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Observed signals of upwelling and downwelling along the west coast of India

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Present study indicates the extension of upwelling to the northern part of the west coast of India. Upwelling along the southwest coast of India starts at the southern tip during April, propagates northward as the summer monsoon progresses and ends by September. However along the northwest coast, the upwelling intensifies during August and continues till October. The southwest coast is characterized by downwelling during October to March, whereas along the northwest coast upwelling comes to an end by November and sinking occurs during December to March. Compared to the northwest coast, both upwelling and downwelling are stronger along the southwest coast of India. During the peak southwest and northeast monsoon, magnitude of the mean vertical velocity with respect to 100m depth is 2.15×10^{-5}m/s and 0.76×10^{-5}m/s along the southwest and northwest coast, respectively.

[Keywords: upwelling, downwelling, isotherms, west coast of India, chlorophyll-a]

Introduction

During the summer monsoon (May-September), both eastern and western boundaries of the Arabian Sea witness upwelling[1]. Although the stronger upwelling regimes are located in the western boundary, about 70% of fishery production is derived from the eastern Arabian Sea[2]. Recent findings of Shankar *et al*.[3] and Vijith *et al*.[4] revealed that primary productivity over the eastern Arabian Sea is not only driven by upwelling but can also be influenced by downwelling favorable coastal Kelvin waves by inhibiting the convective mixing over the north eastern Arabian Sea during the north-east monsoon (November- February). Hence, improved understanding of the timing, duration and locations of upwelling and downwelling over the eastern Arabian Sea is of great scientific importance for the design of fishery management strategies to provide maximum sustainable yields.

Over the last 50 years, several studies on upwelling have been carried out along the west coast of India. Upwelling is an ascending motion, of some minimum duration and extent, by which water from sub surface layers is brought into the surface layer and is removed from the area of upwelling by horizontal flow[5,6], the reverse happens in downwelling. According to previous studies, upwelling along the west coast of India sets in during March- April and is strengthened by the peak southwest monsoon[7-16].

Coastal upwelling along the west coast of India is driven by both local and remote forcing. Local forcing arises from the Ekman dynamics induced by the action of local wind that happens during the southwest monsoon[17-19]. Upwelling can also be forced by remote winds by the radiation of upwelling favorable coastal Kelvin waves. Modelling studies by Shankar *et al*.[20] and observational studies by Gopalakrishna *et al*.[21]

have clearly revealed the influence of these coastal Kelvin waves from the south of Sri Lanka on the coastal circulation and upwelling along the west coast of India during the southwest monsoon[22, 23].

By analyzing the vertical as well as the horizontal thermal structure over the eastern Arabian Sea during southwest and northeast monsoon seasons, Antony *et al*.[24] inferred that the upward and downward oscillation of thermocline due to upwelling and downwelling probably had an offshore extension of 350- 400km from the coast. Unlike previous studies, the work of Shah *et al*.[25] revealed that upwelling was not limited to the southwest (8ºN to 15ºN) coast but was also evident on the northwest (15ºN to 20ºN) coast. Upwelling features were clearly noticed near the surface along the northwest coast during the summer monsoon[25]. Their study also concluded that one of the major difference in the upwelling in the southwest and northwest coast is that upwelled water does not reach the surface along the northwest coast, whereas upwelled water completely replaces the surface water along the southwest coast[25].

Many studies have explained the upwelling phenomenon along the west coast of India[7-26]. But studies on downwelling along the west coast of India are few[15]. Present study is to map the areas and identify timings of upwelling and downwelling events along the west coast of India from 8ºN to 20ºN using satellite and *in-situ* climatological data.

Materials and Methods

Temperature, density and chlorophyll are applied as proxies for identifying zones of upwelling and downwelling. The distribution of chemical properties, such as nutrient concentrations, are significantly altered by the vertical motion owing to upwelling or downwelling. But these chemical variables are not used as proxies to study upwelling and downwelling because the chemical properties are rapidly modified by several biogeochemical processes in the coastal waters. Also the data on these variables are very sparse.

From the earlier studies[7-26] it was evident that upwelling and downwelling areas are characterized by upward and downward movement of isotherms, respectively. Therefore, depth of 26ºC isotherm (D26) is used as a proxy for this study based on the observations of Shah *et al*.[25]. Findings of Sharma[6] concluded that, even though the vertical distribution of temperature is monotonic, it is largely altered by the other localized processes such as variations in solar insolation, cloud cover and evaporation at the surface. Hence, the vertical distribution of density is a preferred proxy for the study of vertical motion because density determines the stratification of the water column and the water movement is along isopycnals. Therefore, the vertical section of sigma-t is used in this paper for identifying upwelling and downwelling. The shallowing and deepening of isopycnals represent upwelling and downwelling, respectively. Sigma-t and D26 used in this paper derived from the north Indian Ocean Atlas by Chatterjee *et al*.[27].

During upwelling, surface water moves away by horizontal advection and relatively cooler subsurface water replaces the surface water. Consequently, to maintain isostatic balance upwelling areas are characterized by lowering of sea level compared with the surrounding waters. During downwelling convergence occurs at the surface and water from surface subsides to deeper level. Thus downwelling areas are characterized by higher sea level compared to surroundings. Merged and blended Sea Surface Height Anomaly (SSHA) with spatial resolution of 0.33º × 0.33º from Archiving, Validation, and Interpretation of Satellite Oceanographic (AVISO) were obtained from Asia-Pacific Data-Research Center (APDRC) and used to distinguish the variability of upwelling and downwelling along the coast.

Studies of Sharma[6] reveal that along the southwest coast of India upwelling starts from 90m depth. Our observations on vertical distribution of sigma-t show a vertical extension of upwelling and downwelling greater than 90m depth. Therefore, in this paper we estimated mean vertical velocity with respect to the 100m depth level for the identification of upwelling and downwelling zones. For the estimation of vertical velocity, horizontal divergence derived from the climatology of SODA currents is used. Estimation of horizontal divergence and vertical velocity is as follows:

Vertical velocity (w),

$$w = -\int_0^h \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) dz = -\int_0^h (\nabla h. V)\, dz$$

where u is the zonal component of current velocity and v is the meridional component of current velocity. Here we assume that h is equal to 100m. Assuming the vertical velocity at the surface is zero (i.e. $w_s = 0$), we can deduce the mean vertical velocity between the surface to 100m depth level following the approach of Sharma[6].

Since primary productivity along any coast is greatly dependent on the vertical circulation, we used the chlorophyll-a concentration from Ocean Colour Climate Change Initiative (OC-CCI) as a proxy in the study of upwelling and downwelling along the west coast of India following Shafeque *et al*.[28]. Since upwelling and downwelling are annually recurrent phenomena along the west coast of India, climatology of all the above mentioned data sets are used in this study. The area selected for this study is shown in figure 1.

Results and Discussion

Since the upwelling areas are characterized by ascending motion of isotherms, the vertical distance between the surface and 26ºC isotherm decreases during upwelling periods and increases during downwelling. Hereafter, we refer to the depth of 26ºC isotherm as D26. Hence, lower values of D26 represent upwelling and the higher values of D26 represent downwelling. The monthly climatology of the D26 along the coastal belt showed upward movement (lower values) of 26ºC isotherms during the southwest monsoon and downward movement (higher values) during the northeast monsoon along the west coast from 8ºN to 20ºN (Fig. 2), an evidence that shows upwelling and downwelling along the west coast are not limited to the southwest coast. Analysis of D26 also revealed that an evident lag in upwelling was observed from 8ºN to 20ºN. These observations substantiate the findings of Shah *et al*.[25]. During the peak summer monsoon from June to September the D26 values range between 10m and 40m along the west coast of India, whereas the values range between 85m and 105m during northeast monsoon from November to February.

In figure 2 it is also evident that along the west coast of India the ascending motion sets up by April (D26 values are markedly lower compared with February and March) and intensifies during the peak summer monsoon. Along the northwest coast, the upwelling intensified by August and continued till October. From 17ºN to 19ºN, low values of D26 are observed during November too. Sinking along the southwest coast starts by October (D26 values are noticeably higher compared to August and September) and intensifies monotonically during December to February. Along the northern latitudes, intense downwelling is observed from January. Analysis of figure 2 also reveals that even though the deepening and uplifting of isotherms are stronger in the southern latitudes from 8ºN to 15ºN, the northwest coast also shows significant upward and downward oscillation with a seasonal periodicity. A limitation of this technique is that it is not possible to separate the deepening of D26 caused by downwelling from that caused by the convective mixing that occurs in the northern Arabian Sea during northeast monsoon.

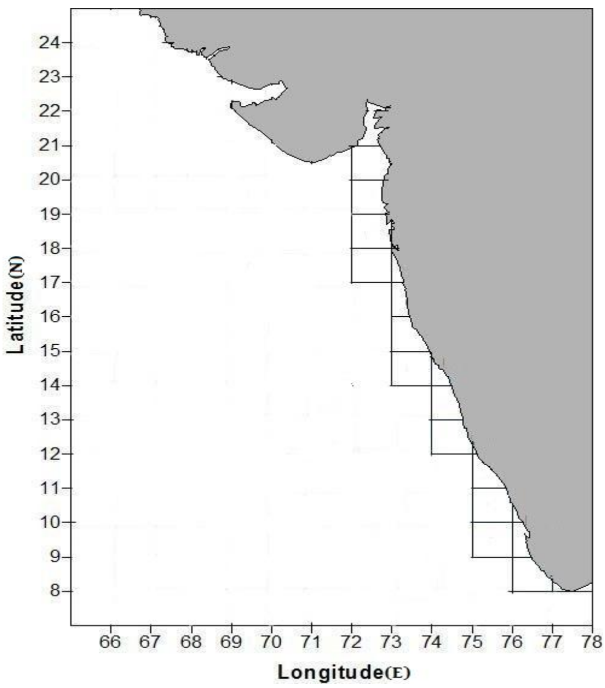

Fig.1─Location map and the 1º × 1º squares represent the study area along the west coast of India.

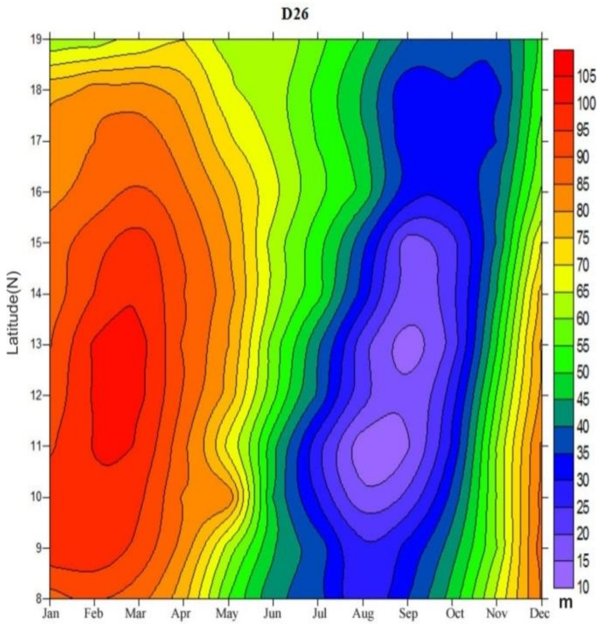

Fig.2─Monthly climatology of Depth of 26º Isotherms (D26) along the west coast of India (Redrawn from Shah *et al.*[25]).

Contrary to previous studies which concentrated on upwelling along the southern latitudes and concluded that upwelling was less evident towards north, the analysis of D26 in the present study revealed that even though strength of upwelling and downwelling were greater along the southwest coast, the northwest coast also experienced significant vertical oscillation with a seasonal periodicity. To check robustness of this finding, we analyzed spatial and vertical distribution of isopycnals at different latitudinal stations along the west coast of India. The isopycnals show clear upward movements during the summer monsoon and clear downward tilt during the northeast monsoon along the west coast of India (Fig.3 to Fig.8).

At the southern tip of the west coast of India, upwelling starts by April, by changing the downward tilt of isopycnals during March to upward (Fig.3 and Fig.6). The upwelling intensifies at this latitude as the monsoon progresses. The vertical section of sigma-t at 12.5ºN indicates that the upwelling at this location starts only during May (Fig.4). That is, there is a lag in the progression of upwelling from south to north. All the stations along the southwest coast show intensification of upwelling during July and August, during the peak summer monsoon.

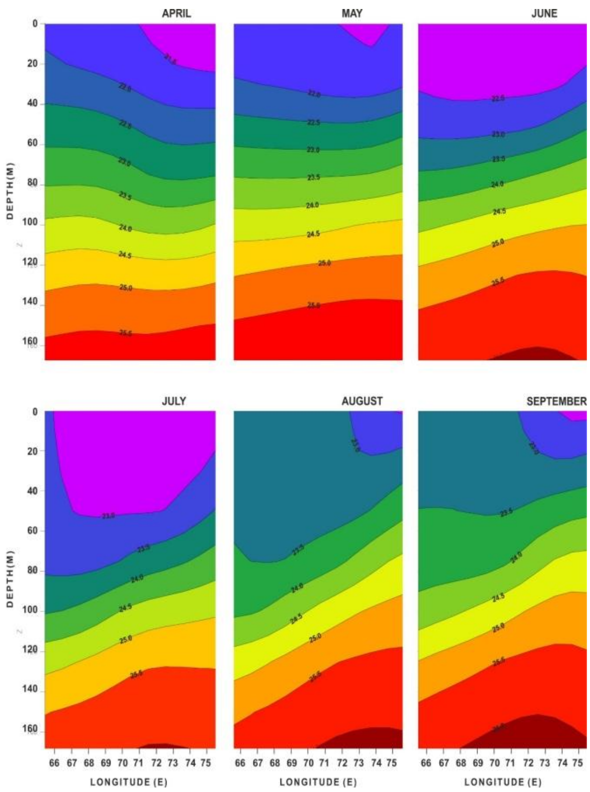

Fig.3‒Vertical section of sigma-t (kg/m^3) at 10.5ºN along the west coast of India during southwest monsoon.

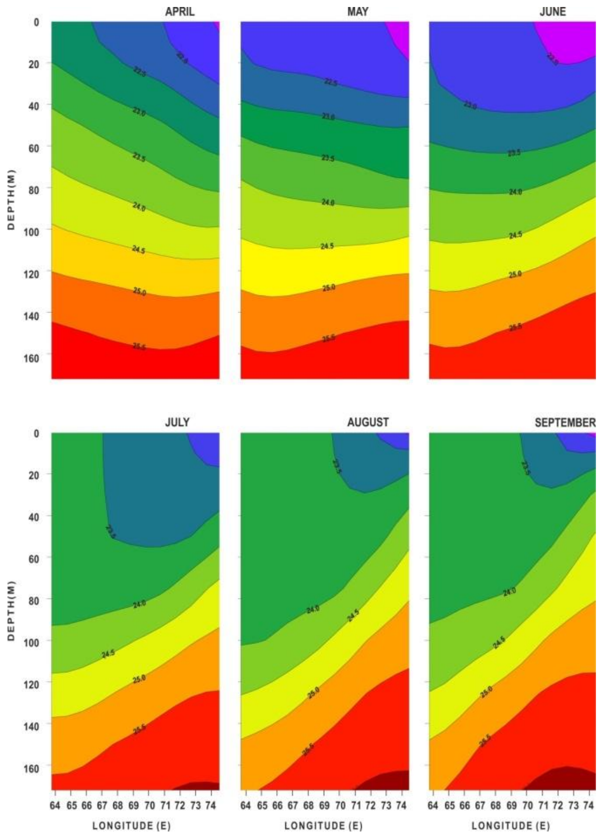

Fig.4‒Vertical section of sigma-t (kg/m3) at 12.5ºN along the west coast of India during southwest monsoon.

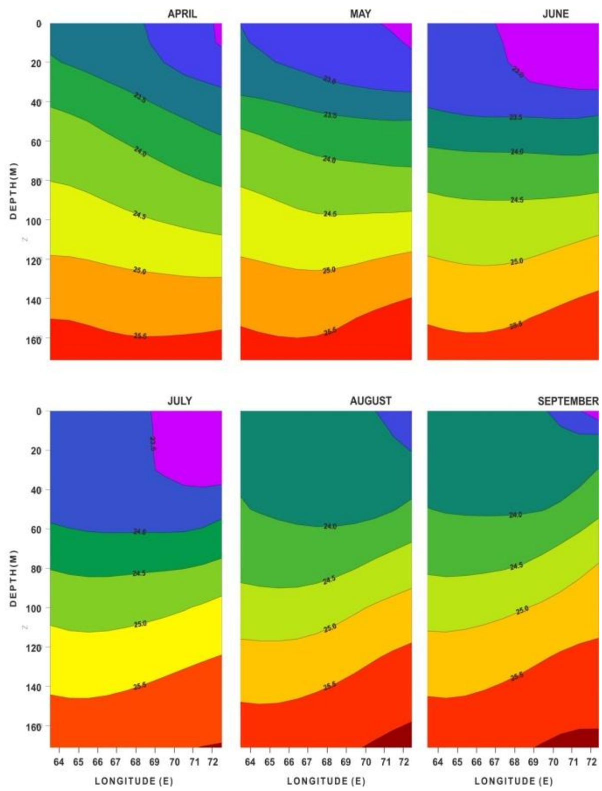

Fig.5‒Vertical section of sigma-t (kg/m^3) at 16.5ºN along the west coast of India during southwest monsoon

Data at 16.5ºN indicate that along the northwest coast upwelling intensified during August and September. Vertical sigma-t structures during June and July do not show any significant upward or downward tilt and isopycnals are nearly horizontal above 80m depth. Below this depth some upward movements are seen (Fig.5). Along the southwest coast of India from 8ºN to 15ºN the downwelling starts in October and continues till March (Fig.6 to Fig.8). It is intensified monotonically during December to February. Along the northwest coast downwelling starts in November and intensifies during January (Fig.8). Consistent with the study of Antony *et al*.[24], who observed an offshore extension of upwelling and downwelling up to 300km or 400km, the present investigation also revealed upwelling and downwelling extending 3º to 5º offshore along the west coast of India (Fig.3 to Fig.8).

To complement the results from the analyses of Sigma-t and D26, the present study has also analyzed SSHA climatology along the west coast of India. From figure 9, it is evident that the entire west coast of India is characterized by a fall in sea level during the summer monsoon months during May to September- a clear indication of upwelling. During May, weak SSHA values were observed along the entire coastal belt. The most intense fall in sea level along the coast was seen during August and continued till September. Compared with September, SSHA was elevated along the west coast of India during October. During December and January, intensification of rise in sea level was observed along the west coast of India. These features diminished along the coast by March. These observations indicate that upwelling occurs along the coast during the southwest monsoon and downwelling occurs during the northeast monsoon.

An ascending motion of subsurface water with a speed ranging about 10^{-6} to 10^{-4}m/s is referred as upwelling[29]. Figures 10& 11 represent the climatology of vertical velocity with respect to 100m depth over the eastern Arabian Sea from January to December. From April onwards, positive vertical velocities (upward) are seen along the west coast of India (Fig.10). During May the vertical velocity intensified along the southern latitudes from 8ºN to 14ºN. During June, intensification of upward vertical velocity is seen over the west coast from 8ºN to 18ºN, but the strength of upwelling was comparatively higher in the southern latitudes compared to the northern ones. During July, August and September, higher values of positive vertical velocity are seen over the southwest coast and moderate values of upward velocity are seen over the northwest coast. Even though strong upward vertical velocity is restricted to the southwest coast, northern latitudes also show considerable upward vertical velocity during the peak summer monsoon.

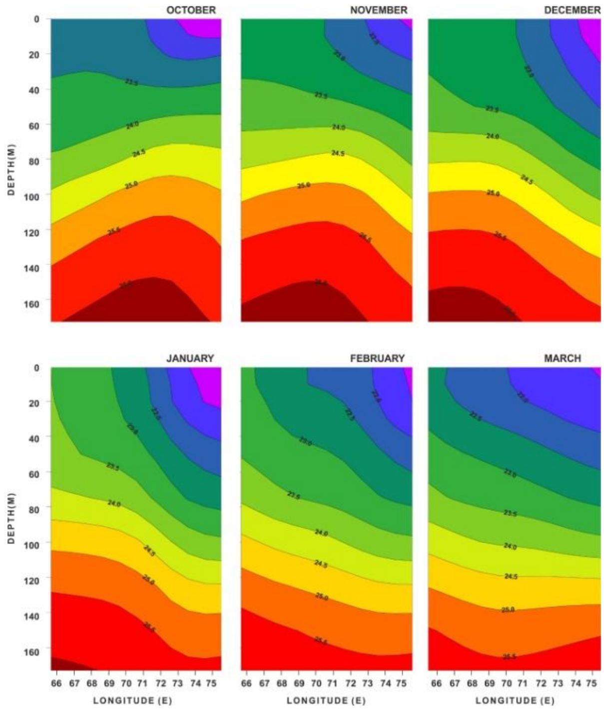

Fig.6─Vertical section of sigma-t (kg/m^3) at 10.5ºN along the west coast of India during northeast monsoon.

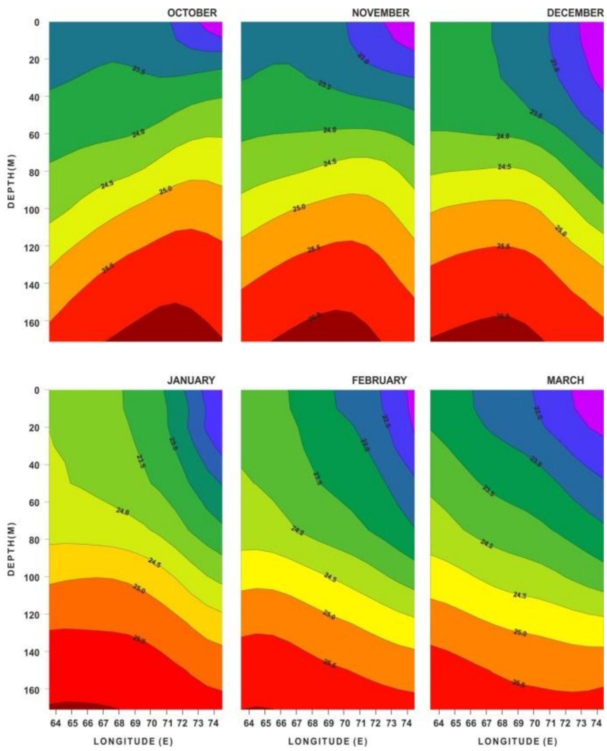

Fig.7─Vertical section of sigma-t (kg/m^3) at 12.5ºN along the west coast of India during northeast monsoon.

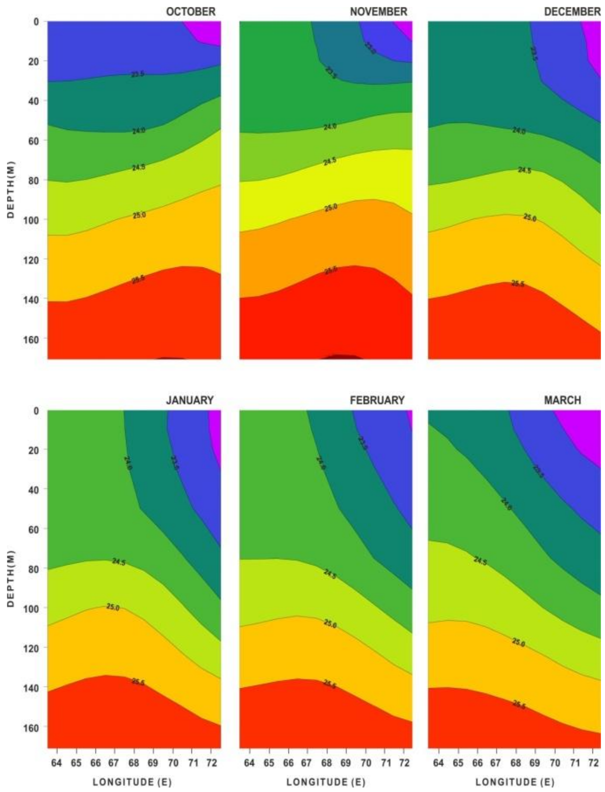

Fig.8─Vertical section of sigma-t (kg/m^3) at 16.5ºN along the west coast of India during northeast monsoon

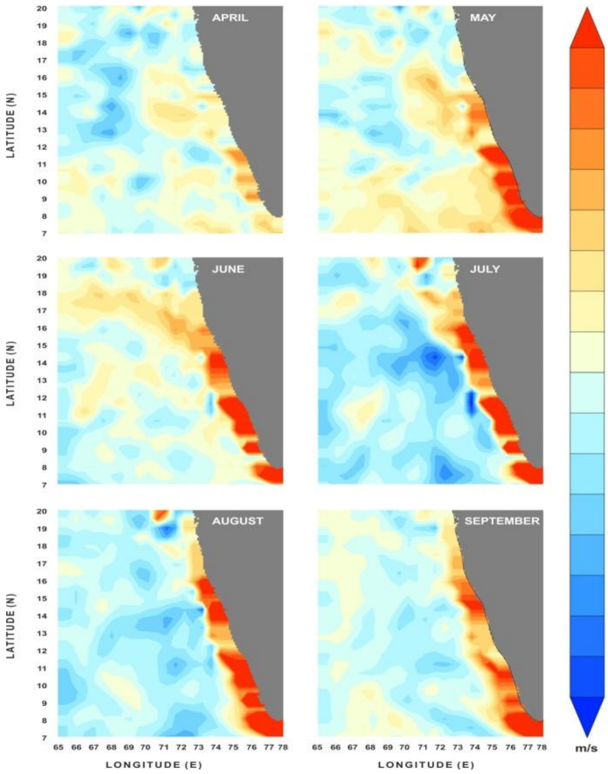

Fig.10─Climatology of vertical velocity (× 10^{-5}m/s) along the west coast of India from 8ºN to 20ºN during the southwest monsoon.

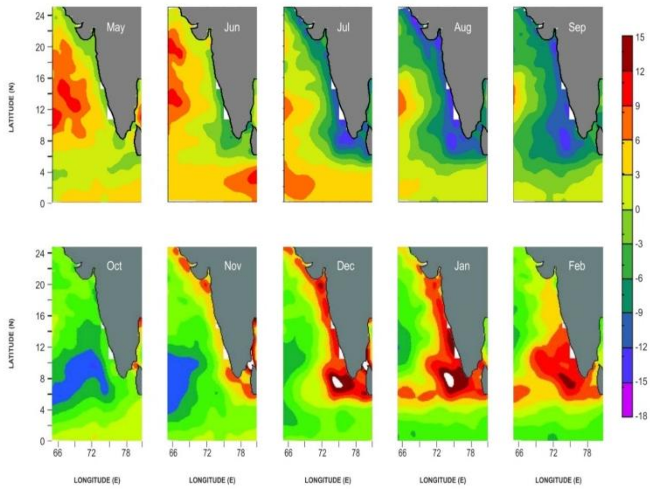

Fig.9─Climatology of SSHA (cm) along the west coast of India during a year.

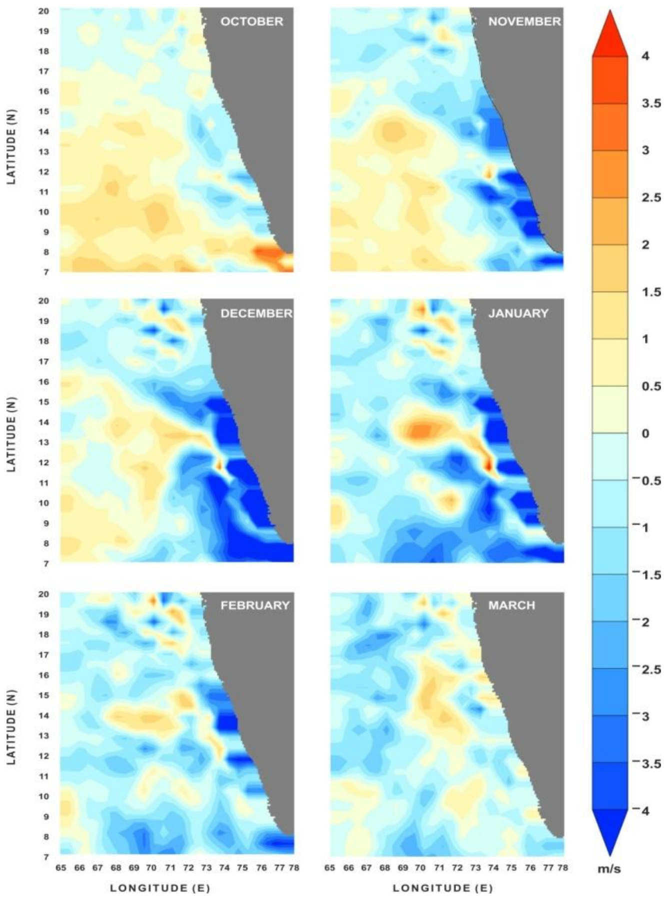

Fig.11─Climatology of vertical velocity (× 10^{-5}m/s) along the west coast of India from 8ºN to 20ºN during the northeast monsoon.

During the northeast monsoon, the west coast of India was characterized by moderate-to-strong downward velocity. From October, the southwest coast shows lower values of downwelling velocities except at 8ºN (Fig. 11). This indicates the cessation of upwelling and evolution of sinking along the southwest coast. During November, December and January, strong downward velocity is observed along the southwest coast from 8ºN to 15ºN and along the northwest coast, moderate velocity is observed. February shows moderate downwelling velocity along the west coast of India. Compared with the northwest coast, the magnitude of vertical velocity is stronger along the southwest coast.

The mean vertical velocity with respect to 100m depth indicates magnitudes of 2.15×10^{-5} m/s along the southwest coast and 0.76×10^{-5}m/s along the northwest coast during the peak southwest and northeast monsoon respectively.

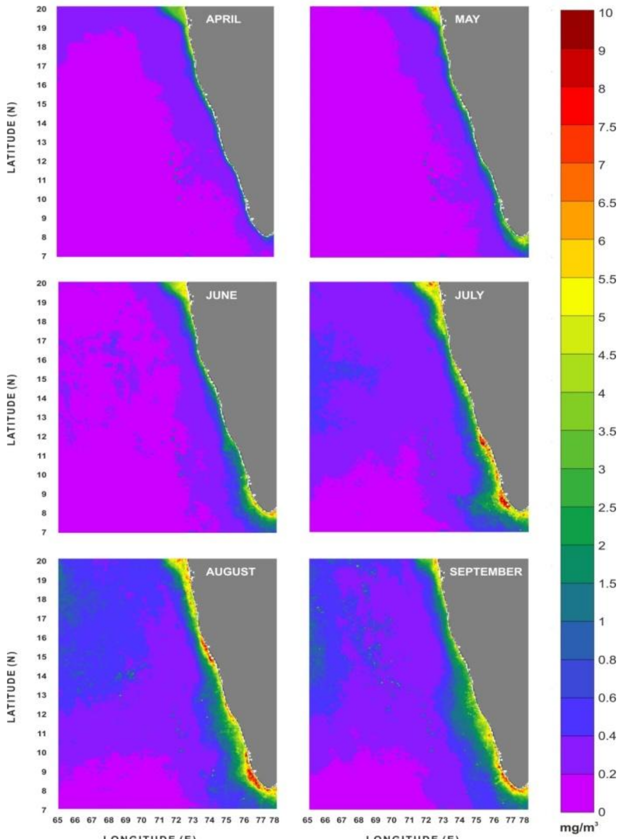

Fig.12─Climatology of Chlorophyll-a concentration (mg/m^3) along the west coast of India from 8ºN to 20ºN during the southwest monsoon.

The analysis of chlorophyll-a over the eastern Arabian Sea reveals that throughout the year northwest coast of India is characterized by higher concentrations of Chlorophyll-a compared with the southwest coast. Along the southwest coast, higher concentrations of chlorophyll-a are seen only during the summer monsoon. This might be due to the ascending motion of nutrient rich subsurface water during this season. During the northeast monsoon, chlorophyll-a concentration along the southwest coast of India was very low (Fig.12 and Fig.13), due to the impact of downwelling. Along the northwest coast during both monsoons, significant chlorophyll-a concentration is observed. This indicates that rather than the vertical motions, chlorophyll-a concentration along the northwest coast of India is mainly determined by some other phenomenon. But during July and August intensification of chlorophyll-a is observed along the northwest coast also. This is also suggests that upwelling is not only limited to the southwest coast, but also active along the northwest coast.

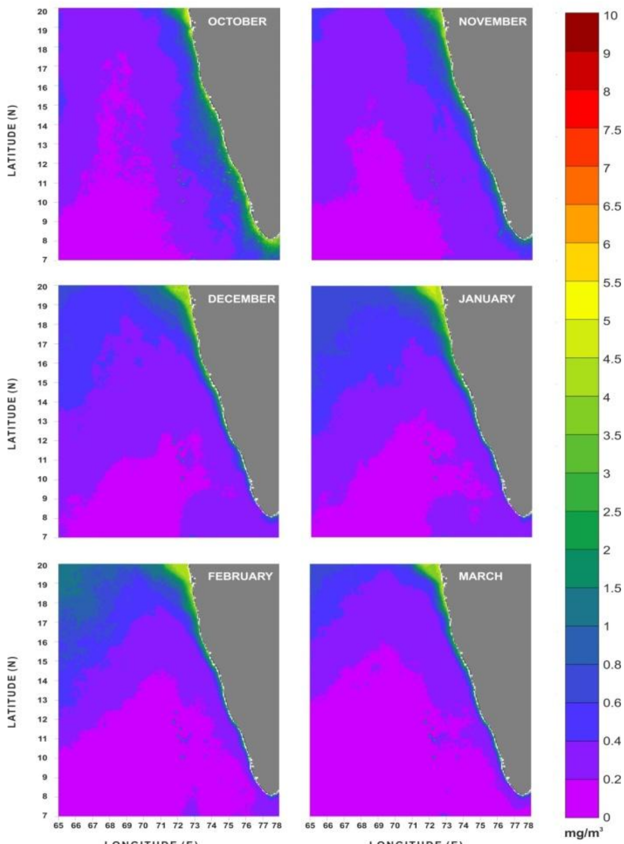

Fig.13─Climatology of Chlorophyll-a concentration (mg/m^3) along the west coast of India from 8ºN to 20ºN during the northeast monsoon.

Conclusions

From the analysis of depth of 26º isotherms, vertical velocity, SSHA, vertical profile of Sigma-t, and chlorophyll-a concentration, it is concluded that the upwelling along the southwest coast of India starts at the southern tip (8ºN) during April, propagates from south to north as the summer monsoon progresses, and comes to an end during September. Consistent with the studies of Shah *et al.*[25], we found that upwelling is not limited to the southwest coast (8ºN to 15ºN) but is also evident at the northwest coast (15ºN to 20ºN). The strength of upwelling is higher in the southwest coast than in the northwest coast. Downwelling along the coast starts at the southern tip during October and continues until April. Downwelling also occurs along the northwest coast of India during the northeast monsoon. Along the southwest coast, the cessation of upwelling starts during the end of September and downwelling sets in during October. On the other hand, along the northwest coast the cessation of upwelling starts during November and the coast is characterized by sinking during December to March. Downwelling along the southwest intensified during December to February. The strength of downwelling is also greater on the southwest coast than the northwest coast.

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