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Seasonal and Inter-annual Variability of Chlorophyll–a in the Arabian Sea from SeaWiFS Data

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Abstract

This study utilizes monthly mean chlorophyll–a concentration (Chl–a) and sea surface temperature (SST) retrieved from Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and Advanced Very High Resolution Radiometer (AVHRR) respectively. In addition surface wind vector derived from SeaWinds observations were used in this study. The Chl–a and the SST data for the period September 1997 to August 2007 were used in the present study. Whereas the wind vector for the period August 1999 to August 2007 is used. The seasonal and inter-annual variations in the Chl-a and SST in the Arabian Sea warm pool region were clearly observed. The winter bloom signatures were seen in the month of February. One interesting result obtained from the study is, post 2002 period shows Chl–a maxima in the month of September. High inter-annual variation in Chl–a and SST were observed during south–west monsoon months after 2002. The effects of wind stress and SST on the Chl–a are studied. It is found that the relation between wind stress induced divergence/convergence of the ocean surface (Cov/Div) and Chl–a is stronger than that of SST. Exceptionally high anomalous Chl–a was observed during 2004 and 2006 summer monsoon period due to increased Cov/Div and low SST during these periods.

Introduction

The Oceans play a major role in shaping the regional and global climate through the exchange of heat, mass and momentum with the atmosphere. The biological processes in World Ocean are mainly controlled by the presence of phytoplankton, which forms the base of the food chain. They fix the atmospheric CO_2 through photosynthesis, taking part in the oceanic carbon cycle. Hence, oceans act as the major carbon sink. The biggest question is how ocean biota reacts to the climate change. Laboratory study suggests that enrichment in CO_2, sea surface temperature and exposure to higher mean radiances have a large influence on the growth of ocean biota, potentially on the particulate inorganic carbon (*i.e.* biogenic particles of $CaCO_3$) to particulate organic carbon (PIC/POC) ratio (Feng *et al.,* 2008; Fabry, 2008). Among the major oceans of the world, the Indian Ocean is a dynamically complex and highly variable system, with circulation features and biogeochemical properties that are unusual in many respects. Arabian Sea is one of the most productive regions in the world and is characterized by strong seasonal oscillations in biological production. In summer, the strong southwest monsoon causes intense upwelling in the western Arabian Sea, while in winter surface cooling in the north results in enhanced vertical mixing. In both the cases, the photic zone gets nutrients from below, resulting high productivity. Also, in the Arabian Sea the oxygen minimum zone is reported at depths of 150–1000m, where de-nitrification takes place (Altabet *et al.,* 1995, Brandes *et al.,* 1998). Emission of N_2O as a result of de-nitrification, which is a potent greenhouse gas, is a cause of concern and has significant implication to the global warming. Although the Indian ocean is more

complex and highly dynamic, it is one of the most under-sampled and least understood of the world's ocean basins. The desired solution is the observation of the ocean from Space. Launch of SeaWiFS in August 1997 made it possible to acquire the biological data over the global ocean from 1997 onward for the cloud free regions. Earlier study shows that, the Indian Ocean is warming rapidly (Alory *et al.,* 2007), but the impacts of this warming on the biota, carbon fixation, and nitrogen cycling are not known. Our study focuses on the intra- and inter-annual variation of Chl–a concentration utilizing the information from the SeaWiFS sensor.

Data and Methodology

The present study has made use of SeaWiFS data for the period 1997 - 2007 over the Arabian Sea region to understand the variability in chlorophyll pattern in the Arabian Sea on seasonal, intra and inter-annual basis. A 8º x 8º grid (10ºN-18ºN, 60ºE-68ºE) is selected in the Case–1 water (open ocean) in the Arabian Sea warm pool region for the present study (see Fig. 1). Atmospherically, radiometrically and geometrically corrected monthly chlorophyll images have been analysed. These are level-3 global gridded product with 9 km resolution distributed by NASA (ftp://oceans.gsfc.nasa. gov/SeaWiFS/Mapped/Monthly/CHLO/) All of the data products from SeaWiFS are stored in the Hierarchical Data Format (HDF). From the global image chlorophyll images for the Arabian Sea has been extracted using SeaDAS software.

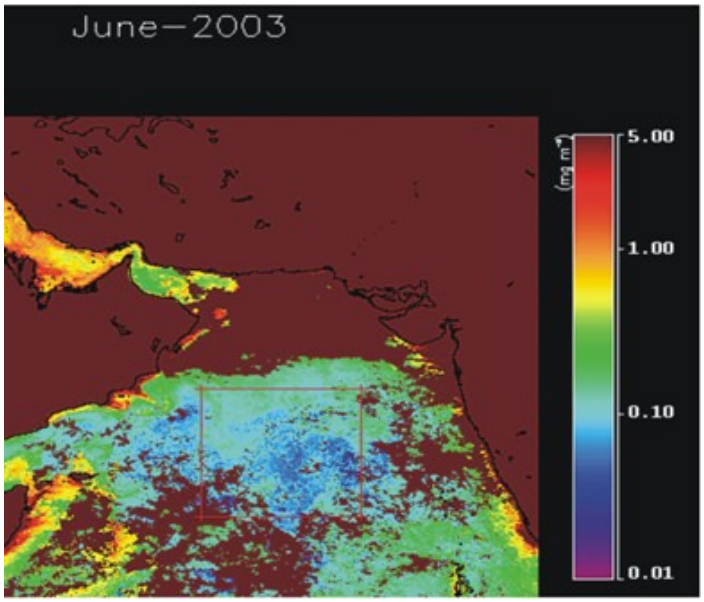
Present study uses the monthly surface wind stress data August 1999 to August 2007. These data sets are available for the whole globe in 0.5º Latitude by 0.5º Longitude grid from CERSAT, at IFREMER, Plouzané (France*)* (ftp://ftp.ifremer.fr/ifremer/cersat/products/gridded/mwf-quikscat/data/monthly/). Concurrent observations of sea surface temperature (SST) over the Tropical Indian Ocean are used to analyze the effect of sea surface cooling due to upwelling on the chl-a concentration. Monthly composite SST data are taken from National Ocean Atmosphere Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) for September 1997 to August 2007.

The convergence/divergence of the water mass on the oceanic surface has been computed from the continuity equation assuming the fluid to be incompressible. The convergence/divergence has been computed using the surface flow fields provided by Pond and Pickard (1983):

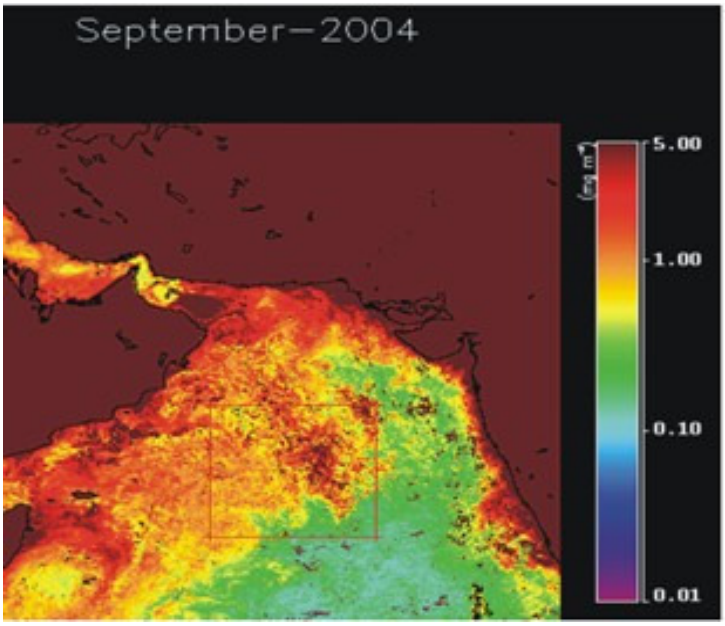
$$C = [\partial \zeta x/\partial x + \partial \zeta y/\partial y] \quad \ldots\ldots\ldots\ldots \quad (1)$$

Where, C is convergence or divergence depending upon sign, ζx is zonal and ζy is meridional components of the surface flow respectively. The direction of "ζx" is taken to be positive towards east and the direction of "ζy" is taken to be positive towards north. The flow vector of the surface water is computed from the SeaWinds wind stress fields by applying the Ekman solution to the equation of motion (Pond and Pickard, 1983). Ekman transport perpendicular to the wind stress varies and upper layer water is forced towards or away from each other, *i.e.* convergences or divergences will develop. Continuity, then requires, that a convergence be accompanied by a downward motion (down-welling) while a divergence is accompanied by upward motion (upwelling). It is to be noted that upwelling (down-welling) of surface water is decided based on whether there is convergence

(divergence) occurring on the ocean surface. The convergence is calculated for all the grid points in the study regions.



Mean chlorophyll-a concentration=0.099458 mg/m3



Mean chlorophyll-a concentration=1.257206 mg/m3

Fig. 1: The monthly mean chlorophyll-a concentration in the Arabian Sea. The study area is shown by a red colour box. Minimum & Maximum in the study region represented by box for the last 10 years (Sep.1997-Aug. 2007).

Results and Discussions

This section is divided into two sub-sections (i) seasonal and Inter-annual variability and (ii) Quantifying the role of SST & Con/Div on Chl–a.

Seasonal and inter-annual Variability:

The variance in the spatial distribution of Chl–a over the study region has been compute to examine the uniformity in distribution of Chl–a. The variance found to be low (not shown here) in all the months for different years, indicating uniformity in the distribution of Chl–a over the study region. The Chl–a, Con/Div and SST for each month of different years are shown in Fig. 2. It has to be noted that the upwelling/down-welling is associated with Con/Div. Here after we have used Con/Div for quantitative description and upwelling/down-welling for physical explanation. The maximum Chl–a occurred in September 2004 (1.257206 mgm-3) whereas the minimum is found in June 2003 (0.099458 mg/m3). Generally, during April – May and November – December Chl–a found to be low compared to other months. This is attributed to the seasonal reversal of tread wind. A quantum increase in concentration is observed from May to July in all the years. Concurrent study of Con/Div for years 1999 to 2007 and the SST form 1997 to 2007 during monsoon months showed increases in Con/Div and decreases in SST (see Fig. 2 c-f) indicating the signature of strong upwelling in the study region. The winter bloom signatures were seen in the month of February in Chl–a. Earlier studies have reported the winter blooms during the same period (Banse and McClain, 1986). It is very interesting to note that after 2002 the maximum Chl–a occurs in September. Investigations are on to find out the cause of the same.

The anomalies in Chl–a, wind stress induced divergence (convergence) of the ocean surface and SST have been studied during (i) South-West monsoon (SWM) period (April to September) (ii) North – East monsoon (NEM) period (October to March). Fig.3 shows the monthly anomaly in Chl–a, Con/Div and SST for the study period. Inter-annual fluctuations in the Chl–a were found to more during June – September *i.e.* during south-west monsoon. One interesting result revels that after 2002 the amplitude of these fluctuations are large (see Fig 2). The years 2004 and 2006 are observed to be the exceptionally high anomalous year in Chl–a (see Fig. 2 a). These variations are attributed to the large anomalous fluctuation in the strength of upwelling/down-welling during these years (see Fig. 2 e). No such types of fluctuations were found in the SST anomalies. Inter-annual anomalies are less during the north-east monsoon. During August the effect of wind induced upwelling is clearly seen. In this month wind stress induced divergence of ocean surface remains –ve, causing upwelling, resulting low SST hence enhancing the production of Chl–a. However, the over all analysis shows that high Chl–a is associated with the upwelling.

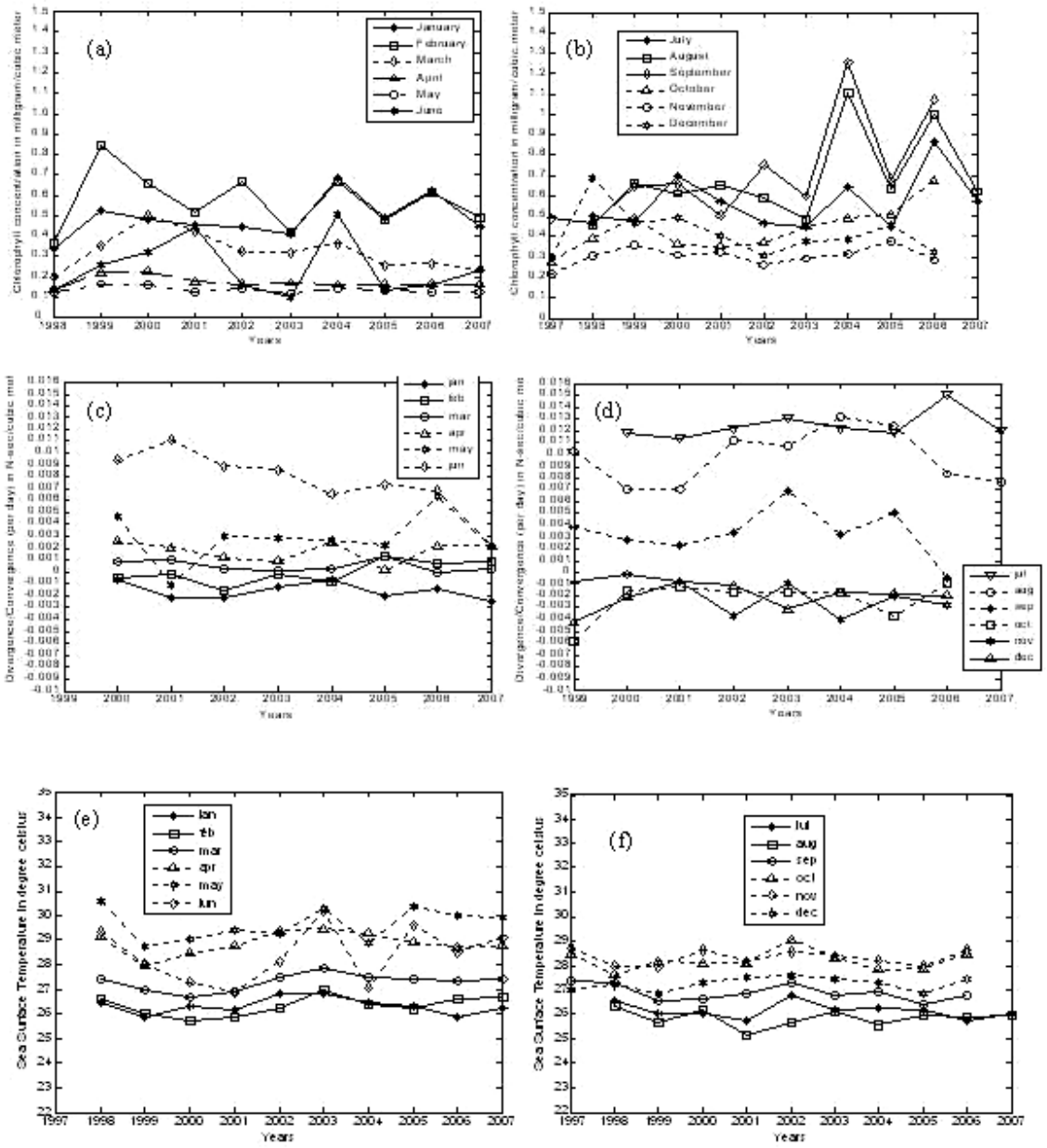


Fig. 2: Mean monthly chlorophyll – a concentration for (a) January – June (b) July – December; Mean monthly wind stress induced divergence (convergence) of the ocean surface for (c) January – June (d) July – December; and Mean monthly sea surface temperature for (e) January – June (f) July – December

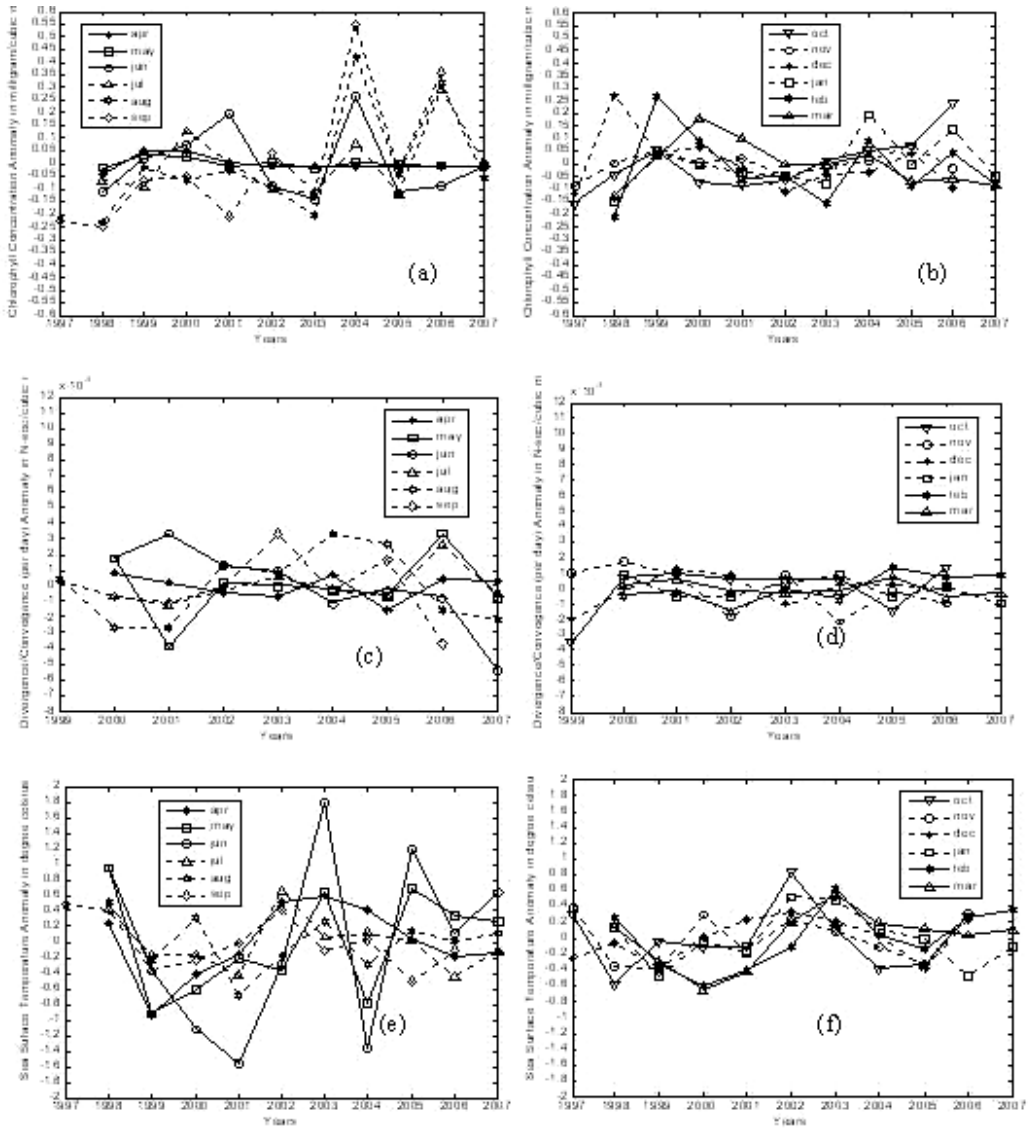


Fig. 3: Monthly anomaly in chlorophyll– a concentration for (a) South-West Monsoon (b) North-East Monsoon; Monthly anomaly in wind stress induced divergence (convergence) of the ocean surface for (c) South-West Monsoon (d) North-East Monsoon; and Monthly anomaly in sea surface temperature for (e) South-West Monsoon (f) North-East Monsoon

Quantifying the Role of SST & Wind Stress on Chlorophyll–a:

The trends of Chl–a in different months over the study region matches well with that of the trends of the wind stress induced divergence (convergence) of the ocean surface, hence the down-welling (upwelling) (see Fig. 4). For example: during March, April, May Chl–a concentration shows a decline trend and the wind stress induced divergence (convergence) of the ocean surface shows an increasing trend. But they are not one to one related. This is because Chl–a is not only a function of wind stress induced upwelling or down-welling and SST but also a function of surface currents and the availability of the nutrients. However, earlier studies showed that

there is a time lag of about four days between the productivity and wind forcing (Dwevedi *et al.,* 2004). Also the strength of the wind is not same through out the year. The northeasterly winds are 50% weaker than the summer monsoon winds (Luis and Pandey, 2005). Keeping the above facts in view a trial has been made to quantify the linear relation between SST, wind stress induced divergence (convergence) of the ocean surface and Chl–a. To a first approximation least square fit method is used to develop the relation between them. The developed equation is given as follows:

$$C = (-0.1363T) + (0.62816\tau) + (4.17521) \quad (2)$$

Where, C is chlorophyll-a concentration in mg/cubic meter, T is SST in °C and τ is the Con/Div.

Correlation coefficient is found to be 0.762 with an R.M.S. error of 0.15. The equation shows that the relation between wind induced surface Con/Div over the ocean and Chl–a is stronger than that of SST. Earlier studies showed that summer productivity in the central Arabian Sea is increased due to increase in sea surface wind (Goes *et al.,* 2005). The effect of variation in SST over the Chl–a during south – west monsoon in post 2002 period is not reflected in equation 2 because whole time series (*i.e.* August 1999 to June 2007) is used to develop the equation. We propose to further develop the relation using longer time series data and using pre and post 2002 data separately.

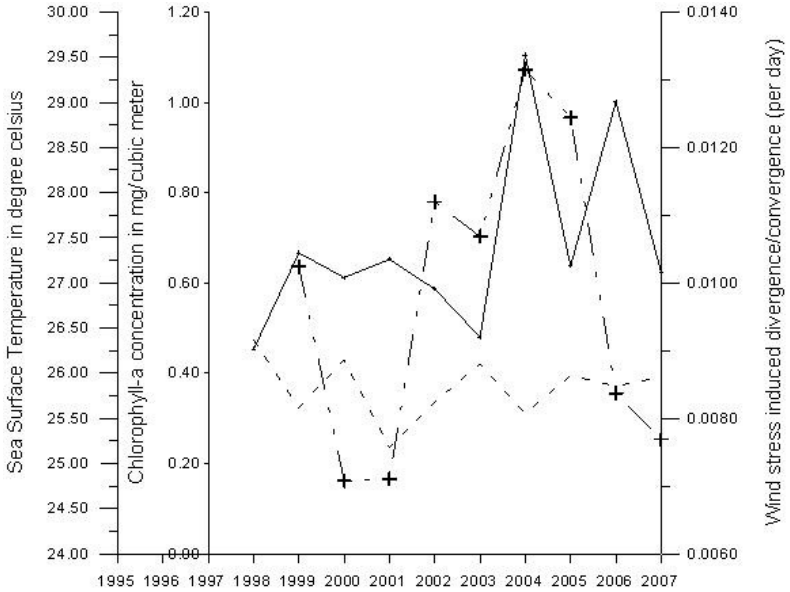


Fig. 4: Interannual variability of chlorophyll-a concentration (mg/m3) (solid line), wind stress induced divergence (convergence) of the ocean surface (per day) (N-sec/m3) (solid–dash line with legend) and sea surface temperature (^{o}C) (broken line) over the study region during the month of August.

Conclusions

Our analysis demonstrated the seasonal and inter-annual variations in the Chl-a in the Arabian Sea warm pool region. The SST and the wind play a very important role in Chl-a and its variability. The winter bloom signatures were seen clearly in the month of February. A significantly high Chl-a was observed during 2004 and 2006 summer monsoon period is due to increased wind stress induced divergence (convergence) of the ocean surface and decreased SST during these periods. Significant changes have been observed after 2002. Anomalous high fluctuations in Chl-a and SST have been observed in post-2002 south – west monsoon months. Maximum Chl-a was observed in the month of September after 2002. Anomalous high fluctuations in Chl-a and SST were observed during south – west monsoon months after 2002. The effect of wind stress and SST on the Chl-a is studied. It is found that the influence of wind stress induced divergence (convergence) of the ocean surface on Chl-a is stronger than that of SST. Exceptionally high anomalous Chl-a was observed during 2004 and 2006 summer monsoon period due to increased wind stress induced divergence (convergence) of the ocean surface and decreased SST during these periods. More investigations are on to study the non-linear relationship between Chl-a, SST and wind stress induced divergence (convergence) of the ocean surface.

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