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RESEARCH ARTICLE

Effect of surface wind and wind vectors on sea surface chlorophyll *a* distribution in the ocean waters surrounding Sri Lanka for the period 1999 – 2003

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Abstract: Ocean colour and surface wind data derived from Sea viewing Wide Field of view Sensor (SeaWiFS) were examined to understand the relationship between a biological parameter, chlorophyll *a* and a physical parameter, surface wind. SeaWiFS data of 1.1 km resolution for the period 1999–2003 were processed and mapped to produce daily maps of chlorophyll *a*, wind speed, meridional wind (mwind) and zonal wind (zwind) speeds within the area of latitudes between 2.0N – 13.5N and longitudes between 76.5E – 88.0E. Monthly composites for the period 1999–2003 were produced.

The chlorophyll concentration variability showed a very strong relation to the monsoonal pattern in the Indian Ocean region. A strong co-variability was found between the wind parallel to the coast, and the chlorophyll concentration in South and Southwest regions during the southwest monsoon period and in Northeast and East regions during the northeast monsoon period, respectively, and the corresponding correlation coefficients were found to be between 0.92 – 0.99 in the four regions. It was observed that mwind is the major contributor to the wind parallel to the coast, in the Northeast and East regions with correlation coefficients in the range 0.82 – 0.88 during northeast monsoon period. Whereas zwind contributes to the wind parallel to the coast, in the South and Southwest regions exhibiting correlation coefficients in the range 0.97 – 0.99 during southwest monsoon period. High chlorophyll *a* concentrations observed in these waters can be a result of coastal upwelling.

Keywords: Chlorophyll *a*, correlation coefficient and coastal upwelling, mwind, wind speed, zwind.

INTRODUCTION

Remotely sensed ocean colour data is available to scientists through ocean monitoring satellites. Sea viewing Wide Field of view Sensor (SeaWiFS) launched in 1997, was the long operating successor after CZCS (Coastal Zone Colour Scanner), which seized operation in 1986. SeaWiFS has provided a nearly continuous archive of remotely sensed global data on routine basis. Ocean colour is affected primarily by marine plants, suspended sediments and dissolved organic matter, especially in the coastal region (IOCCG, 2000) and is used as an indicator of chlorophyll *a* concentration; it is one of the valuable oceanographic parameters derivable from satellite data. Most of the chlorophyll *a* in marine systems is present in microscopic marine plants, phytoplankton. The most well established use of ocean colour data is to study the phytoplankton distribution in oceanic waters.

Chlorophyll *a* is a valuable tool to assess the ocean's role in the global carbon cycle (Feely *et al*., 2001). Also, chlorophyll along with other oceanic parameters such as sea surface temperature, surface currents and surface winds, help scientists to identify possible upwelling regions (Tomczak & Godfrey, 1994) in the coastal ocean (Banse *et al*., 1996).

Calibration of changes in ocean colour against changes in the concentration of chlorophyll *a* in the surface layers of the ocean is used in construction of algorithms for interpretation of satellite data. Simple algorithms designed work best, if existence of substances other than phytoplankton is insignificant (IOCCG, 2000). These algorithms may have a higher probability of failure in waters, in which yellow substances, suspended particles or bottom effects exert an important influence. Therefore, oceanic waters are partitioned (Morel & Prieur, 1977)

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into case I and case II waters where, by definition, case I waters are those in which phytoplankton are the principal agents responsible for variations in optical properties of the water. Case II waters are those influenced by phytoplankton, as well as by other substances such as inorganic particles in suspension and yellow substances. It is assumed that over 90 % of the oceans of the world can be considered as case I waters (IOCCG, 2000) or open ocean waters. Coastal waters are generally considered as case II waters.

The waters around Sri Lanka are linked to basins, namely, the Arabian Sea waters in the West and the Bay of Bengal waters in the East. Also, the two monsoon seasons, the southwest monsoon and the northeast monsoon heavily influence the ocean processes in the Indian Ocean. The southwest monsoon (May - September) brings heavy rain with high winds, contributing to strong upwelling (Cushing, 1969) along the coastal belts of Somalia, Yemen, Oman and along the Western coast of India. The northeast monsoon (December - March) brings much weaker winds and less rainfall, resulting in lighter activities in the Eastern Indian ocean region. The southwest monsoon current (Schott & McCreany, 2001) flows eastward South of Sri Lanka and brings chlorophyll rich waters from the Indian coast towards Sri Lanka (Vinayachandran *et al*., 2004). Though there have been many studies using remotely sensed ocean data in the western Indian Ocean (Solanlki *et al*., 2001), the Arabian sea (Watts *et al*., 2005) and the Bay of Bengal (Dwivedi, 1993) through the years, much less attention has been paid to the ocean waters that surround Sri Lanka (Yapa, 2000). In this paper, a detailed analysis of the influence of monsoons and the effects of surface winds on the variability of chlorophyll *a* distribution in the coastal waters that surround Sri Lanka is presented.

METHODS AND MATERIALS

In this study, the data was processed from SeaWiFS for a 05 year period from January 1999 to December 2003 to produce chlorophyll maps for the ocean area within latitudes 2.0N – 13.5N and longitudes 72.5E – 88.0E using SeaDAS software from NASA. The data have a spatial resolution of approximately 1.1 km. Daily chlorophyll *a* maps were constructed for relatively cloud free days in each month. Each map contained 800 × 800 pixels (each pixel is 1.1 km) and were sub sampled from 2801 by 1502 scenes. Monthly and seasonal composites for each year and finally, the composites for each month, using the available data for the whole period were constructed. About 60 – 70 data files for each month were available for the final period averages. A similar procedure was followed to construct composite maps for the other parameters, wind speed, zonal wind (zwind) and meridional wind (mwind). The seasons are defined roughly as follows: first inter monsoon (March-April), southwest monsoon (May - September), second inter monsoon (October - November) and northeast monsoon (December-March). The coastal ocean waters around the island were divided into six sub-areas of varying sizes mainly in the directions covering the Northeast (NE), East, Southeast (SE), South, Southwest (SW) and West. As each sub-area box contained a large number of data, monthly and seasonal averages for each box were computed. These mean values, as well as original data from the selected sub-areas were compared and computed to find possible relationships between winds and the biological parameter, chlorophyll *a*.

Various sources of random and systematic errors (i.e. characterization of the sensor, atmospheric and bi-directional corrections, errors in geo-location, contamination with light emanating from adjacent pixels, uncertainties in the algorithms, etc.) contribute to uncertainties (IOCCG, 1999) in satellite measurements and in derived products such as ocean colour. The calibration/validation activities of each ocean colour mission are designed to assess and minimize the magnitude of this uncertainty. Therefore, absolute chlorophyll values are considered to have an uncertainty of ± 35 % (Aiken *et al*., 1998) for 0.1< [chl] <1.0 mg m^{-3} in open ocean waters, and an even greater uncertainty in waters with higher chlorophyll concentrations. Due to the complexity in evaluation of uncertainties in remotely sensed data and in the derived parameters, any error estimates of calculated averages in chlorophyll *a* or wind data used in this study were not included. However, spatial and temporal variability of those dynamical parameters are clearly presented in the figures.

RESULTS

Figure 1 shows monthly composite chlorophyll *a* maps of the waters around Sri Lanka for the period 1999 – 2003. The chlorophyll *a* concentration is shown using a logarithmic colour scale depicting values in a range of four orders of magnitude from 0.01 to a cutoff value of 64.77 mg m^{-3}, with colours varying from purple to red, correspondingly (same colour scale is repeated in Figure 2). Though the cutoff value of 64.77 mg m^{-3} for chlorophyll concentration seems quite high for ocean waters, this value or even higher derived values in some pixels, especially in coastal waters, are not surprising from remotely sensed data due to many inherent factors such as bottom effect, sediments, yellow substance, etc. However, as seen from the maps, more than 95 % of data are in the range 0.01 – 5.0 gm m^{-3}.

All maps in Figure 1 indicate that the waters in Gulf of Mannar and Palk Bay area (Northern waters of Sri Lanka closest to India) have high surface chlorophyll values (approximately between 0.5 – 5.0 mg m^{-3}). This is a shallow water area of < 100 m in depth (Dwivedi, 1993), and can be considered as a case II water, where suspended particles and dissolved organic matter, which interfere with the optical signature of chlorophyll *a*, enhance the derived chlorophyll *a* values. Additionally, the bottom effect is also a factor to consider in these shallow waters. The maps in Figure 1(f) to 1(i) exhibit areas of higher mean chlorophyll values (~1.0 – 5.0 mg m^{-3}) with colours varying from green to yellow in the Southern and Western waters, during the months of June - September. During the months of February to March [Figures 1(b) – 1(d)], most of the waters around the island are blue colour, which corresponds to low chlorophyll values (< 1.0 mg m^{-3}).

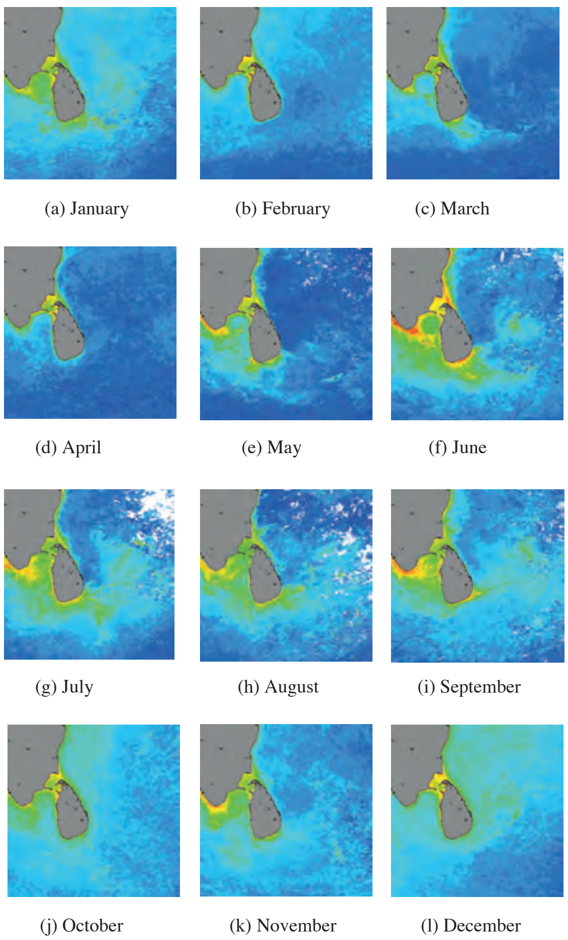

Figure 1: Chlorophyll *a* composites for each month [(a) January – (l) December] using data for the whole period 1999 – 2003. The logarithmic colour scale used in the plots is shown in Figure 2. The white patches seen in some maps [i.e., top right corner in Figure 1(g) for July] illustrates areas with no data due to heavy cloud cover. The northeast monsoon period falls during December - March whereas the southwest monsoon period falls during May - September.

Figure 2 illustrates six sub-area boxes in a clockwise direction from Northeast to West, drawn on a chlorophyll distribution map (similar area boxes were used to extract data from maps of wind speed and its components). The mean values of data from the boxes have been used for the plots shown in Figures 3 to 5 and also for correlation analysis. Figure 3 shows the mean monthly chlorophyll variability during the two monsoons, northeast [Figure 3(a)] and southwest [Figure 3(b)], for the entire study period from 1999 – 2003. During the northeast monsoon period, the chlorophyll concentrations stay below 0.6 mg m^{-3} except in the East during December, 2000 when values in some areas reached 1.0 mg m^{-3}. In the Northeast and East regions, the highest averages were recorded in the month of December (around 0.5 mg m^{-3}) and the values do not vary much from year to year. The lowest mean values for both regions were recorded in 2003. The average chlorophyll concentrations in the Western and Southern regions appear to have considerably high monthly and annual variability during the southwest monsoon throughout the study period. Generally, the southwest monsoon peaks during the months of June - August and is stronger than the northeast monsoon. The SW monsoon primarily impacts the Southern and Western waters as illustrated in Figure 3(b). These areas exhibit high chlorophyll values and a considerable variation in the pattern from year to year. The year 2000 exhibits lower averages in all three regions comparatively, and South and Southwest having lowest average values of around 1.0 mg m^{-3}. However, the Eastern region exhibits a higher value than the average value of chlorophyll, during the northeast monsoon in 2000.

Figures 4 and 5 show monthly variability of the four parameters: chlorophyll *a* concentration and wind speed in Figure 4(a) and 4(b), respectively; and zwind and mwind in Figure 5(a) and 5(b), respectively. The entire period averages for each month are used in these plots. Figure 4(a) shows that the highest average chlorophyll *a* concentrations (between 2.5 – 3.0 mg m^{-3}) are found in the Western region during the months of June to September. The average concentrations for East and NE region waters are below 1.0 mg m^{-3} throughout

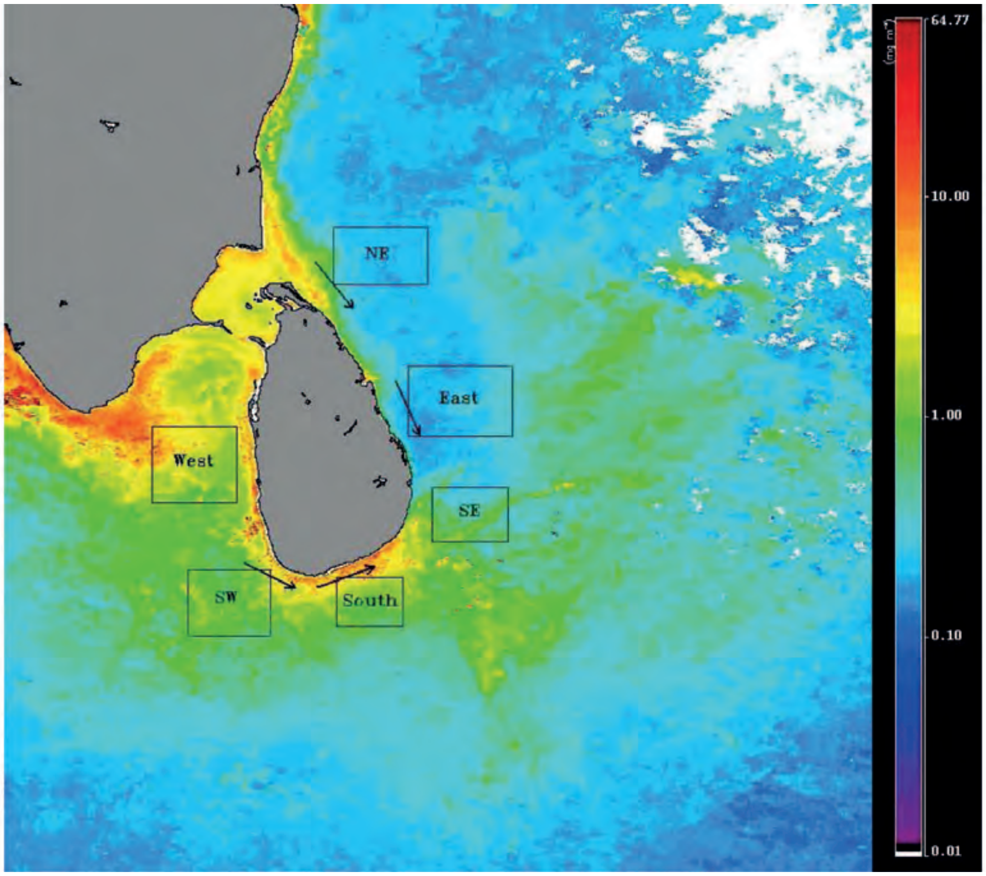

Figure 2: Enlarged chlorophyll *a* composite map for the month of July is shown as an example with the logarithmic colour scale depicting chlorophyll concentrations. The data from the six boxes shown in the directions Northeast (NE), East, Southeast (SE), South, Southwest (SW) and West are used in the analysis. The winds parallel to the coast in the South and SW during the southwest monsoon and in the NE and East during the northeast monsoon, respectively, are marked with arrows.

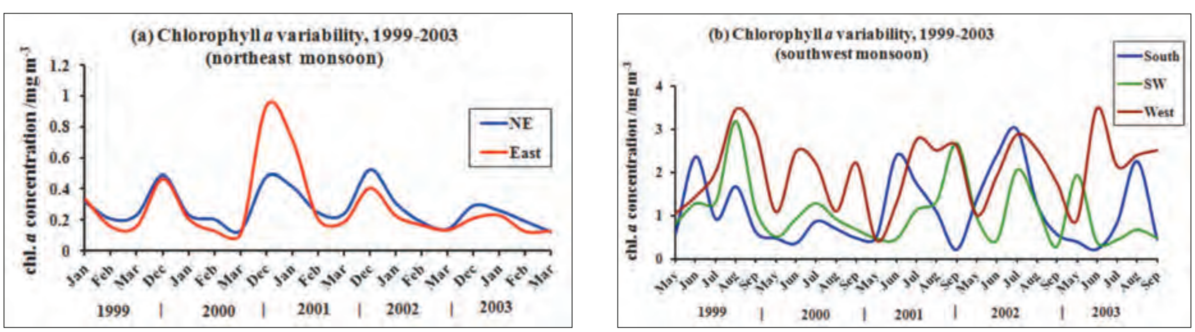

Figure 3: Time series plots of chlorophyll *a* concentration

(a) Chlorophyll *a* for the NE and East regions during northeast monsoon and

(b) Chlorophyll *a* for the South, Southwest and West regions during southwest monsoon. Mean values of the boxes (the regions in the six directions shown in Figure 2) are used in the plots.

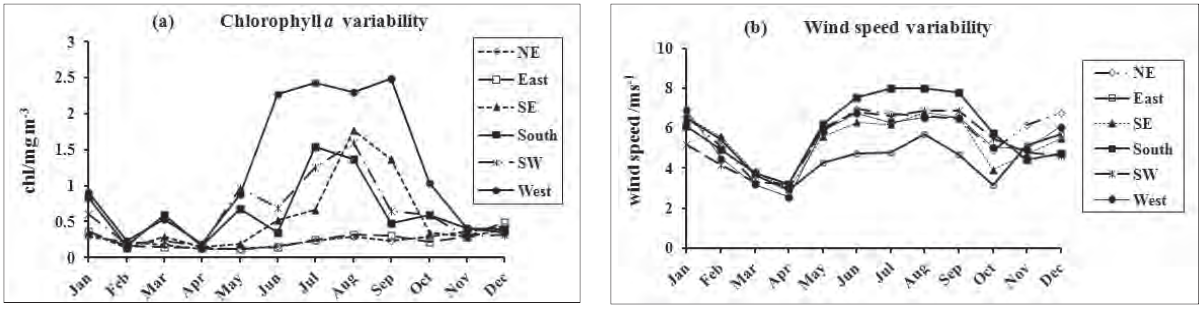

Figure 4: Mean annual variability of chlorophyll *a* and wind speed are shown in the plots (a) and (b), respectively. Mean values of the boxes (in the six directions shown in Figure 2) of chlorophyll *a* and wind speed composites for the whole study period are used in the respective plots.

the year. From Figure 4(a) and 4(b), it is clear that the surface winds strengthen during the southwest monsoon between June - September and peaks around July - August. Chlorophyll concentrations also reach peak values in the South and West during the same time. Wind speed averages reach approximately 8 ms^{-1} during the peak of the southwest monsoon. Also, from Figure 5(a) and 5(b), it is clear that the surface winds reverse during the southwest monsoon period (both zwind and mwind components change from negative in the northeast monsoon period to positive in the southwest monsoon). In a horizontal coordinate system, the zonal wind is positive if it blows from West towards East and the meridional wind is positive if it blows from South towards North. The plots in Figure 5 agree with the fact that, during northeast monsoon the winds blow from the Northeast direction (since both components are negative) and during southwest monsoon the surface winds blow from the Southwest direction, resulting in a complete reversal. The zonal wind component is stronger than the meridional wind component during the southwest monsoon [about twofold in magnitude – Figure 5(a)] whereas the meridional component becomes only slightly stronger than the zonal wind component during the northeast monsoon period [about 30 % more in magnitude – Figure 5(b)]. Plots (a) and (c) in Figure 6 illustrates the trends of the parameter chlorophyll *a*, against wind speed parallel to the coast in the regions NE and East, respectively, whereas (b) and (d) represent plots of chlorophyll *a* against mwind in the same two regions. In the South and Southwest regions, there is a strong trend for the chlorophyll concentration to increase with the increase of the wind speed parallel to the coast during the southwest monsoon period as shown in Figure 7 [plots (a) and (c)]. Also, zwind is the major contributor to the wind parallel to the coast, hence for the chlorophyll *a* variability as seen in plots (b) and (d) in Figure 7.

Correlation coefficients between (1) chlorophyll and the wind speed parallel to the coast, (2) chlorophyll and m/z wind components, have been calculated for the northeast and southwest monsoon periods using mean monthly data (averaged for the whole five year period) of the relevant months for each box. Most relevant results are given in Table 1 and Table 2, for the two seasons. Directions of the winds parallel to the coast are shown in Figure 2 with pointing arrows near each of the four boxes, NE, East, South and SW. During the northeast monsoon period (December - March) the winds blow from the Northeast direction and the wind parallel to the coast is very strongly correlated with chlorophyll *a* concentration. The values of the correlation coefficients (referred to as CC from here) are in the range 0.92 – 0.95 in NE and East regions as given in Table 1. It also shows that the meridional wind component is the major contributor to the total wind, hence the chlorophyll *a* variability during northeast monsoon period, with CC in the range 0.82 – 0.88. From Table 2 it is clear that chlorophyll *a* concentrations in the South and Southwest regions are strongly positively correlated with the winds parallel to the coast during the southwest monsoon period (May - October), with CC values between 0.94 – 0.99. The zonal wind components contribute more than 90 % to the total winds and hence the chlorophyll *a* variability with CC values in the range 0.97 – 0.99 (Table 2). With the winds blowing parallel to the coast towards the East, the upwelling phenomenon is very likely to occur in the Southern waters and hence the observed high chlorophyll *a* concentrations during southwest monsoon. A similar trend, though less strong, can be observed in the Southwestern region as well.

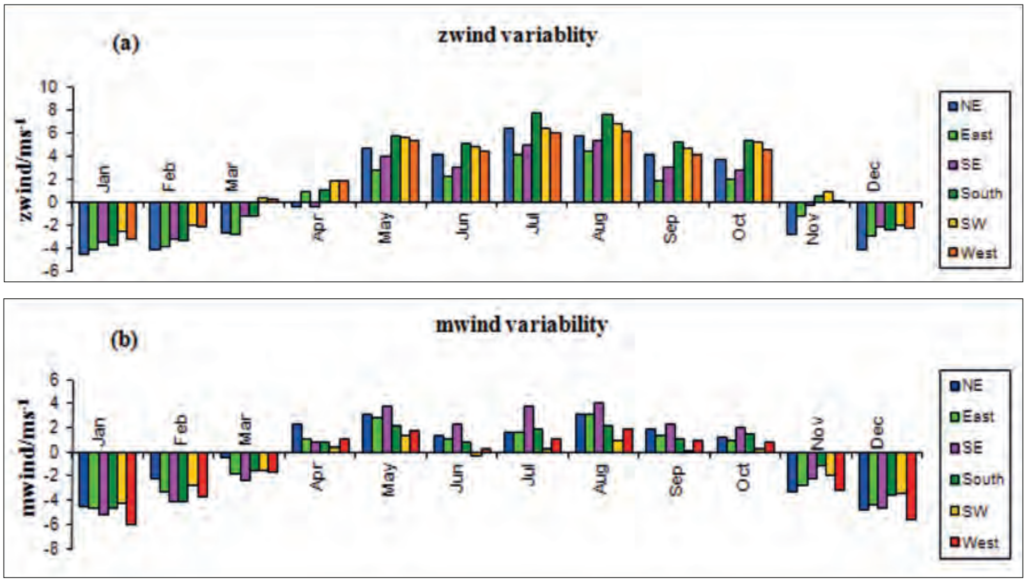

Figure 5: Mean annual variability of zwind and mwind are shown in the plots (a) and (b), respectively. Mean values of the boxes (in the six directions shown in Figure 2) of zwind and mwind composites for the whole study period are used in the plots.

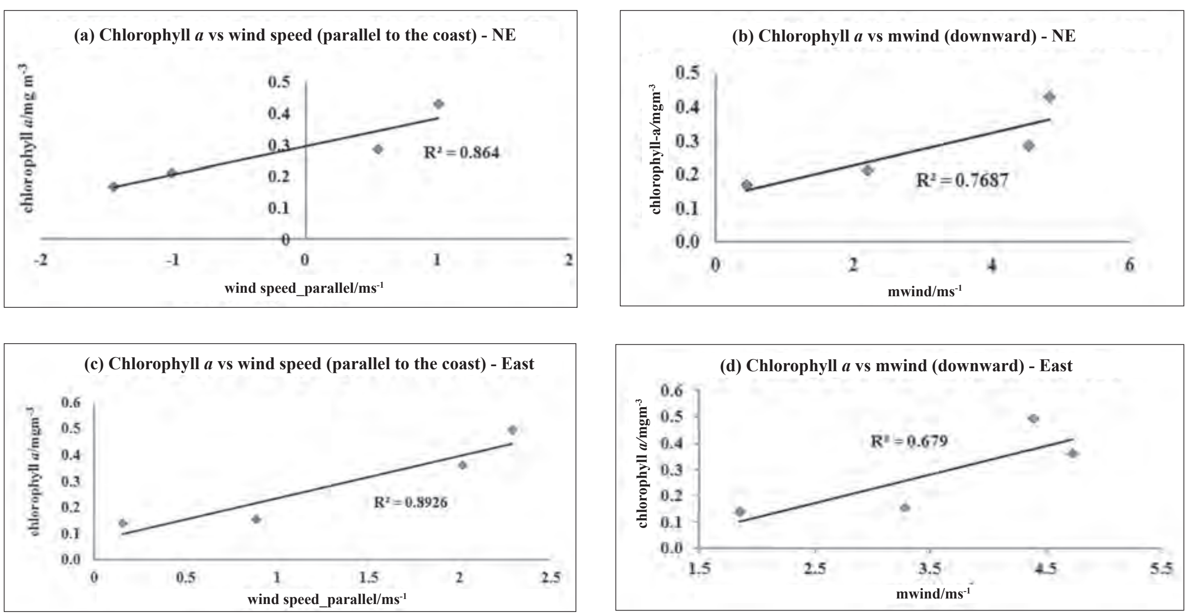

Figure 6: Plots (a) and (c) depict correlation between chlorophyll *a* and wind speed parallel to the coast in the Northeast and East regions during the northeast monsoon period (four data points in a plot represent period means of chlorophyll and wind for the months December, January, February and March), respectively. Plots (b) and (d) show the correlation between chlorophyll *a* and mwind for the same two regions.

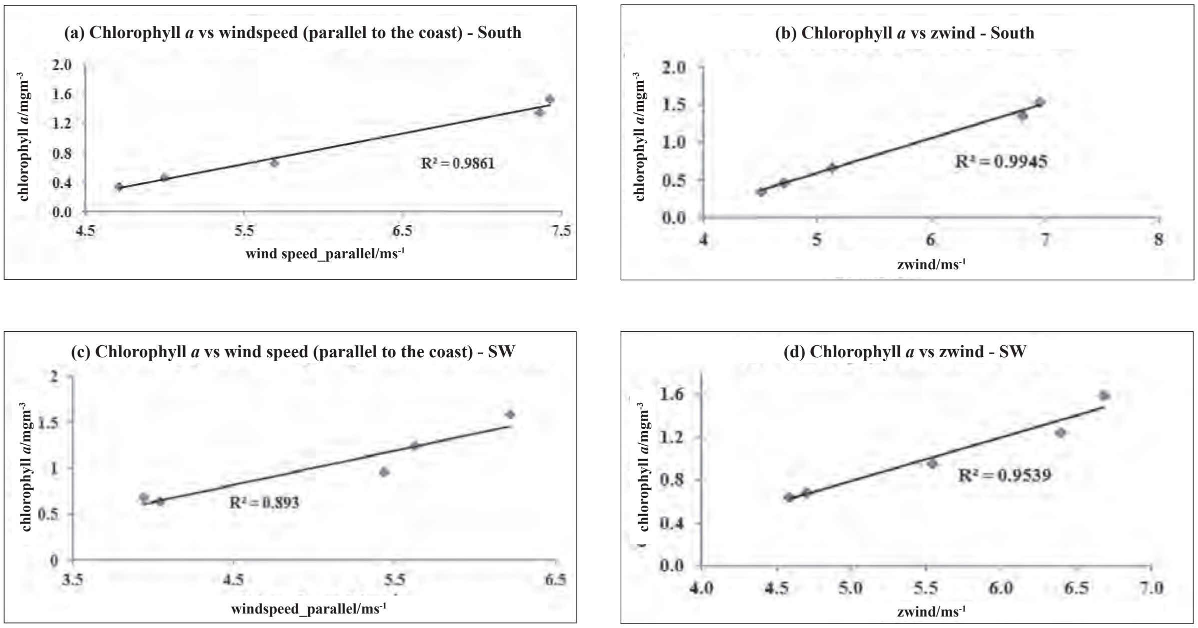

Figure 7: Plots (a) and (c) depict correlation between chlorophyll *a* and wind speed parallel to the coast in the South and SW regions during the southwest monsoon period (five data points in a plot represent period means of chlorophyll and wind for the months May, June, July, August and September), respectively. Plots (b) and (d) show the correlation between chlorophyll *a* and zwind for the same two regions.

Table 1: Correlation coefficients (CC) between chlorophyll *a* and the wind parallel to the coast and CC between chlorophyll *a* and mwind during the northeast monsoon period for the NE and East regions, respectively (Data used for plots in Figure 6 have been used in calculating CC).

Region	Wind speed (parallel to the coast) and chlorophyll *a*	mwind and chlorophyll *a*
NE	0.9296	0.8767
East	0.9447	0.8240

Table 2: Correlation coefficients (CC) between chlorophyll *a* and the wind parallel to the coast and CC between chlorophyll *a* and zwind during the southwest monsoon period for the South and SW regions, respectively (Data used for plots in Figure 7 have been used in calculating CC).

Region	Wind speed (parallel to the coast) and chlorophyll *a*	zwind and chlorophyll *a*
South	0.9930	0.9972
SW	0.9450	0.9767

DISCUSSION

Remotely sensed data for a five year period from 1999 – 2003 were used to study the spatial and temporal variability of the ocean parameters, surface chlorophyll *a*, surface wind speed and its components, and how these parameters are influenced by the southwest and northeast monsoons. Generally, the northeast monsoon is considered to be a moderate phenomenon. The low chlorophyll values and somewhat decreased wind speeds seen from the data in the East and NE regions during the months of December – March confirms this observation. Mean monthly variability of surface chlorophyll *a* concentration showed a marked difference during the southwest monsoon period (May - September) compared to the rest of the year. South and Southwest waters exhibit high concentrations of chlorophyll that are linked, likely to the high productivity in those waters during this period. As Southern and Southwestern waters are deeper (Solanlki *et al*., 2001) and can be considered as case I waters, high satellite chlorophyll values in this region are unlikely to be an artifact of high particulate loads from sediment resuspension or high organic matter input from terrestrial sources. Additionally, we attribute these high values to the enhanced phytoplankton productivity caused by wind driven upwelling. The zonal wind component and the total wind parallel to the coast exhibiting very high co-variability with chlorophyll *a* also suggests the possible upwelling in the area. The transport of nutrients into the surface layer through upwelling driven by alongshore winds, results in high phytoplankton concentrations (Vinayachandran *et al*., 2004). High chlorophyll concentrations may indicate high primary productivity in the region and in turn, may sustain high fish production (Cushing, 1969). Identification of these high production areas can be very helpful to the local fishermen to enhance their fish catch. A study is underway to identify and locate such coastal and open ocean upwelling areas using remotely sensed data from MODIS (moderate-resolution imaging spectroradiometer), by combining, in particular, ocean colour and sea surface temperature with other relevant ocean parameters.

The southwest monsoon current (SMC) flows South of Sri Lanka towards the East (Vinayachandran *et al*., 2004) and ultimately turns Northeast into the Bay of Bengal (Vinayachandran *et al*., 1999). SMC brings chlorophyll rich waters from the Indian coast towards Sri Lanka (Vinayachandran *et al*., 2004) enhancing the chlorophyll concentrations in the Western region. Upwelling linked changes in chlorophyll *a* are primarily discernible in Southern and Southwestern waters. This study also suggests a possible upwelling in the NE and East regions during the northeast monsoon period, though less strong compared to that seen in the South and SW regions during the southwest monsoon. This study implies that the wind can be a major factor in chlorophyll *a* variability in the waters around Sri Lanka, but it may not be the only factor as some regions with reasonably high chlorophyll exhibits opposite or no relation to the wind. i.e. chlorophyll and wind or chlorophyll and m/zwind show no correlation in the Western region (results are not shown). More studies are required for further quantification and to assess the relative contribution from various processes to these phenomena. The Indian Space Research Organization's Oceansat-2 satellite launched in 2009 is equipped with sensors for ocean colour and wind vectors, and is especially designed to identify potential fishing zones. This represents an excellent opportunity to expand on the work presented in this paper.

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