remarkable shoaling of thermocline towards the coast is again reflected in the density distribution indicating active upwelling (Fig. 4f). Salinity near the coast was almost 0.9 psu less than the farthest offshore station (Fig. 4e).

Vertical section of temperature (Fig. 4g) along leg 3, off Mangalore also shows fine upward tilt of isotherms. Here the shoaling of isotherms starts from 220 m depth and it is much deeper compared to the shoaling of isotherms observed off Kanyakumari and off Cochin. SST near the coast is 1.2°C lower than the offshore values. Surface salinities near the coast were 0.7 psu lower than the offshore values (Fig. 4h). Below 200 m, however, there were no appreciable changes in the salinity. Isopycnals follows the isotherms in this section also indicate active upwelling (Fig. 4i).

Analysis of horizontal section of temperature at the surface reveal the presence of strong thermal front off

Kanyakumari and off Cochin, is the manifestation of an active upwelling system (Fig. 5a). Similar feature was not observed off Mangalore. The high salinity tongue near Mangalore was an indication of on-shore transport of surface water as a result of the prevailing winds. The surface salinities near the coastline were observed to be low at Mangalore and Cochin but high off Kanyakumari (Fig. 5b). The surface density distribution showed the occurrence of lighter waters along the shelf and denser water offshore at Mangalore and Cochin but high-density water was observed near the coast off Kanyakumari indicating the dominance of salinity over temperature in the density field (Fig. 5c).

Thermal field at 50 m shows cooler waters near the coastline at all stations (Fig. 5d). A strong thermal front is observed between 73° - 75°N longitudes. The thermal gradient was 0.02°C per km. This gradient is observed in the Salinity and Density field also. The intrusion of high salinity water from the central Arabian Sea, as observed at the surface, was less conspicuous at this depth. At this depth low saline water is observed along the coastline (Fig. 5e). The lateral density distribution reversed with denser water along the coastline and lighter waters offshore (Fig. 5f).

The temperature field at 100 m depth indicates the intrusion of relatively warm waters from the north at 13°N , similarly a cold water intrusion from the south

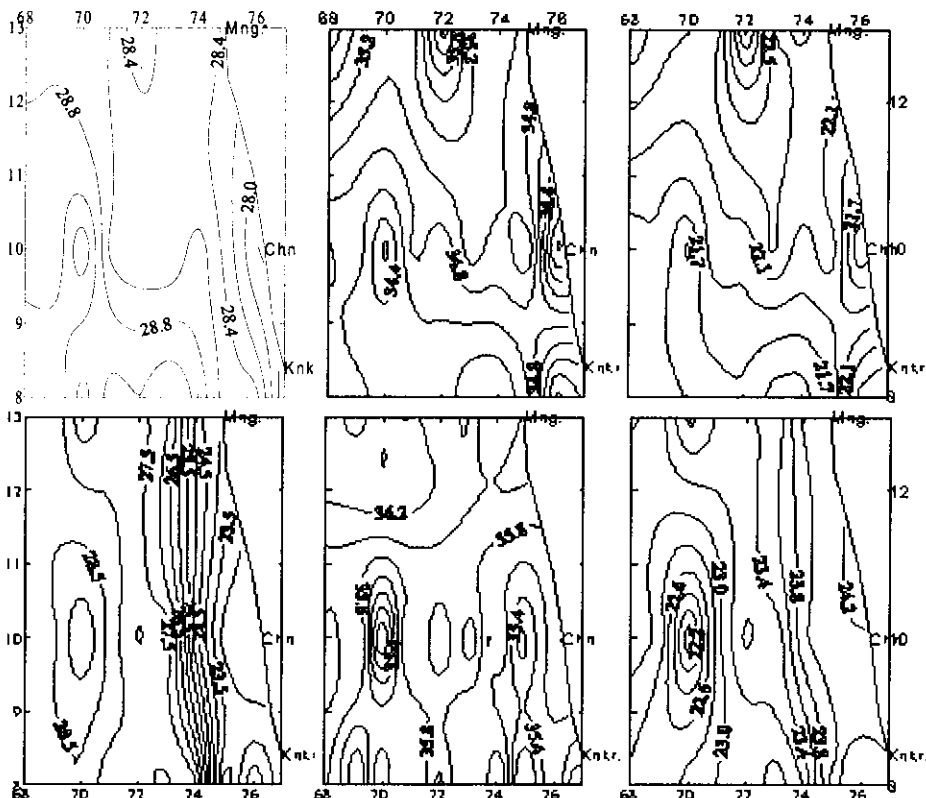


Fig. 5. Distribution of temperature (a,d) salinity (b,e) and density (c,f) at the surface (top panel) and 50 m (bottom panel).

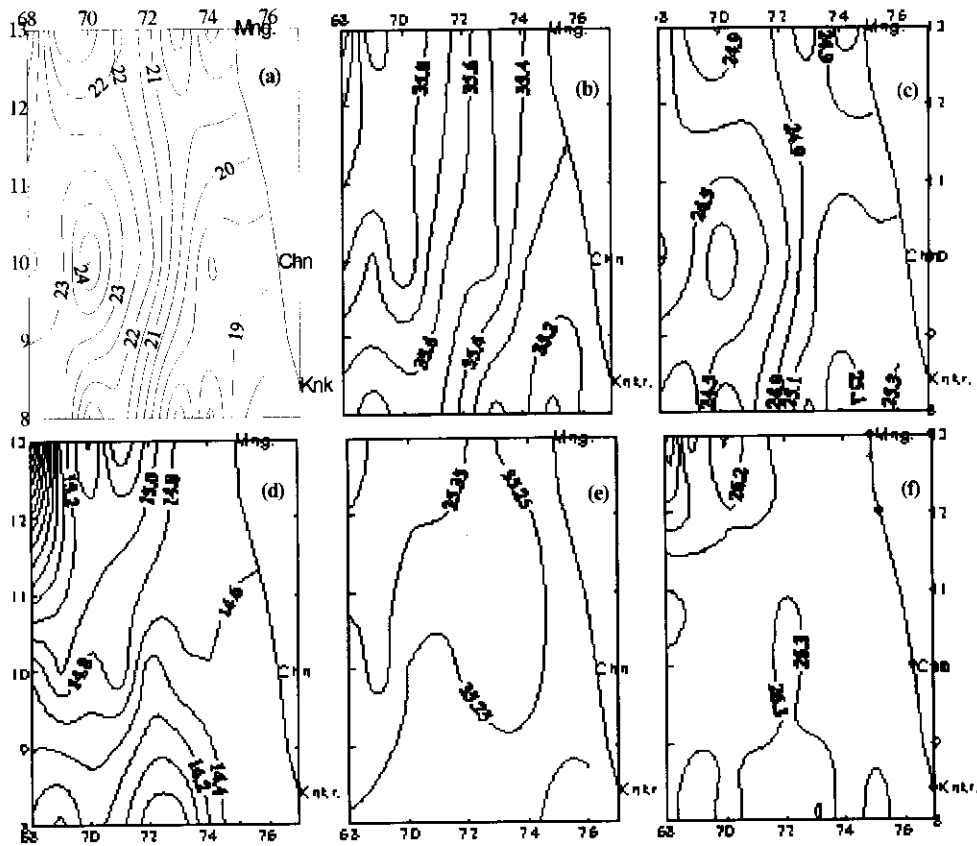


Fig. 6. Distribution of temperature (a,d) salinity (b,e) and density (c,f) at 100 m (top panel) and 200 m (bottom panel).

is observed around 8°N (Fig. 6a). At this depth also low saline water is observed all along the coastline. An intrusion observed in the thermal field at 8°N is reflected in the salinity and density fields with low saline water flow from the south indicating the presence of Bay of Bengal waters at this depth (Figs. 6b, 6c). The temperature field at 200 m shows the intrusion of warmer waters from the north at 13°N, similarly a cold water intrusion from the south is observed around 8°N (Fig. 6d). Both salinity field and density field reflects the intrusion (Figs. 6e, 6f). This intrusion is also noticed at 100m depth but not prominent like this depth. At this depth also cold, low saline, low dense water from the Bay of Bengal and warm, high saline and denser Persian Gulf Water is observed.

3.5 T-S Characteristics

T-S diagrams in the region surveyed exhibit more or less same pattern in the three legs (Fig. 7). Salinity increases with depth for sigma-t less than about 23.5 g cm⁻³. This near surface water mass has salinity ranging between 34.5 ppt and 36.5 ppt, and the temperature is around 28.5°C. This is the Equatorial Surface Water (Darbyshire, 1967). In the region very close to the coast cooler water is observed indicating upwelling

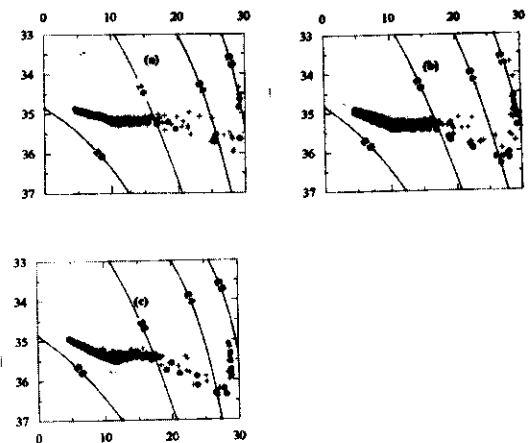


Fig. 7. T-S plot for (a) leg 1 (b) leg 2 and (c) leg 3. Data for the two stations farthest from the coast are given by circles; the rest are given by crosses.

phenomenon. Along 10°N the salinity is lower than 34.5 ppt in the station near the coast in the upper 15 m. In this leg, there were differences between the salinity variation of the inshore and offshore stations between 22 - 25.5 g cm⁻³ sigma-t interval.

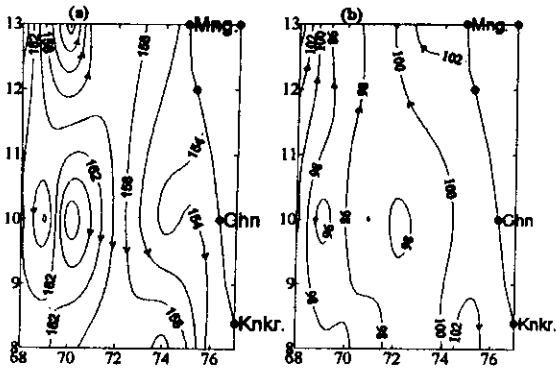


Fig. 8. Dynamic topography (dyn.cm) of the (a) sea surface and (b) 150 db surface, relative to 1000 db.

3.6 Circulation

During the southwest monsoon, the surface flow is towards the equator, with thermocline shallowing near the coast. A significant feature of the large-scale surface circulation in the Arabian Sea during the Southwest monsoon is the northward flowing Somali current system, reaching maximum strength in July (Schott 1983). Ship-drift charts of Rao (1995) also indicate this phenomenon. Thus, there is a significant southward flow occurrence during the Southwest monsoon months along the west coast of India.

The dynamic topography of the sea surface and 150 db with respect to 1000 db is shown in the Figs. 8a, 8b. Surface equatorward flow was noticeable from 13°N. This equatorward flow intensified south of 10°N. The sea surface topography increased from 154 dyn.cm near the coast to 164 dyn.cm at 69°E. This sea surface slope towards coast indicates the coastal upwelling phenomenon. The 150/1000 topography indicates the presence of an active poleward undercurrent.

4. Conclusions

The wind field along the West Coast of India favours upwelling during the southwest monsoon season. Analysis of hydrographic characteristics reveals the presence of cool upwelled water by the month of May itself. This confirms the hypothesis that upwelling in this region commences in deeper layers by March. Strong upwelling has been observed off Kanyakumari,

relatively less strong off Cochin and relatively weak off Mangalore indicating the migration of this unique phenomenon towards north with time. Signatures of a coastal undercurrent as observed by many authors was prominent which deepens, as moving towards north.

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