Influence of alongshore wind in the bio-productivity of coastal waters of Somalia and South peninsular India

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ABSTRACT

The connection between the presence of along shore wind and marine bio productivity is well established in this paper. Mutual relationship of the presence of Ekman mass transport associated with alongshore wind is better explored during south west monsoon season in the coastal locations of Indian Ocean such as Hobyo, Cochin, Hambantota and Pondicherry. Formation of high marine bio-productivity evidenced from high chlorophyll-a concentration observed at the same time when alongshore wind strengthens indicate that alongshore wind is a factor that influences bio-productivity.On further analysis on evaluating factors affecting the strength and duration of alongshore wind, we have found that location of monsoon organized convection is responsible for the variation in alongshore wind and subsequent Ekman mass transport in Cochin and Pondicherry. Variation in cross equatorial flow is found to affect directly on the strength on alongshore wind over Hobyo station.

INTRODUCTION

The phenomenon of upwelling is a well known process in the Indian Ocean especially in the Arabian Sea during summer monsoon months. The most observed upwelling zones are Somalia, Oman, Yemen and southern tip of India (Wyrtki, 1973; Brock et al., 1991; Bauer et al.,1992; Lee et al., 2000, Madhupratap et al. 2001; Luis and Kawamura 2004; Rao et al., 2008; Smitha et al., 2008; Yayaram et al., 2010; Smitha et al., 2014).The formation of a clockwise circulation pattern in the Arabian Sea due to the intense low-level wind jet (Findlater Jet) is manifested as the driving mechanism of upwelling in the nearby coastal regions (Wyrtki, 1973). The behavior of Bay of Bengal (BOB) is somewhat different than that of Arabian Sea due to the large freshwater influx (Martin et al., 1981) and it is known to be a region of low biological productivity compared to the Arabian Sea (PrasannaKumar et al., 2002; Jyothibabu et al., 2004; Gauns et al., 2005).Shenoi et al., in 2002 explained that strongsouthwest monsoonal (SWM) winds are unable to break this strong stratification and hence the reason for low biological productivity.But the effect of local alongshore winds on biological productivity in those regions were reported by Shetye et al., 1991 and Gomes et al., 2000 ;Madhupratap et al., 2003 ; Muraleedharan et al., 2007 ;Madhu et al., 2006. Coastal upwelling also leads to an increase in chl-a along the southern coast of Sri Lanka (Vinayachandran et al., 2004). The open ocean Ekman pumpingdriven by positive cyclonic wind stress curl enhances chl-a in the southwestern part of the bay during the northeastmonsoon (NEM) (Vinayachandran and Mathew, 2003 ; Vinayachandranet al., 2005b) and within the Sri Lanka dome (Vinayachandran and Yamagata, 1998) during the SWM (Vinayachandran et al., 2004).

The factors affecting the process of the intrusion of subsurface nutrient rich water into the surface levels resulting enhancement of bio-productivity as a reflection of upwelling scenario (Wiggert et al., 2005; Lachkar and Gruber 2011) are the prevailing winds, coastal currents and remote forcings such as Kelvin and Rossby waves (Amol et al., 2012; Brandt et al., 2002; Bruce et al., 1998; Durand et al., 2007; Huang and Kinter 2002; Kumar and Sanilkumar 2005; Rao et al., 2010; Schott and McCreary 2001; Shankar and Shetye 1997; Shankar, Vinayachandran, and Unnikrishnan 2002; Shetye et al., 1990; White 2000; Wu and Kirtman 2004, 2007; Yang et al., 1998).The strength of upwelling can then be estimated based on the wind speed and the wind induced offshore mass transport [Ekman transport] (Bakun 1973). Thus the strength of the Ekman transport can be considered as a proxy for determining the features of upwelling for that region. The phenomenon of Ekman mass transport (transport of water mass horizontally in a direction rightward perpendicular to the direction of alongshore wind) is proposed by Ekman (1905). The intrusion of nutrient rich cold water from subsurface to surface thus enhances bio-productivity (Chlorophyll-a concentration) in the upwelling regions. Ocean colour sensors captured these changes in terms of the variability in chlorophyll-a concentration (Jayaram 2011; Sarma 2006). The variation in alongshore wind magnitude can also be connected with the location of monsoon organized convection as the wind always converge to the center of the convection and the strength of cross equatorial flow affects the behavior of flow pattern over western Arabian Sea region.Even though many studies reported on the coastal upwelling features of Arabian Sea and BOB, factors responsible for variation in coastal upwelling especially reasons for the variability in intensity of coastal upwelling during the monsoon season are not addressed properly. The objective of the paper is to understand the meteorological factors responsible for the variability in bio productivity in the coastal regions of Indian Ocean such as Cochin, Pondichery, hambantota and Pondichery.

DATA AND METHODOLOGY

The regions selected for the present study are the major coastal regions such as Cochin (10.03^0N/76^0E), Pondichery (11.91^0N/79.8^0E), Hambantota (6.14^0N/81.15^0E) and Hobyo (5.34^0N/48.54^0E). The selection of the above stations is because of the variable intensity in upwelling process over these locations during monsoon season since these are all looking favorable for the same. The study period is the SWM season (2011-2013) and the analysis is carried out from 15 May to 15 September. The alongshore wind at the same time is derived using u and v components of daily surface wind from NCEP/NCAR reanalysis data of 0.25^0X0.25^0 resolution, latitude and coastal angle of each location. The coastal angle (angle at which the coast is oriented from the true north) selected for Cochin, Pondichery, Hambantota and Hobyo are 161^0, 20^0, 70^0 and 28^0 respectively. The Upwelling intensity is thus obtained in terms of Ekman mass transport ($kgm^{-1}s^{-1}$) which is perpendicular to the direction of wind in that location, using the equation, $\mu_e = \zeta/f$, where $\zeta = \rho C_d Vc$, where ζ is the wind stress due to alongshore wind, f is the Coriolis parameter, ρ is the density of air and C_d is the wind dependent drag coefficient, V is the wind speed and c is the alongshore wind.The subsequent variability in nutrient production is examined from SeaWiFS weekly data of surface chlorophyll-a at a spatial resolution of 9 km × 9 km. The strength of alongshore wind in Hobyo is verified

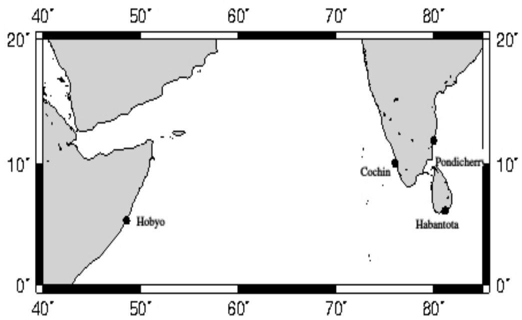

Figure 1.Location of study regions such as Cochin, Pondicherry, Hambantota and Hobyo.

in terms of cross equatorial flow over the region 8^0-12^0N/48^0-52^0E. Location of monsoon organized convection is identified using IITM OLR daily data of 0.25°X0.25° resolution and it is considered as a factor which determines the direction of alongshore wind over Kerala, Colombo, Arugam Bay and Pondichery regions.

In this analysis, the influence of meteorological factors on bio-productivity such as alongshore wind is evaluated in detail during the time of upwelling. Causes for variation over all the selected regions are also examined using the available data sets.

RESULTS AND DISCUSSIONS

The clockwise circulation of wind pattern over Arabian Sea during monsoon months has been taken as the main mechanism favorable for the development of alongshore winds. The word 'alongshore wind' means the wind which is blowing parallel to the coast with a capability to trigger Ekman Mass transport. These winds are mainly southwesterlies in Somali coast, north-northwesterlies in Kerala coast. The direction of monsoon winds from AS to BOB are then becomes southwesterlies when it bypasses through southern tip of India and Sri Lankan landmass. This situation may changes due to the presence of low pressure systems in the Head Bay or Southern Bay. Generally, the alongshore winds over Hambantota and Pondicherry are observed to be southwesterlies.

Presence of alongshore winds over all the 4 coastal waters during the monsoon period from 15 May-15 September have been derived from NCEP daily values of u and v components. The comparison between actual wind and alongshore one have been then depicts the fact that the derived wind component is strong enough to trigger mass transport through the process shown in fig.2.

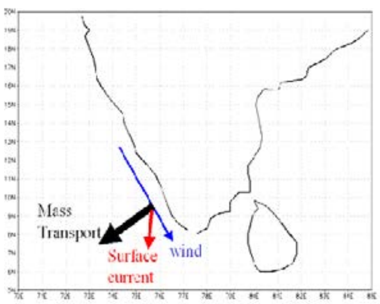

Figure 2. Depicts the action of alongshore wind on surface water. Process of Ekman mass transport right angles to the wind direction and the corresponding movement of surface water resulting in upwelling phenomenon by nutrient intrusion.

Mutual connection between the actual wind (925hPa) and alongshore wind is evidenced over Cochin (fig.3). We have observed peak values (6-6.5 m s^{-1}) of alongshore component (07-Aug, 28-Aug) when north-northwesterly winds are there and the magnitude are found to be little weaker than the actual wind. Frequency of occurrence and persistence nature of alongshore wind is observed to be high in the month of August.

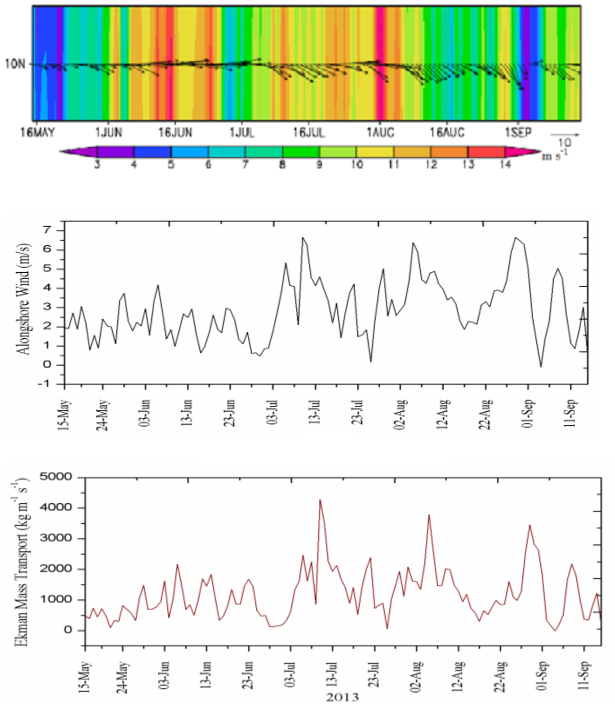

Figure 3. shows the variations of actual wind (top), alongshore wind (middle) and Ekman mass transport (bottom) over Cochin during the SWM season of 2013.

Corresponding one to one variation in Ekman mass transport is also observed at the same time (07-Aug, 28-Aug). We have observed maximum (3500-4000 kg m^{-1} s^{-1}) and minimum (0-500 kg m^{-1} s^{-1}) values throughout the entire study period and the presence of sustained winds of minimum up to 3 or more days are found to trigger considerable mass transport favoring the process of upwelling. The observed time lag is mainly due to the density difference between the atmosphere and water. Since, water is 3 times denser than the air; it takes much time to transfer its momentum to the surface water. Evidence of biological productivity is also observed after significant mass transport (fig.4) periods. Since we use 8 day averaged chl-a data, presence of increase in bioproductivity is observed after the date of maximum mass transport (10-Aug, 11-Sep). The values are in the range of 14-16 mg m^{-3}.

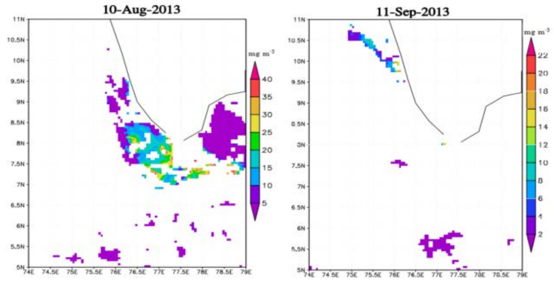

Figure 4. SeaWIFS 8 day averaged chl-a concentration. Presence of significant amount of chl-a concentration (nearly 14-16 mg m^{-3}) near Cochin coast is clear after high Ekman mas transport. The white patches indicate non availability of data.

The process of upwelling is then also supported by the change in SST. From fig.5, remarkable decrease in SST is observed during 5-12 August where we have maximum sustained winds and the peak value in Ekman mass transport is also there. Throughout all the study period we observe considerable decrease in SST with a time lag of about 1-2 days followed by the production in bio-productivity which can be indicated by the increase in chl-a concentration.

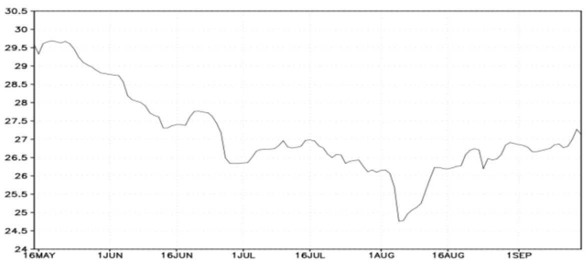

Figure 5. The decrease in SST in the coastal waters of southwest peninsular India (Cochin) during 5-12 August, 2013 is associated with coastal upwelling due to depletion of surface water by Ekman mass transport.

We then checked out the main causes for the existence of alongshore wind over all the coastal locations. The analysis then leads to the point that position of monsoon organized convection causes changes in wind direction over Cochin and Pondicherry stations. The above statement can be seen in fig.6 which represents the position of monsoon organized convection from 23-Aug to 03 –Sep during that period we found strong and sustained winds. The organized convection is present at the equator during all these days and the most favorable time is observed to be from 29-Aug to 03-Sep where the monsoon organized convection locates both in equatorial and south of Cochin coast. The mechanism responsible for acquiring alongshore behavior was observed to be the wind convergence associated with the latent heat release from these convective cloud bands. The release of latent heat is associated with increase in pressure gradient over that region which then causes the surrounding air to converge towards that region (asha et al., 2013) resulting the alongshore pattern of wind.

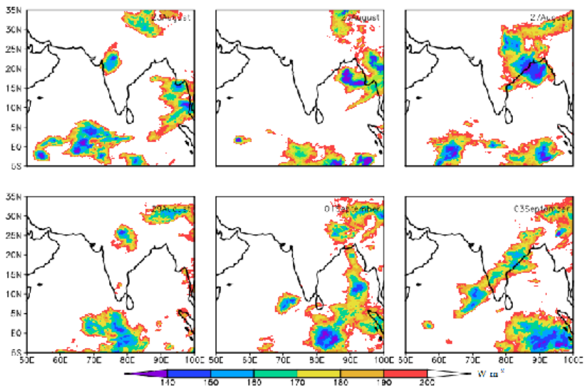

Figure 6. Position of monsoon organized convection at the time of presence of significant alongshore wind.

To identify the change over Pondicherry coast, same analysis has been carried out. The coastal angle obtained for the coast is 20^0. Strong and significant alongshore winds (6.5-7 m s^{-1}) are observed in the middle of May and in the beginning of June and then ceases throughout the entire monsoon season. Corresponding peak in Ekman mass transport were also seen there. Presences of monsoon organized convection in the BOB were assumed to be the main driving factor responsible for the presence of alongshore winds at these times (figure not shown). Mutual interaction of wind driven mass transport on bio-productivity is clear from chl-a concentration ie., maximum chl-a concentration (14-16 mg m^{-3}) is found on 12 June that is the reflection on 5 June (maximum value of alongshore wind and mass transport).

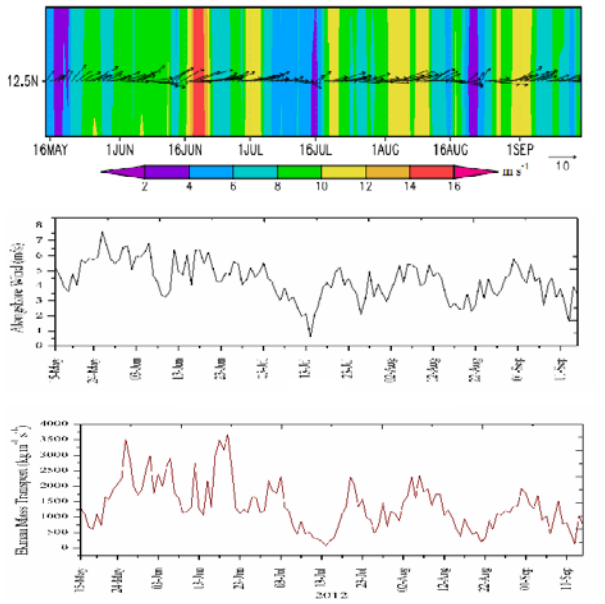

Figure 7. shows the variations of actual wind (top), alongshore wind (middle) and Ekman mass transport (bottom) over Pondicherry coast during the SWM season of 2012.

Fig. 8 shows two cases where we have obtained wind induced bio-productivity. High chl-a concentration is obtained at the time of maximum sustained alongshore wind. Since, weak alongshore wind persist near Pondicherry coast in most of the days during the monsoon season, we have less remarkably found the mutual interaction between wind induced mass transport and bio-productivity.

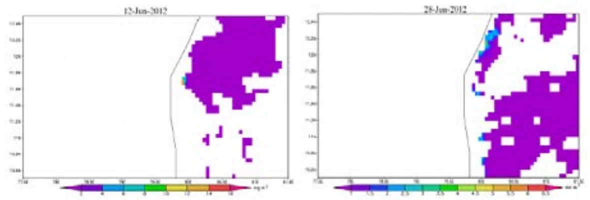

Figure 8. Chl-a concentration (mg m^{-3}) near Pondicherry coast during the presence of significant alongshore wind.

But the case is found to be somewhat different in southeastern SriLanka (Hambantota). Steady and continues winds prevailed throughout the entire season (fig.9 top). Magnitudes reaching upto 17-18 m/s have been noted. This strong wind (24 May-03 June) produces corresponding alongshore winds and they attain a magnitude of 11 m/s. Corresponding high mass transport then yields considerable nutrient production (fig.10). Phase to phase correspondence have been obtained between the alongshore wind and ekman mass transport. We have then checked out the bio-productivity at the time of weak alongshore winds (06-13 June). Chlorophyll production was restricted during that period (fig.10). This region is highly productive with chl-a values of about 35-40 mg m^{-3} during the time of maximum sustained winds. Hence, the mechanism of bio-productivity in this coast is noticed to be highly influenced and driven by the alongshore winds.

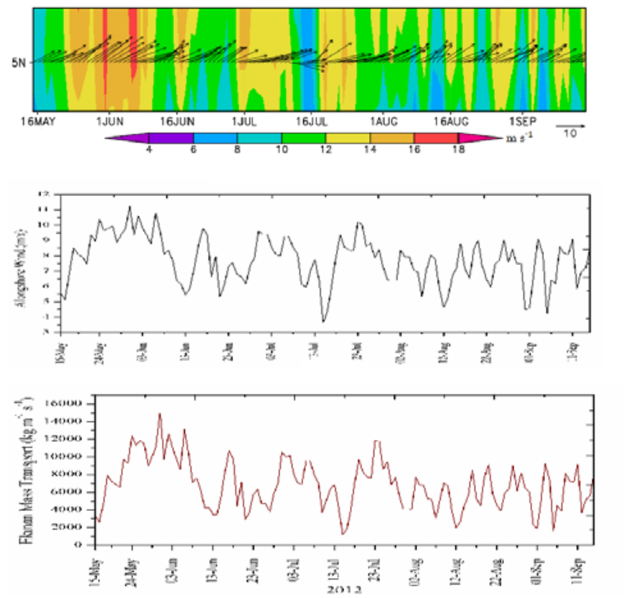

Figure 9. . shows the variations of actual wind (top), alongshore wind (middle) and Ekman mass transport (bottom) over Pondicherry coast during the SWM season of 2012.

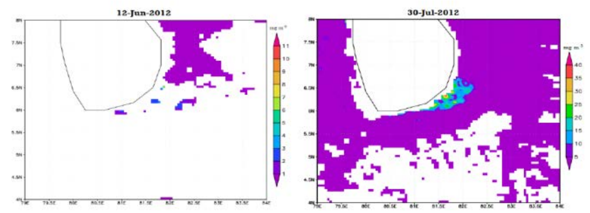

Figure 10. Chl-a concentration (mg m^{-3}) near Hambantota coast during the presence of significant alongshore wind.

The variation in Hobyo (Coast) is then cross checked. Since the coast is located in such a way that the strong flow developed in the middle of May crosses equator and attains southwesterly direction preferably at this location. Hence, these winds are parallel to the coastal locations of Somalia. They attained maximum strength

(16-20 m/s) during July and August (Fig.11 top) and the alongshore wind attains its peak value (11-12 m/s) during the month of July. The wind remains steady almost throughout the entire season. This is the most favorable situation required for sufficient bio-productivity.

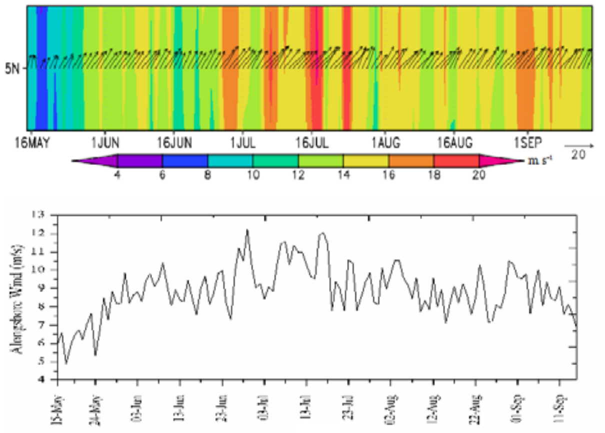

Figure 11. Variations in actual wind and alongshore wind over Hobyo coast during the monsoon season of 2011.

Fig. 12 indicates the variation in Ekman mass transport. The same trend is again noted throughout the entire monsoon season. Sustained winds again favor mass transport and the chl-a variation at the same time (Figures are not shown) indicates that all are mutually connected. A sudden decrease in SST with minimum values of about 24^{0}C (Figures are not shown) were noted on 10-13 July and 24-26 July. This can be interpreted by the strong upwelling process occurred at the same time which is clear from fig. 11 and fig.12. This area is observed to be one of the highly productive regions among the world with chl-a concentration reaches a value of 35-40 mg m^{-3} at peak times.

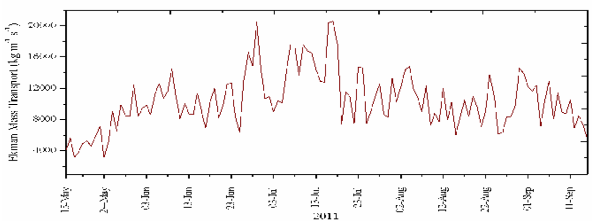

Figure 12. Ekman mass transport during the monsoon season of 2011 over Hobyo coast.

We analyzed the variation in alongshore wind with the strength of cross equatorial flow over the grid box of 8^0-12^0 N/48^0-54^0 E (Fig.13). The strengthening of cross equatorial flow occurs in July and August. Consequent increase in alongshore wind is also noted during the period. Since both are symmetrical and the actual flow is completely alongshore, strong wind forcing occurs over that region. This is responsible for the variation in the magnitude of alongshore wind over Hobyo coast.

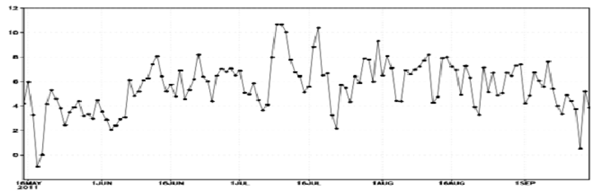

Figure 13. Strength of cross equatorial flow over the region 8 ° N -12 ° N/48 ° E-52 ° E.

Ekman Mass transport as a measure of upwelling intensity according to the induced wind stress due to the strong alongshore winds results in the formation of phytoplankton blooms with a phase lag of 2 to 4 days is observed throughout the analysis.

CONCLUSIONS

We concluded our findings from the entire analysis as,

1) Strong interaction between alongshore wind, wind stress and Ekman mass transport is observed in all the four coastal regions.
2) The presence of monsoon organized convection in the equatorial region strengthens alongshore wind over Kerala and Pondicherry coasts and subsequently produces high Ekman mass transport and upwelling.
3) The mechanism in Pondicherry is somewhat different since it is strongly influenced by the dynamics of BOB. This overrides the contribution due to alongshore wind.
4) Hambantota and Hobyo coasts are found to be strongly influenced by the alongshore wind driven upwelling phenomenon. Both have enriched with high nutrient production.
5) Strong cross equatorial flow is responsible for along shore wind over Hobyo and hence enhanced bio productivity in the coastal

region.

6) Meteorologically, along shore wind plays vital role in bio productivity. However, factors associated with wave dynamics and river run off are important for the occurrence of high chlorophyll-a concentration, we can fully explain the phenomenon of upwelling only by the incorporation of these two factors.

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