# Monitoring Long-term Ocean Health Using Remote Sensing: A Case Study of the Bay of Bengal

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## ABSTRACT

Oceans play a significant role in the global carbon cycle and climate change, and the most importantly it is a reservoir for plenty of protein supply, and at the center of many economic activities. Ocean health is important and can be monitored by observing different parameters, but the main element is the phytoplankton concentration (chlorophyll–a concentration) because it is the indicator of ocean productivity. Many methods can be used to estimate chlorophyll–a (Chl-a) concentration, among them, remote sensing technique is one of the most suitable methods for monitoring the ocean health locally, regionally and globally with very high temporal resolution.

In this research, long term ocean health monitoring was carried out at the Bay of Bengal considering three facts i.e. i) very dynamic local weather (monsoon), ii) large number of population in the vicinity of the Bay of Bengal, and iii) the frequent natural calamities (cyclone and flooding) in and around the Bay of Bengal. Data (ten years: from 2001 to 2010) from SeaWiFS and MODIS were used. Monthly Chl–a concentration was estimated from the SeaWiFS data using OC4 algorithm, and the monthly sea surface temperature was obtained from the MODIS sea surface temperature (SST) data. Information about cyclones and floods were obtained from the necessary sources and in-situ Chl–a data was collected from the published research papers for the validation of Chl-a from the OC4 algorithm. Systematic random sampling was used to select 70 locations all over the Bay of Bengal for extracting data from the monthly Chl-a and SST maps. Finally the relationships between different aspects i.e. i) Chl-a and SST, ii) Chl-a and monsoon, iii) Chl-a and cyclones, and iv) Chl-a and floods were investigated monthly, yearly and for long term (i.e 10 years). Results indicate that SST, monsoon, cyclone, and flooding can affect Chl-a concentration but the effect of monsoon, cyclone, and flooding is temporal, and normally reduces over time. However, the effect of SST on Chl-a concentration can't be minimized very quickly although the change of temperature over this period is not very large.

**Keywords:** Ocean health, chlorophyll-a concentration, sea surface temperature, season, natural disaster

## 1. INTRODUCTION

The ocean plays an important role in many of the Earth's systems including climate and weather (NOAA, 2012). Phytoplankton, one of the microscopic organisms that inhabit the upper layer of ocean and it contains of chlorophyll which absorb sunlight in the process of photosynthesis. It plays an important role in the global carbon cycle and climate change (Chisholm, 2000). It causes climate change by changing the SST through the absorption of solar radiation for photosynthesis (Marzeion et al., 2005). Therefore, changes in phytoplankton biomass will bring momentous effect on ecosystem structure. There are several factors that can affect the Chl-a concentration, including variability of SST, season and occurrence of natural disaster. Hood et al., 1990, carried out a study at coast of Northern California and found that there is an inverse relationship between the SST and chlorophyll concentration. From previous studies (Wiggert et al., 2005; 2006), it is known that phytoplankton bloom activity is the result from the semiannual wind reversals associated with the monsoon system. Besides that, the occurrence of cyclone can induce the phytoplankton blooms by

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vertical mixing and upwelling (Price et al., 1981). There are many oceans in the world, BOB is the largest bay in the world and it has tropical climate, high rainfall, seasonal variation and monsoon. All these components influence the surface water circulation and stratification (Gomez et al., 2000). The BOB is a place where natural disaster such as cyclone occurs very frequently (Rahul et al., 2008). This research investigated the long term ocean health in relation to the SST, natural disaster, and seasonal variability of the BOB.

## 2. STUDY AREA

The study area of this research is the Bay of Bengal (Figure 1). It is bordered by India and Sri Lanka to the west, Bangladesh to the north, and Burma to the east. The coordinate of BOB is N 13° 31' 54.2634", E 87° 32' 22.4982".


Figure 1. Study area.

The study area was divided into two categories, coastal and offshore region. The coastal regions were including A, B, F and H (Figure 1). While offshore regions were including C, D, E, G, I and J (Figure 1).

## 3. MATERIALS AND METHOD

In this study, Sea Viewing Wide Field of View Sensor (SeaWiFS) level 2 daily data and Moderate Resolution Imaging Spectroradiometer (MODIS) level 3 monthly data were used. Both datasets were downloaded from 'http: //oceancolor.gsfc.nasa.gov'. The 10 years data from year 2001 to 2010 were used for this study. Apart from the satellite data, the date and the location of the previously occurred (from year 2001 to 2010) natural disaster (such as flooding, cyclone) were recorded to examine the effect of the natural disaster on the ocean productivity.

The Chl-a concentration variation of the BOB in this study were obtained by averaging the daily level 2 SeaWiFS data from 2001 to 2010. The daily data was mosaic to produce monthly data, and the averaging process was carrying out simultaneously during the process of mosaic. The averaging was done based on every pixel in the image. On the other hand, SST variation in the BOB was extracted from the level 3 MODIS Terra data from 2001 to 2010. Chl-a concentration and SST were extracted from different parts of the BOB by averaging 10 to 15 pixels in each region. After the extraction of Chl-a concentration and SST, correlation between Chl-a concentration and SST was carried out to investigate the relationship. Besides that, the variability of Chl-a concentration on seasonal variation, monsoon and natural disaster were investigated. Due to cloud cover and satellite problem, data was not available for some months, this problem was overcome by replacing the missing data with the previous month data.

# 4. RESULT AND DISCUSSION

## 4.1 Variation of chlorophyll-a concentration in the Bay of Bengal

The estimated Chl-a concentration in offshore areas varied from 0.01 mg/m3 to 0.87 mg/$m^3$. Whereas, in coastal areas, the observed Chl-a concentration value generally range from 0.4 mg/$m^3$ to 12 mg/$m^3$ for ten years. In river mouth areas (region A and region H), Chl-a concentration was high throughout the 10 years time (Figure 2 (a and d)). It was found that region A always had a Chl-a concentration more than 2 mg/$m^3$, while region H always had a Chl-a concentration more than 4 mg/$m^3$. The trend of the Chl-a concentration variation was almost the same for all offshore regions in the 10 years time.

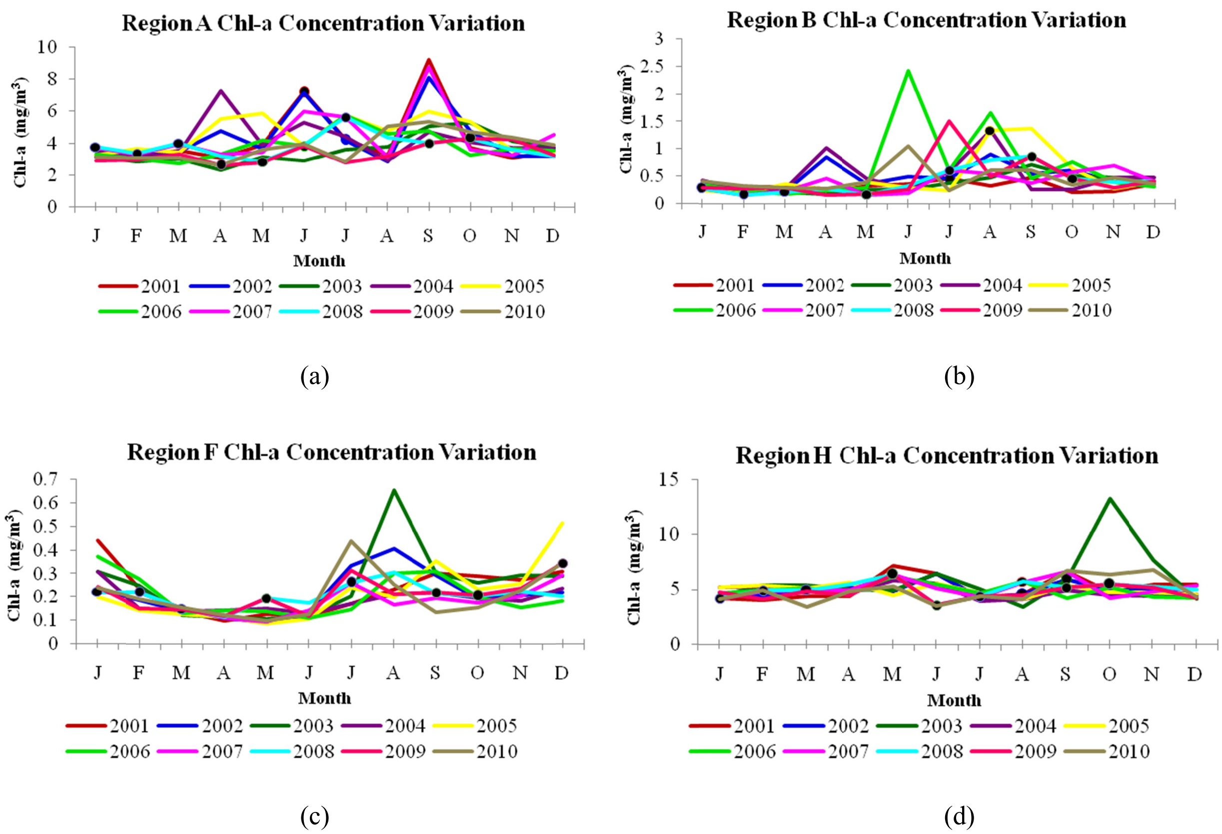



Figure 2. Coastal areas chl-a concentration variation in BOB for region A (a), region B (b), region F (c), and region H (d).

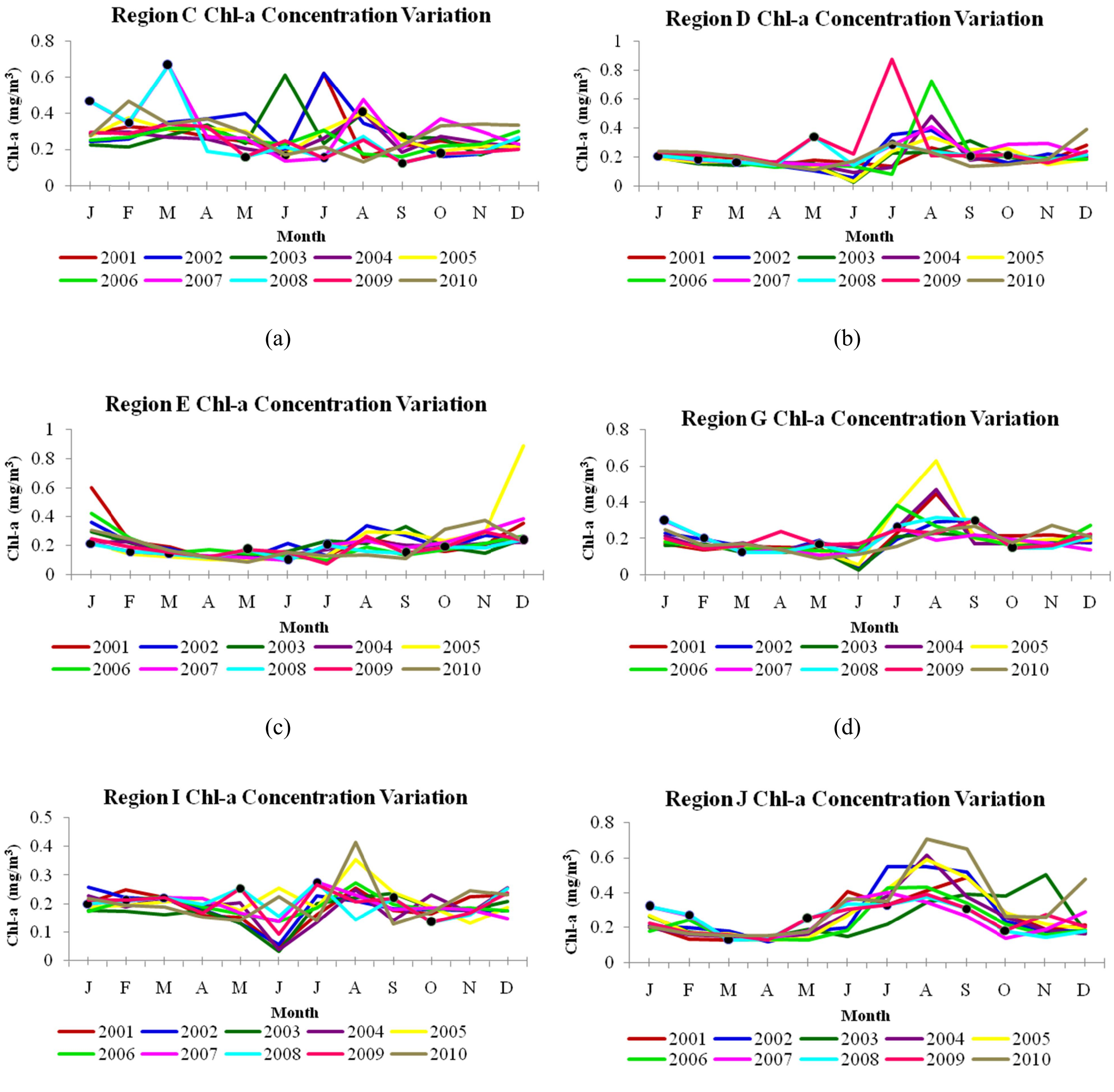



Figure 3. Offshore areas chl-a concentration variation in BOB for region C (a), region D (b), region E (c), region G (d), region I (e), and region J (f).

In this research, high Chl-a concentration was observed in coastal region, this is likely due to several factors including coastal upwelling, fresh water discharge from river, and eutrophication. Previous study (Tilstone et al., 2011), indicated that BOB is an area that receive a lot of freshwater and sediment from Ganges-Brahmaputra and Irrawaddy Rivers. This large amount of water discharge brings the nutrient or organic matters to the coastal area and caused high Chl-a concentration in coastal region (Gauns et al., 2005). Eutrophication is also a factor that caused high Chl-a concentration in coastal regions. Balachandran et al., 2008, who found that high Chl-a concentration occurred in coastal region due to eutrophication or high concentration of nutrient. According to Verlekar et al., 2006, the activity of eutrophication can cause an enormous blooming of certain species of phytoplankton. In this study, it is also depicted that some coastal areas of the BOB have higher Chl-a concentration but these areas are not at the river mouth. This can be explained based on the finding from Vinayachandran et al., 2004 who found that coastal upwelling help to trigger phytoplankton bloom in coastal areas. Coastal upwelling process brings the rich nutrient water to the surface and it can trigger phytoplankton bloom in coastal areas. Lower level of Chl-a concentration was observed in the offshore areas compared to coastal region. According to Chaturvedi, 2011, low Chl-a concentration in offshore area is because of the stable water column that prevents upwelling activity and vertical mixing process that can transport nutrient rich water from the bottom to supply the nutrient needed for phytoplankton bloom.

Results also indicated that the Chl-a concentration varied monthly for all regions. The monthly Chl-a concentration in coastal areas tend to have more fluctuation compared to offshore areas. This can be observed from the trend results (Figure 2) that showed there were drastic changes in Chl-a concentration from one month to another in coastal areas especially at river mouth. In deep sea or offshore areas, the result showed a different trend compared to coastal areas. The offshore areas had a less monthly Chl-a variation compared to coastal regions (Figure 3). It is observed that almost all the offshore regions had a similar trend of Chl-a concentration variation i.e. Chl-concentrations were increased from July to September. This type of variation was observed clearly in the region D and G which were located in offshore areas. The monthly Chl-a concentration variation that happened was due to the river discharge and monsoon period and this result agrees the finding of the previous study (Vinayachandran and Mathew, 2003).

### 4.2 Variation of the sea surface temperature in the Bay of Bengal

The SST for coastal areas was about 28˚C to 30˚C for all the month, but the SST in the early of the year was comparatively low (about 25˚C to 26˚C). However, the early year SST for region F was a bit higher (≈27˚C) than other coastal regions (Figure 4(d)). In contrast, it was observable that SST in offshore areas changed according to seasonal variation but this did not happen all the time (Figure 5). During summer, the SST in offshore areas was high (≈30˚C) while in winter, the SST in offshore area was low (≈26˚C). In region D and G, which were classified as offshore areas, the SST remained almost the same throughout certain year. Furthermore, based on the results, it can be said that SST in coastal areas was higher than offshore areas.

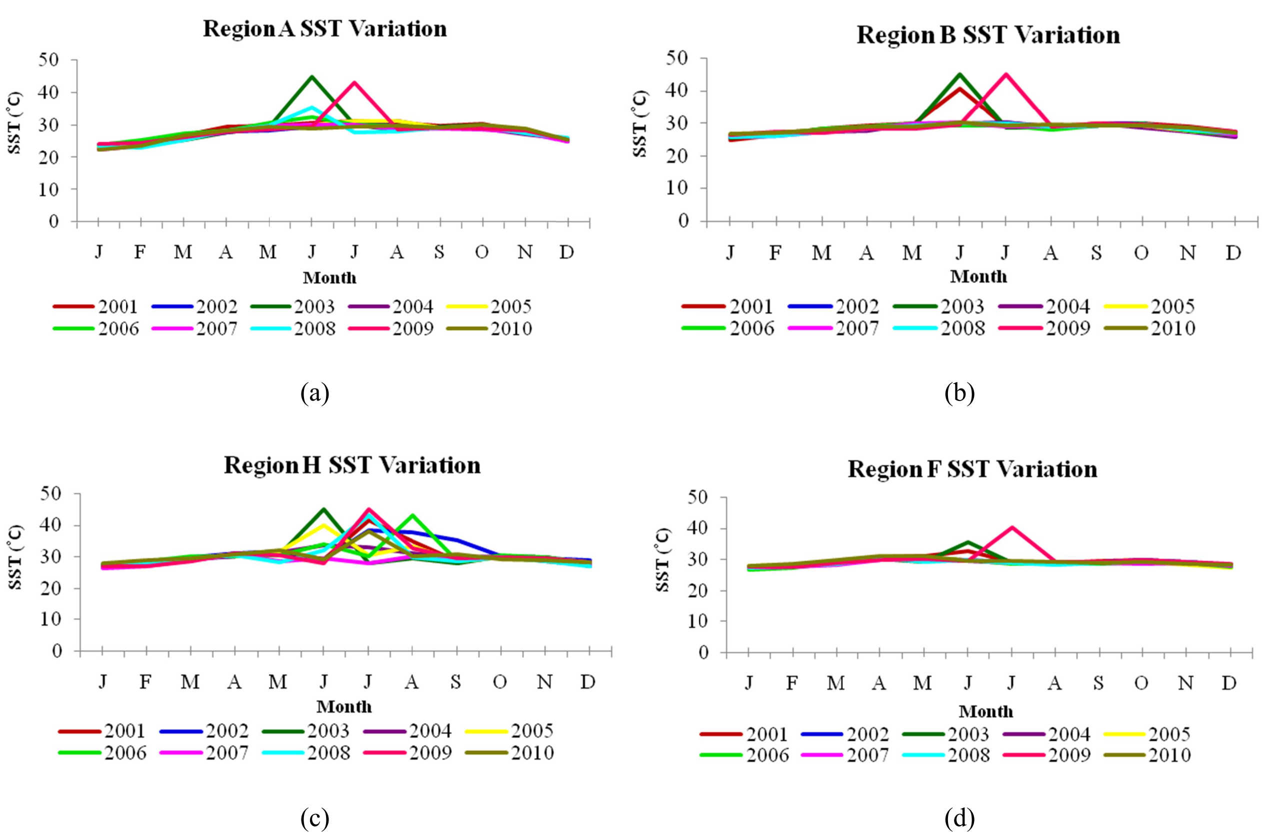



Figure 4. Coastal areas SST variation in BOB for region A (a), region B (b), region H (c), and region F (d).

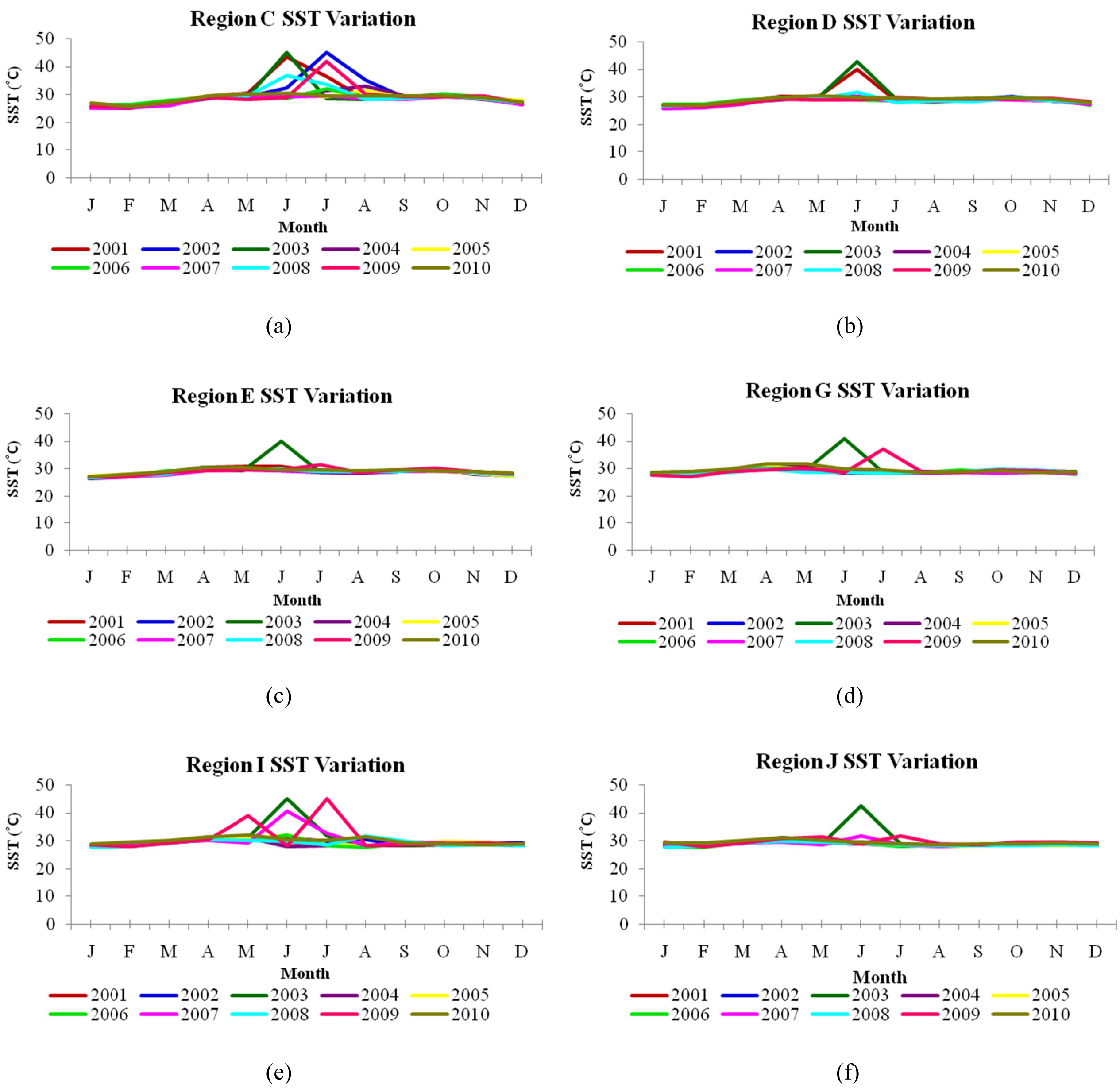



Figure 5. Offshore areas SST variation in BOB for region C (a), region D (b), region E (c), region G (d), region I (e), and region J (f).

It can be observed that there was a relationship between the location of the ocean and SST, and SST also changed as a result of seasonal variation. The SST on coastal area had more fluctuation compared to offshore areas. From Figure 4, it can be seen that coastal regions i.e. A, B, C and H have a high fluctuation in SST throughout these ten years time. Whereas for offshore area, the SST variation was smaller, in other word, the SST in offshore was more stable. A common trend of SST variation for coastal and offshore area is that the SST increased from the early in year (January – March), then achieved peak SST for certain region in the middle of the year (May – July) and finally started to reduce by the end of the year (August – December).

### 4.3 Correlation between chlorophyll-a concentration and sea surface temperature in the Bay of Bengal

This study depicted that there was relationship between Chl-a concentration and SST. However the relationship between Chl-a concentration and SST was not constant and depends on the location of the ocean. Generally, coastal region showed a positive relationship for SST and Chl-a concentration (Table 1), but some coastal region gave the relationship in the opposite way (Table 1). For example, Region A and B which were categorized as coastal regions were having a positive correlation for most of the past ten years, but region H and F were having a negative correlation for most of the ten years. Whereas for offshore areas, the relationship between Chl-a concentration and SST showed a good negative correlation (Table 1) and the highest negative correlation value was -0.88 (Table 1). Regions that are located in offshore areas had a negative correlation almost throughout the 10 years time. Positive correlation value was found in 2008 and 2009, though the positive correlation was very weak (≈0.1-0.4). Besides, one of the regions (region I) which were located around Andaman Island, the correlation between SST and Chl-a concentration was not so obvious. However, all regions in the BOB did not have negative or positive correlation value for the 10 years (Table 1).

Table 1. The correlation value between SST and Chl-a concentration from year 2001 to 2010 in BOB.

| Region / Year | A | B | C | D | E | F | G | H | I | J |
|---|---|---|---|---|---|---|---|---|---|---|
| **2001** | 0.07 | 0.057 | -0.88 | -0.37 | -0.77 | -0.71 | -0.36 | -0.46 | -0.45 | -0.47 |
| **2002** | 0.22 | 0.121 | 0.71 | -0.25 | -0.73 | -0.40 | -0.44 | -0.35 | -0.60 | -0.56 |
| **2003** | -0.0096 | -0.142 | 0.69 | -0.68 | -0.31 | -0.36 | -0.83 | -0.22 | -0.88 | -0.64 |
| **2004** | 0.22 | 0.095 | -0.69 | -0.23 | -0.70 | -0.53 | -0.36 | -0.16 | 0.15 | -0.64 |
| **2005** | 0.69 | 0.346 | -0.64 | -0.071 | -0.61 | -0.71 | -0.34 | 0.031 | -0.029 | -0.66 |
| **2006** | -0.31 | 0.282 | -0.69 | -0.25 | -0.82 | -0.73 | -0.13 | -0.83 | -0.10 | -0.56 |
| **2007** | 0.32 | 0.175 | -0.53 | -0.037 | -0.33 | -0.70 | -0.65 | -0.024 | 0.11 | -0.51 |
| **2008** | 0.65 | 0.362 | 0.19 | 0.43 | 0.33 | 0.30 | 0.27 | 0.20 | 0.00056 | 0.23 |
| **2009** | -0.021 | 0.850 | -0.50 | 0.14 | -0.62 | 0.26 | 0.22 | -0.51 | 0.066 | -0.049 |
| **2010** | 0.274 | 0.549 | -0.63 | -0.56 | -0.43 | -0.10 | -0.78 | -0.03 | 0.10 | -0.67 |

The probable reasons for this negative relationship are: i) stable water column in the offshore ocean, and ii) increasing in SST can increase the stress of the organism (Iius, 2008). However, negative relationships between Chl-a concentration and SST is very common and this result is in agreement with other researchers (Kamykowski, 1987; Chaturvedi, 2011) who found that Chl-a concentration has inverse relationship with SST and the relationship is known to be changed according to differ in location. Positive relationship was also observed some parts of the BOB especially in coastal area except for the two regions (region F and H). A positive correlation value indicates the variation of Chl-a concentration was not depending on SST variation. This can be explained by the fact that there were many factors that can affect the Chl-a concentration variation near the coastal area, including coastal upwelling, eutrophication, sediment and nutrient from river discharge. Though this result is not directly in agreement with other studies but in principle it agrees with previous findings of other study (Kumari and Babu, 2009) that the correlation between chlorophyll and SST is not always negative.

Moreover, alongside the positive relationships between Chl-a concentration and SST in the coastal region, negative correlation between Chl-a concentration and SST was also found in coastal region especially in two regions such as F and H regions. Although this trend is different from the normal relationship, previous study (Kumari and Babu, 2009) found region F is located in the area of BOB that undergoes two monsoon seasons. During the south west monsoon, this region was experienced surface wind forcing and caused the SST to reduce. Moreover, Ali et al., 2007, found that this wind forcing during south west monsoon can be attributed to cyclone-induced mixing, and this lead to the increase of Chl-a concentration for region F. Based on these findings, it showed that the finding of negative relationship between SST and Chl-a concentration for the region F agrees the previous studies. Region H had a negative correlation (high SST and low chl-a concentration) maybe due to the stratification. As mentioned before, region H is located at the river mouth where it receives a large amount of freshwater from the river. As a result, the waters are less saline compared to the other area (Gauns et al., 2005). Higher SST plus low salinity condition lead to strong stratification makes chl-a concentration to reduce.

### 4.4 Effects of season and monsoon on chlorophyll-a concentration in the Bay of Bengal

The result of this study showed that the seasonal variation affect the Chl-a concentration. Based on the trend graph (Figure 2 to Figure 5) from 2001 to 2010 in the BOB, SST was lower during winter and the winter monsoon and higher during summer and the summer monsoon. During winter the SST started to decrease from November and started to increase from January. In contrast, Chl-a concentration during winter monsoon and winter was started to increase from November and started to decrease from January. This kind of variation was almost the same for the ten years time. The SST during winter was lower (27˚C) compared to the SST during summer (30˚C). However the SST was also varied according to location. During winter the SST for region that one near to coastal area was about 30˚C and during summer it was about 32˚C.

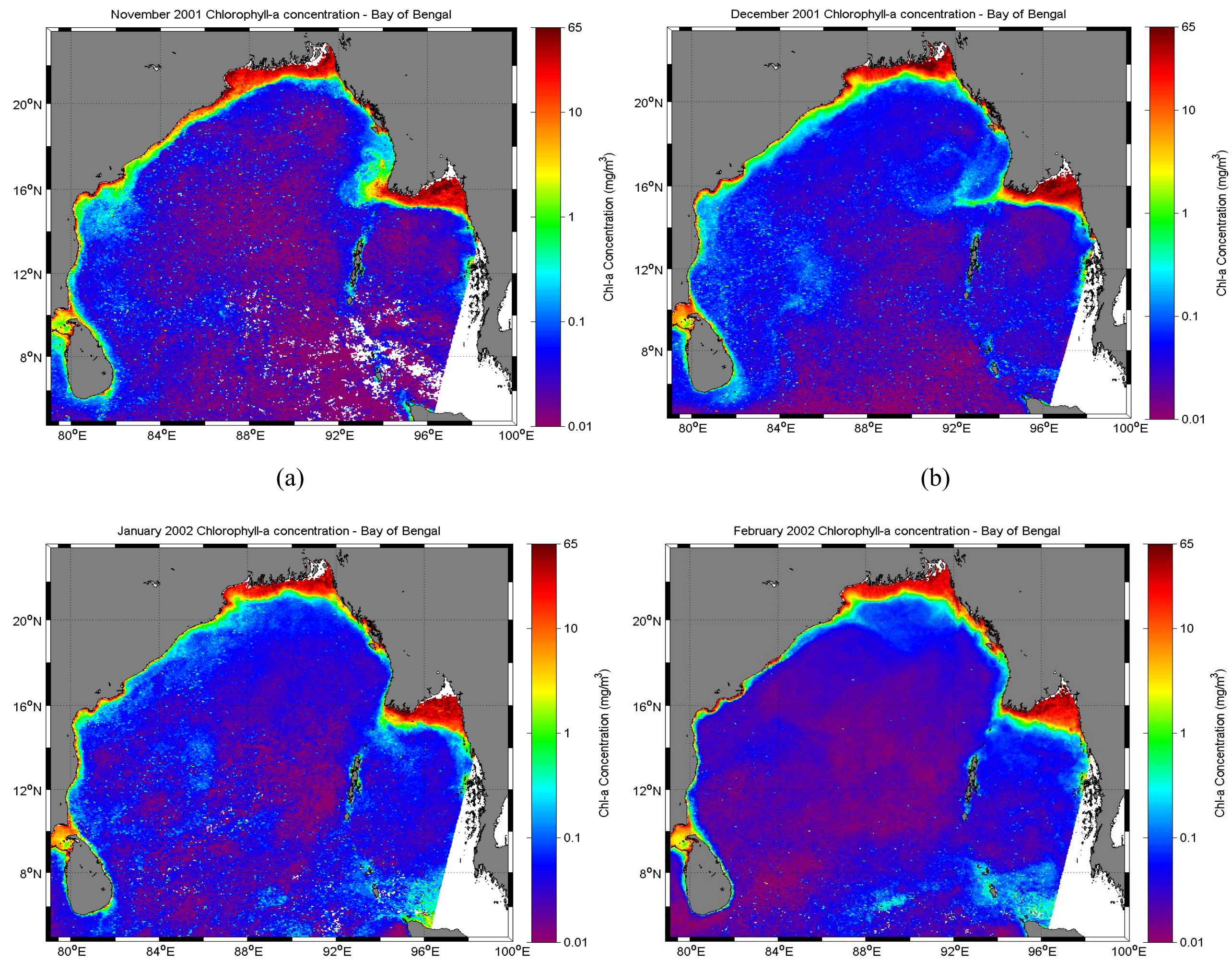
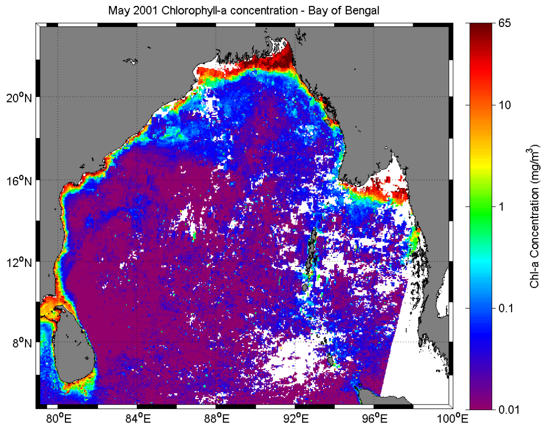
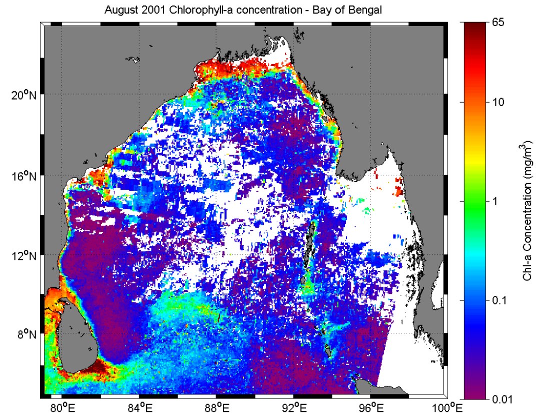


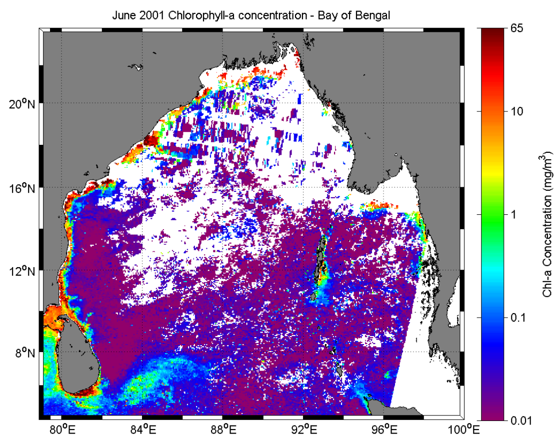

Figure 6. Chl-a concentration variation map in BOB during winter for November (a), December (b), January (c), and February (d) 2001.



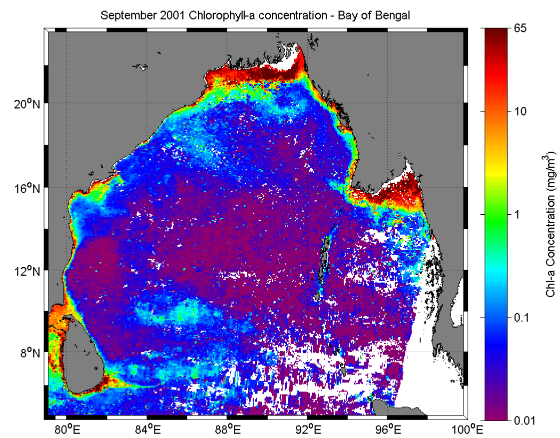

(a)



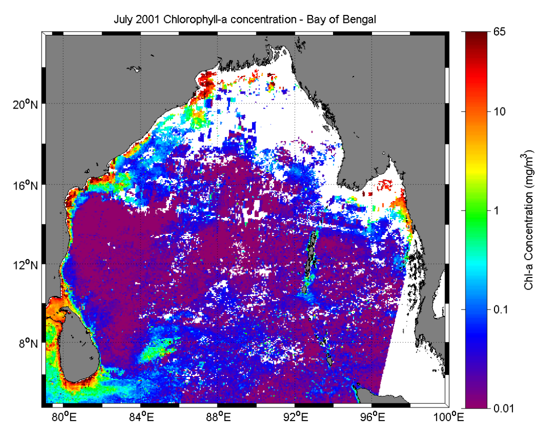

(b)




(c)




(d)




(e)

Figure 7. Chl-a concentration variation map in BOB during summer for May (a), August (b), June (c), September (d), and July (e) 2001.

According to the results from Figure 2 and 3, it showed that during the winter monsoon period (November to December), region E and F which were located in northwestern region of the BOB near Sri Lanka had an obvious Chl-a concentration variation during this monsoon period compared to other regions. It was observable that throughout the 10 years time, these two regions had the same trend pattern all the time i.e. Chl-a concentration increased between the months of November and February. This type of variation was also shown in the Chl-a map for the winter monsoon period (Figure 6). The Chl-a concentration increased as much as up to 0.6mg/m$^3$ during the winter monsoon. The increase of Chl-a concentration around Sri Lanka area during winter monsoon was due to local Ekman pumping process which injected the nutrient to upper surface and triggered phytoplankton bloom (Vinayachandran and Mathew, 2003). While other regions remained less variant throughout the monsoon period.

From the results (Figure 2 and 3), it showed that during the summer monsoon period (May to September), regions that are located in the Northeastern part of the BOB underwent obvious Chl-a concentration variation compared to other regions. During the summer monsoon period, the peak Chl-a concentration in region A was achieved which was up to 9 mg/m$^3$, while at region H it was about 7 mg/m$^3$. The probable reason of this variation is that during summer monsoon the wind blow from southwestern part and passes through BOB, on the meanwhile, the wind pick up moisture from BOB and pour large amount of moisture in eastern Himalaya. The moisture was then discharge trough Ganges-Brahmaputra River to BOB (Wikipedia 2013). The large amount of discharge provided the nutrient for coastal area phytoplankton bloom during summer monsoon especially in region A and region H. During this monsoon period, Chl-a concentration in the middle part of the BOB also showed some variation (Figure 7). The variation of Chl-a concentration resulted in an increase of 0.59 mg/m$^3$. This type of variation was found from 2001 to 2010.

In this research, the effect of natural disaster on the concentration of Chl-a was investigated but due to the limitation of data and time constraints this research only considered a few issues. It is observed from the result (Figure 2 and 3) that during inter monsoon period Chl-a concentration was increased in the region B (April, 2004). The probable reason for this increased of Chl-a concentration is the effect of Cyclone. Cyclone often occurs during inter monsoon period (from March to April and October to November) and Tropical cyclone creates anticlockwise wind in the Northern Hemisphere. Previous study (Taylor, 1989) indicated that cyclonic storm can induce phytoplankton bloom, and when cyclone happens, it churns up the water and transports the nutrient from the bottom to euphotic layer and finally trigger phytoplankton bloom (Vinayachandran, 2009). Besides that, according to NASA (2013), during late summer in year 2002, massive flood disaster happen in India and Bangladesh, and it was caused by monsoon rainfall. The massive flood discharged large amount of water in to BOB trough Ganges-Brahmaputra River. Based on the results (Figure 2) it showed that region A which is located at the river mouth of Ganges- Brahmaputra River has peak Chl-a concentration in September. These findings proved that natural disaster such as cyclone and flood has a potential to affect Chl-a concentration in BOB.

## 5. CONCLUSION AND RECOMMENDATION

Satellite remote sensing provides good opportunity to observe long term ocean productivity or ocean color. Ocean color monitoring plays an important role to monitor the world climate change, ocean productivity and fisheries activity. Seasonal variation, monsoon season, SST and natural disaster are able to affect the ocean productivity. There is a relationship between SST and Chl-a concentration. But the relationship depends on geographical location of the BOB. However in generally, coastal areas have positive correlation and region at offshore area have negative correlation between SST and Chl-a concentration.

Seasonal and monsoon period also affected the Chl-a concentration in BOB. During summer and winter, Chl-a concentration in BOB had negative relationship in offshore area and coastal area. However, the monsoon season is knows to affect the Chl-a concentration in BOB and the occurrence of seasonal monsoon increased the Chl-a concentration in certain area. The Northeastern monsoon increased the Chl-a concentration near Sri Lanka area, while the Southeastern monsoon increased Chl-a concentration near the northeastern part of the BOB.

Beside monsoon, natural disaster also affected the Chl-a concentration in BOB. Occurrence of cyclone during inter monsoon period increased the Chl-a concentration in BOB because cyclone act as strong wind force that transport nutrient from bottom to upper layer and cooling the SST, and this process triggered the bloom of phytoplankton. Flooding also affected the Chl-a concentration in BOB due to the large amount of nutrients water discharge from land which induced phytoplankton bloom.

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## REFERENCES

[1] Ali, M. M., C. M. Kishtawal, and J. Sarika, "Predicting cyclone tracks in the north Indian Ocean: An artificial neural network approach," Journal of Geophysical Research. - Oceans, 34, 1119–1125 (2007).

[2] Balachandran, K.K., Jayalakshmy, K.V., Laluraj, C.M., Nair, M., Joseph, T., & Sheeba, P., "Step-up Multiple regression model to compute chlorophyll a in the coastal waters of Cochin," southwest coast of India. Environmental Monitoring Assessment 139, 217 – 226 (2008).

[3] Chaturvedi, N., "Variability of Chlorophyll Concentration in the Arabian Sea and Bay of Bengal as observed from SeaWiFS data from 1997-2000 and its Interrelationship with Sea Surface Temperature (SST) derived from NOAA AVHRR," International Journal of Remote Sensing, 26(17), 3695-3706 (2011).

[4] Chisholm, S.W., "Oceanography: Stirring times in the Southern Ocean," Nature, 407, 685-687 (2000).

[5] Gauns, M., Madhupratap, M., Ramaiah, N., Jyothibabu, R., Fernandes, V., Paul, J. T., and Prasanna Kumar, S., "Comparative accounts of biological productivity characteristics and estimates of carbon fluxes in the Arabian Sea and Bay of Bengal," Deep Sea Research, Part II, 52, 2003– 2017 (2005).

[6] Gomes, H.R., Goes, J.I., and Saino, T., "Influence of physical processes and freshwater discharge on the seasonality of phytoplankton regime in the Bay of Bengal," Continental Shelf Research, 20, 313-330 (2000).

[7] Hood, R., Abbot, M.R., "Surface patterns in temperature, flow, phytoplankton biomass and species composition in the coastal transition zone off Northern California," Journal of Geophysical Research, 95, 18081-180984 (1990).

[8] Kamykowskiw, D., "A preliminary biophysical model of the relationship between temperature and plant nutrients in the upper ocean," Deep Sea Research, 34, 1067-1079 (1987).

[9] Kumari, B. and Babu, K.N., "Provincial nature of chlorophyll and sea surface temperature observed by satellite," International Journal of Remote Sensing, 30(4), 1091-1097 (2009).

[10] Marzeion, B.A., Timmermann, A., Murtugudde, R. and Jin, F.F., "Biophysical feedbacks in the tropical Pacific," Journal of Climate, 18, 58-70 (2005).

[11] NOAA. 2012. OCEAN. http://www.noaa.gov/ocean.html.

[12] Price, J.F., "Upper ocean response to a hurricane," Journal of Physical Oceanography, 11, 153–175 (1981).

[13] Rahul P.R.C., Salvekar P.S., Nayak S., "Super cyclone induces a mesoscale phytoplankton bloom in the Bay of Bengal," IEEE Geoscience and Remote Sensing Letters, 5, 588-592 (2008).

[14] Taylor GT, "Variability in the vertical flux of micro-organisms and biogenic material in the epipelagic zone of a North Pacific central gyre station," Deep Sea Res 36, 1287-1308 (1989).

[15] Tilstone, G.H., Angel-Benavides, I.M., Pradhan, Y., Shutler, J.D., Groom, S. and Sathyendranath, S., "An assessment of chlorophyll –a algorithm available for SeaWiFS in coastal and open areas of the Bay of Bengal and Arabian Sea," Remote Sensing Environment, 115, 2277-2291 (2011).

[16] Vinayachandran, P. N., P. Chauhan, and S. R. Nayak, "Biological response of the sea around Sri Lanka to summer monsoon," Geophysical Research Letter, 31, 1302 (2004).

[17] Vinayachandran, P.N. and Mathew, S., "Phytoplankton bloom in the Bay of Bengal during the northeast monsoon and its intensification by cyclones" Geophysical Research Letter, 30, 1572 (2003).

[18] Vinayachandran, P.N., "Impact of Physical Process on Chlorophyll Distribution in the Bay of Bengal," Indian Ocean Biogeochemical Processes and Ecological Variability Geophysical Monograph Series 185, 71-84 (2009).

[19] Verlekar, X.N., Desai, S.R., Sarkar, A., and Dalal, S.G., "Biological indicators in relation to coastal pollution along Karnataka coast," Water Research, 40, 3304 – 3312 (2006).

[20] Wiggert, J. D., R. R. Hodd, K. Banse, and J. C. Kindle, "Monsoon driven biogeochemical processes in the Arabian Sea," Prog. Oceanogr, 65, 176– 213 (2005).

[21] Wiggert, J. D., R. G. Murtugudde, and J. R. Christian, "Annual ecosystem variability in the tropical Indian Ocean: Results of a coupled bio-physical ocean general circulation model," Deep Sea Research, 53, 644– 676 (2006).