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Onset and Evolution of Upwelling along the West Coast of India

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ABSTRACT

To describe the onset and evolution of upwelling along the south west coast of India, authors collected a series of conductivity temperature depth measurements on board *INS Sagardhwani* extending from 7 °N – 15 °N during the period extending from February 2017 to October 2017. In this paper we utilised the undulations of 23 °C isotherm as a proxy to study the upwelling phenomenon. The upward movement of the waters at the southern tip off India (77.5 °E) in the subsurface levels was observed to commence from late February 2017 in depths around 80 m and by the end of May 2017, it is observed to rise rapidly to the surface. The upwelled waters reach the surface during the 2nd week of July all along the Indian coast, and then intensified during August 2017. Beyond 12 °N maximum upwelling is seen in July and thereafter in early August 2017 upwelling was intense till October 2017.

Keywords: Upwelling; Southwest coast of India; Isotherms

1. INTRODUCTION

Upwelling involves the offshore transport of surface water and its replacement by cold, nutrient rich subsurface waters. The discovery of this large upwelling system along the south west coast of India was the result of a systematic subsurface temperature sampling on the open shelf off Kerala during the southwest monsoon of 1959[1]. Coastal upwelling occurs along the coast during the southwest monsoon season (June, July, August, September) between 7 °N and 15 °N and it was observed to be a wind-driven process like any other upwelling systems found elsewhere. The strengthening of the alongshore wind stress enhances upwelling and results in lower SST over the shelf[2-8]. Under the United Nations sponsored Pelagic Fisheries Project (1971-1978) an extensive survey was conducted to study the upwelling phenomenon. It was observed during this survey that the process of upwelling were mainly wind driven. Later various studies have hypothesised that bottom signature of upwelling were caused by a northward propagating Kelvin wave[9-13] propagating from the Bay of Bengal around Sri Lanka and northward along the southwest coast of India. Gopalakrishna[14], *et al.* using XBT data in the Lakshadweep sea proposed that, in the South Eastern Arabian Sea (SEAS), upwelling is influenced mainly by the remote forcing from the propagating coastal Kelvin waves originating from south Sri Lanka which was forced by the alongshore wind stress off the southwest coast of India and not due to the equatorial forcing.

The present observations compliment the earlier studies regarding the upwelling along the south west coast of India. We also address the mean hydrographic conditions across the shelf as measured during pre-monsoon and monsoon seasons. With the aid of comprehensive high-resolution data sets of surface wind data, sea surface height and sea surface temperature data, we are able to enhance the picture of the across-shelf structure of wind driven upwelling. Our over arching goal is to contribute to the understanding of upwelling, its onset and propagation along the coast of India.

2. DATA AND METHODS

As a part of a new initiative to understand the upwelling phenomenon a series of hydrographic cruises on board *INS Sagardhwani* were conducted from Tuticorin (Gulf of Mannar) to Goa during June 2016 and October 2017. The cruise tracks are as shown in Fig. 1. Each spatial survey covered an area extending from 7 °N to 15 °N. A total of 113 ship days were utilised for covering the area during various months (Table 1). A total of 349 CTD profile data were used for the study. The monthly wind stress was computed from Advanced Scatterometer (ASCAT) and the sea surface temperature (SST) data acquired from the group for high resolution sea surface temperature (GHRSST). Sea surface height (SSH) data was utilised to derive the surface signature of upwelling. The CTD data along the hydrographic sections 77.5 °E, 8.25 °N, 9 °N, 10 °N, 11 °N, 12 °N, 13 °N, 14 °N and 15 °N in the SEAS repeatedly covered by *INS Sagardhwani* from February 2017 to October 2017 (Fig. 1) were used for the study. The CTD measurements were utilised for this study to describe the onset and progression of upwelling. CTD casts made from these transects were thoroughly quality controlled using standard quality check procedure and accordingly vertical temperature and salinity sections were prepared.

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Table 1. The tables shows the Cruise dates and survey in the region of Gulf of Mannar- Goa

Month	Date
October	3-14, 2017
August	18-27, 2017
July	18-27, 2017
June	15-27, 2017
May	19-29, 2017
April	18-28, 2017
February-March	26-05, 2017

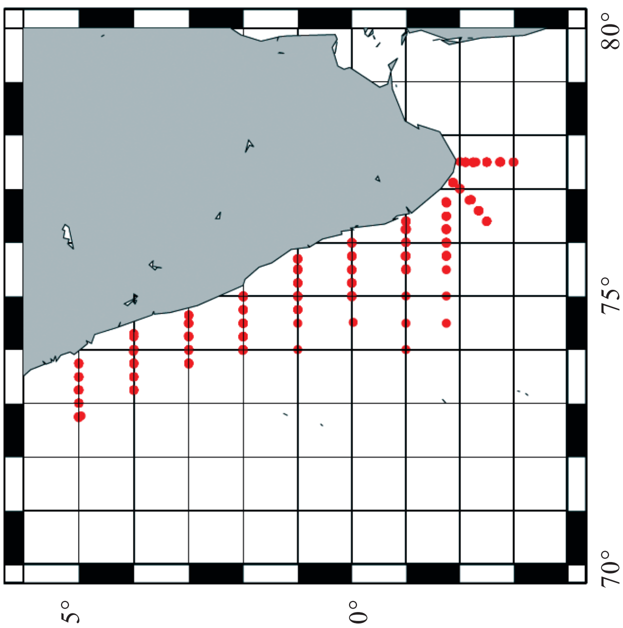

Figure 1. The station locations of CTD cast for all cruise tracks.

3. RESULTS AND DISCUSSION

The wind stress computed from ASCAT winds (Fig. 2) for the year 2017 was utilised to explain the wind stress components responsible for coastal upwelling and SST from GHRSST was used to describe the temperature drop associated with upwelling (Fig. 2). It was observed that wind plays a major role in the coastal upwelling after the month of February. In order to understand the effect of local wind stress on coastal upwelling, monthly averaged wind data for the year 2017 (U and V components) from ASCAT for the observation period were used. The alongshore component of the wind stress is computed as,

$$\tau = \rho_a C_d U^2$$

where ρ_a is density of air, ρ_a = 1.175 kg/m³; C_d is the non-dimensional drag coefficient, C_d = 0.0013; U is wind speed at 10 m.

In majority of the eastern Arabian Sea, the wind is southwesterly and it turn northerly along the west coast of India with a wind stress of the order of 0.02 Pa. It can be seen from the Fig. 2, that the wind is westerly and tangential to the coast in the southern tip of India. During April the winds are northerly and intense warming causes higher SSTs in

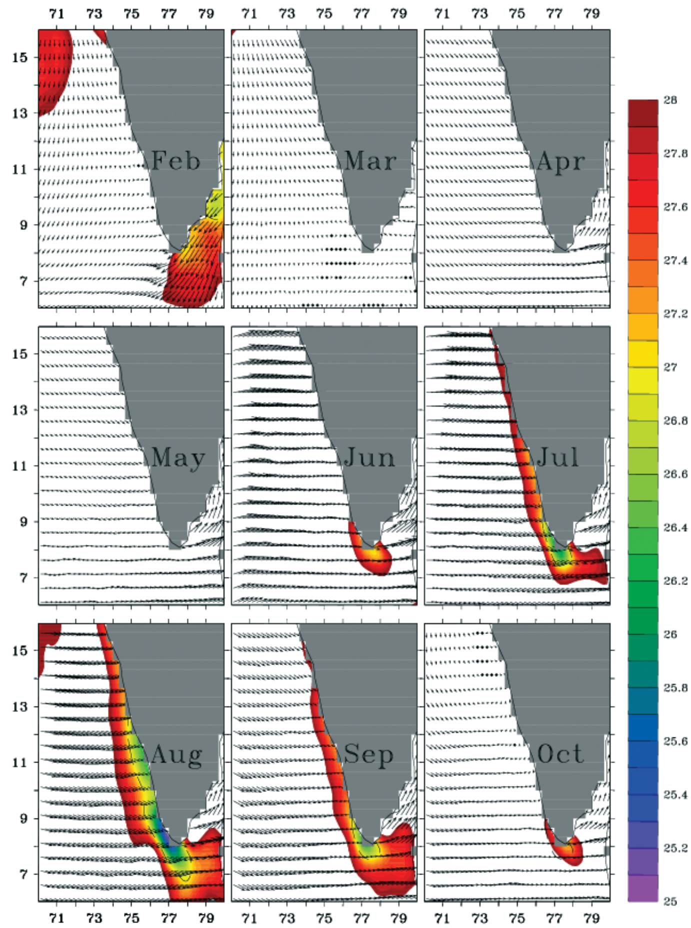

Figure 2. The monthly averaged wind stress (ASCAT) for the year 2017 is overlaid on monthly averaged SST derived from GHRSST for the south west coast of India.

the region. However at the southern tip of India winds are westerly. The surface SST plunge drastically due to upwelling (upliftment of cooler waters from sub surface depths) is observed to occur from early June to September. In June[15] explained in detail the existence of a mini cool pool caused by strong upliftment of the thermocline accompanied by enhanced blooming of chlorophyll. Ganer[16], *et al.* simulated the cool pool at the southern tip from a thermodynamical model and reported the extensive cooling from July to September, they concluded that the intense cyclonic gyre of currents supported the cooling.

3.1 Onset of Upwelling along the Southwest Coast of India

The ascending motion of isotherms along the west coast of India sets up by late February. The 23 °C isotherms are used as proxy to determine the upliftment of the thermocline. The 23 °C isotherm hereafter referred as D23 can be used as a good index for thermocline undulations. From Fig. 3 it can be noticed at the southern tip of India, i.e 8.25 °N, The D23 isotherm marked in black is being undulated from Cape Comorin (77.5 °E) offshore to 11 °N in the northern most transect. The D23 is observed to be uplifted from 120 m to 100 m. However the steady upliftment is not noticed and the wave like nature of these undulations can signify as the onset of upwelling as reported by earlier researchers. Beyond 11 °N no undulations are observed. However Shah[17], stated that upwelling starts only during May, their observations were based on North Indian Ocean Atlas[18] which is an average of all available temperature and salinity profiles available over a long period of time. The makers of the atlas used an objective analysis with a wide search area for averaging a profile to represent a particular grid point. The climatological data cannot represent the small scale undulations of the thermocline, thus the upwelling onset was assumed to start in April. The clear transition of undulation of temperature structure can be observed from Fig. 4, the upward tilt of isotherms and mainly the D23 is well observed from 80 m at 8.25 °N to 70 m and much shallower depths.

3.2 Northward Evolution of Upwelling along the West Coast of India

During late May the upward tilt of isotherms is well observed (Fig. 5). The upwelling intensifies at these latitudes as the monsoon winds start to dominate over the Arabian Sea area. The vertical sections of temperature indicate strong upwelling beyond 12 °N. The intensification and northward progression is well established during May. During June the 26 °C isotherm, hereafter referred as D26 is chosen as a proxy to define the isotherm that reaches the top layers and seen at the surface. The D26 during June is uplifted from 40 m off shore to 20 m near the coast. The D23 is observed to be at shallower depths (~ 40 m) near the coast for all locations along the southwest coast (Fig. 6). During July the D26 is uplifted

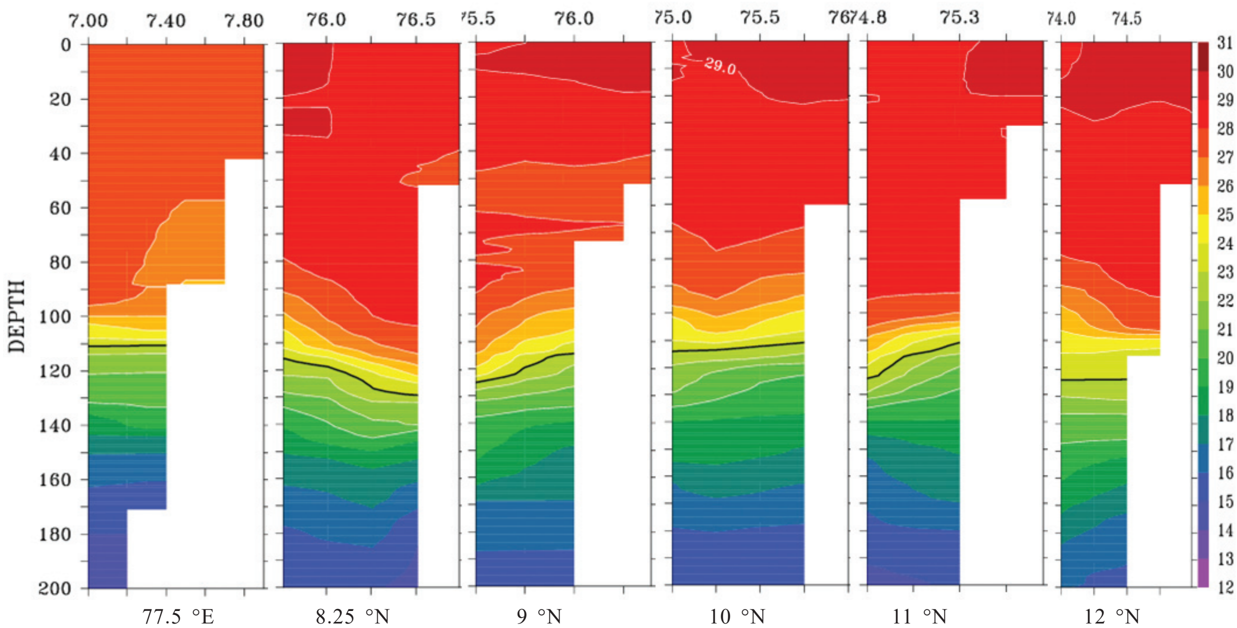

Figure 3. The depth – space section of temperature in the February 2017 along 77.5 °E, 8.25 °N, 9 °N, 10 °N, 11 °N, 12 °N.

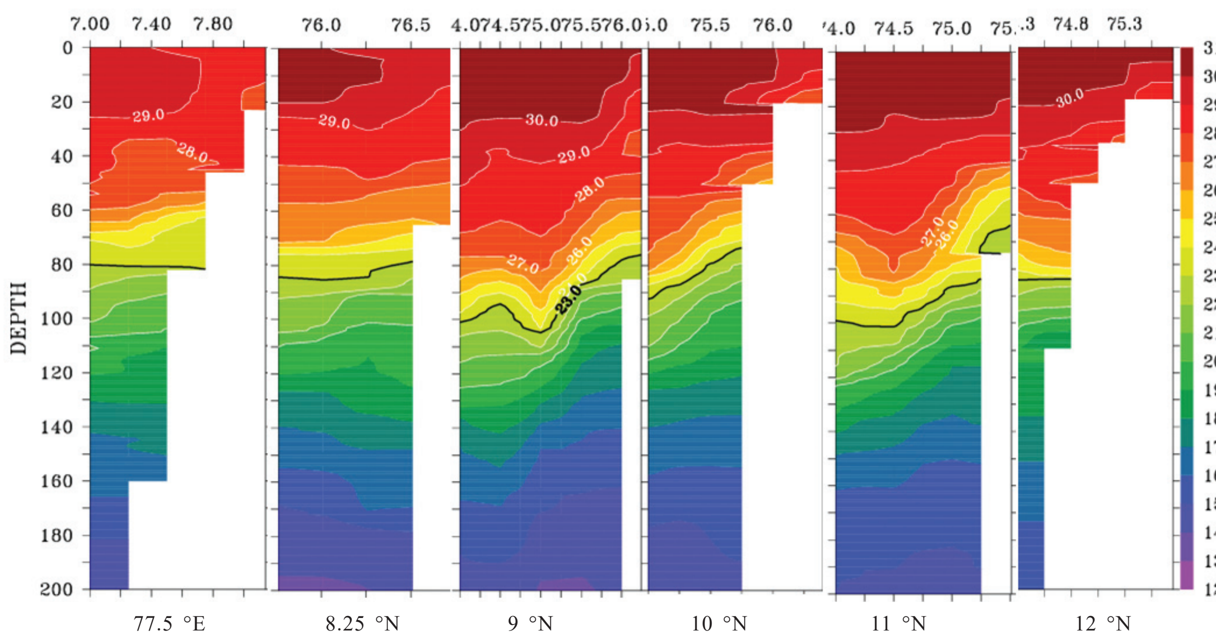

Figure 4. The depth – Space section of temperature in the April 2017 along 77.5 °E, 8.25 °N, 9 °N, 10 °N, 11 °N, 12 °N.

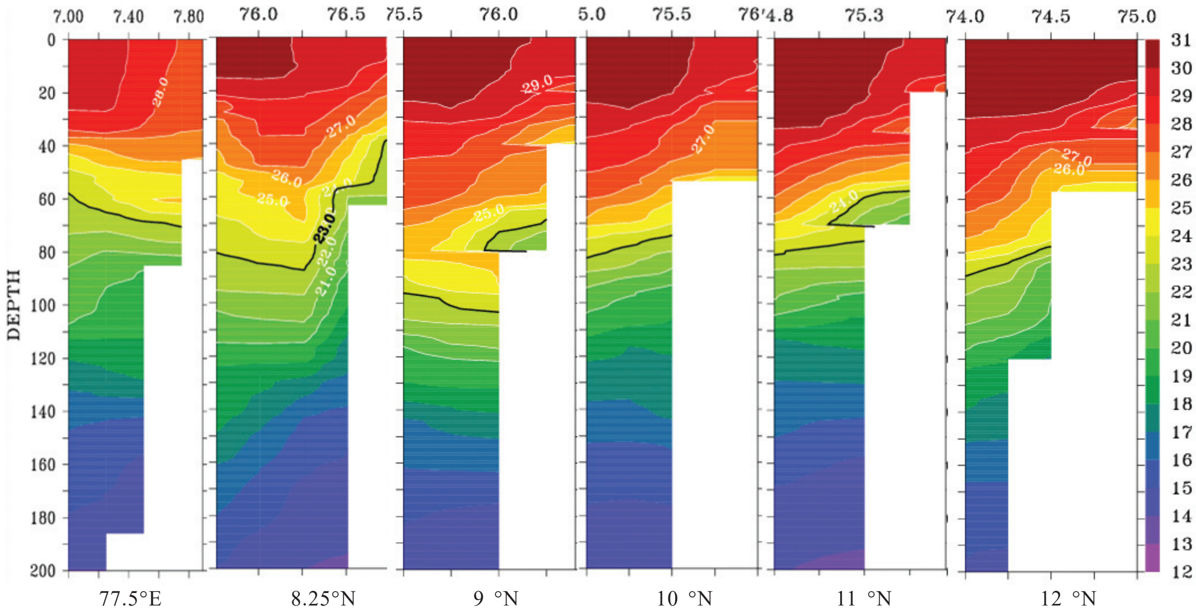

Figure 5. The depth - Space section of temperature in the May 2017 along 77.5 °E, 8.25 °N, 9 °N, 10 °N, 11 °N, 12 °N.

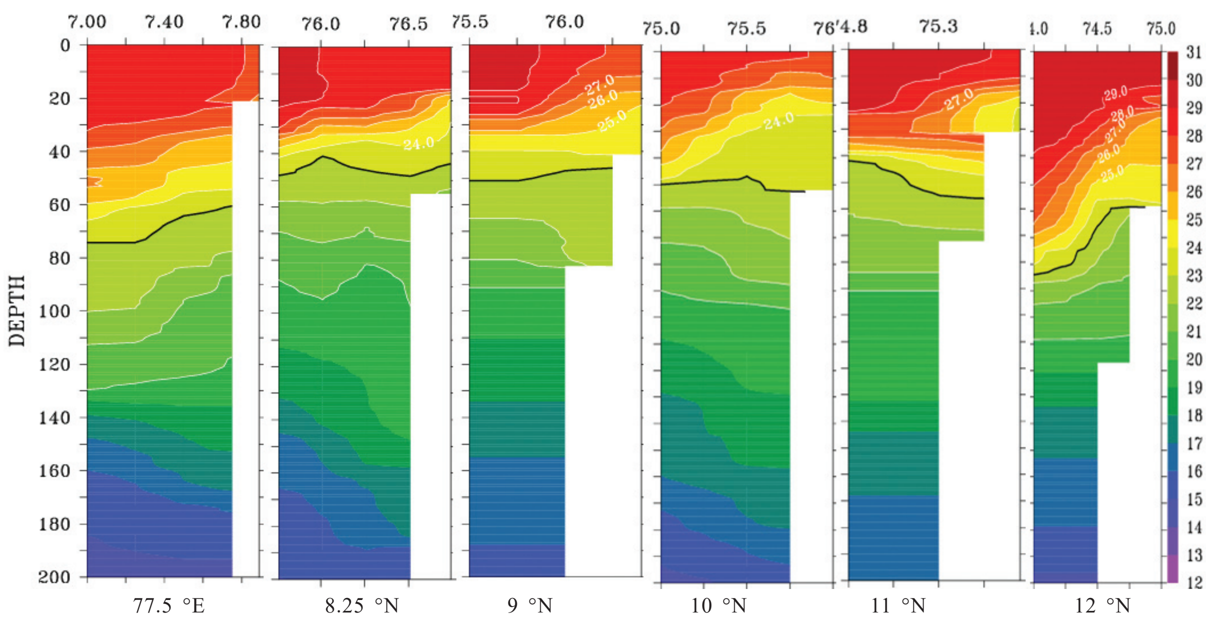

Figure 6. The depth - Space section of temperature in the June 2017 along 77.5 °E, 8.25 °N, 9 °N, 10 °N, 11 °N, 12 °N.

from 40 m off shore to 10 m - 15 m near the coast. The D23 is also observed to be uplifted well at 20 m - 25 m depths near the coast for all locations along the southwest coast. The offshore Ekman transport of cool waters from 40 m depth levels is seen at the surface ~200 km off shore (Fig. 7). Along the northern most transect beyond 12 °N, upwelling is well intensified. The wind system in July is westerly and it's observed to blow directly perpendicular to the shore unlike a northwesterly direction. The westerly winds cause equatorward component of wind stress, this intensifies the equator ward surface currents on the contrary the north eastern inclination of the coast and the orographic effect of the Western Ghats form a favourable situation for the wind system to cause intense upwelling near the coast. The upwelling intensification starts in July with the advancement of the South West Monsoon winds, thereafter in August (Fig. 8) it can be observed to the further progress beyond 12 °N. The upwelling signatures are well observed in October (Fig. 9) in the upper levels in all the sections considered for the study.

The Sea Surface Height Anomaly (SSHA) derived from AVISO SSHA data was used to study the influence of remote forced upwelling, which was observed to occur at deeper levels (80 m) by the end of February. In the west coast of India, the fall in sea level during February is clearly seen in Fig. 10. During March to May there is a gradual drop in sea level of about 0.1 m all along the west coast. The sea level drop during the summer season from June to August denotes a clear indication of upwelling. The sea level fall was very severe during August. Intensification of sea level rise was observed during the months December and January.

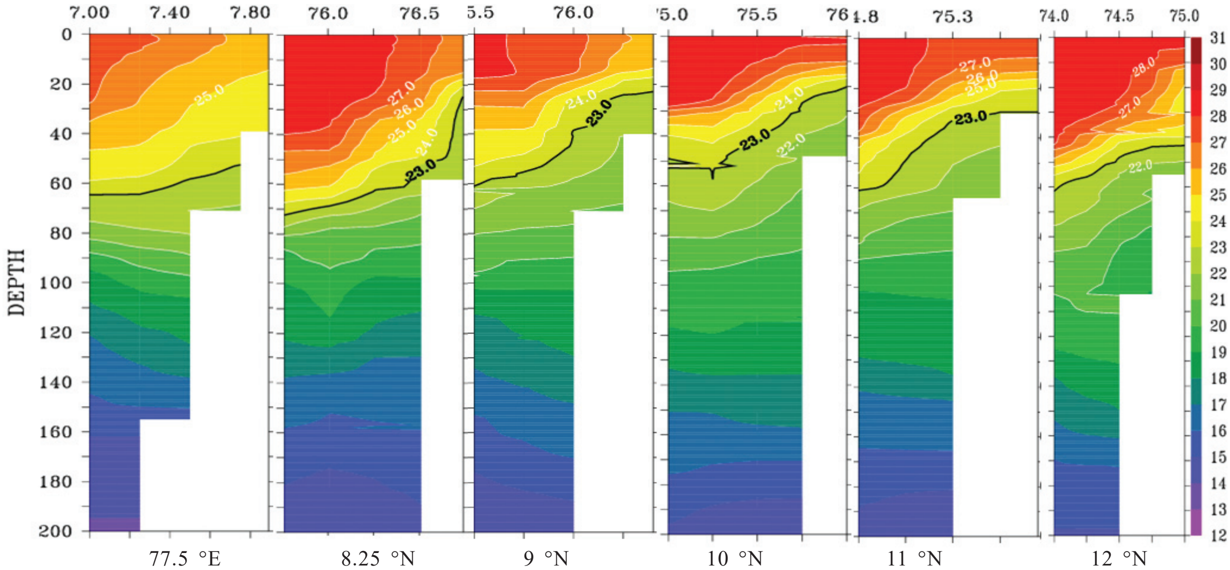

Figure 7. The depth – Space section of temperature in the July 2017 along 77.5 °E, 8.25 °N, 9 °N, 10 °N, 11 °N, 12 °N.

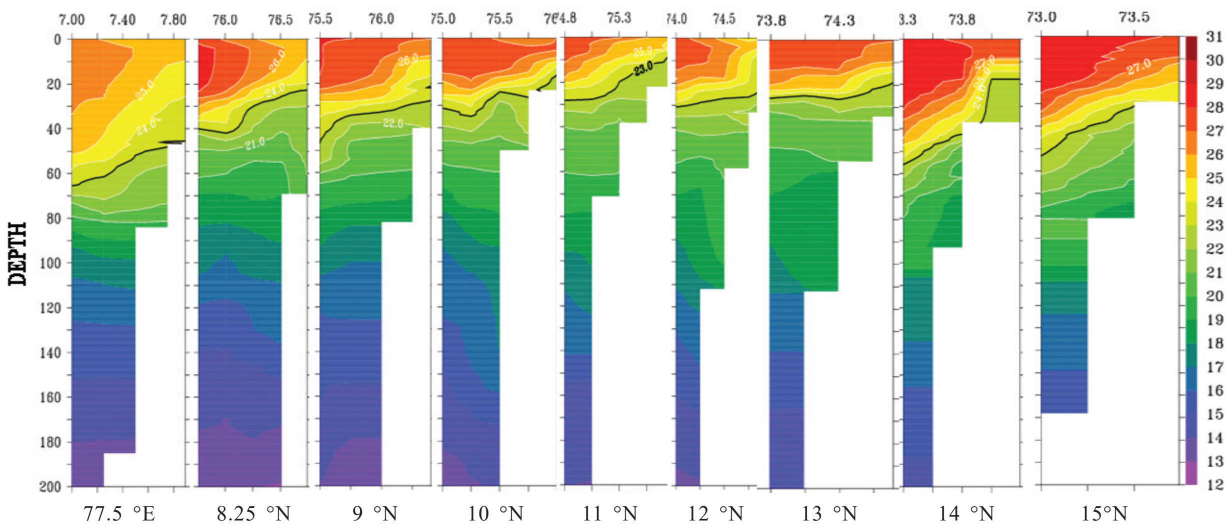

Figure 8. The depth – Space section of temperature in the August 2017 along 77.5 °E, 8.25 °N, 9 °N, 10 °N, 11 °N, 12 °N, 13 °N, 14 °N, 15 °N.

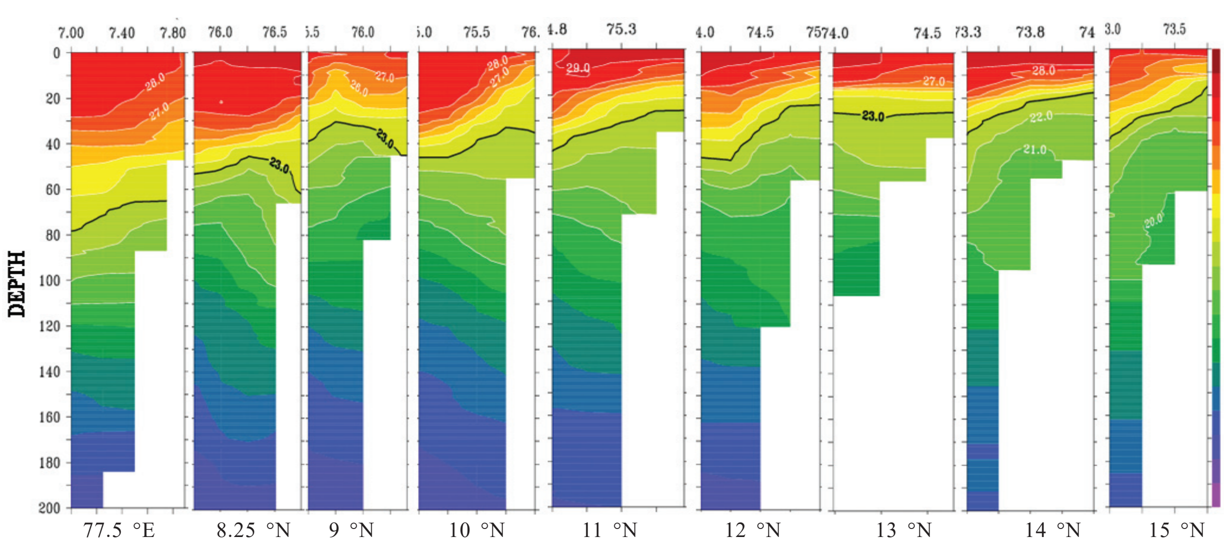

Figure 9. The depth – Space section of temperature in the October 2017 along 77.5 °E, 8.25 °N, 9 °N, 10 °N, 11 °N, 12 °N, 13 °N, 14 °N, 15 °N.

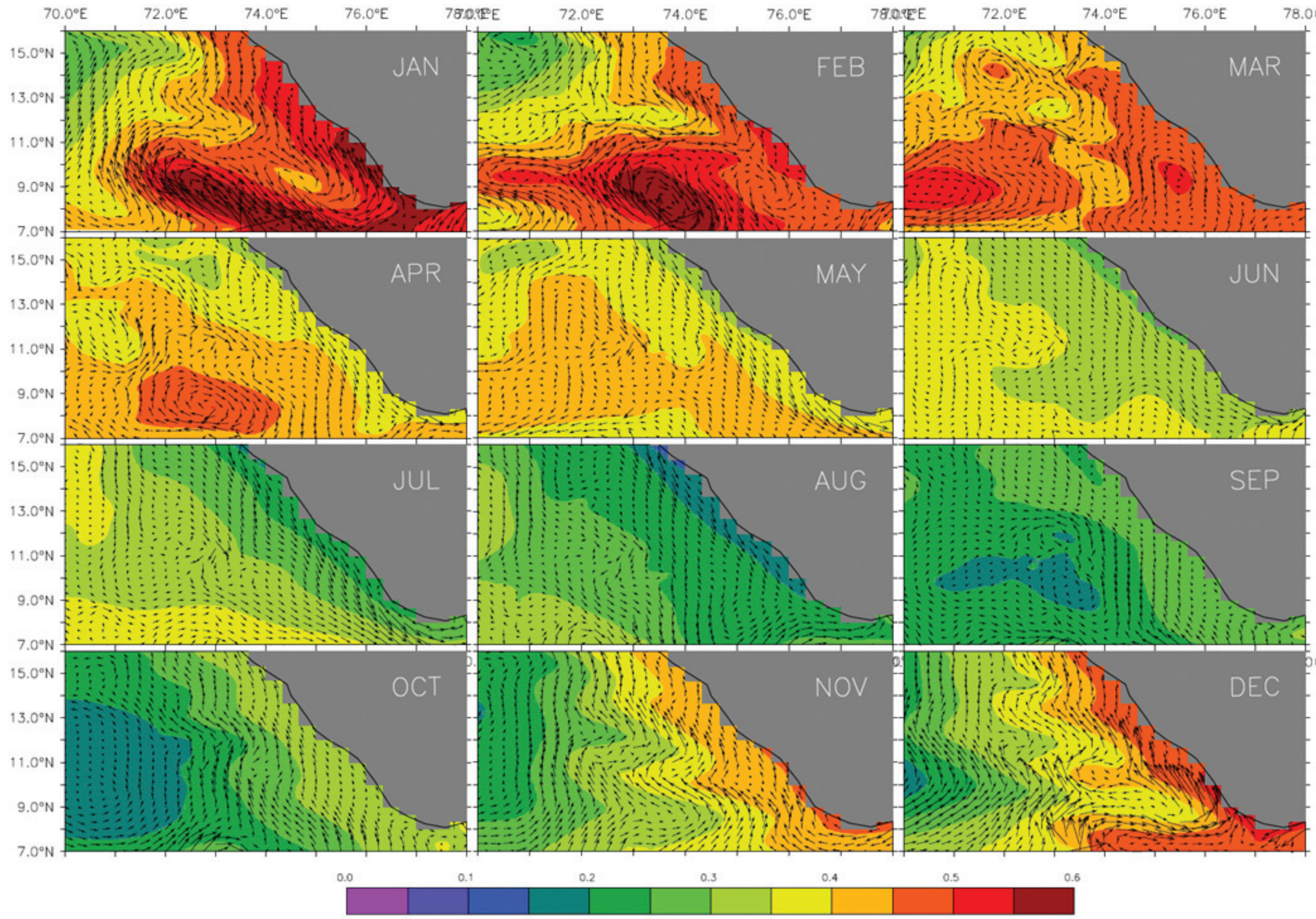

Figure 10. The monthly averaged altimeter derived geostrophic currents overlaid on sea surface height for the year 2017.

4. CONCLUSIONS

In the west coast of India, coastal upwelling begins during the month of February in the southern tip i.e. at 8 °N. The upliftment of the D23 isotherm starts with a gradual rise and it is swiftly uplifted to the surface by June as the winds align favourably during the peak of the summer monsoon. The upward movement of the water at the southern tip in the subsurface levels begins from late February in depths around 80 m and towards the end of May, it is observed to move rapidly upwards to the surface. The upwelled waters reach the surface during the 2nd week of July and was observed all along the Indian coast, and it further intensifies during August. The spreading of surface waters nearly 200 km offshore around 9 °N – 11 °N was also observed. Beyond 12 °N maximum upwelling is seen in early July. Thereafter in early August upwelling was intense and its offshore spreading was beyond 220 km.

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