Monitoring of monthly scale chlorophyll concentration variability in the Bay of Bengal and Arabian Sea using MODIS Aqua Satellite Data

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Abstract: Study has been carried out to monitor the phytoplankton biomass in Bay of Bengal (BoB) and Arabian Sea (AS) using Moderate Resolution Imaging Spectroradiometer (MODIS) Aqua satellite data. Cloud masking, geometric corrections and subsets generations were performed to retrieve chlorophyll images from MODIS-Aqua data during the periods January - December for the years 2007 and 2008. The two regions (BoB & AS) have been divided into four subsets; subset-1 (Northern Bay of Bengal), subset-2 (Southern Bay of Bengal), subset-3 (Northern Arabian Sea) and subset-4 (Southern Arabian Sea). The results were analyzed and confirmed that chlorophyll concentration mean range was high (0.97-1.89 mg m^{-3}) in northern Arabian Sea during the months of July for both years 2007 and 2008 and low concentration range (0.12-0.35 mg m^{-3}) was obtained during April month for both years in southern Bay of Bengal. This study found to be important as information about the chlorophyll concentration in the Northern Indian Ocean.

Keywords: Phytoplankton, Bay of Bengal, Arabian Sea, MODIS-Aqua, chlorophyll

1. Introduction

Oceans occupy almost 70% of the Earth's surface, which play an important role in climatic conditions of the adjacent land regions. In ocean, the physical, chemical and biological processes are linked in intimate manner (Tang et al., 2002). Oceanic features such as currents boundaries, sea surface temperature, ocean fronts and eddies, suspended particulate matter and dissolved organic matter influence the ocean dynamics and its interaction with the atmosphere. Long-term ocean colour satellite monitoring provides an important tool for better understanding of the marine processes, ecology and coastal environmental changes (Yoder et al. 1993; Tang et al. 1998 & 1999; Tang & Kawamura, 2001; Tang et al. 2002). Remote sensing of ocean colour yields information on the constituents of seawater such as concentration of phytoplankton pigments, suspended sediments and yellow substance. The methods of detecting and mapping seawater constituents from aircraft and from space-borne platform have been successfully developed during past three decades. Routine monitoring of regional and temporal variability of ocean chlorophyll provides information on primary production and subsequent assessment of secondary and higher order production processes such as zooplanktons and marine fisheries (Chauhan et al. 2001). The phytoplanktons are critical to all life on earth because of their great contribution to food webs and their generation of large amounts of atmospheric oxygen through photosynthesis (Sarangi et al. 2005).

Ocean colour is determined by the interactions of incident light with constituents present in the water. Accurate measurements of light radiance at visible wavelengths produce ocean color data, which are related to constituents present in the water. Such measurements are used to monitor the level of biological activity and presence of materials in ocean water. Ocean colour information on a global scale is also important in studying the bio-geochemical cycles of carbon-nitrogen and sulfur (Chauhan et al. 2002). Efforts have been made to study the chlorophyll distributions in Arabian Sea (Nakamoto et al. 2000; Madhupratap et al. 1996 & Tang et al. 2002) and its influence on the sea surface temperature (Sathyendranath et al. 1991), whereas limited efforts on the detailed study with high-resolution data have been made in coastal regions of Arabian Sea and Bay of Bengal. The northeastern part of the Arabian Sea is one of high productive zones and southern part of the Bay of Bengal is not much productive compared to northern Bay of Bengal (Chauhan et al. 2001). The continental shelf in this part of Arabian Sea is much shallower compared to shelf in Bay of Bengal. Arabian Sea (AS) and Bay of Bengal (BoB) are two basins in Northern Indian Ocean. Though AS and BOB are landlocked to the north, they show large contrast in salinity, SST and even productivity pattern. Both the basins are influenced by south westerly wind in summer and north easterly wind in winter season. Rather than monsoonal wind very high intense but short duration cyclonic winds are frequent in

both the basins. There are increases in occurrences of intense cyclones in AS as well as in the entire world basin and change of oceanic property was observed after cyclone travel (Madhumita et al. 2012). Cyclonic disturbances caused an enhanced phytoplankton biomass in Open Ocean of upper stratified water column in Bay of Bengal (BoB) and Arabian Sea (AS). Higher cyclonic wind speed caused high phytoplankton biomass in Indian Ocean. The earlier studies have reported that chlorophyll biomass was increased more than five times after cyclone passage in Indian Ocean compared with before occurrence of cyclone. The objective of the present study is to study the variability of chlorophyll concentrations in these regions, Arabian Sea and Bay of Bengal for the years, 2007 and 2008 since more number of cyclones has been documented.

2. Data and Methodology

The retrieval of ocean color parameter such as phytoplankton pigment (Chlorophyll-a) in oceanic waters, involves two major steps, the atmospheric correction of visible channels to obtain normalized water leaving radiances in shorter wavelengths and application of the bio-optical algorithm for retrieval of phytoplankton pigment concentrations.

2.1 Study area

Phytoplankton productivity was determined based on chlorophyll concentrations from two regions, Bay of Bengal and Arabian Sea (68° - 91°E Longitude; 5°- 23.8° N Latitude) from January - December during the years, 2007 and 2008. The Bay of Bengal region is divided into two subsets, subset 1 is Northern Bay of Bengal (Longitude: 77.5° - 91° E, Latitude: 14° - 23.8° N) and subset 2 is Southern Bay of Bengal (77.5° - 91° E, 5° - 14° N), correspondingly Arabian sea region is also divided in to two subsets, subset 3 is Northern Arabian sea (68° - 77.5° E; 14° - 23.8° N) and subset 4 is Southern Arabian sea (68° - 77.5° E; 5° - 14° N).

2.2 Satellite Chl- a data

MODIS datasets were processed in order to analyze the monthly changes in chlorophyll pattern from Bay of Bengal and Arabian Sea. The MODIS sensor onboard Terra and Aqua satellites has been boon to scientific community and involved in analysis and characterization of global dynamics and processes occurring on land, in oceans, and in lower atmosphere. It also played vital role in development of validated, global, interactive earth system models able to predict global change accurately enough to assist policy makers in making sound decisions concerning the protection of environment. MODIS sensor has 36 spectral bands between 0.405 - 14.385 µm and acquires data at three spatial resolutions 250m, 500m and 1000m and viewing swath width of 2,330 km and revisit cycle of 2 days.

2.3 Data Processing

Two years monthly cloud free and less cloud cover Level-3 MODIS Aqua data were averaged from January-December during the years, 2007 and 2008 and has been analyzed. Processing and analysis of the MODIS data derived chlorophyll-a images has been done using ENVI- 4.4 software. The chlorophyll concentration of Bay of Bengal and Arabian Sea ranged 0 - 2 mg m^{-3}.

3. Results

3.1 Chlorophyll concentration in Bay of Bengal and Arabian Sea during 2007

The results revealed that chlorophyll concentration was determined from two regions, Bay of Bengal and Arabian Sea. MODIS derived chlorophyll-a images of Bay of Bengal and Arabian Sea during 2007 & 2008 are given in Figure 1 & 2 and different four subsets (subsets 1, 2, 3 & 4) during 2007 & 2008 are shown in Figure 3 & 4. Chlorophyll concentration mean values for four subsets (subsets 1, 2, 3 & 4) were calculated for the year, 2007 at different months. The results are discussed that, subset-1 (Northern Bay of Bengal - NBoB) showed chlorophyll concentration ranged between 0.19 - 0.56 mg m^{-3}, the maximum chlorophyll concentration was found in August and minimum was found in June. Correspondingly, subset-2 (Southern Bay of Bengal - SBoB) showed the chlorophyll concentration ranged from 0.14 - 0.50 mg m^{-3}, chlorophyll level was high in July and low in April. Subset-3 (Northern Arabian Sea - NAS) illustrated that chlorophyll concentration range was 0.35 - 0.97 mg m^{-3}, highest level was present in July and lowest level was in May. Subset-4 (Southern Arabian Sea - SAS) displayed that chlorophyll concentration range from 0.12 - 0.38 mg m^{-3}, more value was obtained from the month of September and less value was in April. Among four subsets, NAS exhibited high concentration of chlorophyll (0.97 mg m^{-3}), moderate level was observed from NBoB (0.56 mg m^{-3}) and SBoB (0.50 mg m^{-3}) and low concentration was recorded from SAS (0.38 mg m^{-3}).

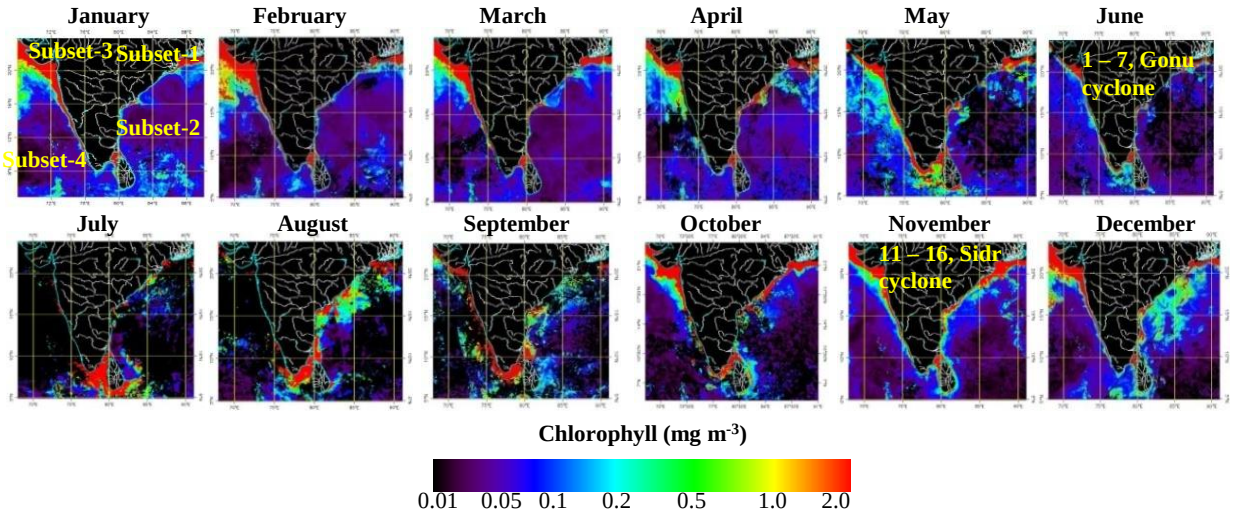

Figure 1. January-December monthly chlorophyll image during 2007 displaying subset 1-4

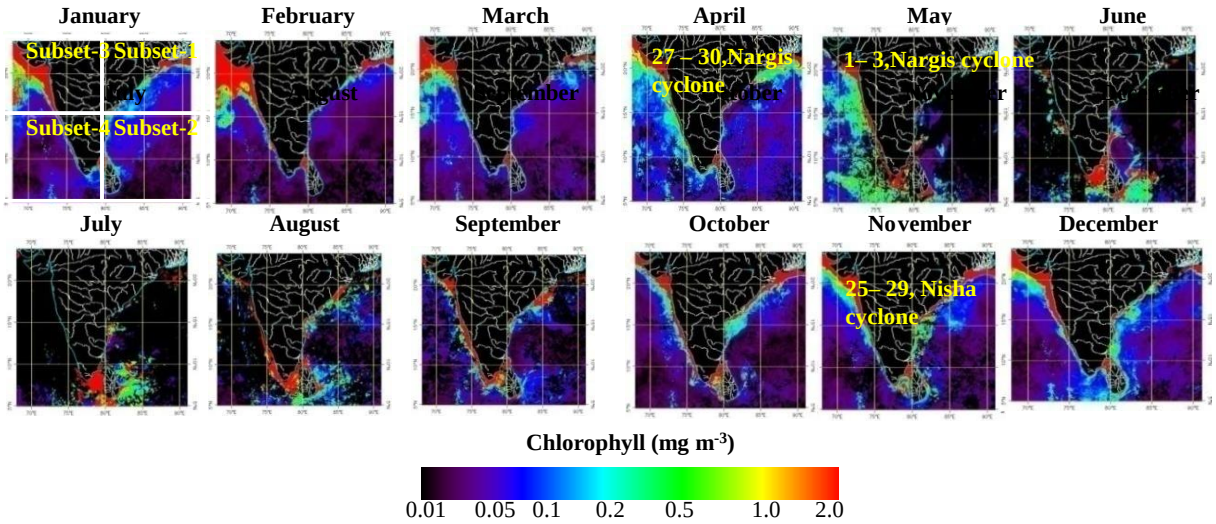

Figure 2. January-December monthly chlorophyll image during 2008 displaying subset 1-4

Chlorophyll concentration standard deviation (SD) values of four subsets during the year, 2007 at different months (January - December) are determined. The results concluded that NBoB showed the SD values from 0.28 - 0.57 mg m^{-3}, maximum variation of chlorophyll concentration (CC) in October and minimum was in June, subsequently SBoB (0.21 - 0.61 mg m^{-3}), more variation was found in July and less in February & March. In NAS (0.50 - 0.75 mg m^{-3}), highest level of variations between CC was noticed from July and lowest level was in May. Similarly, SAS (0.11 - 0.47 mg m^{-3}), CC variation was high in September and low in April. Compared with four subsets, NAS exhibited more (0.75 mg m^{-3}) variations of chlorophyll concentration followed by SBoB, NBoB and SAS.

3.2 Chlorophyll concentration in Bay of Bengal and Arabian Sea during 2008

The chlorophyll concentrations (CC) for four subsets at different months for the year, 2008. The results showed that NBoB shows the mean value from 0.22 - 0.57 mg m^{-3}, maximum value was observed in July and minimum value was observed in April followed by SBoB is 0.14 - 0.51 mg m^{-3}, highest level was obtained from month of July and lowest level was found in April; NAS is 0.33 - 1.89 mg m^{-3}, maximum value was documented from July and minimum value was from May and SAS is 0.15 - 0.47 mg m^{-3}, mean value was high in August and low in April & November. Between four subsets, NAS exhibited the maximum mean (1.89 mg m^{-3}) value of chlorophyll compared with other subsets. The SD values of chlorophyll for four subsets during the year, 2008 at different months. From these results, NBoB showed the maximum and minimum SD values from 0.34 - 0.57 mg m^{-3}, maximum variation of chlorophyll concentration (CC) in September and minimum was in April, subsequently SBoB (0.19 - 0.56 mg m^{-3}), more variation was found in July and less in April. Equally, NAS (0.35 - 0.75 mg m^{-3}), highest level of variations between CC was noticed from February and lowest level was in July and SAS (0.13 - 0.62 mg m^{-3}), CC variation was high in August and low in April. Compared with four subsets, NAS showed highest (0.75 mg m^{-3}) variation of chlorophyll concentration consequently, SAS, NBoB and SBoB.

3.3 Correlation between Chlorophyll concentrations in Bay of Bengal and Arabian Sea during 2007 and 2008

Interrelations of chlorophyll mean four subsets (ss-1, ss-2, ss-3 & ss-4) of BoB and AS for the year, 2007 are given in Table 1.

Table-1 Interrelations of chlorophyll mean for Bay of Bengal & Arabian Sea during 2007 & 2008.

Iterations	Interrelations of Chlorophyll mean of subsets (ss-1 to ss-4)	R^2 value (Year 2007)	R^2 value (Year 2008)
1	ss-1 vs ss-2	0.27	0.52
2	ss-1 vs ss-3	0.17	0.37
3	ss-1 vs ss-4	0.10	0.47
4	ss-2 vs ss-3	0.64	0.27
5	ss-2 vs ss-4	0.62	0.70
6	ss-3 vs ss-4	0.33	0.17
7	ss-1 & 2 vs ss-3 & 4	0.31	0.43

Correlation between chlorophyll concentrations of subsets-1&2, subsets-1&3, subsets-1&4, subsets-2&3, subsets-2&4 and subsets-3&4 during Jan - Dec, 2007 are shown in Table 1. Since these results confirmed that NBoB observed chlorophyll concentration (CC) was less (R^2 value = 0.27) correlated with SBoB (a), subsequently, NBoB was lowest level (R^2 = 0.17) correlated with NAS and SAS (R^2 = 0.10). Also, SBoB of CC was maximum (R^2 = 0.64) correlated with NAS and SAS (R^2 = 0.62), followed, NAS of CC was minimum (R^2 = 0.33) correlated with SAS respectively. Correlation between chlorophyll concentrations of subsets-1&2, subsets-1&3, subsets-1& 4, subsets-2&3, subsets-2&4 and subsets-3&4 during Jan - Dec, 2008 are shown in Table 1. The results shows that NBoB observed chlorophyll concentration was higher (R^2 value = 0.52) correlated with SBoB, followed shows minimum correlation (R^2 = 0.37) with NAS and maximum correlated with SAS (R^2 = 0.47). SBoB was incredibly less (R^2 = 0.27) correlated with NAS and highest correlated with SAS (R^2 = 0.70), subsequently, NAS was lowest (R^2 = 0.17) correlated with SAS.

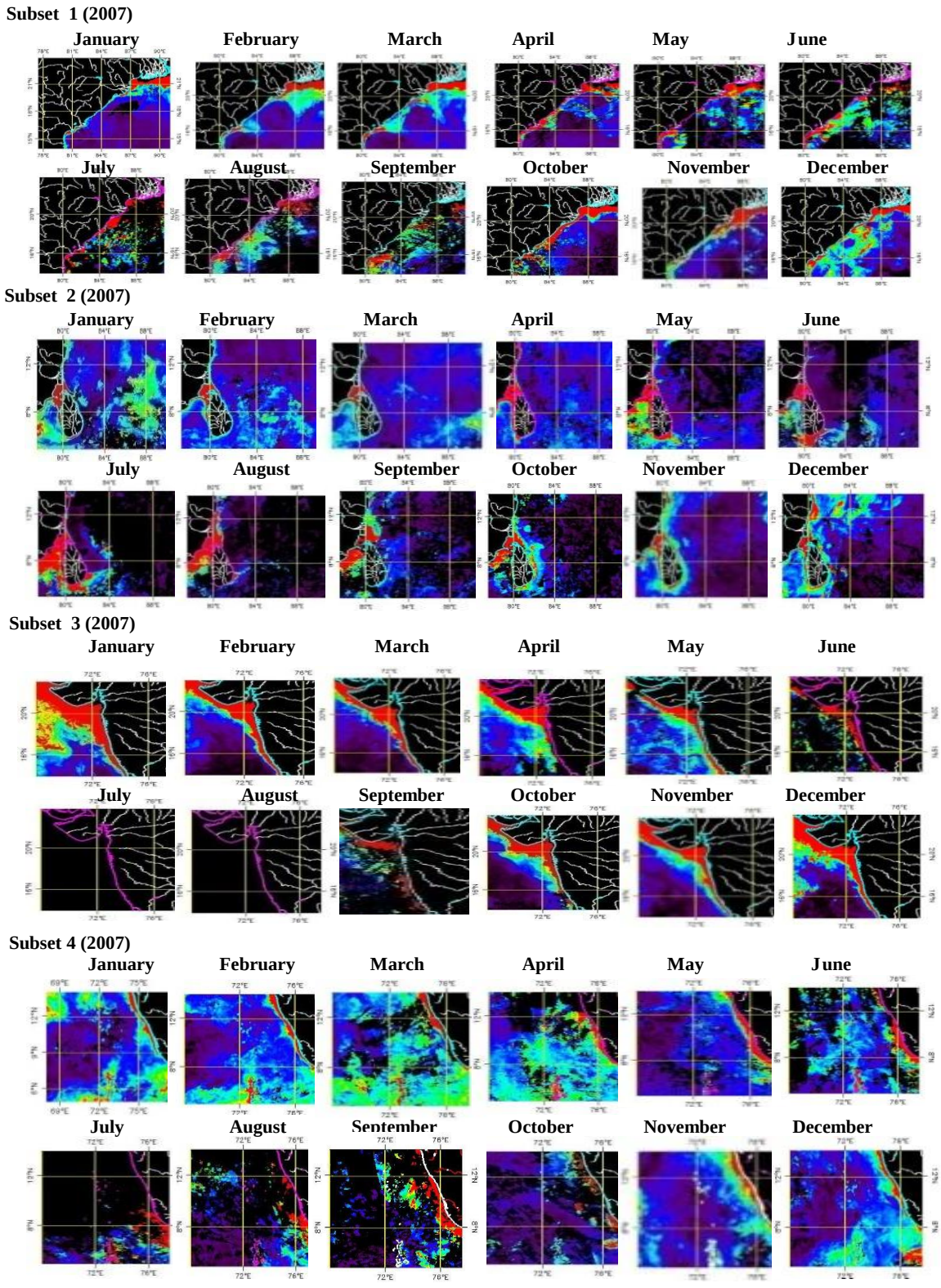

Figure 3 Chlorophyll image for four subset during January-December , 2007

Table-2 Interrelations of chlorophyll mean for Bay of Bengal & Arabian Sea during Jan - Dec, 2007 & 2008

Iterations	Chlorophyll mean of subsets	R^2 value (Years 2007 & 2008)
1	Subset-1	0.06
2	Subset-2	0.72
3	Subset-3	0.56
4	Subset-4	0.49
5	ss-1 & 2 vs ss-1 & 2	0.39
6	ss-3 & 4 vs ss-3 & 4	0.69
7	Four subsets	0.65

Association between chlorophyll concentrations of subset-1, subset-2, subset-3 & subset-4 during Jan - Dec, 2007 & 2008 are displayed in Table 2. The results are demonstrated that, chlorophyll concentration of NBoB during the year, 2007 was extremely less (R^2 = 0.06) correlated with NBoB for the year, 2008, equally, SBoB during the year, 2007 was exhibited highest (R^2 = 0.72) correlated with SBoB for the year, 2008 (b), followed NAS (2007) was maximum (R^2 = 0.56) correlated with NAS (2008) and SAS (2007) was minimum correlated (R^2 = 0.49) with SAS during 2008. Chlorophyll concentrations of subsets-1&2, 3&4 and subsets-1&2, 3&4 during January - December, 2007 and 2008 are shown in Table 1. The results are concluded, chlorophyll concentrations of NBoB & SBoB was less (R^2 = 0.31) correlated with NAS & SAS during the year 2007 and chlorophyll concentrations of NBoB & SBoB was more (R^2 = 0.43) correlated with NAS & SAS during the year 2008.

Comparison of Chlorophyll mean concentrations of Bay of Bengal subsets-1&2 (2007&2008) and Arabian sea subsets-3& 4 (2007&2008) during Jan - Dec, 2007 and 2008 are illustrated in Table 2. From these results, NBoB & SBoB (2007) was showed minimum (R^2 = 0.39) correlation with NBoB & SBoB for the year, 2008, followed, NAS & SAS (2007) was expressed maximum (R^2 = 0.69) correlation with NAS & SAS for the year, 2008. Differences between chlorophyll mean concentrations of Bay of Bengal & Arabian Sea four subsets (Subsets 1-4) during January - December, 2007 and 2008 are mentioned in Table 2. From these results, chlorophyll concentrations of four subsets (NBoB, SBoB, NAS & SAS) for the year, 2007 was moderately (R^2 = 0.65) correlated with four subsets during the year, 2008.

4. Discussion

Cyclonic events are characterized by a low-pressure center and numerous thunderstorms. The response of the chlorophyll concentration to propagating cyclones should be associated with phase of seasonal cycle of the concentration, as well as translation speed of the cyclone. Cyclones, eddies and circulation pattern have significant influence on distribution of chlorophyll pattern in Ocean. The present study, spatial and temporal distributions of the chlorophyll concentrations in parts of the Bay of Bengal and Arabian Sea have been observed during these years, 2007 and 2008. The present study results show higher chlorophyll concentration (CC) in northern Arabian Sea and more variations of CC also high in that region during July month compared with other months of NBoB, SBoB and SAS regions for the year, 2007. Correspondingly, NAS has highest value of CC variations were recorded from the month of July compared with other months of NBoB, SBoB and SAS regions during 2008. In addition, chlorophyll concentration was also high in NBoB during August month and variations of CC were high in October month compared with SBoB & SAS for the year, 2007. In 2008, maximum CC value was recorded from July month in NBoB followed by SBoB and SAS and variations between CC was found maximum in NBoB during September compared with other months.

Similar earlier studies have reported, seasonal variation has very prominent in Arabian Sea. The northern Arabian Sea is characterized by offshore and onshore chlorophyll blooms during the northeast monsoon period (Tang and Kawamura, 2001), where the southern Bay of Bengal is found to produce no such bloom. Yoder (2000) has found anomalous pattern of chlorophyll concentration caused by monsoon wind-induced upwelling in North Indian Ocean compared to other oceans. In Arabian Sea, similar trend has been found reported by previous studies (Chauhan et al., 2001;2002; Dey & Singh, 2003; Sarangi et al., 2001; 2005; Singh & Chaturvedi, 2010; Maneesha et al., 2011; Patissier et al., 2014), from this study findings are proved that chlorophyll biomass high in Arabian Sea compared with Bay of Bengal region (Dey & Singh, 2003; Chauhan et al., 2001; Chaturvedi et al., 2013) confirmed with high resolution data.

The present study findings are concluded that Arabian Sea has high chlorophyll biomass compared with Bay of Bengal (BoB) during the year, 2008 than 2007 for the reason that more cyclonic events were documented from October – December 2007 in Arabian Sea, accordingly end of cyclones passages leads to enhanced nutrients level in waters is responsible for more chlorophyll concentration in that region was found during the year 2008. In addition, BoB has lower nutrient concentrations and less cyclonic events were documented than AS.

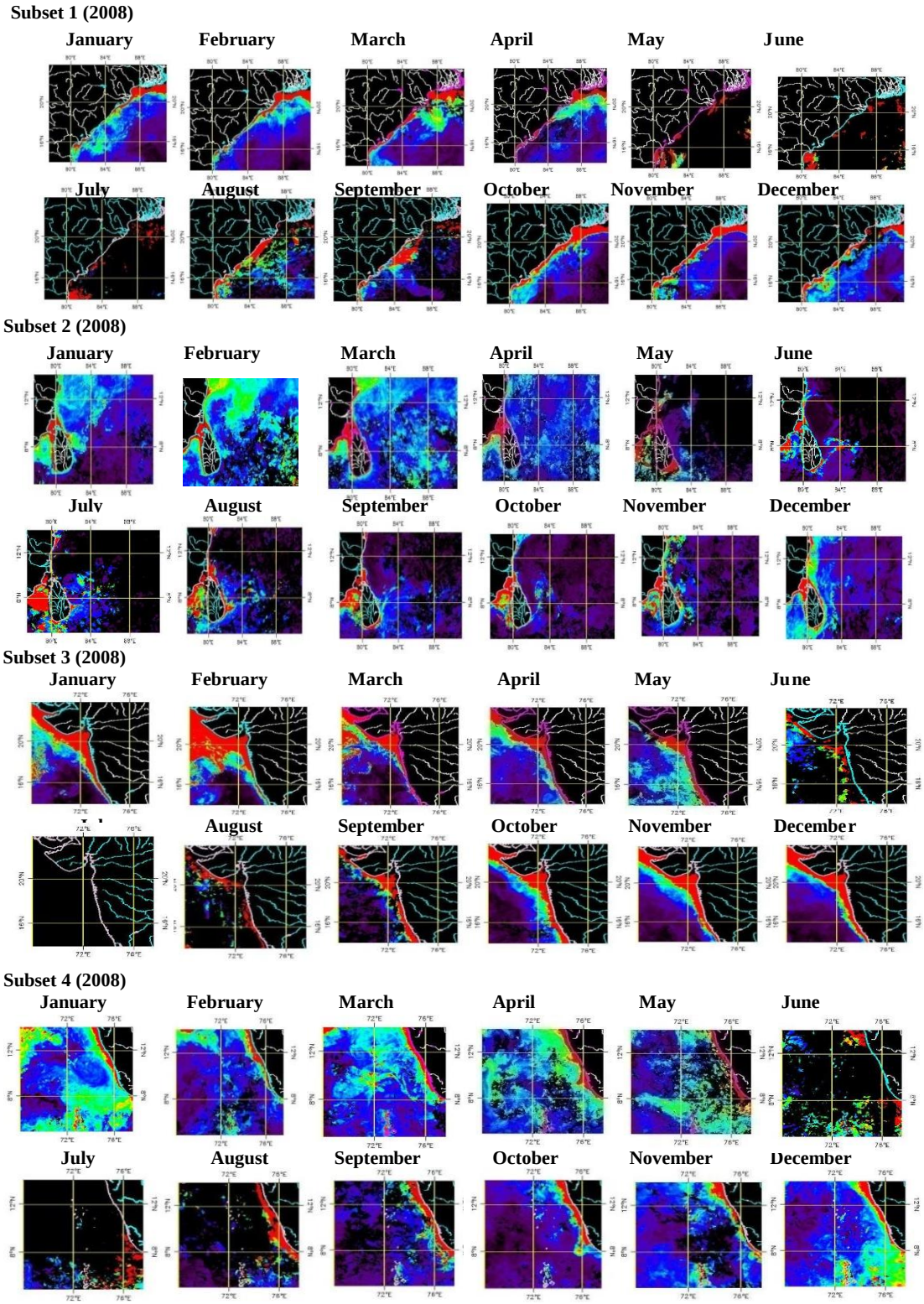

Figure 4 Chlorophyll image for four subset during January-December , 2008

The low nutrients content in BoB waters are prime cause of low chlorophyll concentration. In addition, vertical mixing and upwelling of the nutrients are not strong enough to support high primary production in BoB compared to AS. Various similar studies are supported observed that nutrients supplied by super cyclone enhanced Chl-*a* concentrations (5–10 times) also noted enhanced nutrient concentrations and the consequent increase in primary production in Indian Ocean by super cyclone. Satellite Chl-*a* imageries revealed the occurrence of phytoplankton bloom in southwestern Bay during monsoon due to upwelling caused by cyclones. Maneesha et al. (2011) examined the influence of extreme atmospheric events, such as heavy rainfall and cyclone Sidr, on phytoplankton biomass in western Bay of Bengal using both *in situ* time-series observations and satellite derived Chlorophyll *a* and sea surface temperature (SST). From this study findings, similar increase in Chl *a* by 3 to 10 times was observed in central Bay of Bengal after the cyclone Sidr which also enhanced 40% of fishery production during October–December 2007 compared to same period in 2006.

The present study, two years (2007&2008) assessment of CC and correlation between CC are documented, from these results proved; higher chlorophyll concentration in Northern Arabian Sea during July month for both years 2007 & 2008. Tang et al. (2002) have also found similar chlorophyll concentrations in northern Arabian Sea using OCTS images. In Bay of Bengal, though higher chlorophyll concentrations are found during the months of August for 2007 & July for 2008 due to more numbers of cyclonic events and rivers fluxes of Krishna and Godavari delta in NBoB is basis for high chlorophyll biomass compared with SBoB and SAS. In contrast, compared with SAS, NAS is characterized by cooling and densification phenomenon and cyclonic disturbances. This leads to high salinity of the Arabian Sea water, which initiates convective mixing and injection of nutrients into sea surface from thermocline regions. The nutrient injection is responsible for higher chlorophyll concentrations in NAS. The NBoB & SBoB, though experiences the onset and retreat of monsoon compared to Arabian Sea, the low nutrient concentration of water, and the lack of upwelling of nutrients due to its typical ocean dynamics, caused low chlorophyll biomass compared to those in the AS and supplementary basis for variations of chlorophyll concentration occurred due to river fluxes. The higher CC values in NAS due to cyclones passages and also mixing of major rivers fluxes of Narmada, Tapi, Mahi, sabarmathi and Indus on the west coast, On the east coast of India, large-scale river fluxes (Krishna, Godavari, Brahmaputra, Ganges, Mahanadi and Kaveri rivers) extending deep in to the open ocean has been detected, although, BoB region has less numbers of rivers fluxes compared to AS, its reasons for high phytoplankton biomass in AS (Sarangi, 2016; Shanthi et al., 2015.

However, in evaluation with previous reported studies the chlorophyll concentration ranges from 0.4 - 1.0 mg m^{-3} was observed in Arabian Sea using satellite data reported by Chauhan et al., 2001; 2002; Dey & Singh, 2003; Sarangi et al., 2001; 2005; Singh & Chaturvedi, 2010 and recently Madhumita et al. (2012) reported increased chlorophyll was observed by super cyclones roughly from 0.25 - 0.4 mg m^{-3} in Arabian Sea in May 2007. Chaturvedi et al. (2013) studied the SeaWiFS derived eight-day average chlorophyll images for 10 years (1997 – 2008) reported chlorophyll concentration was increased (0.3 - 0.8 mg m^{-3}) every year in northwest Arabian Sea compared to previous report (0.05 - 0.3 mg m^{-3}) in 1980's from OCTS images. The present study was recorded the maximum chlorophyll biomass values (1.89 mg m^{-3}) in NAS for the year, 2008 compared with 2007 (0.97 mg m-3) because more number of cyclonic events were documented during April – December, 2008 in North Indian Ocean however end of cyclones passages leads to enhanced more nutrients level in that region is answerable for highest chlorophyll concentration was obtained for the year 2008 compared with 2007 and previous studies also.

5. Conclusion

The present study summarizes that chlorophyll concentration observed higher in northern Arabian Sea compared to southern Arabian Sea, northern and southern Bay of Bengal. Higher chlorophyll values in the northern Arabian Sea are associated with cyclones passages and winter cooling phenomenon. During this period, atmospheric forcing that leads to observed changes in upper layer of the ocean (reduction in sea surface temperature) this leads to formation of Arabian Sea has high salinity waters, which further leads to sinking and convective mixing of nutrients to upper layers of water column triggers the higher primary production and river fluxes also played a major role for high chlorophyll biomass in that region and moreover southern Arabian Sea has minimum chlorophyll biomass observed, but northern and southern Bay of Bengal has reflected moderate chlorophyll biomass. In addition, northern Bay of Bengal being evaluated with southern Bay of Bengal, shows high chlorophyll biomass due to more number of cyclonic events and river fluxes from Krishna and Godavari and its leads to vertical mixing of nutrients in that region caused maximum biomass than southern Bay of Bengal. There is no mixing of river fluxes found from southern Bay of Bengal, hence low chlorophyll biomass was obtained. To conclude, the present study will useful for studying the changes of primary production and new production in Arabian Sea and Bay of Bengal regions and moreover, to find out oceanic and coastal processes, cyclonic effects, phytoplankton diversity and their growth and distribution prior and end of cyclones passages in Indian Ocean for future evaluation.

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