Does SST Explain the Seasonal Variability of Chlorophyll in the Upper Indian Ocean?

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Abstract

Quantitative analyses of chlorophyll concentration in relation to Sea Surface Temperature (SST) can explain the spatiotemporal distribution of phytoplankton in oceans. In this study, the response of chlorophyll in the Bay of Bengal (BoB) and the Arabian Sea (AS) to seasonal SST was investigated using remotely sensed Moderate Resolution Imaging Spectroradiometer (MODIS) data. MODIS SST data were validated with in-situ data derived from the World Ocean Database. Thus, satellite-based SST estimates were more reliable for BoB than that of AS. In general, SST was comparatively high in BoB; the lowest 27.88° C recorded in January and the highest 30.33° C in April. In contrast, maximum SST in AS was 29.82° C in May and minimum 26.66° C recorded in January. The chlorophyll concentration in BoB was minimum (0.31 mg m-3) in April and maximum (0.46 mg m-3) in September. While the chlorophyllin AS was minimum (0.34 mg m-3) in April and maximum (1.18 mg m-3) in September. These results suggest a significant negative association between SST and chlorophyll in BoB and AS that can explain 32% variability of chlorophyllin both areas. Other than SST, a large number of biotic and abiotic factors, such as nutrient availability, presence of sunlight, mixing layer depth, grazing etc. affect the seasonal variation of chlorophyll. Nevertheless, this study will provide useful information to understand the phytoplankton dynamics in tropical seas.

Keywords: Phytoplankton, Temperature, Dynamics, Bay of Bengal, Arabian Sea.

Introduction

Oceans, which occupy ~72% of the earth's surface, play an important role in the climatic conditions of adjacent land areas. The information about ocean waters, its nutrients and circulation dynamics along the coast have paramount importance in understanding the ocean processes. The physical and biological processes are closely coupled and vary

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over a wide range of time and space scales (Hutchings et al., 1995; Smith, 1995; Hickey, 1998 and Mackas et al., 2006).In the ocean, physical, chemical, and biological processes are linked in an intimate manner (Tang et al., 2002). Oceanic features influence ocean dynamics and its interaction with the atmosphere. The biological processes in world oceans are mainly controlled by the presence of phytoplankton, which forms the base of the food chain. The presence of phytoplankton is also known to affect the sea surface temperature (SST) by interception of short radiation absorption and thereby increasing SST (Sathyendranath et al.,1991). The influence of phytoplankton on the colour of sea has been studied for decades. It is well understood that chlorophyll concentration and the photosynthetic pigments in phytoplankton absorb relatively more blue and red light than green and the spectrum of backscattered sunlight or colour of the ocean water progressively shifts from deep blue to green as the concentration of phytoplankton increases (Yentsch, 1960).

To assess the seasonal variability of chlorophyll and temperature, and their relationship in the open ocean, cruise data were used for the Arabian Sea (AS) (Chaturvedi et al., 2000), but laboratory study suggests that enrichment in CO_2, SST and exposure to higher mean radiances have a great influence on the growth of ocean biota. The north-eastern part of AS is one of the high productive zones, while the southern part of Bay of Bengal (BoB) is not that productive compared to the Ganges-Brahmaputra delta in the northern BoB (Chauhan et al., 2001). The continental shelf in AS is much shallower compared to the shelf in southern BoB (Dey and Singh, 2003). In northern AS, the rate of phytoplankton cell division is controlled by nutrient availability rather than light, while light inhibition of photosynthesis near the surface is negligible (Tang et al., 2002). The boundary and open ocean processes of AS are influenced by upwelling during summer and cooling in winter that brings in a high amount of nutrients into the upper ocean enhancing primary productivity, and ultimately the fisheries (Madhupratap et al., 2001). A conspicuous surface salinity gradient could be seen from the northeast Bay to the north-central AS (Shenoi et al., 2002). For the freshwater balance of the north Indian Ocean, an efficient conduit for the export of low salinity water from BoB was observed (Jensen, 2001). This low salinity water eventually finds its way into the southeastern AS and plays an important role on the formation of a mini warm pool during the pre-monsoon months (Rao and Sivakumar, 1999; Shenoi et al., 1999).

The optical properties of oceans are of fundamental interest in oceanographic studies. Their variability is largely determined by variations in the ecology and biological response to physical and chemical environments. This study aims to characterise and interpret the spatial and temporal variability of chlorophyll and SST in AS and BoB, by coupling US NASA Ocean Colour Web (OCWEB) and World Ocean Database 2009 (WOD09). Specifically, to compare two regional thermal and bio-optical fronts in satellite imagery, examine chlorophyll and SST variability, and describe the role of SST on chlorophyll in the tropical seas of the Indian Ocean.

Materials and Methods

Study Area

This study was carried out in BoB and AS belonging to the northern Indian Ocean (Figure 1). The Indian Ocean is the third largest oceanic divisions in the world, and bounds the waters along the west of Africa, east of Malay Peninsula, Sunda Islands, Australia, south of the Southern Ocean and north of Asia including the Indian peninsula, which is the region of interest. The Indian peninsula is known to have unusual climate variability due to the monsoon wind system. The northeast monsoon blows from October to April/ December to July and the southeast monsoon blows from May to October. The Indian Ocean current system is largely influenced by the Indian monsoon current. During winter, currents blow towards the westward near the Indonesian Archipelago to AS. However, during summer, the direction of currents reverses, going toward BoB.

Data Source and Data Processing

For the analysis of seasonal variability of SST and chlorophyll concentration in BoB and AS, Moderate Resolution Imaging Spectroradiometer (MODIS) data with 4 km resolution

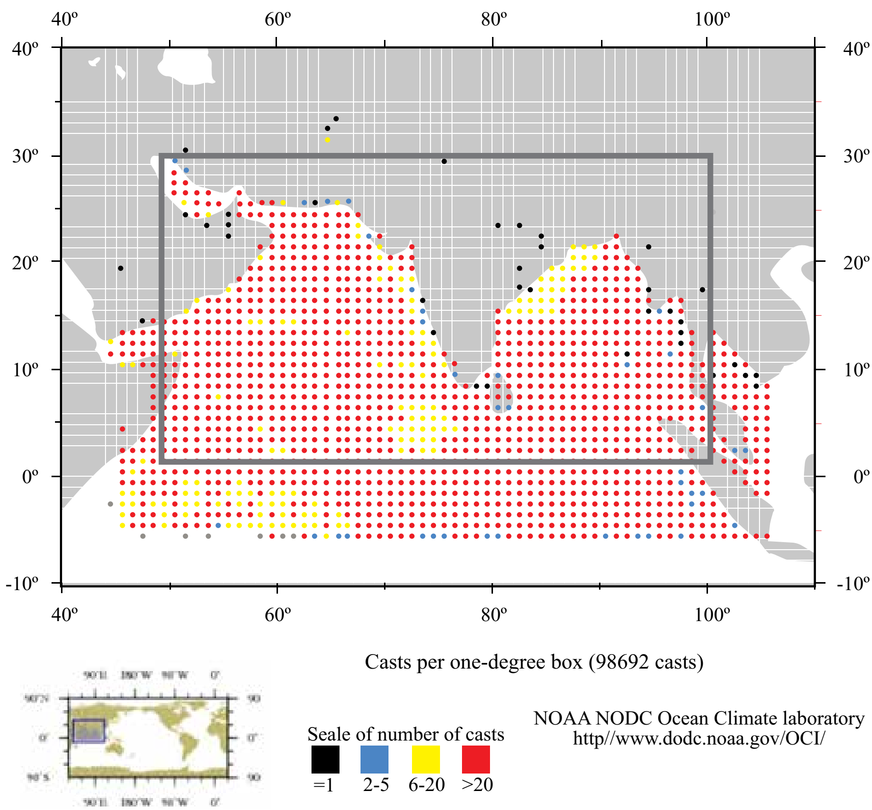


Figure 1.The geographical location of the northern Indian Ocean.

were used. The Ocean Colour Web (OCWEB) sensor onboard aqua-MODIS satellite has been a boon to the scientific community involved in the analysis and characterisation of chlorophyll concentration and SST in the oceans. The level-2 files are spatially averaged into level-3 daily binned files using the 12 bin programme developed by the Ocean Biology Processing Group (OBPG) and the daily files are further composited into weekly, monthly, annual, seasonal and climatological time periods using the 13 bin code (replaced time bin). For binning we followed Campbell et al., (1995). The bin products are then used to generate mapped products for chlorophyll-a concentration and SST on 4 km equirectangular projection. These image products are in Standard Mapped Image (SMI) format. They are produced using the smigen programme. The climatological binned and mapped products are produced in the refined processing stream.

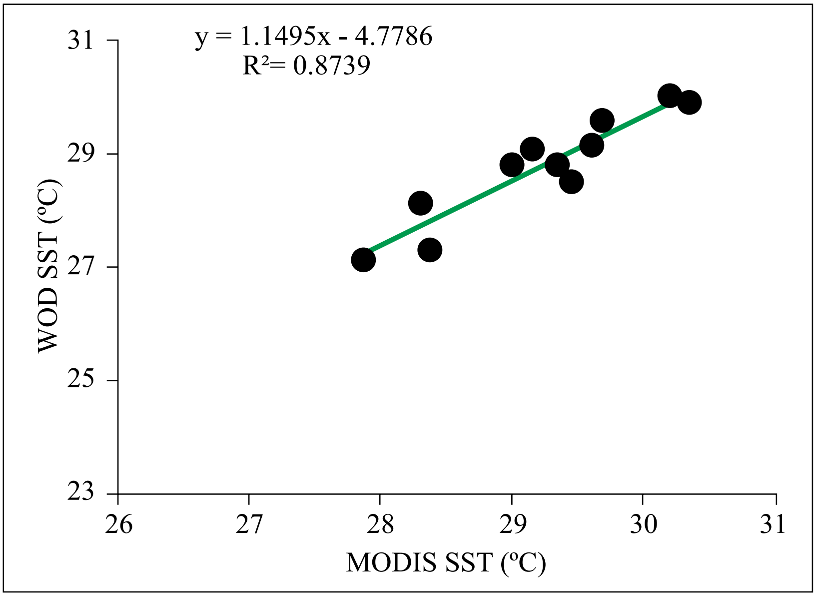
The present study has made use of aqua MODIS monthly climatology data from OCWEB for the period 2002 - 2011 over AS and BoB region to understand the variability in chlorophyll and SST pattern. Atmospherically, radiometrically and geometrically corrected monthly chlorophyll images have been analysed. These are the level-3 global gridded product with 4 km resolution distributed by NASA (http://oceancolor.gsfc.nasa.gov/). All of the data products from MODIS are stored in the Hierarchical Data Format (HDF). From the global chlorophyll and SST images for AS and BoB has been extracted using Saga GIS software. To validate the satellite data, the archived field data were collected from WOD09 for SST for the same time as MODIS data were collected. These data were visualised in Ocean Data View (ODV).

Results

In this study, a 20-year data set of seasonal SST and chlorophyll concentrations in BoB and AS were examined. The satellite data were validated with observed data obtained from the World Ocean Database. The monthly mean data were prepared and presented. Regression and correlation analyses were carried out for all relationships in order to describe the interactions between SST and chlorophyll.

Variability in SST

Comparison of observed data with satellite-derived SST showed that satellite data can explain 87% and 41% ($p<0.001$ and $p<0.05$) variation in observed SST data in BoB and AS respectively. SST of BoB was found relatively higher than that of AS throughout the year (Figure 2). December to February is characterised by low SST with the lowest (27.88° C) in January (Figures - 3 and 4). April and May are characterised by high temperature with the highest value of 30.33° C in April. A secondary peak in SST was observed in October and November in the BoB. Similar to BoB, in the AS, the primary and secondary peak in SST were observed from April to May and October to November respectively. Maximum SST was found 29.82°C in May and the minimum temperature was found 26.66°C in January.



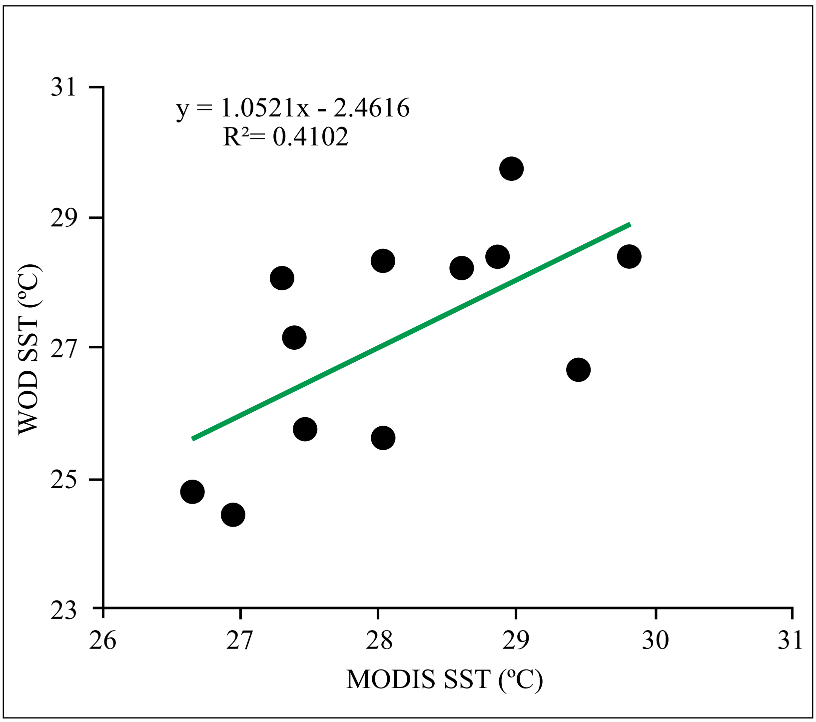


Figure 2. Validation of satellite-derived SST data with WOD data for the Bay of Bengal (top) and the Arabian Sea (bottom)

Variability in Chlorophyll Concentrations

Chlorophyll data are not sufficiently available for the northern Indian Ocean in the World

Ocean Database. Therefore, in this study, a comparison of satellite-derived chlorophyll data with observed data was not possible. Seasonal chlorophyll concentrations in the BoB did not show significant variation (Figures 4 and 5). The lowest chlorophyll concentration was found 0.31 mg m-3 in April and the maximum was found 0.46 mg m-3 in September in the BoB. Seasonal chlorophyll concentrations declined from January to May and then increased from the end of May to end of August. From the September to end of December, chlorophyll concentrations did not show any significant variations. In contrast to BoB, a significant seasonal variation in chlorophyll concentrations in the AS was observed. A peak in chlorophyll concentration was found in September (1.18 mg m-3) while the lowest value was found in April (0.34 mg m-3). Chlorophyll concentrations increases from January to end of February, then decline until the end of April and again increase from June to September. From October to December are characterised by low chlorophyll concentrations.

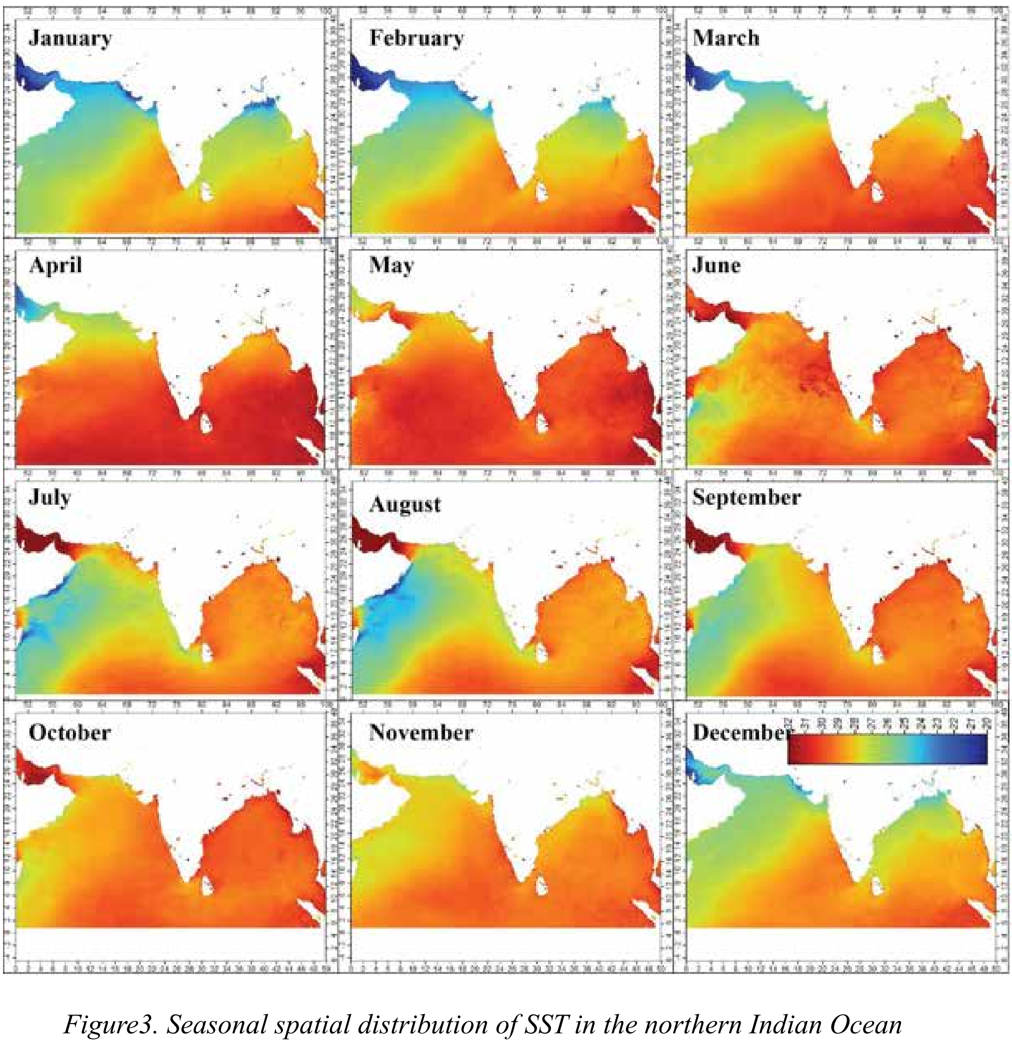


Figure3. Seasonal spatial distribution of SST in the northern Indian Ocean

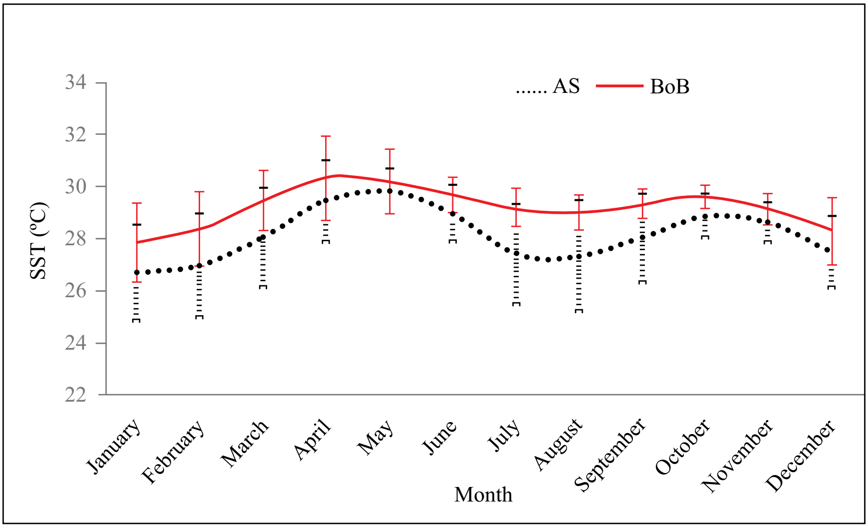


Figure 4. Seasonal variation of SST in the Bay of Bengal and the Arabian Sea

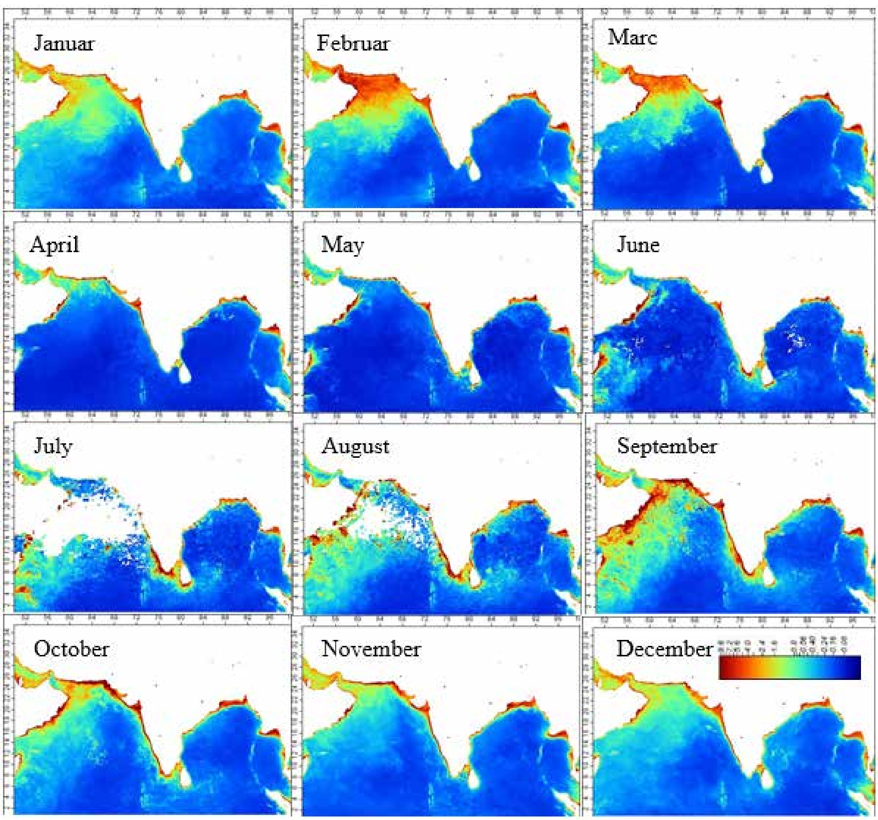


Figure 5. Seasonal spatial distribution of chlorophyll concentrations in the northern Indian Ocean

Relationship Between SST and Chlorophyll

To examine if the SST can explain the seasonal variation in chlorophyll concentrations in the BoB and AS, a linear regression analysis was performed (Figure 6). It showed that for both BoB and AS, SST is a significant predictor of chlorophyll distribution. In both cases, SST can explain 32% variation in chlorophyll concentrations. Interestingly, we observed a significant negative association between SST and chlorophyll concentrations. During March to June, SST was higher than the seasonal mean and chlorophyll was lower than the average in the BoB (Figure 6). During January, February and from August to December it was vice versa. In the AS, from January to February SST was lower than the average value while the chlorophyll was higher than the average (Figure 7). From April to June SST was lower than the average value and chlorophyll was higher. During August to December, SST was low but chlorophyll concentrations were higher than the seasonal average. The anomaly of SST and chlorophyll in BoB and in ASis shown in figure 8. Findings show that in BoB chlorophyll shows positive anomaly from July to March while negative anomaly was observed from April to June. Reverse condition in SST anomaly was observed in BoB. A similar pattern in SST and chlorophyll anomalies was observed in AS. However, the magnitude in SST and chlorophyll anomalies varies significantly betweenBoB and AS.

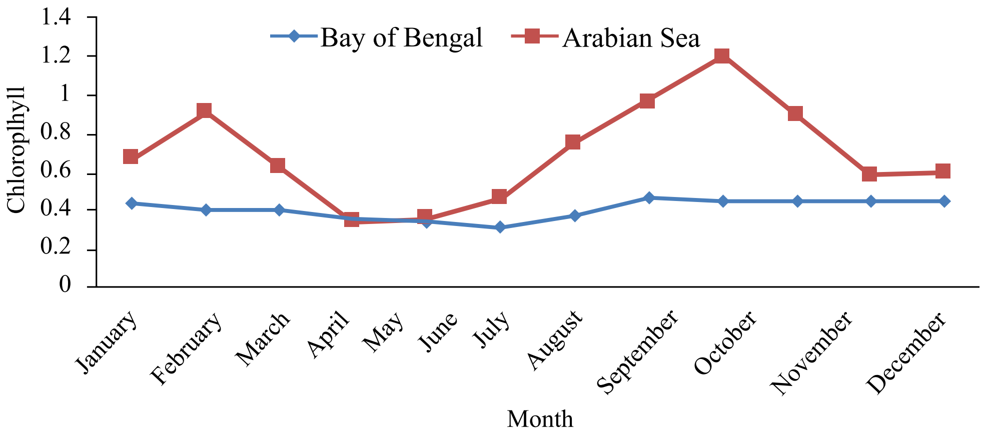


Figure 6. Seasonal variation of chlorophyll in the Bay of Bengal and the Arabian Sea

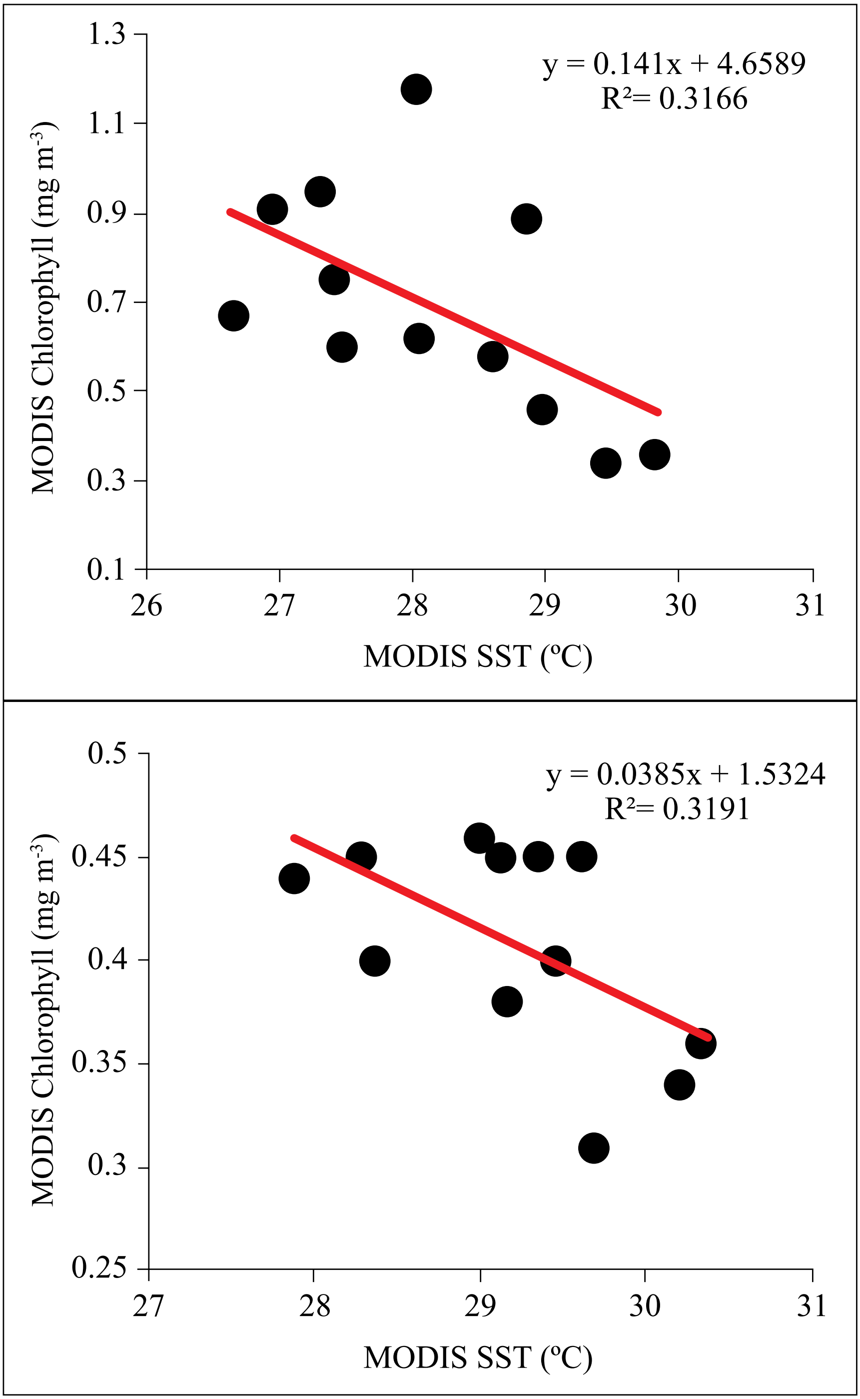


Figure 7. Relationship between SST and chlorophyll in the Bay of Bengal (top) and in the Arabian Sea (bottom)

Discussion

This study aimed to examine the role of seasonal SST in explaining the variation in chlorophyll concentrations in tropical seas. We selected the BoB and AS of the northern Indian Ocean as our area of interest. Variability in long-term seasonal chlorophyll concentrations and SST in the BoB and the AS were studied using satellite-derived data. Here we used seasonal MODIS data on chlorophyll and SST from 2000 to 2011. MODIS SST data were validated with the World Ocean Database derived in-situ data. Findings showed that satellite data provide more reliable SST for the BoB than for the AS. Sea surface temperature was found higher in BoB than the AS. In BoB, the lowest SST was found 27.88° C in January and the highest value 30.33° C was found in April. Maximum SST was found 29.82° C in May and the minimum was found 26.66° C in January in the AS. The lowest chlorophyll concentration was found 0.31 mg m-3 in April and the maximum was found 0.46 mg m-3 in September in the BoB.

Remotely sensed SST explains oceanic environment suitable for enhanced production. Our current analyses showed the difference in a monthly pattern in the AS and the BoB. In the dry season (January-February-march) SST was found low where high SST was observed in April-May. In the months of June-July-August (wet season) SST was found declining due to rain. After that, it was increasing during September-October. Monthly and spatial variability of AS and BoB from remote sensing MODIS derived SST images are seen of three distinct months and from in situ WOD derived in-situ SST images are seen of the same month. We observed almost the same pattern of SST in both types of data sets. Winter cooling of surface water has been reported the lowest SST 25°C in the northern Indian Ocean in January (Murthy et al., 1992). SST increased in April-May and also in September-October in this region (Sarangi et al., 2008) and the same pattern of SST was found in this study.

High values of chlorophyll were measured by MODIS in the region of AS compared to BoB. Although, some uncertain values of chlorophyll were found in the nearest coastal region of both areas. Four distinct months were identified through observing twelve months of chlorophyll concentration from MODIS data. In the northern AS chlorophyll concentration was found higher in January to March compared to other regions due to low SST in the same months. AS water leads cool water which initiates convective mixing and injection of nutrients into the sea surface which is responsible for the higher chlorophyll concentrations in the northern AS in January to March (Kumar & Prasad, 1996). This mixing of water indicates upwelling areas leading to highly productive zone and thus the development of the localised ecosystem. The average monthly basis chlorophyll showed a peak in January during 1998-2000 in the northeast AS (Chaturvedi, 2005). Chlorophyll values were high in November and declined after January and remained constant from December onwards (Chaturvedi, 2005). In this study, it was declining January to June with little values where September to December Chlorophyll concentration was found as same as 0.45 mg m-3 in BoB.

Phytoplankton productivity and biomass in the world ocean are limited by nutrients (i.e. N, P, Si, Fe) concentrations (Chisholm and Morel, 1991) and/or the mean light level, which is modulated by vertical mixing and seasonal variability in daily insolation (Siegel et al., 2002). The relationship between temperature and chlorophyll has been emphasised by previous studies (Bailleulet al., 2007). In this study, BoB and AS showed an inverse relationship between chlorophyll and SST with an R2 value 0.319 for BoB and 0.316 for AS. Barnard et al. (1997) observed the distribution of chlorophyll and SST are inversely correlated. The enhanced chlorophyll concentration in winter is that Wyrtki jets and wind stirring are responsible for bringing up the mixed layer of rich nutrients to the surface and the enrichment of the mixed layer through cool thermocline water. This cooling event is responsible for the increase in surface chlorophyll concentrations (Vinayachandran and Saji, 2008). Strutton et al. (2015) evaluated this hypothesis using moored chlorophyll observations and modelled results and found credence to the hypothesis. It is well established that mixing of deeper water with the surface water causes a decrease in SST and supplies nutrients to the upper layers which enhances the productivity and hence the high surface chlorophyll concentrations (Prakash and Ramesh, 2007). Based on the direction of winds, they could trigger upwelling or downwelling signal. Since the dominant wind direction in the equatorial Indian Ocean is westerly, it normally triggers downwelling Kelvin signal and, therefore, reduces the chlorophyll concentrations during summer (Kumar et al., 2016).

Conclusion

In conclusion, the results demonstrated the monthly climatological variability and inter-relationship of the Chlorophyll and SST in BoB and AS. The SST plays an important role in Chlorophyll concentration and its variability. The lower chlorophyll concentration has been found in BoB compared to those in AS. The higher chlorophyll concentration in AS is attributed to the vertical mixing of its water and upwelling of water, rich in nutrients, whereas chlorophyll concentration and productivity in BoB are low. Monthly variability in chlorophyll and SST shows an inverse relationship in both regions. And the variability in chlorophyll also shows an inverse relationship in BoB and AS. The persistent co-occurrence of colour and thermal features indicate the close coupling between the physical and biological parameters. Chlorophyll features appear to be well defined and contain more information compared to SST features. The application of chlorophyll and SST would be useful to improve the methodology for exploring living marine resources.

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