Variability of SeaWiFS-derived surface chlorophyll-*a* of waters around Sri Lanka for 1999

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Abstract

Ocean colour data obtained from SeaWiFS through NASA's Goddard DAAC Center are processed and analyzed. Raw data of 1km resolution within the area of latitudes 2N-13.5N and longitudes between 76.5E-88.0E on relatively cloud free days from December 1998 to December 1999 are processed using OC4 algorithm of Seadas to produce chlorophyll maps. Processed data include about 95 single day maps and composite maps were made for each month and season.
The seasons are defined approximately as follows: Northeast (NE) Monsoon (December-February), First Inter-monsoon (March-April), Southwest (SW) Monsoon (May-September) and Second Inter-Monsoon (October-November). During SW Monsoon waters off west and southwest coasts exhibit higher surface pigment concentrations (> 1 mg m). This region exhibits a shallow mixed layer (only about 30m deep) during SW monsoon, which supports possible upwelling in the region. During SW Monsoon currents originate from the Arabian Sea, where strong upwelling is observed, flow from west to east in south of Sri Lanka and bring nutrient rich upwelled waters towards south. This enhances surface pigment concentrations as well. During the SW Monsoon patches of high chlorophyll are visible to the east of Sri Lanka where colder Sri Lanka Dome is located. During NE Monsoon and First Inter-monsoon, waters around Sri Lanka show relatively low chlorophyll-a concentrations (< 0.5 mg m^{-3}) except at few areas off northeast coast. The effect of surface wind forcing on variability of surface chlorophyll is studied as well. During the month of March when the Northeast Monsoon tapers down and when winds are somewhat weaker, over 60% correlation is found between chlorophyll and meridional wind stress in the Northeast region.

Introduction

Remote sensing is the technique of obtaining information about objects or phenomena through devices, which are not in physical contact with objects or phenomena under investigation. The sensor systems involved in electromagnetic remote sensing where the sensor detects natural radiation reflected or emitted from the target falls in the category of passive remote sensing. It is the most widely used remote sensing technique for monitoring world oceans. Multi-spectral scanning devices aboard earth-orbiting satellites provide synoptic views of large areas of the ocean. Valuable oceanographic parameters such as sea surface pigment chlorophyll-a and sea surface temperature (SST) are derivable from such satellite data. In this paper we focus mainly on the variability of pigment concentration on ocean surface waters and effects of wind forcing.
The pigment chlorophyll-a found in microscopic plant phytoplankton, is known to produce systematic variations in the colour of the ocean. In open ocean waters, ocean colour is used as an indicator of pigment chlorophyll-a concentration. An ocean colour sensor receives upward radiant flux from the sea surface, after modification by the intervening atmosphere. It is possible to arrive at a value of water-leaving radiance known as emergent flux after applying atmospheric correction procedures. Emergent flux is the light that upwells through the sea surface after the incident light goes through scattering and absorption processes in the water. This emergent flux contains the information about the optical properties of the medium and thermal features of the ocean. Such information is acquired through empirical relations derived from theoretical modeling of the underwater light field. Studying this emergent flux by remote sensing instruments, located at a considerable distance above the earth surface, provides information about the ocean surface as well as underwater environment over a large area of the ocean in a very short time. Also, as a satellite can be operated for long periods, remote sensing provides time series data over time periods ranging from weeks to years.
Ocean colour is affected by marine plants, suspended sediments and dissolved organic matter. The ocean colour data are considered to be very critical by the oceanographic community for studies of ocean primary production and ocean biogeochemistry. Primary production refers to organic materials in the sea that are produced by "primary producers", such as algae and bacteria, using sunlight or chemical energy. It is believed that marine plants remove carbon from atmosphere at a rate almost equivalent to terrestrial plants, but the knowledge of inter-annual variability of this carbon removal is very poor. The

concentration of phytoplankton can be derived from satellite data and quantification of ocean colour. Thus, it is a valuable tool to assess the ocean's role in the global carbon cycle and exchange of other critical elements and gases between ocean and the atmosphere. Thus, local information of pigment variability is very crucial in such global assessments.
Remotely sensed raw data from SeaWiFS (Sea viewing Wide Field of Sensor) obtained through NASA's Goddard DAAC is used here to study ocean waters around Sri Lanka. The knowledge of surface chlorophyll-a distribution can be used as a valuable tool in identifying possible fishing areas in the ocean. Waters around Sri Lanka have not been explored due to various reasons, mainly due to the fact that the filed of oceanography in the country is still a field in its infancy. Also, most of the waters around the country, especially, in north and east are inaccessible for scientific explorations. Therefore, remotely sensed data is a valuable option for ocean scientists in Sri Lanka to gain some knowledge about relevant physical and biological parameters. We studied seasonal chlorophyll variability in waters around Sri Lanka using data of 1km resolution obtained from the Coastal Zone Colour Scanner (CZCS)[1]. However, lack of continuous archiving of high-resolution data for ocean waters in this part of the world during its operation, has made interpretation of results a rather difficult task. In this paper we hope to use data from SeaWiFS (Sea viewing Wide Field of Sensor) to provide a much broader understanding of these waters.

Materials and Methods

Remotely sensed data from SeaWiFS (Sea viewing Wide Field Sensor) obtained through NASA's Goddard Distributed Active Archive Center is used here to study ocean waters around Sri Lanka. Raw data of about 1 km resolution for the period between December 1998 – December 1999 were processed to produce pigment chlorophyll-a maps of waters around Sri Lanka within latitudes between 2N – 13.5N and longitudes between 76.5E – 88E. The area was so chosen to study influences of waters around Sri Lanka from both Arabian Sea and Bay of Bengal during Southwest and Northeast Monsoon periods. Raw data were processed using OC4 algorithm of seadas on ENVI/IDL environment in derivation of pigment concentrations using the three bands of wavelengths centered at 443 nm, 490 nm and 510 nm. The radiance (flux per unit area per unit solid angle) received by the sensor, $L_{tot}(\lambda)$, can be given as

$$L_{tot}(\lambda) = L_r(\lambda) + L_a(\lambda) + L_{ra}(\lambda) + tL_g(\lambda) + tL_w(\lambda) \qquad \text{---------------------} \quad (1)$$

where $L_W(\lambda)$ is the water leaving radiance, $L_r(\lambda)$ is the contribution due to is the contribution due to Rayleigh scattering, $L_a(\lambda)$ is the contribution due to aerosol scattering, $L_{ra}(\lambda)$ is the contribution due to Rayleigh – aerosol scattering, $L_g(\lambda)$ is the sun glint (direct reflection of radiation from the sea surface) and t is the atmospheric transmittance factor. The remote sensing reflectance, R_{rs} is defined as

$$R_{rs}(\theta,\phi,\lambda,0) = \frac{L_w(\theta,\phi,\lambda,0)}{E_d(\lambda,0)} \qquad \text{-----------------------} \quad (2)$$

where $E_d(\lambda,0)$ is the downwelling irradiance at the sea surface. The chlorophyll-a concentration is derived from the empirical relation

$$\text{chl - a (mg m}^{-3}) = 10^{(a(0)+a(1)R+a(2)R^2+a(3)R^3+a(4)R^4)} \qquad \text{-----------------------} \quad (3)$$

where $R = \frac{\log_{10}(R_{rs}(443) > R_{rs}(490) > R_{rs}(510))}{R_{rs}(550)}$ and a(0) = 0.366, a(1) = -3.067, a(2)=1.93, a(3)=0.649 and a(4)=-1.532. The wavelengths 443 nm, 490 nm and 510 nm are used for chl-a in the ranges 0.01-0.1, 0.1-1.0 and chl-a >1.0, respectively. While processing the data, the days with heavy cloud cover left unprocessed, as they did not provide any chlorophyll information after atmospheric corrections. The processed data set for the period from Dec. 1998 to Dec. 1999 includes about 95 single day maps. These single day maps were then used to make monthly and seasonal composites. The seasons are defined approximately as follows; First Inter-Monsoon (March – April), Southwest Monsoon (May – September), Second Inter-Monsoon (October – November) and Northeast Monsoon (December – February). Surface wind field at 10 m height (wind speed, meridional wind, zonal wind and wind angle) provided through NMC (National Meteorological Center) model is also derived and mapped at the same resolution as pigment concentration. Co-variability of surface meridional wind speed and chlorophyll-a concentration is studied for the month of March in 1999 for the North Eastern waters of Sri Lanka.

Results and Discussion

Figure 1 shows the seasonal composites of the concentration of surface chlorophyll-a for the Northeast Monsoon (Dec-Feb), First-Inter Monsoon (March-April), Southwest Monsoon (May-Sep) and Second-Inter Monsoon (Oct-Nov) periods, respectively. The logarithmic false colour bar varies from purple to red with the increase of pigment concentration (from 0.01-64.0 mg m^{-3}). White patches seen in the maps represent no data due to cloud cover. It is apparent from the map for the Northeast Monsoon (Dec-Feb) season in Figure 1 that the waters show very low concentration of chlorophyll-a (from 0.01-0.5 mg m^{-3}) except in some coastal areas, which reach around 1 mg m^{-3}. Northern waters between Sri Lanka and India (between Gulf of Mannar and Palk Bay) show high chlorophyll concentrations (over 1 mg m^{-3}). This is apparent in other maps as well. The waters in this area are very shallow (< 100 m in depth) and can be considered as case II waters. As OC4 algorithm is not tuned well to case II waters, suspended sediments and dissolved organic matter that present in these waters may have interpreted as chlorophyll by the algorithm. During Northeast Monsoon the winds blow from Bay of Bengal region towards Sri Lanka. The East Indian Coastal Current flows from Bay of Bengal along the east coast of Sri Lanka towards south[2]. This current may also contribute to moderately high chlorophyll concentrations visible in the eastern coastal region. The map for the First-Inter Monsoon period (March-April) in Figure 1 exhibits very low chlorophyll concentrations (< 0.5 mg m^{-3}) in open ocean waters all around the island.

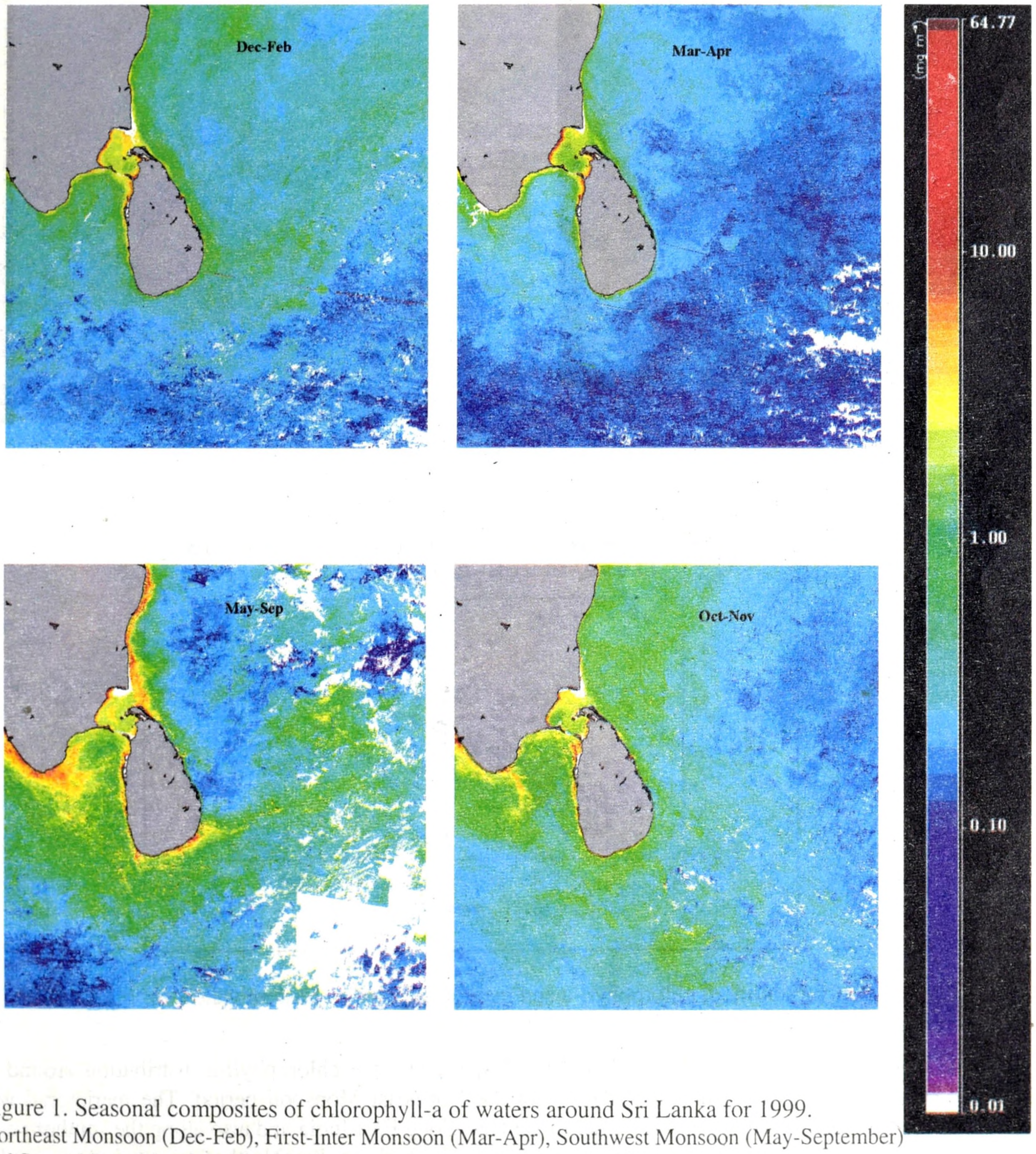

Figure 1. Seasonal composites of chlorophyll-a of waters around Sri Lanka for 1999.
Northeast Monsoon (Dec-Feb), First-Inter Monsoon (Mar-Apr), Southwest Monsoon (May-September) and Second-Inter Monsoon (Oct-Nov).

Southwest monsoon prevails during the period from May until September. The map in Figure 1 shows high spatial variability of surface chlorophyll-*a* for this period. The winds blow from west towards east during the southwest monsoon period. The surface currents originate in the Arabian Sea region, such as, the West Indian Coast Current[3] and the Southwest Monsoon current[3] flow towards south of Sri Lanka and move towards east moving anti-clockwise around Sri Lanka Dome[4] in the east. High surface chlorophyll-a concentrations (well over 1 mg m^{-3}) are visible in the south and southwest waters extending from the coast towards deep ocean waters. A patch of high chlorophyll concentration (over 2 mg m^{-3}) is visible around latitude of 85E where cold water Sri Lanka Dome is found. During this period a rather shallow mixed layer of only about 30 m has been found[5] in the southwestern oceanic region, which suggests possible upwelling in the area. Southern coastal waters exhibit an area of upwelling during southwest monsoon as seen in Figure 1, with chlorophyll concentrations of over 10 mg m^{-3}. Unlike other coasts, these waters are much deeper, lying within 2000 m depth contour line. Therefore, we may assume that high chlorophyll values represent nutrient rich productive waters in the area. The effects of Southwest Monsoon on chlorophyll-a distribution can be seen in the map for the Second-Inter Monsoon (Oct-Nov) as well. The southwestern and southern waters exhibit moderately high chlorophyll concentrations during this period.

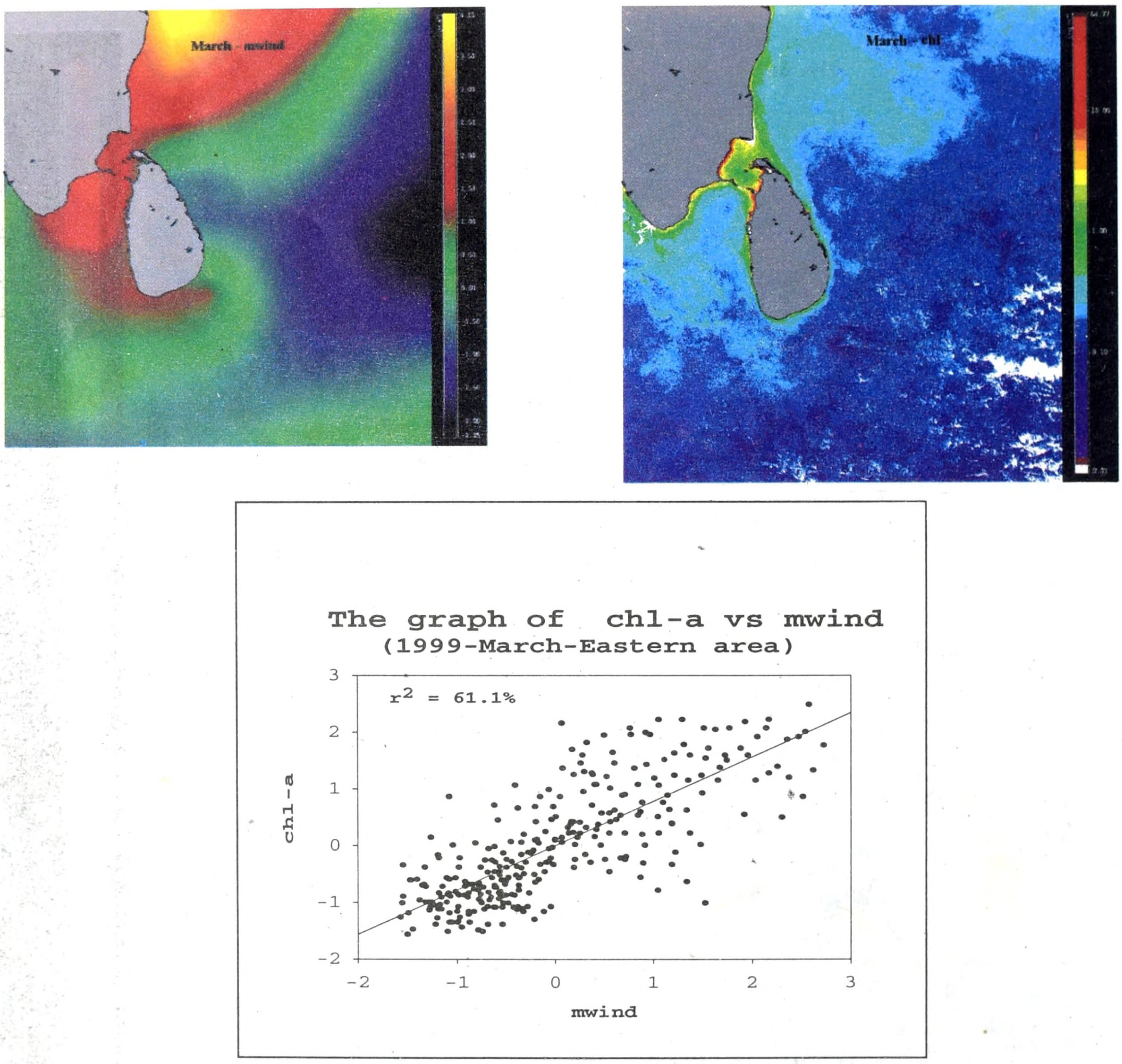

Figure 2. Co-variability of chlorophyll-a and meridional wind in Eastern waters for March 1999.

Figure 2 shows the variation of meridional wind speed and the chlorophyll-a distribution around the island for March 1999, which is the tail end of the Northeast Monsoon period. The meridional wind speed is higher (between 1 - 4 m s^{-1}) closer to the land along East India and also along the southern coast of Sri Lanka. Chlorophyll-a distribution is moderately high in the Northeast waters compared to

Southeast. The plot in Figure 2 exhibits over 60% co-variability of chlorophyll-a concentration and the meridional wind in the oceanic waters in the eastern part of Sri Lanka. The wind forcing effect in the eastern region during March is somewhat weaker as the Northeast Monsoon tapers down. However, apparent co-variability exhibits the fact that Northeast Monsoon winds have a significant impact on the distribution pattern of pigment chlorophyll-a.

Conclusion

Variability of SeaWiFS-derived surface chlorophyll-a of waters around Sri Lanka during year 1999 is presented in this paper. This study reveals that the Southwest Monsoon triggers upwelling in the western and southern ocean waters of Sri Lanka. High concentrations of surface chlorophyll-a observed in the southwestern waters during Second-Inter Monsoon period may be due in part to after effects of Southwest Monsoon. The patch of high chlorophyll present in the east during Southwest Monsoon period supports the forming of the cold water Sri Lanka dome in the area. The currents originating from Arabian Sea during SW Monsoon and currents originating from Bay of Bengal during NE Monsoon periods influence surface chlorophyll-a in the western and eastern waters, respectively. A high co-variability between surface chlorophyll-a and meridional wind exists in the Northeastern waters during March. Further studies of co-variability of physical and biological parameters of ocean waters around Sri Lanka are being carried out at present.

Acknowledgements

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