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OCM Derived Chlorophyll-*a* Dynamics in the Nearshore Region of the Central West Coast of India: Implications for Fish Catch in the Area

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Abstract

This paper deals with the influence of wind and coastal currents on the distribution and concentration of Chlorophyll-*a* in the nearshore waters off the northern Karnataka coast (between towns of Karwar and Bhatkal), along the central west coast of India. In general, concentrations of Chlorophyll-*a* were high (0.6-1.50 mg/l) in this region. High concentrations of Chlorophyll-*a* in the nearshore waters during the monsoon season were related to local upwelling and river input. During the upwelling, the surface water moved offshore and is replaced by nutrient-rich subsurface water leading to high concentrations of Chlorophyll-*a* in a narrow zone along the coast, and preventing the dispersion of Chlorophyll-*a* into the ocean. Higher concentrations of Chlorophyll-*a* observed in the nearshore water during the winter months (December) were related to vertical mixing due to winter cooling effect. During the pre-monsoon season, high concentration zone was narrow and bordered the coast. These variations corresponded to the wind and the coastal currents in the area. Though the central west coast of India represents a typical tropical coast in terms of cyclicity in wind, waves and river input, the prevailing upwelling and downwelling resulted in the unique dispersion of Chlorophyll-*a*. There were lower concentrations of Chlorophyll-*a* beyond the zone of down- and up-welling (corresponding to water depth of 35-40 m), suggesting that fishing-related activities along the coast are more viable within this zone corresponding to water depth less than 35-40 m.

Keywords

Ocean color monitor (OCM) data; Chlorophyll-*a* dynamics; Central west coast of India; Coastal current; Upwelling/down-welling

Introduction

Tropical coasts of the world are characterized by seasonal variations and cyclicity in wind and wave patterns. The Indian coast, apart from the seasonality of its wind and wave patterns, experiences variable inputs of freshwater from rivers due to the southwestern and northeastern monsoons. In particular, the Arabian Sea is unique among low-latitude Sea by terminating at latitude of 25°N and being under-marked continental influence, experience a complex oceanographic process. This results in unique nearshore dynamics in temperature and salinity [1]. These surface features along with the wind and ocean currents strongly influence the biological processes and ocean ecosystem. Chlorophyll-*a* concentration, which is an index of phytoplankton biomass and sea's productivity, is among the most important property of the marine ecosystem. Biomass concentration also influences the thermodynamics of the upper layer [2].

Several studies have indicated that high Chlorophyll-*a* concentrations develop in the eastern Arabian Sea during the southwestern and northeastern monsoons [3,4]. The timing of productivity varies both spatially and temporally [5], and their concentration zone migrates from one place to another in the nearshore as a response to wind, wave activities, and currents [6]. It is well known that nearshore waters in the tropical coast are highly dynamic: winds control the wave activities which then generate currents in the nearshore water, while both wind and waves show seasonal variation in their approach directions and speeds. For effective coastal zone management (particularly for fishery activities), it is important to know how Chlorophyll-*a* dynamics respond to the prevailing wind and coastal currents. Though, in the Central West Coast of India, many rivers bring nutrients to the sea from the Western Ghats and the sea is productive, fish catches are often uncertain.

The oceanic and coastal processes rapidly alter the optical properties of waters and these effects get manifested in the color of the water [7]. Especially in the ocean margin where features like upwelling and downwelling are common, ocean color imageries are particularly useful [1]. Remote sensing images of ocean color converted into Chlorophyll-*a* concentration, provide a window into the ocean ecosystem, oceanic biological and physical processes and for monitoring ocean waters [8,9]**.** Ocean color data from satellites provide a practical means for monitoring the spatial and temporal variation in Chlorophyll-*a* dynamics. In recent years, ocean patterns from the Indian Remote Sensing satellite P-4 (IRS P-4) and other satellite data products have been successfully utilized to understand Chlorophyll-*a* concentrations in seawater along the Indian coast [10-12]. IRS P-4 is particularly useful for tracing Chlorophyll-*a* dynamics due to its high spatial resolution of 360 m, narrow spectral band, and repetitive coverage (every alternate day) with ocean color sensors in 8 spectral bands (412, 443, 490, 510, 555, 670, 765 and 865 nm [13]. Although several studies are carried out to understand the chlorophyll distribution in the eastern Arabian sea, most of the studies are focused either to the north of 17° latitude [14,15] or to the south of 10° latitude [16]. Studies are scarce on the chlorophyll distribution in the region between 13° and 17° latitude especially the nearshore water off the Central west coast of India [17]. Therefore, in the present study, Chlorophyll-*a* dynamics in the inner-shelf off Karwar-Bhatkal, along the Central West Coast of India (CWC), were examined using data from the IRS P-4 OCM.

Methods

For validation of the OCM-derived chlorophyll-concentrations, *in-situ* data were collected from the inner-shelf region of the coast between Honnavar and Bhatkal, along the central west coast of India during March and October 2003 (Figure 1). Water samples were collected using a Niskin reversing water bottle. Samples were collected

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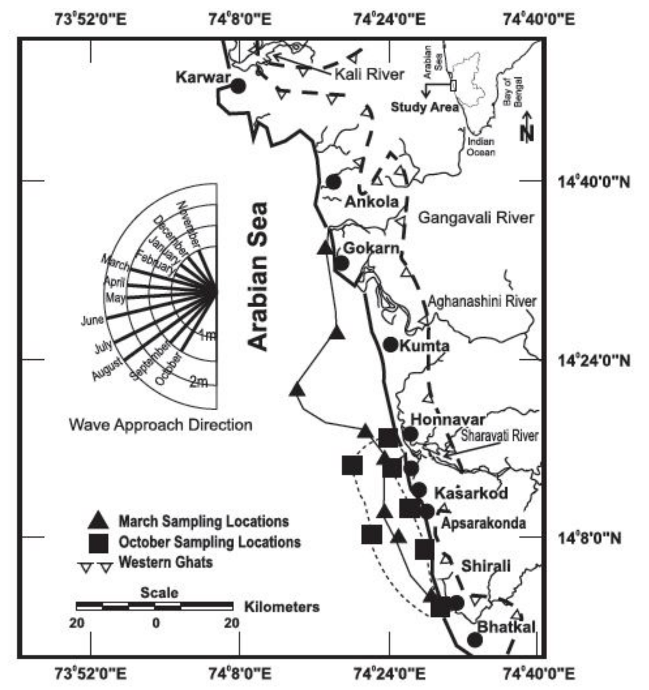

Figure 1: Location of the study area showing rivers of the Uttara Kannada district joining the Arabian Sea and the locations of the water samples collected for chlorophyll analyses.

at the time of IRS P-4 satellite pass over the area, coordinated using data from the National Remote Sensing Centre (NRSC) (Hyderabad, India). Water samples were collected from the euphotic zone during the pre-monsoon (March), and post-monsoon seasons (October) in the inner-shelf region. The location of the samples was recorded using a Garmin Global Positioning System. The Chlorophyll-*a* content in the water sample was determined using the fluorometric method [18].

The retrieval of ocean color parameters such as Chlorophyll-*a* in the nearshore waters involved two major steps.

- **Step 1:** Atmospheric correction of visible channels to obtain normalized water-leaving radiances (nLw)
- **Step 2:** Retrieval of water constituents, such as Chlorophyll-*a*. In the ocean color remote sensing, the signal received at the altitude where the satellite is orbiting is dominated by the contribution of radiance from the atmospheric scattering processes; only 8%-10% of the signals correspond to oceanic reflectance. Therefore, it is necessary to correct the radiance received by a sensor at the top of the atmosphere (TOA).

The Regional Remote Sensing Centre (Nagpur, India) has developed algorithms for this atmospheric correction specific to the conditions in Indian. The OCM scenes were corrected for the atmospheric effects of Raleigh and aerosol scattering. Aerosol scattering was computed using an approach called the long wavelength atmospheric correction. This approach uses the two near-infrared channels at 765 and 865 nm to correct visible wavelengths at 412, 443, 490, 510 and 555 nm. The radiances leaving the water derived from the atmospheric correction procedure were used to compute Chlorophyll-*a*.

A number of bio-optical algorithms for retrieval of Chlorophyll-*a* have been developed to relate measurements of the ocean radiance to in-situ concentrations of Chlorophyll-*a*. An empirical algorithm (also known as ocean chlorophyll-2 or OC2) captures the inherent sigmoid relationship between the ratio of Rrs 490 to Rrs 555-band and chlorophyll-*a* concentration C (where Rrs is remote sensing reflectance). The algorithm has been proven to retrieve both low and high Chlorophyll-*a* concentration (0.01-50.00 mg/l) and hence can be used for case I and case II waters. The algorithm operates with five coefficients and has the following mathematical form:

$$\mathrm{Log}_{10} C=[0.341-3.001 \times x+2.811 \times x_2-2.041 \times x_3] \quad (1)$$

Where C is Chlorophyll-*a* concentration in mg/l and x=log10 (Rrs 490/Rrs 555).

OCM data provided by the National Remote Sensing Centre (NRSC) for the coastal parts of the Karwar and Bhatkal regions for different seasons were used to estimate Chlorophyll-*a* concentration. The algorithm developed for case II waters [19] was used for the present study. The OCM data in the eight bands have been imported using ERDAS Imagine 8.5 version, and the images have been displayed in eight bands. These images are georeferenced by taking suitable ground control points with the help of toposheets of the area. The OCM-derived Chlorophyll-*a* data were correlated with the ground-truth data collected by us, by matching with the dates and times of sample collection (12.10 PM and 1.30 PM), which corresponded to when the satellite passed over the area (Figure 2). Using the above algorithm, the OCM derived Chlorophyll-*a* were also compared with the ground truth data collected by Gerson et al. [17] for case 1 waters of the West Coast of India (Sample 781 and 782; our OCM data covers these two samples locations) for the winter season (December 2000). OCM derived results were found to be consistent with the ground observed values.

Results

Chlorophyll-*a* contents and their seasonal variations in the seawater is a function of the climate in the study area, wind, and coastal current pattern. These aspects are presented in the section.

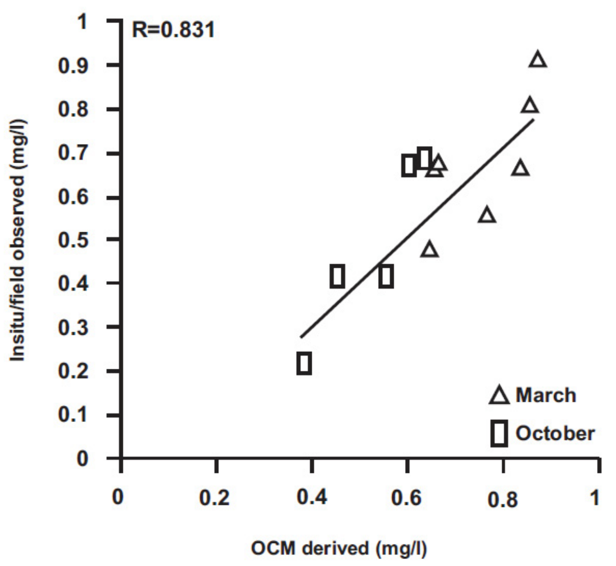

Figure 2: Correlation between observed chlorophyll-a and OCM-derived chlorophyll-a for the study area for two different seasons showing good correlation.

Study area

The area under investigation covers the nearshore region off the coast bordered by Karwar on the north and Bhatkal on the south in Central West Coast of India. The coast is oriented north-northwest (NNW). Important rivers, including the Kali, Gangavali, Aghanashini, Sharavati and Venkatapur rivers originating in the Western Ghat region, join the Arabian Sea and contribute both freshwaters as well as nutrients into the Arabian Sea near this coast. The area receives around 300 cm of rainfall, 85% of which occurs between June and September with a peak in July. Tidal ranges in the study area were <2 m during most of the year (Figure 3), defining microtidal conditions [20]. According to “Dean and Walton” [21], where microtidal conditions prevail, waves are the dominant force in the nearshore region. Fishery activities are prevalent along the coast, however, these activities are discouraged near Karwar due to a project to protect sea-birds and port activities, while the estuarine regions of the Aghanashini and

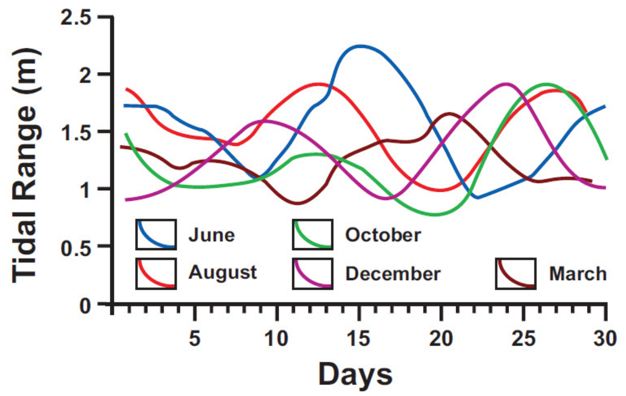

Figure 3: Tidal cycle along the coast between Karwar and Bhatkal, Central west coast of India, showing microtidal condition during the study period.

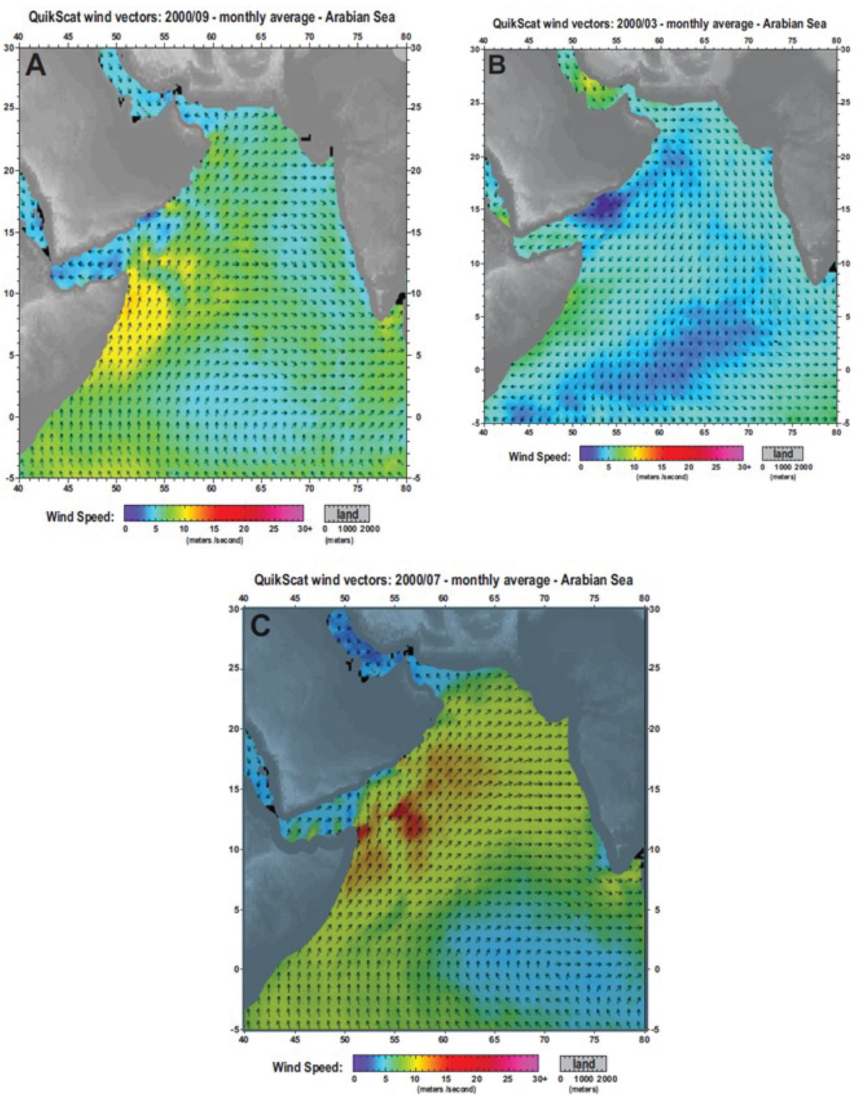

Figure 4: Quick scat-derived wind pattern for the coastal region between Karwar and Bhatkal along the central west coat of India during different seasons indicating weak winds during September, stronger winds approaching from NW during March and stronger winds blowing from the west during July.

Gangavali rivers are not suitable for construction of fish-landing jetties. This has resulted in the concentration of fishery activities in the coastal region between Honnavar and Bhatkal. Therefore, knowledge of chlorophyll dynamics is especially important for fishermen. In this paper, seasonal variation in the Chlorophyll-*a* concentrations, as well as factors controlling their concentration, are discussed.

Nearshore wave and wind characteristics

Wave energy conditions vary with season along the coast [22]. High wave energy dominates during the monsoon (wave height 2.0 to 2.5 m) and waves approach the coast from the southwest. Due to the NNW orientation of the coast, the approach of waves from the southwest generates northerly longshore drift. During the post-monsoon period, low energy conditions prevail (wave height 1-2 m) and waves approach from the northwest (NW). These waves set up generate weak southerly alongshore currents. During the pre-monsoon season, when wave approach is from the west, wave height ranges 1.5-2 m and circulation cells develop in the nearshore region [23,24]. In the mouth of large rivers, however, due to the interaction of waves and river flow, waves diverge on either side creating a wave shadow area [24,25]. Wind plays a dominant role in generating waves and cause upwelling. Quick scat data (received from PO.DAAC, JPL/NASA website), were processed and wind vectors were generated for the study area (Figure 4). The wind pattern along the coast suggests that NNW approaching winds during September which become nearly west-east during November-December and is weak, while those approaching from NW during March are strong. During July, stronger winds blow from the west.

Chlorophyll-*a* concentration

Chlorophyll-*a* concentration in the nearshore waters off the Central West Coast varied from 0.43 to 1.45 mg/l during the pre-monsoon season (March 2003). This concentration was found in the narrow width until 2 km from the shore and decreased beyond this zone (Figure 5). Thus, the nearshore region of the Central West Coast of India, particularly near Kasarkod and Apsarkonda, and regions near the river mouths, were rich in Chlorophyll- *a*. The Chlorophyll-*a* content of the sea, derived from the OCM data was comparable with the ground truth data for this region (correlation coefficient 0.831) as well as other regions of west coast of Karnataka [16,26,27].

During the monsoon season (August 2003), a plume-like distribution (Figure 5) is found in front of the river mouths with high concentrations of Chlorophyll-*a* (~ 1.5 mg/l). Sarma et al. [5] also observed enriched Chlorophyll-*a* to the south of *20*-degree latitude in the Arabian Sea during the southwest monsoon. However,

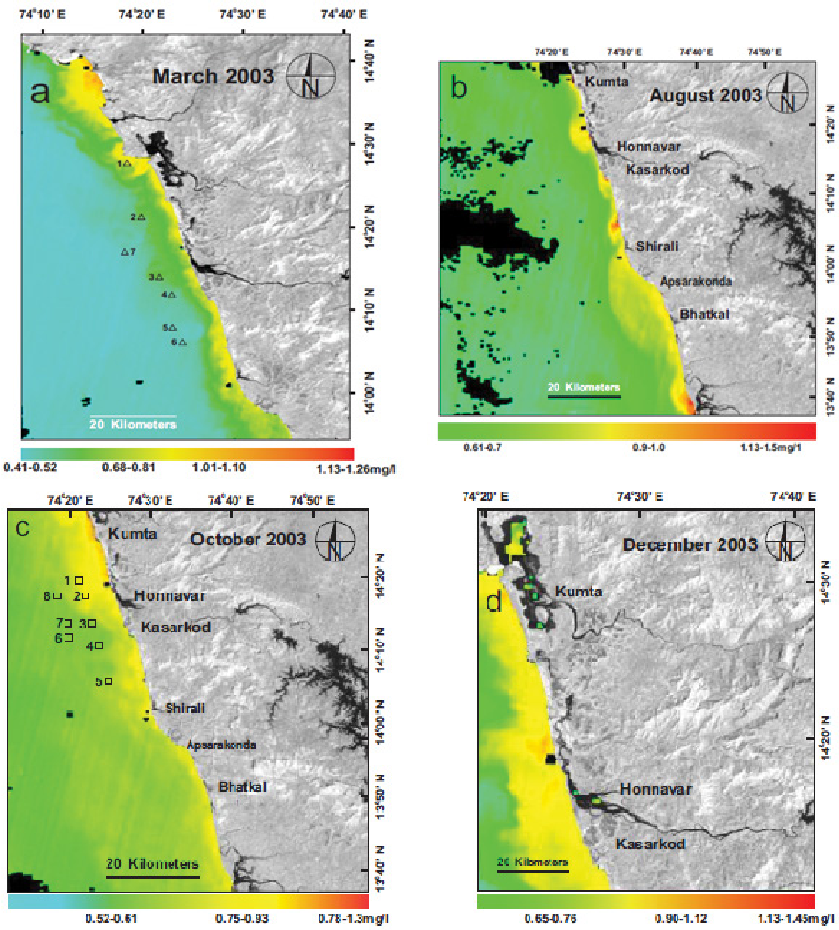

Figure 5: Map showing chlorophyll-a distribution in the near shore region between Karwar and Bhatkal along the central west coast of India: a) Pre-monsoon (March); b) Monsoon (August); c) Post-monsoon (October); d) Winter (December). Note higher chlorophyll-a content in the sea water near Kasarkod and Apsarkonda during March; plume-like distribution in front of the river mouth during August; higher Chlorophyll-a in the northern part which gradually decreased southward during October, and wide band of higher Chlorophyll-a content during December.

there is local variation between the coastal region of Honnavar (on the north) and Bhatkal (on the South): the concentration decreased going northward from the Bhatkal region (southern part in the Figure 5b), whereas transport was southward from the river mouth of the Sharavati (central part in the Figure 5b).

During the post-monsoon period (October 2003), concentrations of Chlorophyll-a (0.78-1.0 mg/l) were generally higher in the northern part (Figure 5) and gradually decreased southward. During December (2002), which represents the peak of winter, there was a wide band with high concentration of Chlorophyll-*a* (1.13 to 1.40 mg/l) in the area (yellow color, Figure 5), with concentrations gradually decreasing seaward.

In general, concentrations of Chlorophyll-*a* were highest during the southwest monsoon and winter months.

Discussion

The observed variations in Chlorophyll-*a* concentration in the study area correspond to the wind pattern for the monsoon, post-monsoon (October) and pre-monsoon seasons. During the winter, unusual patterns of Chlorophyll-*a* variation were observed in the region. The northern Arabian Sea (especially north of 10°N) experiences a net heat loss, about 140 W/m^2 during winter [28]. Due to a northeast monsoon effect, dry continental air blows towards the sea and the wind turns seaward, particularly to the south of latitude 16° [29]. This results in evaporation and cooling effects on the surface. Due to this evaporation over precipitation in the Arabian Sea shelf area, while higher precipitation in Bay of Bengal added by river runoff, resulting in an imbalance in the hydrology of these two basins. This hydrological imbalance is balanced by inter-basin exchange [16]. During winter, East India coastal current is southward while west coastal current is northward, The low salinity water from the Bay moving southward meets the west coast India coastal current flowing northward at the head of the Indian Ocean (Figure 1) and flow as subsurface current northward in the Arabian sea. This intrusion of low saline water into the Arabian Sea, prevailing cold surface temperature (26°C) and high salinity 36.5%, favor advective currents [17] off Honnavar-Bhatkal. In addition to this, rivers from Western Ghats bring cold water during the winter. The net result is that surface cooling and densification which leads to sinking and corresponding upward water circulation (vertical mixing) that results in advective/convective currents in the region. These advective/convective currents might bring the nutrients to the surface, causing higher Chlorophyll-*a* concentration, as also corroborated by high nitrates concentration in the upper water column [16]. A similar winter cooling effect has been observed in the northern Arabian Sea [11,12,15].

During the pre-monsoon season, the wind approaches the coast from the northwest and from WNW, and due to NNW orientation of the coast wind stress is southward which pushes surface water southward whereas subsurface flow is northward [30] which replaces the surface water causing bottom water to move upward and bring the nutrients to the surface.

The plume-like structure and high concentration of Chlorophyll-*a* observed in front of the river mouths during monsoon may be due to the rivers' contribution of nutrients as well as high discharge. Coastal front leading the local upwelling may also add to this enrichment effect [31,32]. Further, the upwelling that takes place at 35-40 m depth along the Central West Coast of India [33], strong wind that pushes the surface water landward to the east of upwelling zone prevent dispersion of coastal water across the nearshore. The general northward variation in Chlorophyll-*a* concentration corresponds to the general northward wind stress during the monsoon while local southerly drift, especially from the Sharavati river mouth southward, could be due to local orientation of the coast and presence of island that may obstruct the wind pattern.

The foregoing account demonstrates the influence of coastal current and wind patterns on the distribution and concentration pattern of the Chlorophyll-*a* in the shelf region of the Central West Coast of India. Similar wind direction and velocity-driven phytoplankton distribution have been observed along the western Arabian Sea near Somalia [34], Yemen, Salalah and Masirah in Oman [5] and north of the current study area (north of 16° latitude along the Central West Coast of India [35] implying regional phenomena controlled by winds and currents. But during December, Chlorophyll-*a* distribution shows a distinct and unique pattern, implying the combined effects of cold water brought by rivers from the western ghat, the dry continental air, and SE monsoon.

Conclusion

Although the Central West Coast of India shares many similarities with the other tropical coasts in terms of seasonality in Chlorophyll-*a* distribution and cyclicity in wind and waves, concentrations and distribution patterns of Chlorophyll-*a* in the area suggest the important role played by upwelling and down-welling. During the southwest monsoon, the upwelling drove the concentrations of Chlorophyll-*a* along the coast, while during the winter months these concentrations were driven by down-welling. The down-welling during the winter were driven by surface cooling and northward coastal current while upwelling during pre-monsoon to monsoon was due to southward wind stress. The effects of upwelling and downwelling prevent dispersion of Chlorophyll-*a* across the sea shelf. Hence, beyond the zone of upwelling (35-40 m water depth), there was a lower concentration of Chlorophyll-*a*. Therefore, the zone extending until a depth of 40 m has the potential for fishery activities along the coast, and wind and wave patterns could guide fishermen to success.

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