Chapter 5

Spatio-Temporal variability of Phytoplankton Productivity in the Arabian Sea

5 SPATIO–TEMPORAL VARIABILITY OF PHYTOPLANKTON PRODUCTIVITY IN THE ARABIAN SEA

5.1 INTRODUCTION

The biological significance of oceans can be acknowledged from the fact that the ocean Primary Production (PP) makes up approximately half of the global primary production *(Field et al., 1998)* and this 50% share of global primary production is contributed by marine phytoplankton *(Falkowski et al., 2004).*

Phytoplankton are microscopic, aquatic plants, that move or drift with the movement of the water masses. They are the base of several aquatic food webs. In a balanced ecosystem, they provide food for a wide range of sea creatures including whales, shrimp, snails, and jellyfishes. Among the most commonly found phytoplankton in the oceans are the cyanobacteria, diatoms, dinoflagellates, green algae and coccolithophores. These phytoplankton in the ocean absorb solar radiation to fix CO_2 to organic carbon through the process of photosynthesis as shown in Equation 7.

$$6CO_2 + 12H_2O + \text{Light energy} \longrightarrow C_6H_{12}O_6 + 6O_2 + 6H_2O \text{ ----------------(Equation 7)}$$

The rate at which photosynthesis occurs is known as **Primary Production (PP)** and it is dependent on the distribution of phytoplankton, their biomass and availability of nutrients. Physical processes like ocean circulation, wind, upwelling, dust events, etc. regulates the distribution of nutrients in the surface layer and in turn affects the growth and productivity of phytoplankton (*Santoleri et al., 2003; Siegel et al., 1999*). Productivity also varies with the temperature of the water (*Thomas et al., 2003*) and availability of light (*Gohin et al., 2003*; *Kogeler & Rey, 1999*) and takes place within the euphotic zone, which extends from the surface to a depth where there is 1% of the light intensity from the surface,

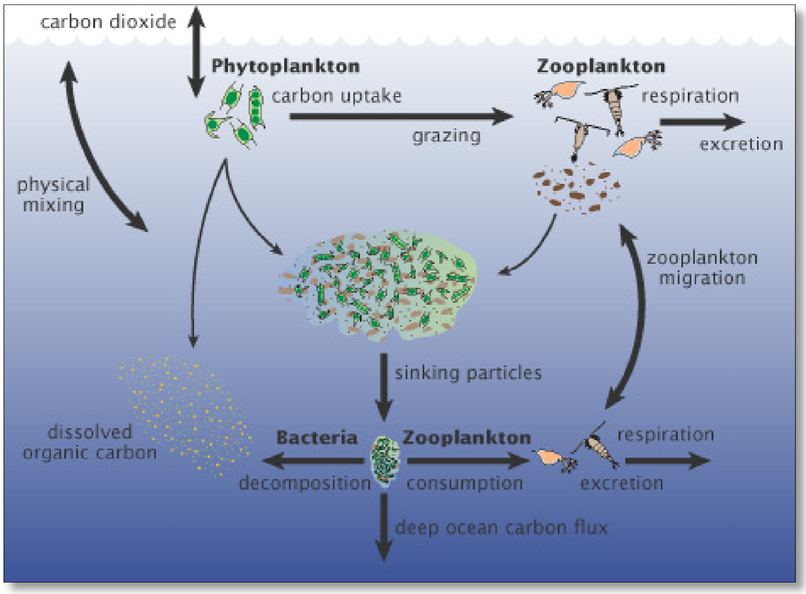


Fig. 5.1: Biological Carbon Pump in Oceans Driven by Phytoplankton *(Source: U.S. JGOFS)*

Photosynthesis by phytoplankton not only fixes CO_2, but also drives the biological carbon pump and play a significant role in the cycling of the carbon. The uniqueness of productivity of oceans is that unlike the other component of the global carbon cycle, the amount of carbon fixed through primary production is much more than the amount of carbon reserved in the marine biota. It is estimated that the phytoplankton transfer about 10 gigatonnes of carbon from the atmosphere to the deep ocean each year (*NASA*). *Broecker (1982)* reported that the phytoplankton in the oceans store more carbon away from the atmosphere than the terrestrial biosphere. Apart from playing a significant role in the carbon cycle, the importance of the phytoplankton can also be evaluated from the fact that **they provide 50% of the oxygen on earth** *(UNESCO/Rio+20)*. Besides, as the phytoplankton form the basis of the marine food chain, their productivity affects the overall productivity of the oceans and can be an indicator of the status and ecological significance of the marine ecosystem.

An assessment of the standing stock or biomass of the phytoplankton gives an inference about the productivity of the oceans. The higher the primary productivity, the higher would be the biomass of phytoplankton, and higher would be the subsequent secondary and tertiary productivity. Hence, it becomes essential to quantify the biomass of the phytoplankton to assess the productivity of the oceans. The most common method of estimation of the phytoplankton biomass and productivity is the quantification of the chlorophyll-a concentration (chl.-a conc.). It has long been used as an index for phytoplankton biomass and as a proxy for estimation of productivity of the oceans (*Ryther and Yentsch, 1957; Strickland, 1960*). *Prakash & Ramesh (2007)* and *Chaturvedi et al. (2013)* reported on the productivity of the Arabian Sea and Indian Ocean respectively, using remotely sensed chlorophyll-a concentration. In recent years, using remote sensing technology, lot of studies have been done to estimate the trend of productivity in the marine ecosystems especially in relation to the changing climatic conditions, warming of the oceans and their acidification (*Worm et al., 2005; Behrenfeld et al., 2006; Doney, 2006; Henson et al., 2009, Boyce et al., 2010)* and for estimation of the long term trends.

Satellite remote sensing is one of the latest technologies that has the advantage of providing a synoptic view of the vast oceans. The ocean colour captured by satellite gives the information regarding the abundance of microflora or phytoplankton of the oceans. Additionally, the repeated regular sampling through satellites help in generating time-series data for a longer period of time.

Hence for climate change related studies, the prime requisite of a long-term continuous data set is provided by the sensors aboard satellites. Ocean colour remote sensing was primarily conceived for producing synoptic fields of phytoplankton biomass indexed as chlorophyll. *Banse & McClain (1986)* highlighted the importance of satellite data sets over the data collected from ship cruises for the study of non-conservative variables (e.g. phytoplankton biomass) over the oceans spread over larger geographical areas. Since then, a lot of innovation and research has gone into developing better ocean colour sensors and their algorithms for providing the satellite data needed for oceanographic studies and monitoring (*O'Reilly et al., 1998; Mc Clain, 2009; IOCCG, 2000; Devi et al., 2015*).

The Ocean Color Remote Sensing captures the presence of phytoplankton in the oceans due to the presence of the main photosynthetic pigment ‘Chlorophyll-a’. The ocean color sensors are able to capture the water leaving radiance from the surface layer of the oceans that is characterized by the presence of phytoplankton as well as the suspended organic and inorganic matter. The phytoplankton exhibit a preferential absorption in the red and the blue part of the electromagnetic solar radiation due to the presence of the green photosynthetic pigment i.e. the chlorophyll-a molecules. Besides, they strongly reflect the light in the green band (*Prieur & Sathyendranath, 1981; Morel, 2007, Bricaud et al., 1995)*. Hence, based on the composition of the oceanic waters, their spectral properties vary, which are captured by ocean colour sensors aboard satellite.

For retrieval of chlorophyll- a concentration (in mg m^{-3}) from the oean colour sensors, different bio-optical algorithms have been developed to relate measurements of ocean radiance to the *in situ* concentrations of phytoplankton pigments. One of the most widely used algorithms for deriving chlorophyll–a concentration is the band - ratio algorithm, which uses the correlations between chlorophyll-a concentration and the spectral blue-to-green ratios of remote sensing reflectance. The blue waveband lies in the visible spectrum, (approx. 440 nm) where the absorption by the phytoplankton due to the presence chlorophyll-a pigment is the highest, whereas the green waveband is typically located in the region of minimal phytoplankton absorption (¨550 to 555 nm) (O'Reilly et al.,1998; Chauhan et al.,2004). This algorithm returns the near-surface concentration of chlorophyll-a in mg m^{-3}, using an empirical relationship derived from *in situ* measurements of chlorophyll-a concentration and remote sensing reflectance in the blue-to-green region of the visible spectrum. For instance, a higher phytoplankton biomass would mean higher chlorophyll-a concentration and hence higher reflection in the blue - green band, which can be easily captured by the ocean color sensors aboard the satellites.

There have been numerous studies done in the field of marine biology where in the chlorophyll-a concentration has been used as an index of phytoplankton biomass and primary productivity. Solanki et al. (2004), used chlorophyll-a concentration retrieved from Ocean Color Monitor aboard IRS P4 satellite, and SST data from AVHRR for identification of zones for bio-physical coupling in the Arabian Sea. They used chlorophyll-a concentration as an index for primary productivity and SST as an index of physical environment which controls the physiology of the marine biota. Based on their observations, they identified zones where bio-physical coupling was observed and carried out in situ fishing operations., only to conclude that the comparatively colder water was rich in chlorophyll- a concentration and hence were high in primary productivity and had higher fish catch per unit. This supported their hypothesis that regions where higher chlorophyll-a concentration were the regions with higher primary and secondary productivity.

Similarly, Piontkovski (2012) studied interannual changes in the productivity of the Arabian Sea from using chlorophyll- a concentration as an index for productivity. In their study they used SeaWiFS level 3 chlorophyll- a data for analysis and concluded that the basin-wide maps of chlorophyll distribution did not show the enlargement of the productive area over time and overall, not only did the Arabian Sea not get more productive, but several regions in its eastern basin showed a decline in chlorophyll a concentration.

Dwivedi et al. (2012) used chlorophyll-a images from Oceansat1/OCM for identifying the areas of phytoplankton bloom in the Arabian Sea to study the influence of bloom (increase in productivity) on primary and secondary consumers. They concluded that higher chlorophyll levels during the bloom in the range of 0.4 -2 mg m-3 reflected higher primary production in deep water. Based on their *in situ* ship based study, they observed that the zooplankton also exhibited an unusual higher growth pattern in the bloom water which eventually also translated into higher fish catches in the bloom water.

Recently, Shah et al. (2017) analyzed the impact of climate change on biological productivity of Indian Ocean using the Coastal Zone Color Scanner (CZCS) and SeaWiFS derived chlorophyll data

Based on the above-mentioned studies, in the present work, the spatio-temporal variability of chlorophyll-a concentration of different sub-domains of the Arabian Sea was analyzed and was used as an index of primary productivity. In this study, chlorophyll-a concentration was obtained from two different ocean color sensors viz. SeaWiFS and MODIS from the period 1997 to 2015, to assess the monthly, seasonal and annual changes in the productivity pattern in the Arabian Sea.

5.2 DATA USED

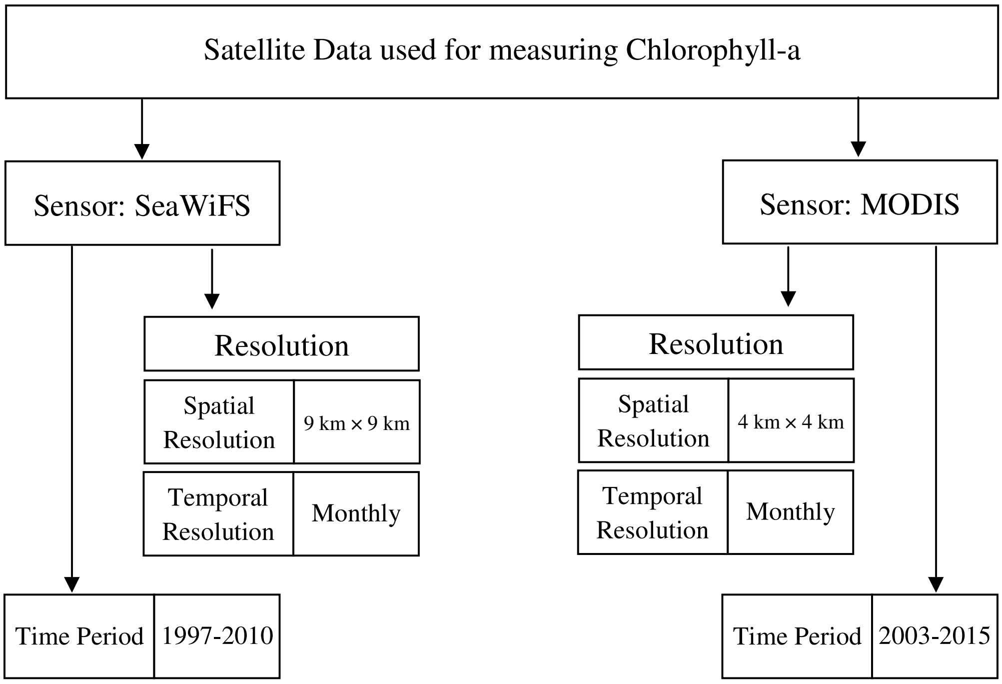


Fig. 5.2: Details of the satellite data used in the present study

In the present study, data sets from two different ocean colour sensors corresponding to the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and the Moderate Resolution Imaging Spectroradiometer (MODIS) were used for analysis of phytoplankton biomass in the Arabian Sea. Fig. 5.2 shows the details of the satellite data used in the present study. Chlorophyll-a measured from the SeaWiFS was used for analyzing the spatial and temporal distribution of phytoplankton for the period 1997–2010. The monthly composites Level-3, 9 km resolution mapped SeaWiFS chlorophyll concentrations data were accessed from http://oceandata.sci.gsfc.nasa.gov. For the period from 2003 to 2015, the monthly, Level-3, 4 km resolution chlorophyll-a images, (Reprocessing 2014.0 version) of Moderate Resolution Imaging

Spectroradiometer (MODIS) were obtained from http://oceandata.sci.gsfc.nasa.gov. The reprocessing 2014.0 MODIS data includes updates for the ocean color product suite and existing product algorithms, to incorporate new knowledge of sensor-specific instrument calibration. A significant change that has been implemented in the 2014.0 version data is for the chlorophyll-a algorithm, where in the standard band ratio algorithm (also known as OCx) has been merged with the color index (CI) algorithm as given by Hu et al. (2012). The CI algorithm is a three-band reflectance difference algorithm employing the difference between the remote sensing reflectance in the green band and a reference formed linearly between the remote sensing reflectance in the blue and red bands (NASA).

5.3 METHODOLOGY

In the present study, chlorophyll- a images from two different ocean color sensors viz. SeaWiFS and MODIS was used. The monthly chlorophyll-a concentration was used as an index for assessment of phytoplankton biomass and productivity as given by Solanki et al. (2004); Dwivedi et al. (2012); Piontkovski et al. (2012); Shah et al. (2017).

For the purpose of detailed examination of the climatological trend of phytoplankton biomass and productivity in the Arabian Sea, the entire Arabian Sea basin was subdivided into the following 10 sub -domains as shown in Table 5.1:

Table 5.1: Sub- domains of the Study Area – Arabian Sea

	Sub- domain	Geographical Location (Lat & Long)
1.	Northern Arabian Sea (NAS)	32°E-78°E; 32°N-15°N
2.	Southern Arabian Sea (SAS)	32°E-78°E; 15°N-0°N
3.	Eastern Arabian Sea (EAS)	64°E-78°E; 32°N-0°S
4.	Western Arabian Sea (WAS)	32°E-64°E; 32^0-0°S
5.	Persian Gulf (PG)	24-3°N; 48-56.5°E
6.	Gulf of Oman (GO)	56°5°E-61°4'E; 22°3'N-26°5' N
7.	Red Sea (RS)	34°36′E-43°30′E; 12°29′N-27°57′N;
8.	Gulf of Aden (GA)	43°E-52°E; 10°N-15°N
9.	Gulf of Kutch (GKTCH)	68°20' E-70°40' E; 22°15'N-23°4' N
10.	Gulf of Khambat (GKMBT)	72°2'E - 72°6'E; 21°N - 22°2'N

For each of the sub-domains of the Arabian Sea, the monthly chlorophyll-a images were processed using the image processing software ERDAS 9.1, ENVI 4.0 and SeaDAS 7.0. The monthly chlorophyll-a images were masked to avoid the influence of the clouds. The land surfaces were also masked. The monthly chlorophyll-a images were then bathymetrically corrected to avoid the overestimation from coastal waters. The bathymetric map of the Arabian Sea was generated using SeaDAS 7.0, ERDAS 9.0 and ENVI 4.0 software where the depth of the Arabian Sea was analyzed as shown in fig. 5.3. Although, these images may not give complete under water topography, yet in the coastal areas where the problem of overestimation of chlorophyll-a comes due the presence of suspended dissolved inorganic material and dissolved organic matter, the images from SeaDAS software helped in identification of zones with less than 50 meters depth. The areas of the sea where the depth was less than 50 meters were identified and these areas were masked in the maps to avoid overestimation of chlorophyll- a concentration.

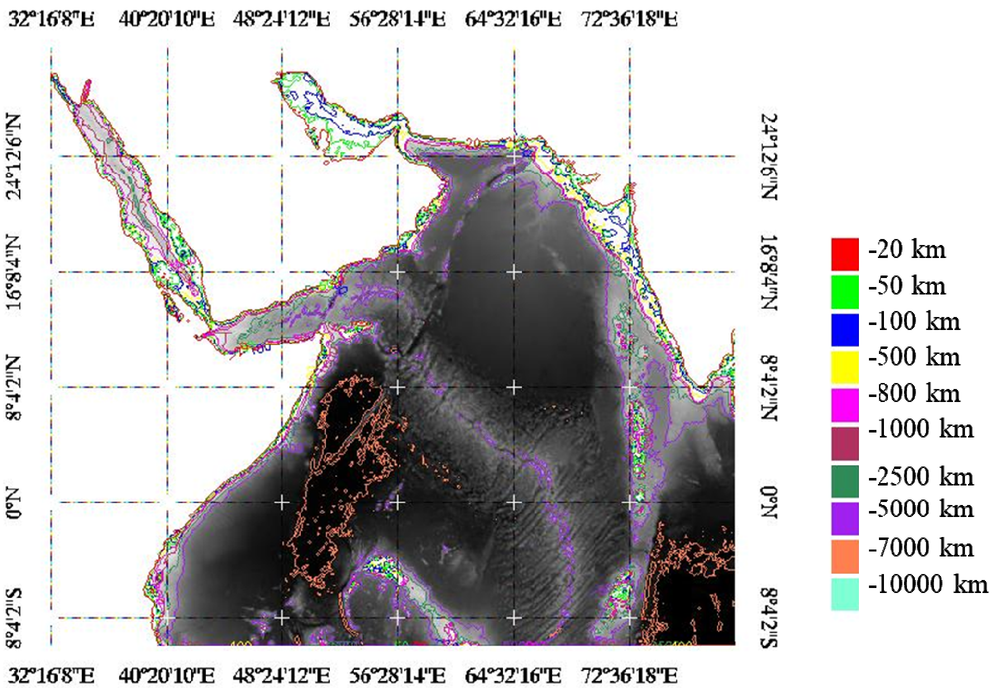


Fig. 5.3: Bathymetry map of Arabian Sea

For each of the domains of the Arabian Sea, the monthly bathymetrically corrected chlorophyll-a images were analyzed using the image processing software ENVI 4.1 and ERDAS 9.0. For analysis all the pixels of the study area were included. Care was taken to exclude the pixels with zero values while averaging. Following Joint Global Ocean Flux Study (JGOFS), the 4 climatological seasons described in the present work are as follows:

1. Northeast monsoon (December - March) (NEM)
2. Spring inter monsoon (April - May) (SIM)
3. Southwest monsoon (June - September) (SWM) and,
4. Autumn inter monsoon (October - November) (AIM)

The bathymetrically corrected SeaWiFS chlorophyll-a concentration maps were used to compute the monthly average chlorophyll-a concentration for all the months from January to December for the years from 1997 to 2010. Similarly, the bathymetrically corrected MODIS chlorophyll-a concentration maps were used to compute the monthly average chlorophyll-a concentration for the all the months from January to December for the years from 2003 to 2015.

For SeaWiFS chlorophyll-a data, the climatological mean (CM_{13}) of 13 years (1998-2010) for each month was calculated by averaging the monthly mean (My(i)). The interannual variability was analyzed using the monthly normalized anomalies, computed by subtracting the monthly climatological mean (CM_{13}) from the monthly mean (My (i)) of each year, and normalized to the standard deviation for that month (SD_{13}) as shown in Equation 8:

$$M"(NA)"="My(i) - CM(_{13})" /"SD_{13}" \quad \ldots\ldots\ldots\ldots\ldots \text{(Equation 8)}$$

The seasonal and annual normalized anomalies were computed by averaging the monthly-normalized anomalies over the respective seasons and years.

Similarly, for the satellite retrieved chlorophyll-a data from MODIS (2003 to 2015), the monthly, seasonal and annual climatological means (CM_{13}) and respective normalized anomalies were computed for 13 years.

The seasonal and annual normalized anomalies were computed by averaging the monthly-normalized anomalies over appropriate seasons and years. Trend analysis was carried out using the Mann-Kendall test.

5.4 RESULTS AND DISCUSSION

5.4.1 Monthly Variability of Phytoplankton Biomass in the Arabian Sea using satellite data from SeaWiFS and MODIS

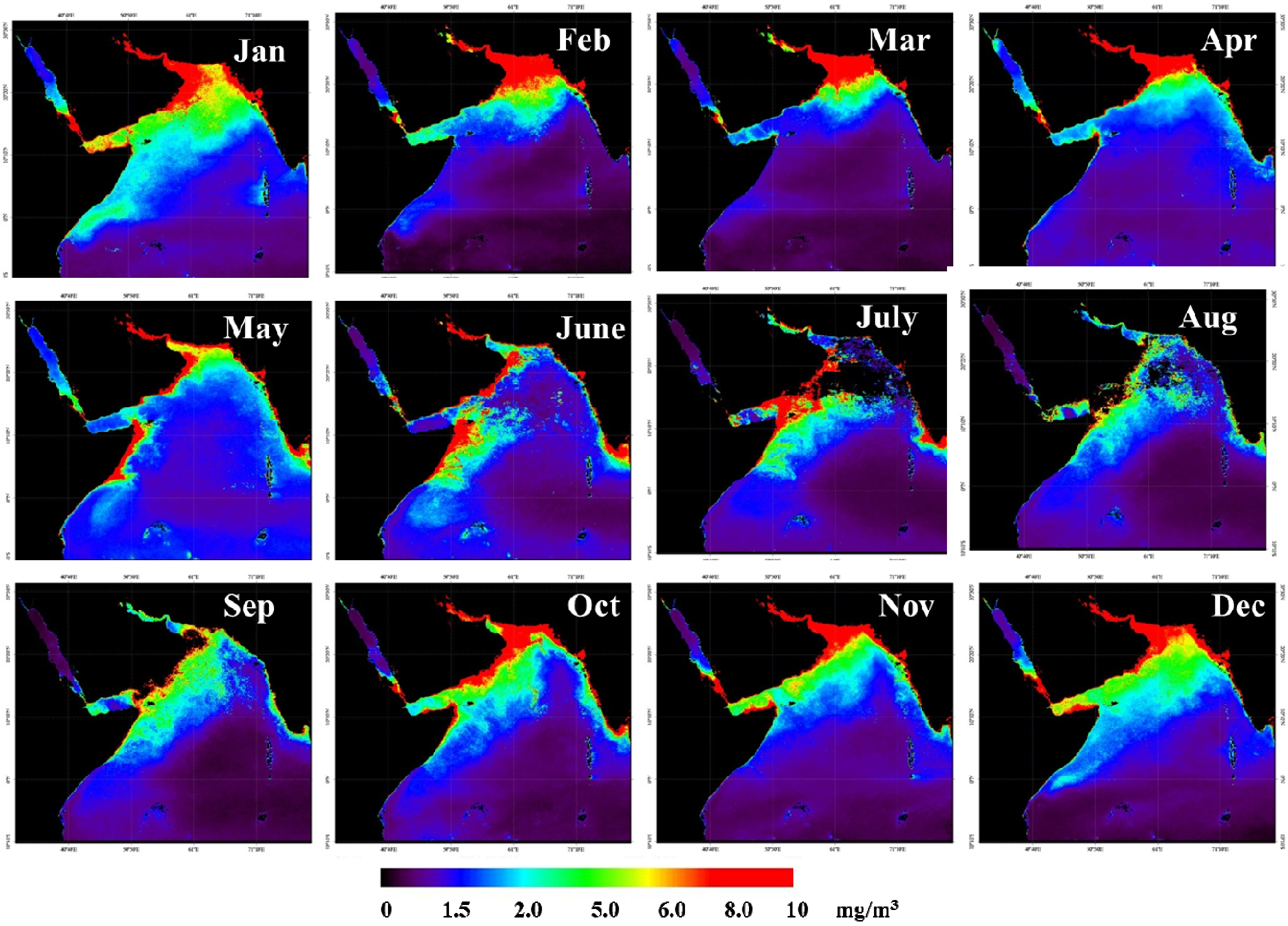


Fig. 5.4 (a): Monthly Climatological Mean Chlorophyll-a conc. in Arabian Sea From 1997 to 2010 using SeaWiFS data

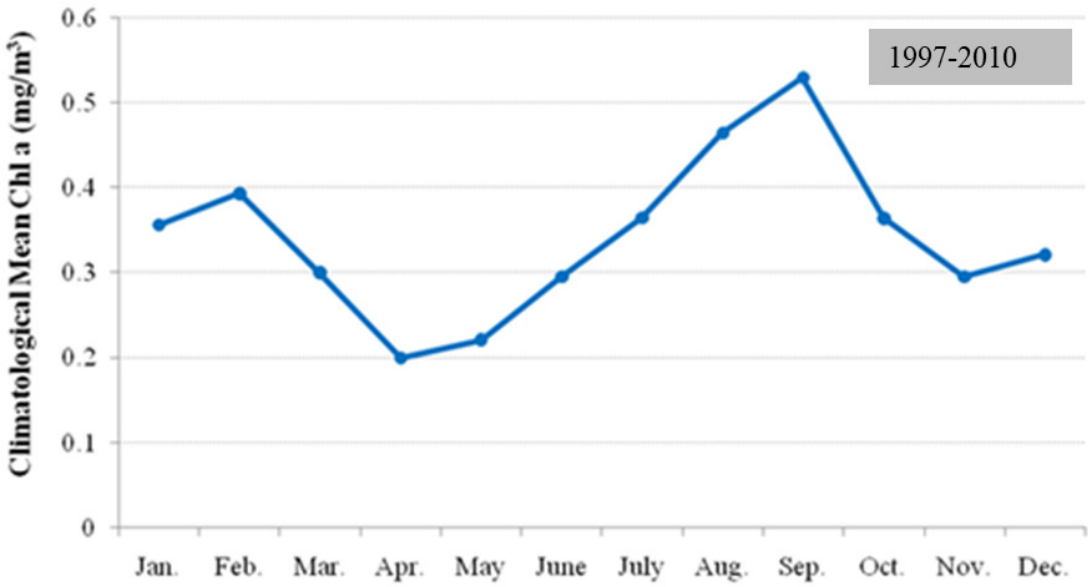


Fig. 5.4 (b): Monthly Climatological Mean Chlorophyll-a conc. in Arabian Sea from 1997 to 2010 using SeaWiFS data

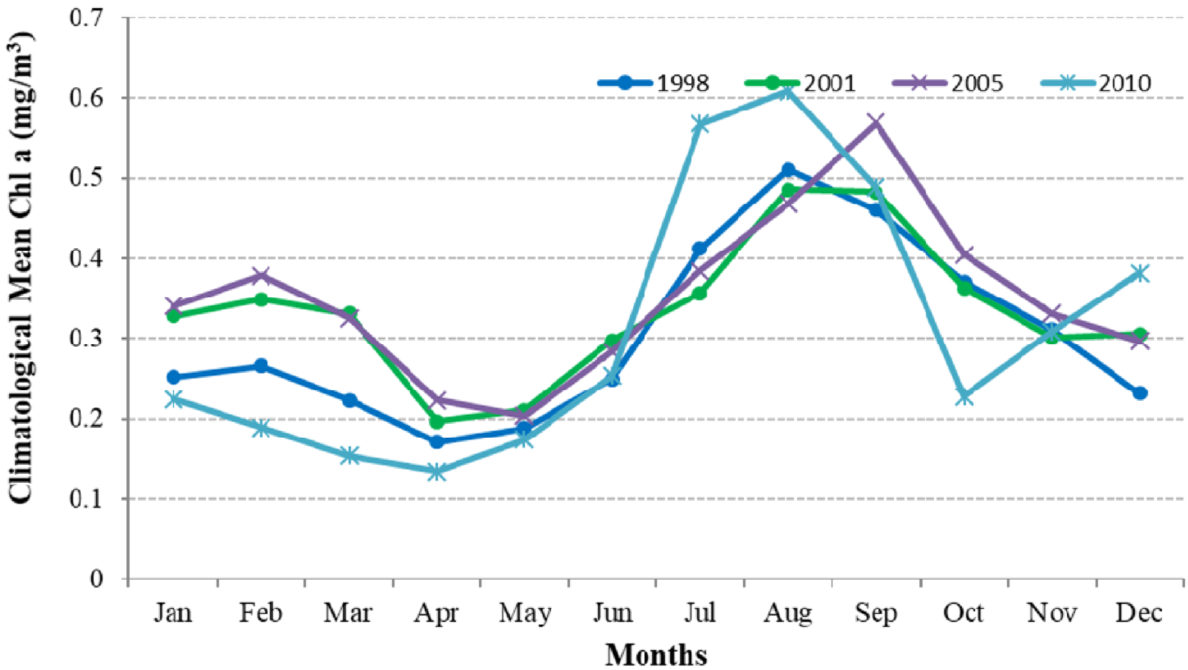


Fig. 5.4 (c): Monthly Average Chlorophyll-a conc. in Arabian Sea in 1998, 2001, 2005 and 2010 using SeaWiFS data

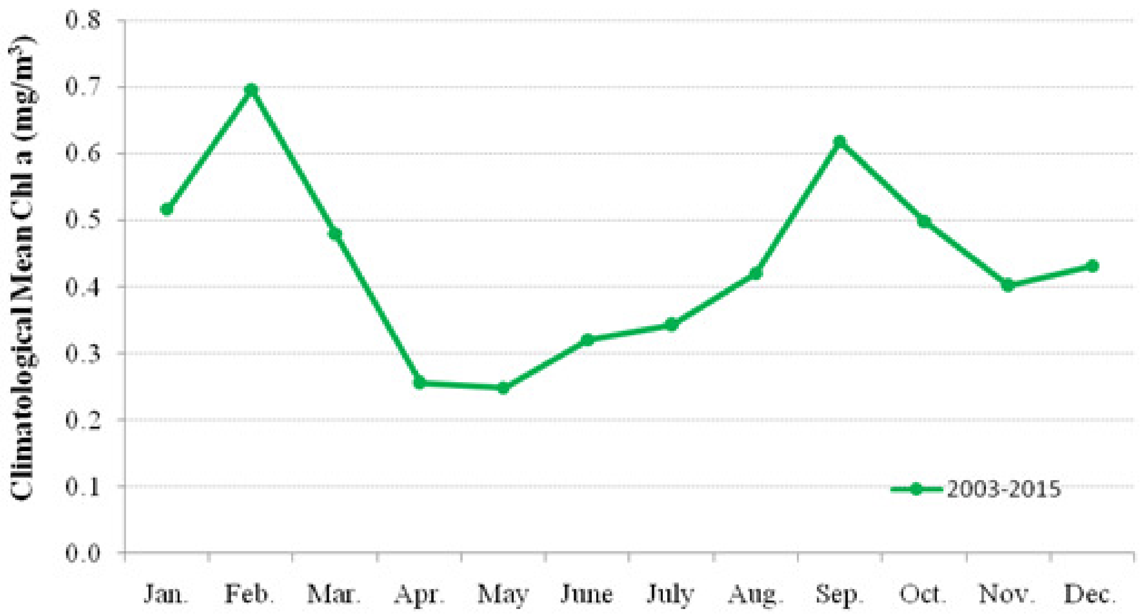


Fig. 5.4 (d): Monthly Climatological Mean Chlorophyll-a conc. in Arabian Sea from 2003 to 2015 using MODIS data

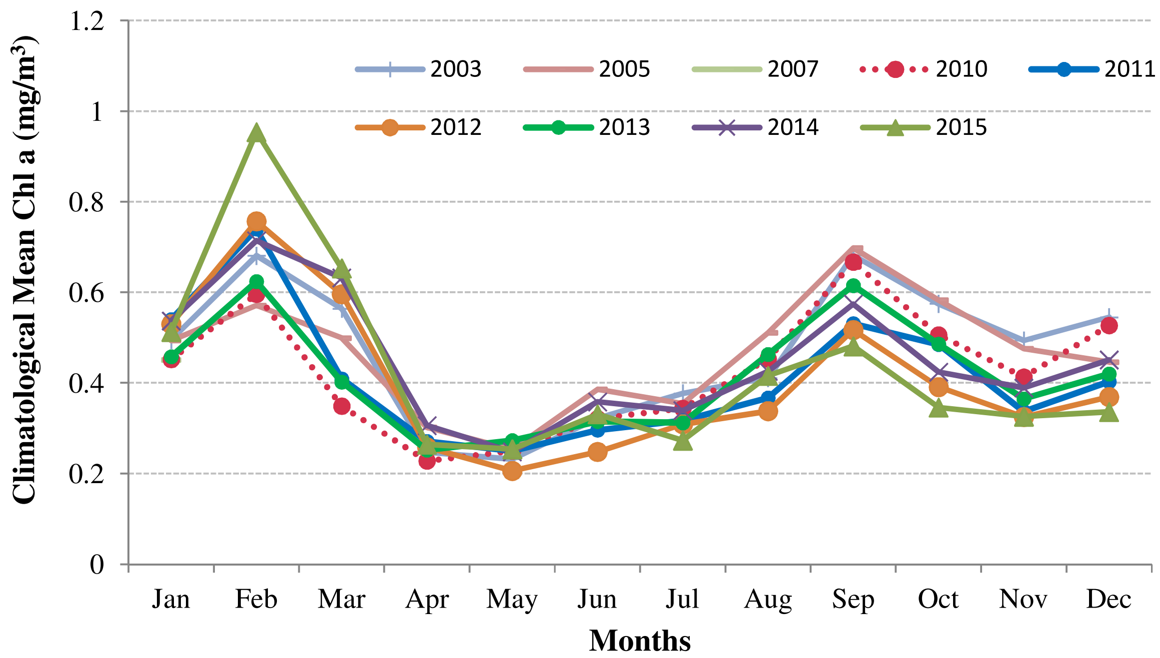


Fig 5.4 (e): Monthly Average Chlorophyll-a conc. in Arabian Sea from 2003, 2005, 2007, and 2010 to 2015 using MODIS data

Fig. 5.4 (a) gives the monthly variability of phytoplankton biomass in the Arabian Sea and it can be clearly seen that the regions of north west Arabian Sea particularly the Persian Gulf and Gulf of Oman are the regions of high phytoplankton biomass and hence are high productive areas. The monthly climatological mean chlorophyll-a concentration derived through SeaWiFS and MODIS data of the entire basin is shown in fig 5.4 (b) and (c) respectively. As seen in the figure 5.4 (b) and (c), the phytoplankton biomass (indexed from chl.-a conc.) in the Arabian Sea was observed to follow a typical bimodal pattern, with peaks during the Northeast monsoon and Southwest monsoon seasons. However, their biomass remained low during the two inter monsoon seasons.

As seen from Fig. 5.4 (b), for the period from 1997 to 2010, the climatological mean chlorophyll-a concentration for the Arabian Sea basin was found to be 0.35 mg/m^3. It was observed to be the maximum during the month of September, reaching up to 0.53 mg/m^3, while the minimum value was found to be during the month of April, when it reached up to 0.2 mg/m^3. The phytoplankton followed a cyclic pattern of growth around the year. Their biomass increased gradually during the southwest monsoon season starting from June and reached their maximum by September. From September onwards there was again a gradual decrease in their biomass which continued till November and the chlorophyll-a concentration valued dropped to 0.3 mg/m^3. However, from December onwards, with the onset of the Northeast monsoon season, their growth again increased and it reached its second peak by February, with chlorophyll-a concentration being 0.393 mg/m^3. April and May were observed to be the unfavorable months for the phytoplankton growth as the chlorophyll-a concentration decreased and varied in the range of 0.2 to 0.22 mg/m^3.

This bimodal pattern of phytoplankton biomass was found for all the years from 1997 to 2010 as shown in Fig. 5.4 (c). However, the interannual variability did exist. The chlorophyll-a concentration value for September (the most productive month) ranged from 0.48 to 0.70 mg/m^3, while the values for February, the month with second peak, ranged from 0.33 to 0.5 mg/m^3.

However, the analysis of monthly mean phytoplankton biomass for the period from 2003 to 2015 using MODIS data (fig. 5.4 d), showed a deviation from the pattern which was followed during 1998 to 2010. It was found, that although, the growth of the phytoplankton remained bimodal, a striking shift in the peak was observed with phytoplankton biomass reaching their maxima during February, instead of September as shown in Fig. 5.4 (d). It was an interesting observation, as it depicts a change in the phenology of the phytoplankton of the Arabian Sea, and is one of the anticipated impacts of climate change in the oceans.

The climatological mean chlorophyll-a concentration of the Arabian Sea basin for the period from 2003 to 2015 was found to be 0.44 $mg/m^{3,}$ with the maximum value reaching up to 0.7 mg/m^3 in February, followed by the second peak of 0.62 mg/m^3 in September, as shown in Fig. 5.4(d). Though it is much higher than the one estimated for the period 1997 to 2010, yet, both cannot be compared as the two data sets were obtained from two different ocean color sensors viz. SeaWiFS and MODIS.

Further, in view of the shift in the peak that was observed from the climatological mean chlorophyll-a concentration during 2003 to 2015, it was further investigated whether the shift was because of the change in the sensors from SeaWiFS (1997 to 2010) to MODIS (2003 to 2015). Hence, the monthly mean chlorophyll-a concentration values of all the months from 2003 to 2015 were analyzed. As seen in fig. 5.4 (e), it was noticed that even for MODIS data, for the years from 2003 to 2009 (the years overlapping in SeaWiFS and MODIS), the peak chlorophyll-a values were during the month of September and not February. However, as shown in Fig. 5.4 (e), from 2010 onwards, a distinct shift in the peak was observed, with February turning out to be the month with the maximum productivity instead of September. Moreover, this shift was not an episodic one, instead it continued for all the successive years from 2010 to 2015, making it evident that it was a phenological change of the phytoplankton of the Arabian Sea.

5.4.2 Decadal Change in Productive Areas of the Arabian Sea

5.4.2.1 Decadal Change from 1998 to 2008

Using SeaWiFS chlorophyll-a concentration data, the decadal changes in the productive areas of the Arabian Sea basin was analyzed. The decadal change in phytoplankton biomass and the productive areas of the Arabian Sea from 1998 to 2008 is shown in Fig. 5.5 (a). It can be clearly seen that there has been a substantial decrease in the extent of the productive areas of the basin from 1998 to 2008. In the year 1998, the western gulfs of the Arabian Sea, viz. the Persian Gulf and the Gulf of Oman exhibited a very high phytoplankton biomass with chlorophyll-a concentration in the range of > 7.5mg/m^3. Even a large area of the Gulf of Aden showed high productivity with chlorophyll-a concentration ranging from 5.5 to 8.0 mg/m^3. The Northern, the Western, and the Eastern Arabian Sea, along the Indian coastline up to the Sri Lankan border, were also found to be rich in phytoplankton biomass with chlorophyll-a concentration ranging from 4.0 to 8.0 mg/m^3. However, as compared to 1998, a significant decrease in the extent of the productive areas of the Arabian Sea, all along the Northern, Western and Eastern sub-domains were observed in 2008. While the Persian Gulf remained the most productive area with chlorophyll-a concentration > 7.5 mg/m^3, the adjoining Gulf of Oman showed a considerable decrease in chlorophyll-a concentration since 1998. The area of the low productive waters with chlorophyll-a concentration in the range 0.2 to 2.0 mg/m^3 extended considerably from the Southern domain up to the Northern domain of Arabian Sea in 2008.

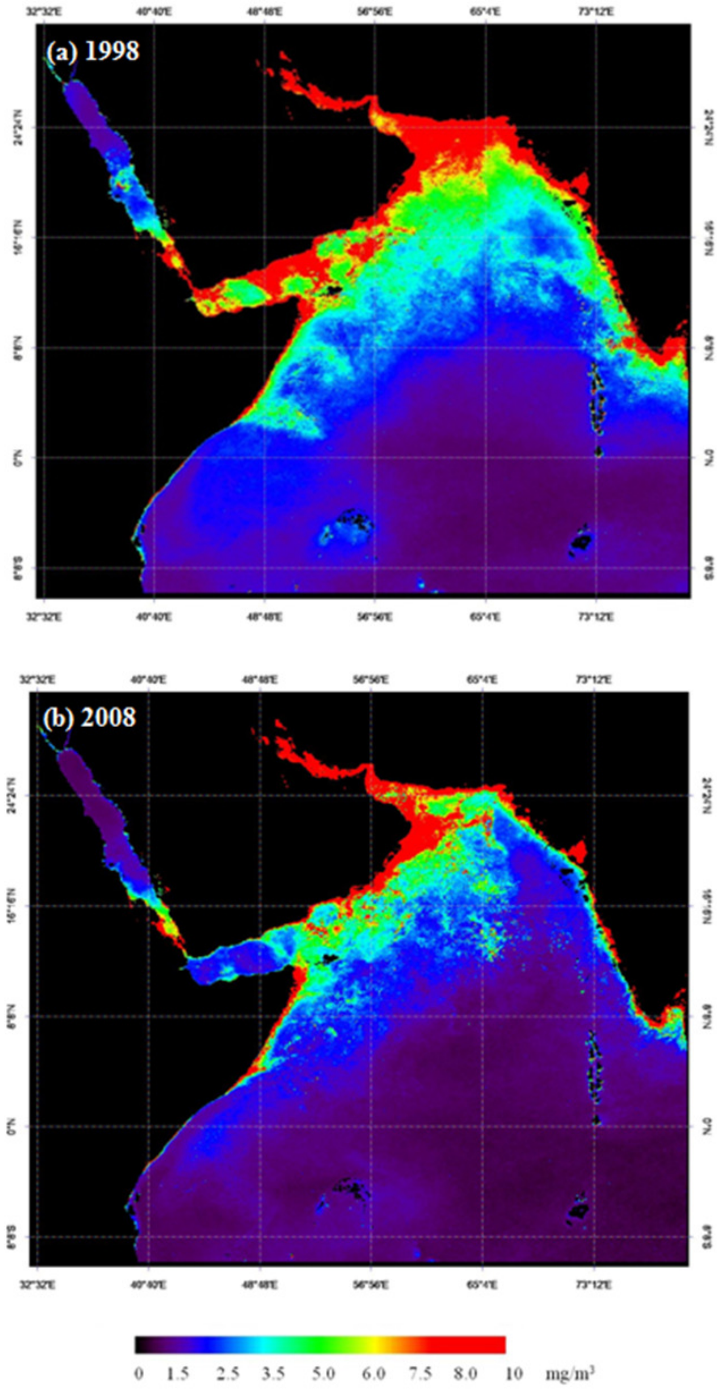


Fig. 5.5 (a): Decadal Change in the Productive Areas of the Arabian Sea from 1998 to 2008 using SeaWiFS Data

5.4.2.2 Decadal Change from 2005 to 2015

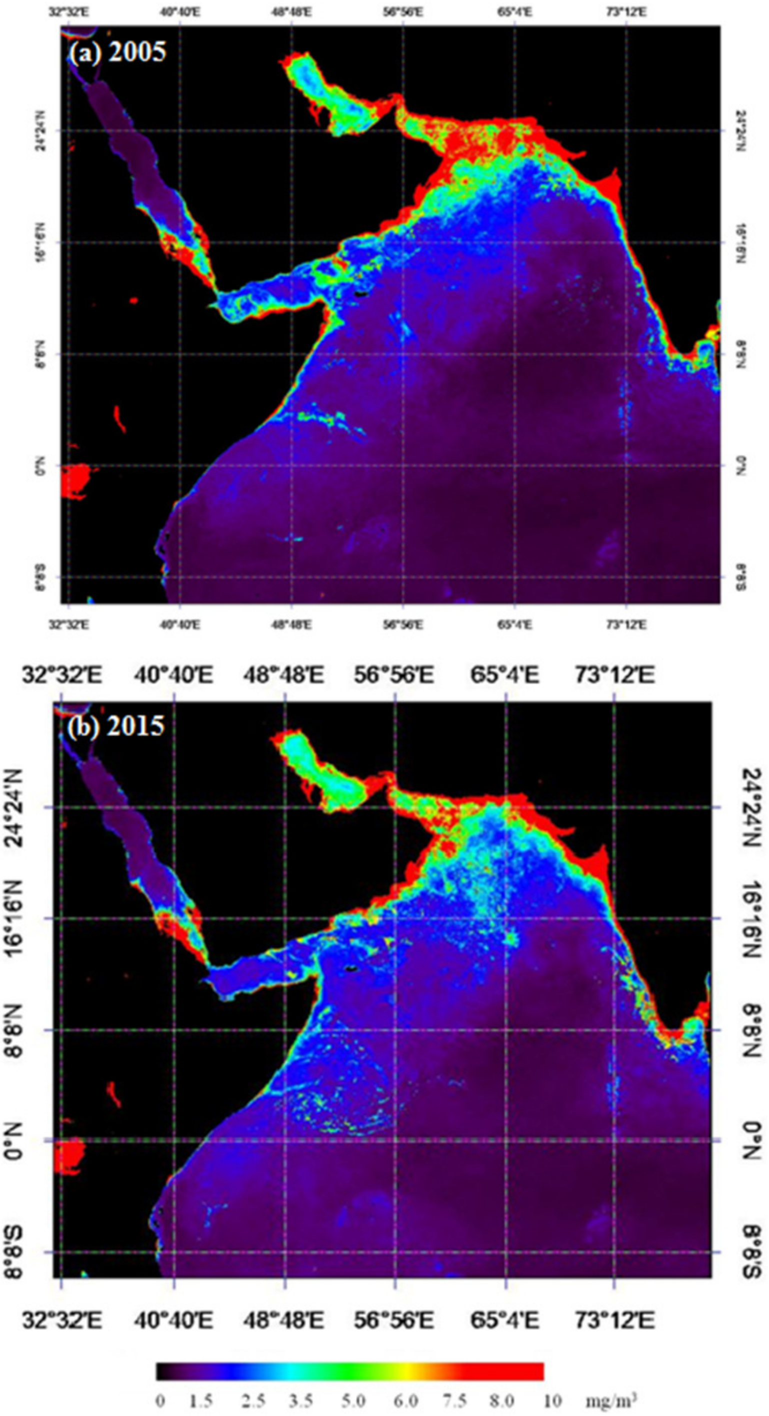


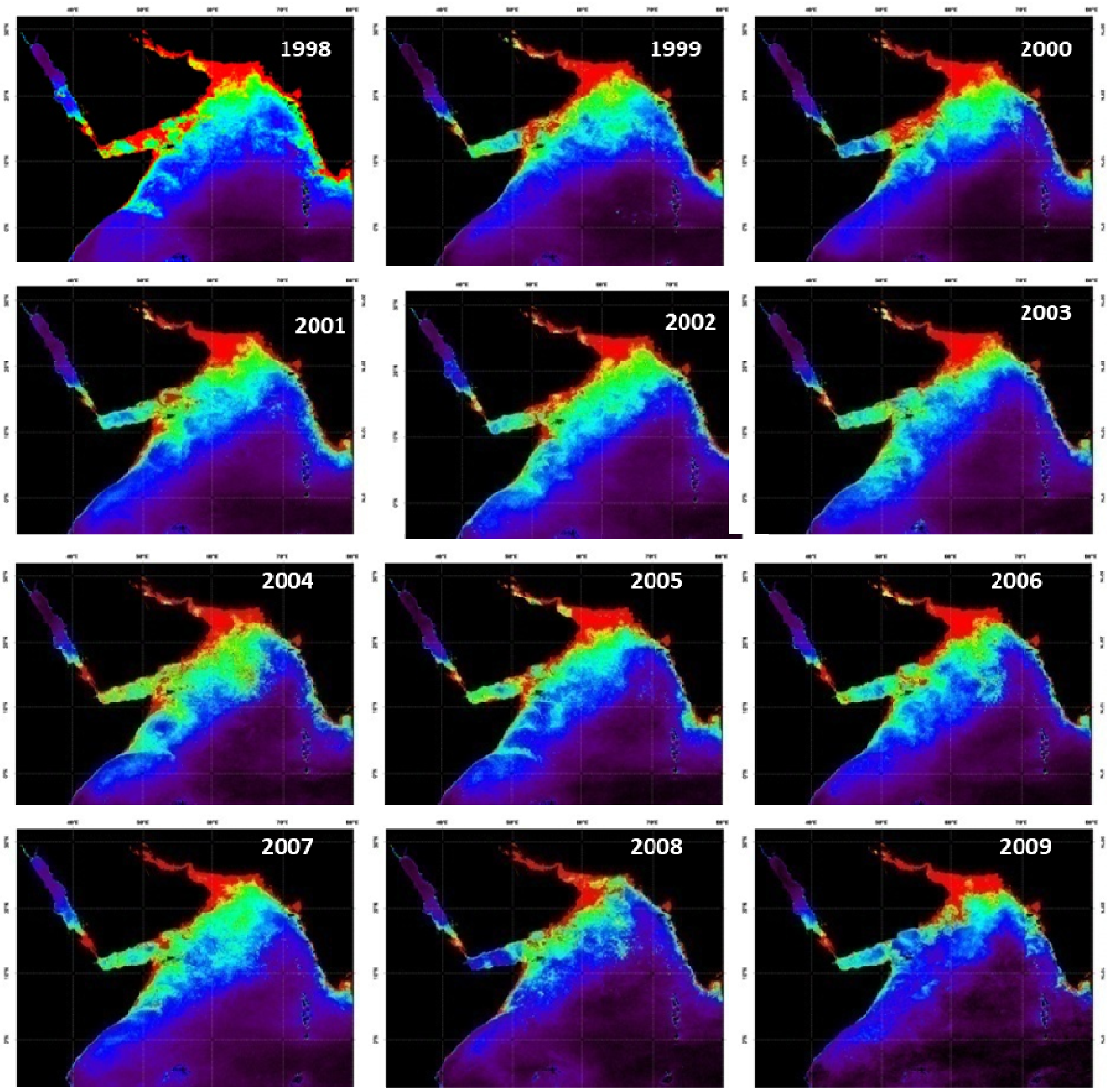
Fig. 5.5 (b): Decadal Change in the Productive Areas of the Arabian Sea from 2005 to 2015 using MODIS Data

For analysis of the decadal change in the productive areas of the Arabian Sea in recent times, MODIS chlorophyll-a concentration from 2005 to 2015 were analyzed as given in fig.5.5 (b). From 2005 to 2015, a considerable decrease in the productive areas of the Arabian Sea was observed. The northwestern domain of the Arabian Sea was found to be the region with highest productivity, with chlorophyll-a concentration ranging from 4.0 to 7.5 mg/m^3. In 2005, major part of the Gulf of Oman, was found to be rich in phytoplankton with chlorophyll-a concentration being > 8.5 mg/m^3. However, by 2015, in the same region the chlorophyll-a concentration decreased to 4.0 - 5.0 mg/m^3, with only the coastal areas of the Gulf remaining high in productivity and showing chlorophyll-a concentration.>7.5 mg/m^3. In the Gulf of Aden also, a substantial decrease in the productivity was observed. In 2005, the coastal areas of the Gulf of Aden had a higher phytoplankton biomass, with chlorophyll-a concentration varying from 3.5 - 5.0 mg/m^3, but by 2015, the range decreased to 2.0 - 2.5 mg/m^3.

Along with the gulfs, the Northern, Western and Eastern sub-domains of the Arabian Sea also showed a decrease in the extent of the productive areas in the decade from 2005 to 2015. In the east, the coastal waters did show some expansion of the productive areas, with regions having chlorophyll-a concentration in the range from 0.2 to 0.8 mg/m^3 in 2005, being replaced by waters with chlorophyll-a concentration values ranging from 2.0 to 3.5 mg/m^3 in 2015. Even in the Southern domain and the Central domain of the Arabian Sea, small regions with chlorophyll-a concentration ranging from 0.2 to 0.8 mg/m^3 in 2005, were replaced by waters with chlorophyll-a concentration ranging from 2.0 to 3.5 mg/m^3 in 2015. However, this increase was limited to small patches, and did not significantly affected the overall decreasing trend of the productive areas of the Arabian Sea from 2005 to 2015.

5.4.3. Variability of Phytoplankton Biomass in the Arabian Sea

5.4.3.1. Temporal Variability from 1998 to 2010



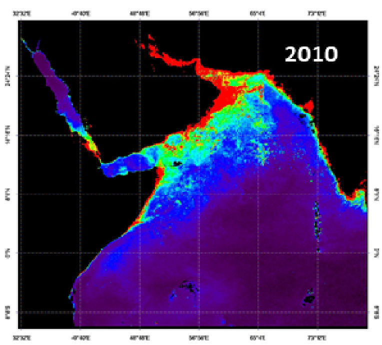


Fig. 5.6 (a): Interannual variability of Phytoplankton Biomass in Arabian Sea from 1998 to 2010 using SeaWiFS data

The annual mean chlorophyll-a concentration for the period from 1998 to 2010 were computed using the monthly mean values. The images of the annual mean chlorophyll-a concentration were generated using the image processing software ERDAS 9.1 and ENVI 4.4. The spatial and temporal variability of annual phytoplankton biomass from 1998 to 2010 can be seen in Fig. 5.6(a). While the northwestern domain of the Arabian Sea remained the most productive zones with high chlorophyll-a concentration across the years, yet significant decrease in the extent of high productive waters was seen from 1998 to 2010. It was observed that although, there was an increase in the phytoplankton biomass from 1998 to 2000, but it was followed by a spell of decrease which continued till the year 2003. In 2005 - 06, a slight increase in the phytoplankton biomass was noticed, but it was again halted by the decreasing phase from 2007 to 2010.

The quantification of the variability of phytoplankton biomass was done by computing the annual normalized anomaly, as shown in Fig. 5.6 (b) and the seasonal normalized anomaly of as shown in Fig. 5.6 (c).

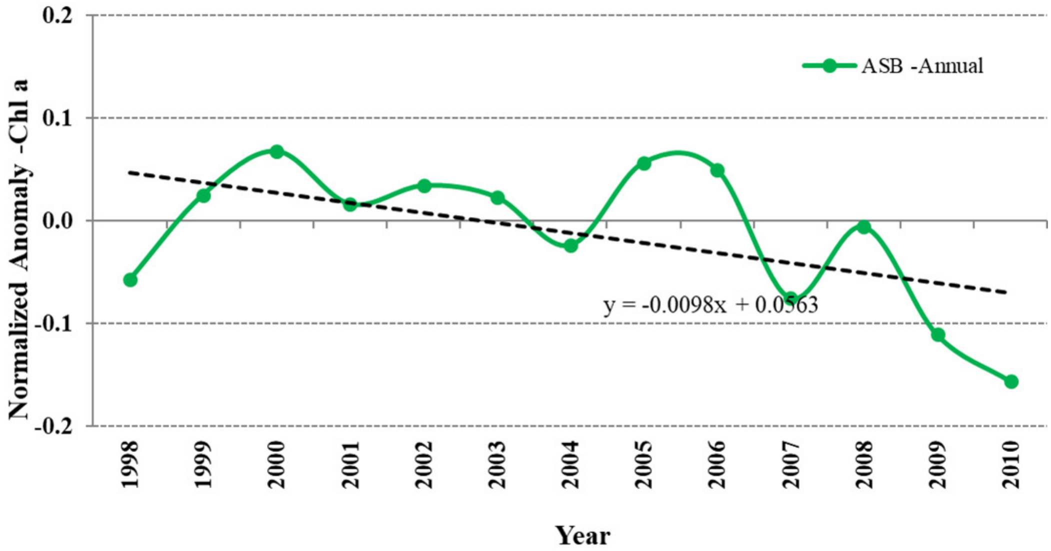


Fig. 5.6 (b): Interannual variability of Phytoplankton Biomass in Arabian Sea from 1998 to 2010 using SeaWiFS data

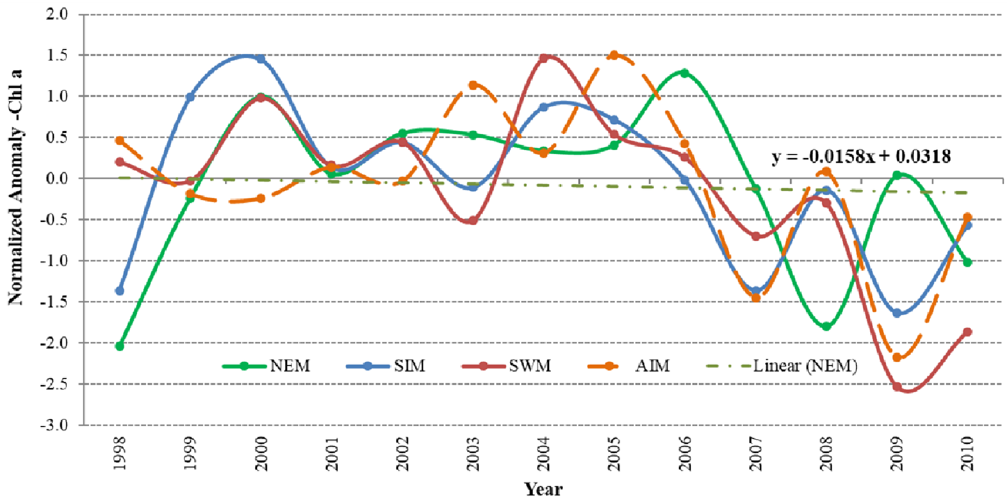


Fig. 5.6 (c): Seasonal variability of Phytoplankton Biomass in Arabian Sea from 1998 to 2010 using SeaWiFS data

As seen in Fig. 5.6 (b), the annual normalized anomaly decreased at the rate of -0.098/year from 1998 to 2010. It was interesting to note that from 1998 to 2010, only 6 of the years had negative anomalies, but the fact that post 2006 most of the years had chlorophyll-a concentration lower than that of the climatological mean resulting in negative anomalies in 2007, 2008, 2009 and 2010.

It was further investigated whether this decreasing trend in phytoplankton biomass was limited to a particular season or was spread across the year. Hence, the seasonal trend of the chlorophyll-a concentration across 13 years from 1998 to 2010, for each of the four seasons viz. NEM, SIM, SWM and AIM were computed and their normalized anomalies were analyzed (Fig. 5.6 c). As can be seen from the figure, for all the four seasons, there has been a decreasing trend of chlorophyll-a concentration. It was observed that even during the two most productive seasons viz. the NEM and SWM, the decrease in chlorophyll-a concentration was more so much so that the highest decrease in phytoplankton biomass was during the SWM season, with the normalized anomaly decreasing at the rate of -0.145/year from +0.24 (1998) to -2.53 (2009) and -1.9 (2010). This poses a serious issue of concern, as rate at which the phytoplankton are dwindling during SWM, it will affect the overall productivity of the Arabian Sea basin, as in the absence of the primary producers, the trophic chain would be disrupted and the growth of the subsequent secondary producers and tertiary consumers would become challenging.

During the SIM, the normalized anomaly decreased at the rate of -0.09/year from -1.36 (1998) to -0.568 (2010), whereas during the AIM it decreased at the rate of -0.13/year from +0.47 (1998) to - 2.17 (2009) and -0.47 (2010). This gives considerable evidence that the annual decrease in phytoplankton biomass as seen in fig. 5.6 (b) is not just limited to a particular season but is in fact spread across all the seasons and months of the year.

5.4.3.2. Temporal Variability from 2003 to 2015

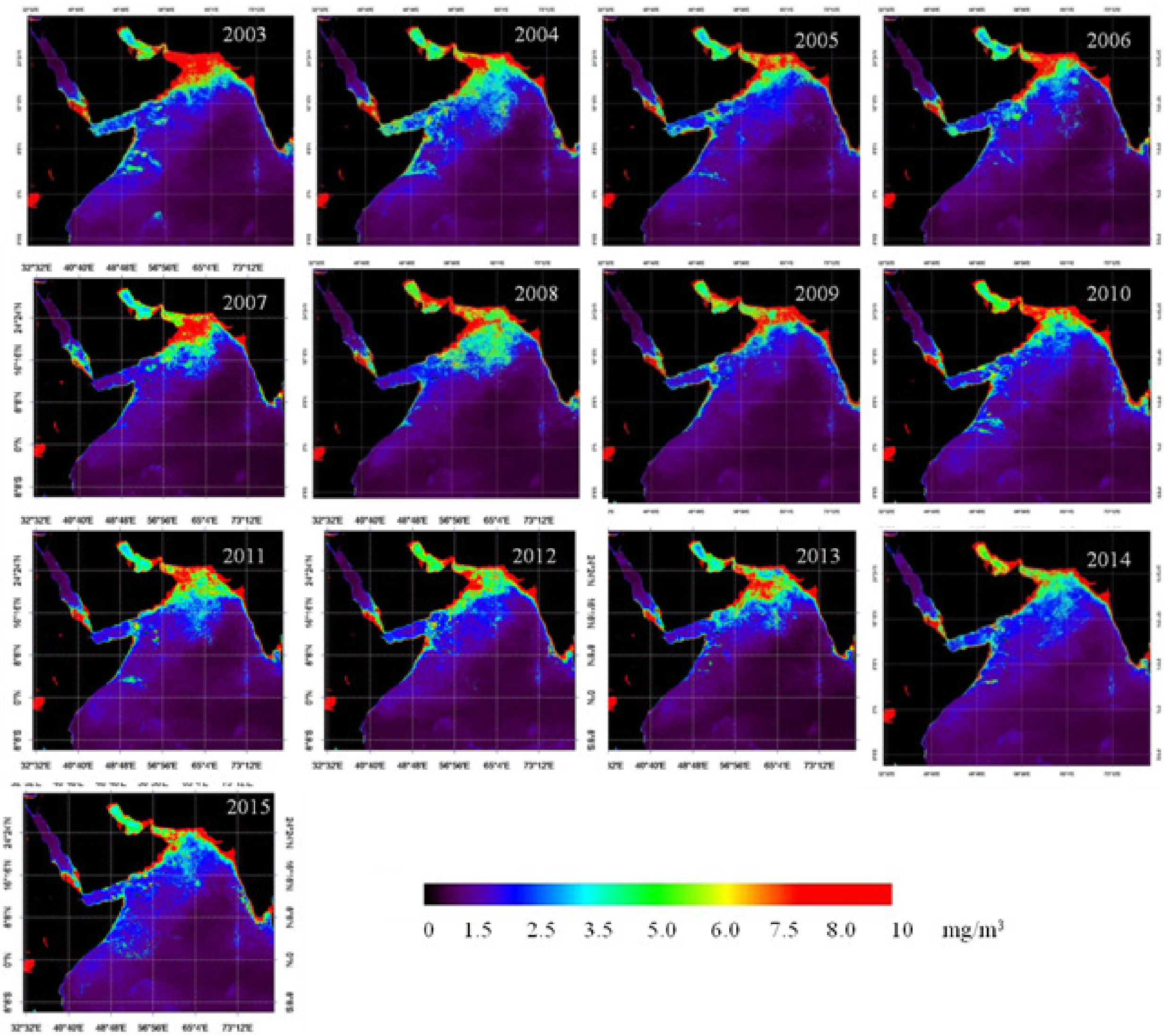


Fig. 5.7 (a): Interannual variability of Phytoplankton Biomass in Arabian Sea from 2003 to 2015 using MODIS data

Similar to the chlorophyll-a concentration data analyzed in the previous section, the annual mean chlorophyll-a concentration for the recent years from 2003 to 2015 were computed using the monthly mean values. The images of the annual mean chlorophyll-a concentration were made using the image processing software ERDAS 9.1 and ENVI 4.4 to analyze the interannual variability of the phytoplankton biomass in the Arabian Sea.

The spatial and temporal variability of phytoplankton biomass from 2003 to 2015 can be seen in Fig. 5.7 (a). While the north western domain of the Arabian Sea, especially the Gulf of Oman and the coastal areas remained the most productive zones with high chlorophyll-a values across the years, yet significant decrease in the extent of high productive waters was seen from 2003 to 2015. It was observed that from 2003 to 2015, there was a substantial decrease in the extent of the area with chlorophyll-a values > 7.5 mg/m^3. Even the areas with chlorophyll-a concentration > 4.0 were replaced low productive water masses with chlorophyll-a in the range of 0.02 to 2.0 mg/m^3.

The quantification of the variability of phytoplankton biomass was done by computing the annual normalized anomaly, as shown in Fig. 5.7 (b) and the seasonal normalized anomaly of as shown in Fig. 5.7 (c).

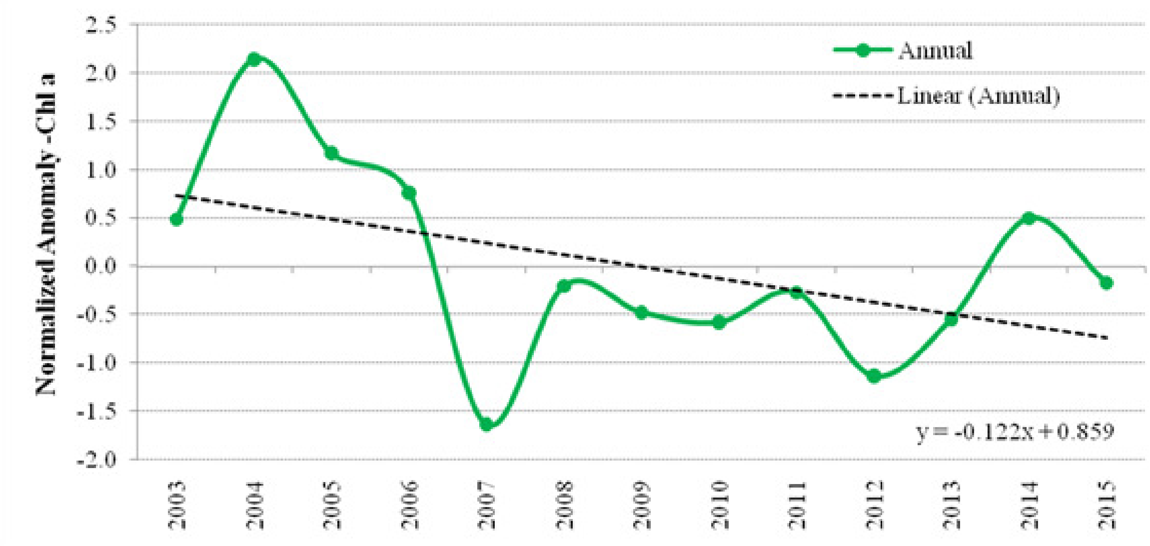


Fig. 5.7 (b): Interannual variability of Phytoplankton Biomass in Arabian Sea from 2003 to 2015 using MODIS data

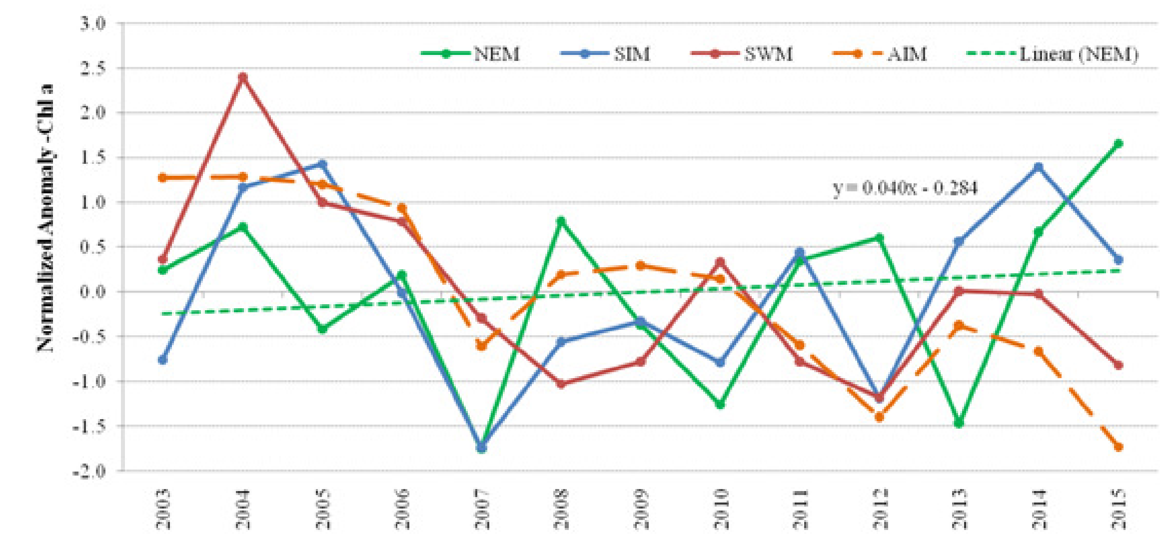


Fig. 5.7 (c): Seasonal variability of Phytoplankton Biomass in Arabian Sea from 2003 to 2015 using MODIS data

As seen in Fig. 5.7 (b), the annual normalized anomaly during the period from 2003 to 2015 also decreased substantially at the rate of -0.122/ year. Although, from 2003 to 2004, a steep rise in phytoplankton biomass was observed and the normalized anomaly reached its highest positive deviation up to +2.14, yet in the subsequent years from 2004 to 2007, an equally sharp decreased was observed and normalized anomaly decreased to -1.64 in 2007. Altogether, from 2003 to 2015, only in the years 2003, 2004, 2005, 2006 and 2014, positive anomalies were found, of which only 2014 was the year post 2007 where positive deviation from climatological mean was observed. Hence it would not be wrong to conclude that although the decrease in phytoplankton biomass has been occurring on a continuous basis yet it has been more rapid in the recent years.

To further study, the seasonal trend in the phytoplankton biomass across 13 years from 2003 to 2015, the chl.-a values for each of the four seasons viz. NEM, SIM, SWM and AIM were computed and their normalized anomalies were analyzed, as shown in Fig. 5.7 (c).

In contrast to the annual decrease in phytoplankton biomass, it was observed that of the four seasons, during the NEM and SIM seasons, there were increase in the normalized anomaly at the rate of +0.04/year and +0.027/year respectively, as can be seen in Fig. 5.7(c). During the NEM season the normalized anomaly increased from +0.24 (2003) to +1.66 (2015), while during SIM season it increased from -0.76 (2003) to +0.36 (2015). The increase in phytoplankton biomass during the NEM season, though at a smaller rate, yet could possibly affect the productivity pattern of the Arabian Sea.

During the SWM, a decrease in phytoplankton biomass was observed. It was found that from 2003 to 2015, the normalized anomaly of decreased at a higher rate of -0.16/year. It decreased from +0.36 in 2003 to -0.82 in 2015, with 2012 being the year with highest negative deviation (-

1.176). Similarly, during the AIM, also a sharp decrease in phytoplankton biomass was observed. It decreased from +1.28 in 2003 to -1.73 in 2015, with an annual decrease at the rate of -0.225/year.

5.4.4 Variability of Phytoplankton Biomass in different sub - domains of the Arabian Sea

5.4.4.1 Variability of Phytoplankton Biomass in the Northern Arabian Sea

Northern Arabian Sea is significant as it is the domain with high productivity round the year. Besides, the occurrence of phytoplankton bloom is a constant feature in the Northern Arabian Sea. The seasonal variability of phytoplankton biomass in this domain was analyzed for both the study periods i.e. from 1998 to 2010, as shown in Fig. 5.8 (a), and from 2003 to 2015 (as shown in Fig. 5.8 (b).

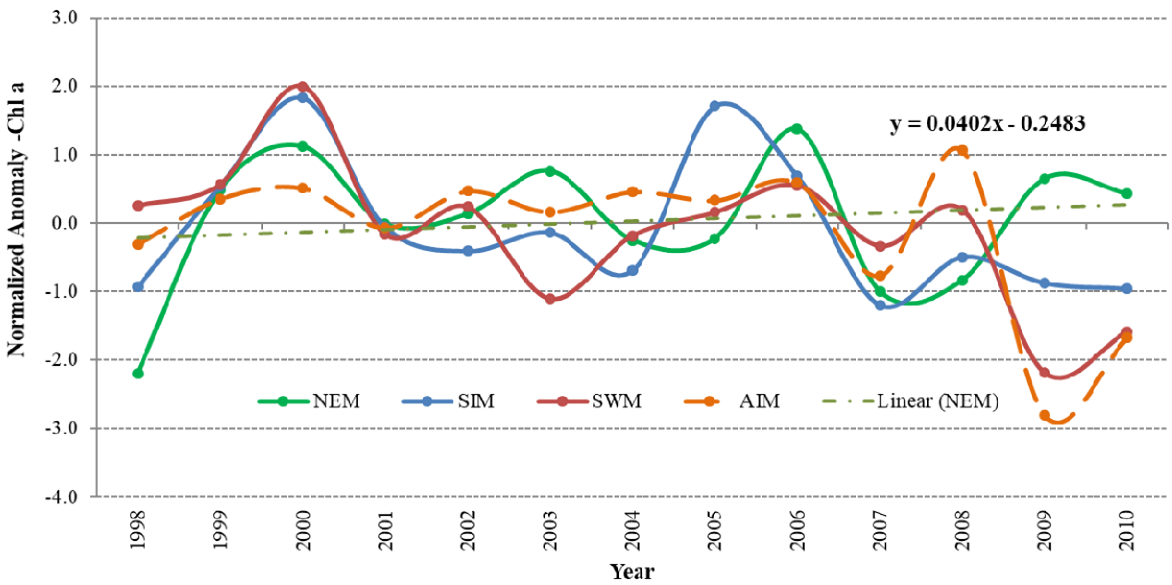


Fig. 5.8 (a): Seasonal variability of Phytoplankton Biomass in Northern Arabian Sea from 1998 to 2010 using SeaWiFS data

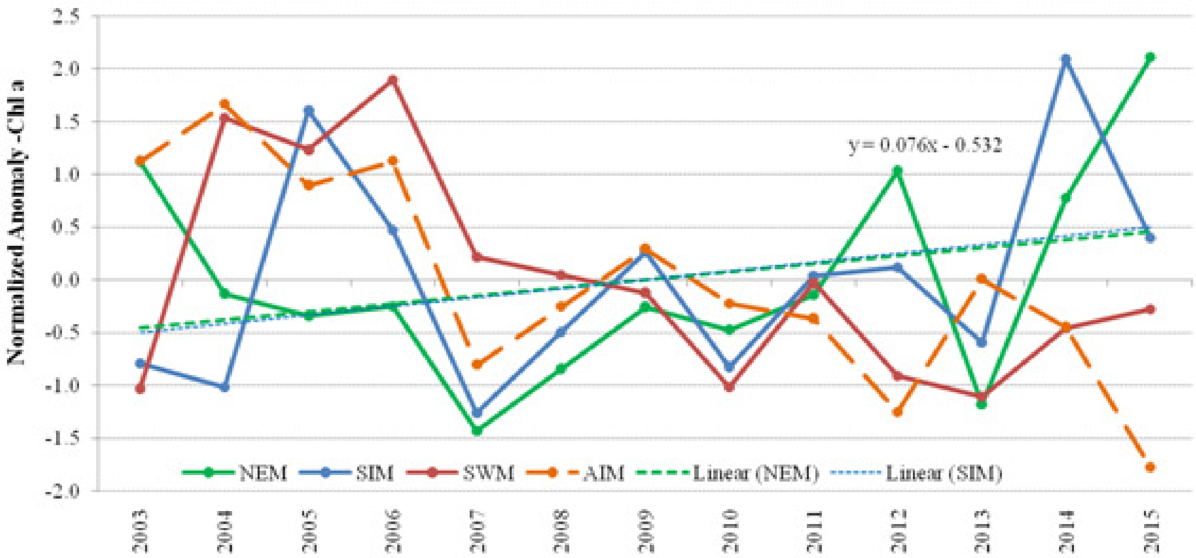


Fig. 5.8 (b): Seasonal variability of Phytoplankton Biomass in Northern Arabian Sea from 2003 to 2015 using MODIS data

As seen in Fig. 5.8 (a), the phytoplankton biomass was observed to increase during the NEM in the northern domain at the rate of +0.07/year from -2.19 in 1998 to +0.65 in 2009 with the highest value in 2006 (+1.37). However, a contrasting sharp decrease was found during the SWM season for the same period. It was observed that the normalized chlorophyll -a anomaly decreased at the rate of -0.14/ year from in +0.256 in 1998 to -2.2 in 2009 and -1.6 in 2010. Even during the SIM and AIM seasons, the anomalies decreased at the rate of -0.05/year and -0.13/year respectively, indicating the decreasing trend in the phytoplankton biomass over the northern domain of the Arabian Sea.

For the period from 2003 to 2015, it was found that of the four seasons, the phytoplankton biomass increased during the NEM and SIM seasons, while it decreased during the SWM and AIM seasons, as can be seen in Fig. 5.7 (b). During the NEM season, the normalized anomaly increased at the rate of +0.076/ year, from in +1.12 2003 to +2.11 in 2015, with a sharp increase in recent years from 2013 to 2015. Whereas during the SIM season, the increase was found to be at the rate +0.083/year, from -0.80 in 2003 to +0.40 in 2015, with the normalized anomaly reaching its highest value in 2014 (+2.10). However, for the next two seasons, sharp decreases in anomalies were observed. The decrease during the SWM season was at the rate of -0.136/year from while during the AIM the decrease was at rate of -2.07/year.

5.4.4.2 Variability of Phytoplankton Biomass in Southern Arabian Sea

The variability of phytoplankton biomass in Southern Arabian Sea during the four seasons is shown in Fig. 5.9 (a) and (b), corresponding to the period from 1998 to 2010 and 2003 to 2015 respectively.

For the period from 1998 to 2010, it was found that the phytoplankton biomass increased during the NEM season, while for the rest of the three seasons it decreased considerably, as shown in Fig. 5.9 (a). During the NEM season, the normalized anomalies increased at the rate of +0.04/year from -2.13 in 1998 to -0.52 in 2009, reaching its maximum value of +1.75 in 2006. In contrast, during the SWM season, there was a sharp decrease in the phytoplankton biomass with normalized anomalies decreasing at the rate of -0.2/year from +0.36 in 1998 to -2.6 in 2009 and -1.94 in 2010. For the two inter monsoon seasons also the decreasing trend in anomalies were observed, with SIM season showing a decrease at the rate -0.15/ year and AIM also exhibiting the decrease at -0.13/year.

For the period from 2003 to 2015, during all the four seasons i.e. NEM, SIM, SWM and AIM, a considerable decrease in the normalized anomalies of was observed, as shown in Fig. 5.9 (b). During the NEM season, it decreased at rate of -0.043/year from -0.07 in 2003 to -1.05 in 2013, with the lowest value reaching -1.61 in 2009. Though, in recent years i.e. 2014 and 2015, small increase in anomalies were observed, yet, they could not disrupt the overall decreasing pattern. It was observed that though a similar pattern of decrease in phytoplankton biomass was noticed for the SWM season, but the decrease was much more rapid and sharp at the rate of -0.15/ year. It decreased from +0.62 in 2003 and reached its lowest value of -1.2 in 2015. During SIM season the anomalies decreased at the rate of -0.076/ year whereas during the AIM, the decrease was higher at the rate of -0.2/year.

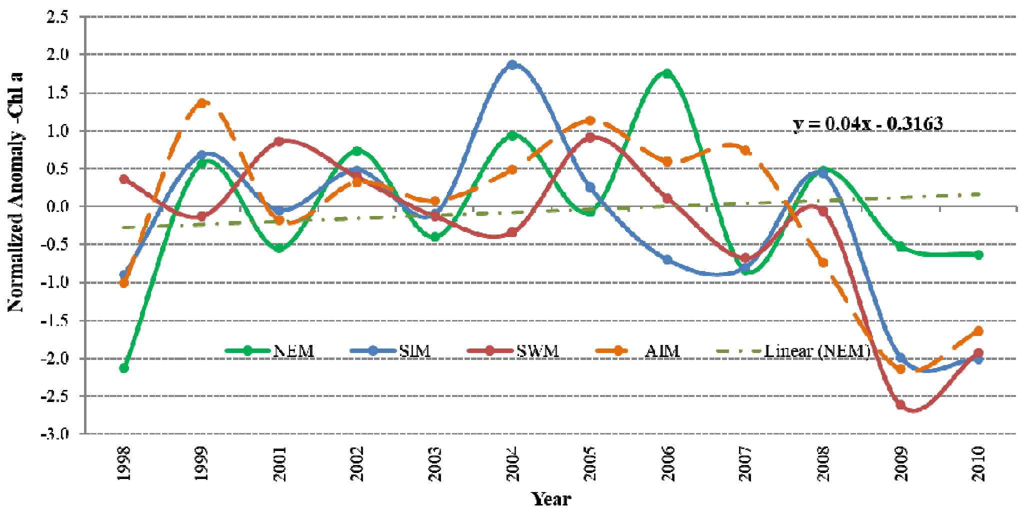


Fig. 5.9 (a): Seasonal variability of Phytoplankton Biomass in Southern Arabian Sea from 1998 to 2010 using SeaWiFS data

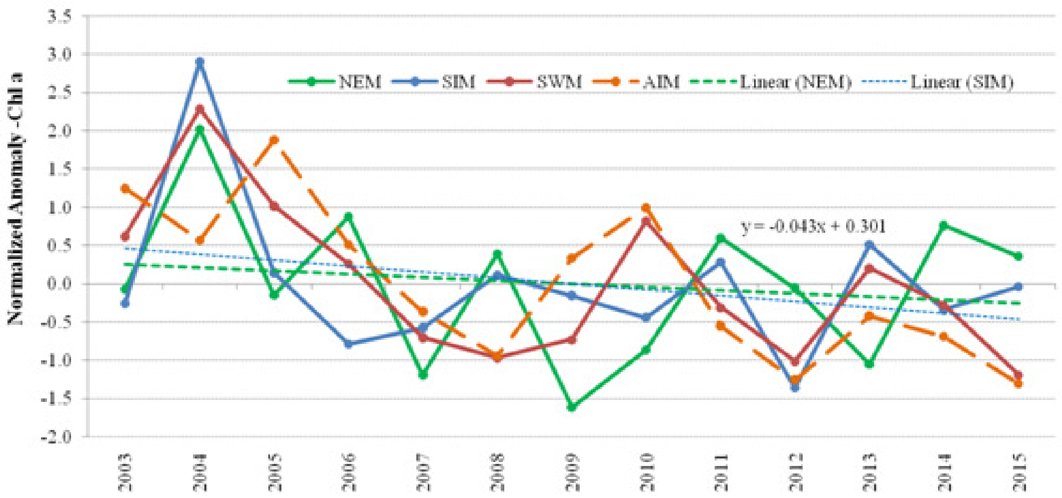


Fig. 5.9 (b): Seasonal variability of Phytoplankton Biomass in Southern Arabian Sea from 2003 to 2015 using MODIS data

5.4.4.3 Variability of Phytoplankton Biomass in Eastern Arabian Sea

The seasonal variability of phytoplankton biomass during in Eastern Arabian Sea is shown in Fig. 5.10 (a) & (b) corresponding to the period from 1998 to 2010 and 2003 to 2015 respectively.

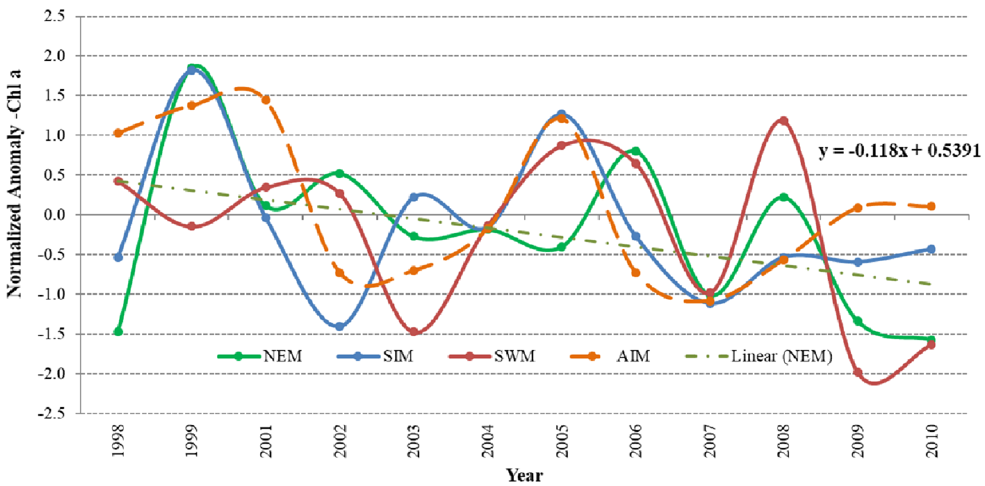


Fig. 5.10 (a): Seasonal variability of Phytoplankton Biomass in Eastern Arabian Sea from 1998 to 2010 using SeaWiFS data

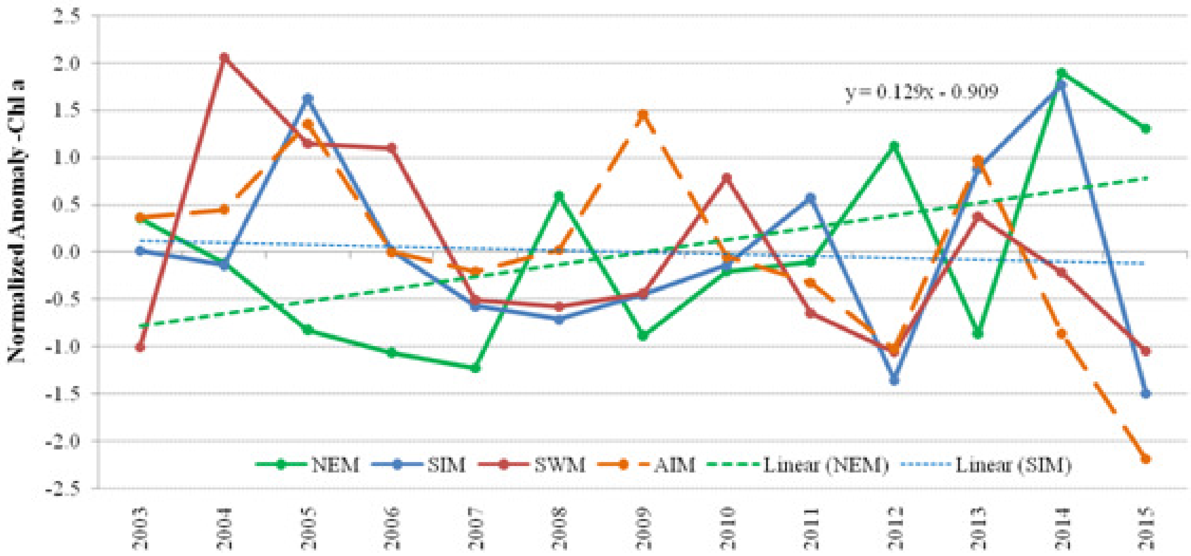


Fig. 5.10 (b): Seasonal variability of Phytoplankton Biomass in Eastern Arabian Sea from 2003 to 2015 using MODIS data

As seen from Fig. 5.10 (a), the phytoplankton biomass decreased during all the four seasons in the Eastern Arabian Sea from 1998 to 2010. During the NEM and the AIM seasons, the normalized anomaly decreased rapidly at the rate of -0.13/year. In the NEM season, the anomaly decreased from in -1.47 in 1998 to -1.57 in 2010, whereas for the AIM the it decreased from in +1.03 in 1998 to -1.08 in 2007 and finally to 0.106 in 2010. Even for the SWM season, the normalized anomaly was found to be decreasing at the rate of -0.11/year from +0.43 in 1998 to -1.99 in 2009 and -1.63 in 2010.

For the period from 2003 to 2015, a different trend for the NEM season was observed. While the decreasing trend of phytoplankton biomass, as found for the period from 1998 to 2010, continued for the SIM, SWM and AIM, it was observed that there was an increase in the phytoplankton biomass during the NEM season, as shown in Fig. 5.10 (b). It was noticed that the normalized anomaly increased at the rate of +0.13/ year, from +0.36 (2003) to +1.31 (2015). The year 2014 showed the highest positive anomaly of +1.90. However, for the rest of the three seasons, a considerable decrease in the anomalies were observed. While the decrease during the SWM season was at the rate of -0.115/year, it was much higher at -0.15/ year for AIM. The decrease during the SIM was at -0.02/year.

5.4.4.4 Variability of Phytoplankton Biomass in Western Arabian Sea

The seasonal variability of phytoplankton biomass in Western Arabian Sea is shown in Fig. 5.11 (a) & (b) corresponding to the period from 1998 to 2010 and 2003 to 2015 respectively.

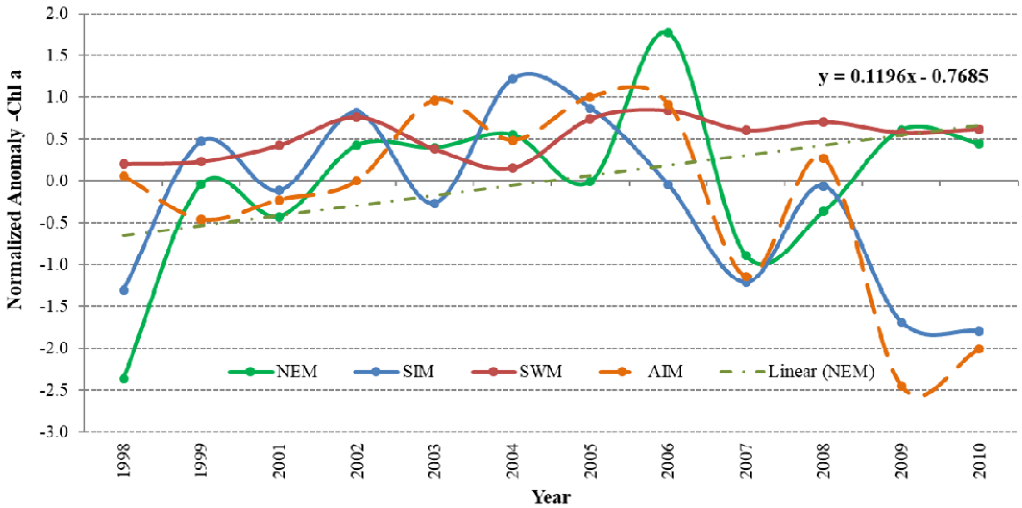


Fig. 5.11 (a): Seasonal variability of Phytoplankton Biomass in Western Arabian Sea from 1998 to 2010 using SeaWiFS data

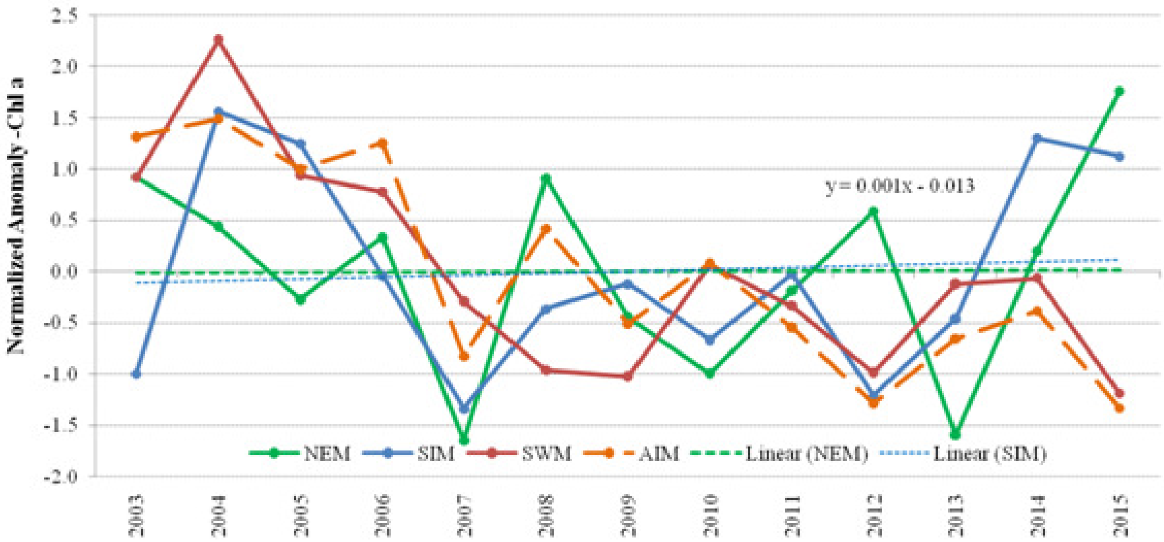


Fig. 5.11 (b): Seasonal variability of Phytoplankton Biomass in Western Arabian Sea from 2003 to 2015 using MODIS data

As seen from Fig. 5.11 (a), during the NEM season, the phytoplankton biomass in Western Arabian Sea, increased considerably during 13 years period from -2.37 in 1998 to +0.61 in 2009 and 0.45 in 2010. It was also noticed that in the year 2006, the normalized anomaly had reached its highest value of +1.77, signifying a very high productivity in the Western domain which was not found in any other sub-domains. However, the scenario was opposite during the AIM and SIM seasons as in these seasons there was a considerable decrease in the phytoplankton biomass with normalized anomalies decreasing at the rate of -0.086/ year for both the seasons. The decrease in phytoplankton biomass during the SWM season was very minuscule with the rate of decrease being -0.003/ year.

Unlike the previous study period, a different pattern of phytoplankton biomass was observed in recent years from the period from 2003 to 2015. The increase in the anomaly as seen during 1998 to 2010 during the NEM season did not continue further. Although a small increase at the rate of

+0.0019/year was noticed, but it did not match the increase of 1998-2010 period. On the contrary, in the years like 2007, 2010 and 2013 the mean chlorophyll-a concentration values were much below the climatological mean, resulting in negative anomalies ranging from -0.99 (2010) to -1.65 (2007, 2013) it was observed that the phytoplankton biomass of the Western Arabian Sea had decreased for all the seasons, except the SIM season, as seen in Fig. 5.11(b), with the rate of decrease being the highest for AIM (-0.216/ year), with its values decreasing from +1.32 in 2003 to -1.33 in 2015. Even during the SWM season, rate of decrease of normalized anomaly was high at -0.184/ year and it was observed to decrease from +0.92 in 2003 to -1.19 in 2015. However, during the SIM season, an opposite pattern of increase was observed, with normalized anomaly increasing at the rate of +0.02/year.

5.4.4.5 Variability of Phytoplankton Biomass in the Eastern and Western Gulfs of the Arabian Sea and the Red Sea

The Gulfs and the marginalized sea i.e. the Red Sea offer altogether different hydrographic features that makes them distinct from the open ocean regions. Hence, for better assessment of the variability of phytoplankton biomass, these sub- domains were analyzed separately. Where as the western Gulfs which includes the Persian Gulf, Gulf of Oman and Gulf of Aden are the regions of high productivity especially during the Southwest and Northeast Monsoon Seasons. These sub-domains are also experiencing extreme ecological pressure in recent years due to the rapid urbanization process which is happening in the coastal areas of Persian Gulf and Gulf of Aden. Using MODIS chlorophyll-a concentration data, the annual variability of phytoplankton biomass in these Gulfs as well as the Red Sea and the eastern Gulfs of Kutch and Khambat were analyzed.

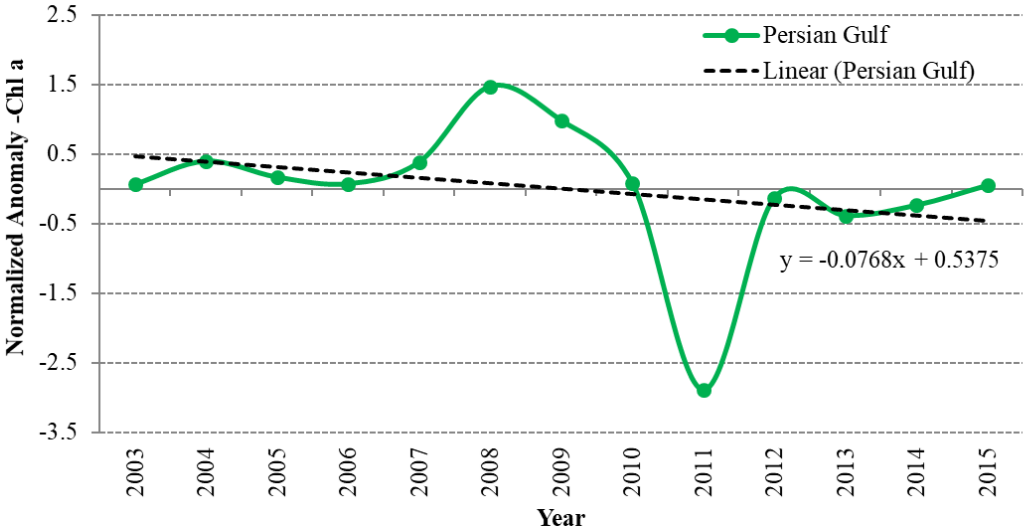


Fig. 5.12 (a): Interannual variability of Phytoplankton Biomass in the Persian Gulf from 2003 to 2015

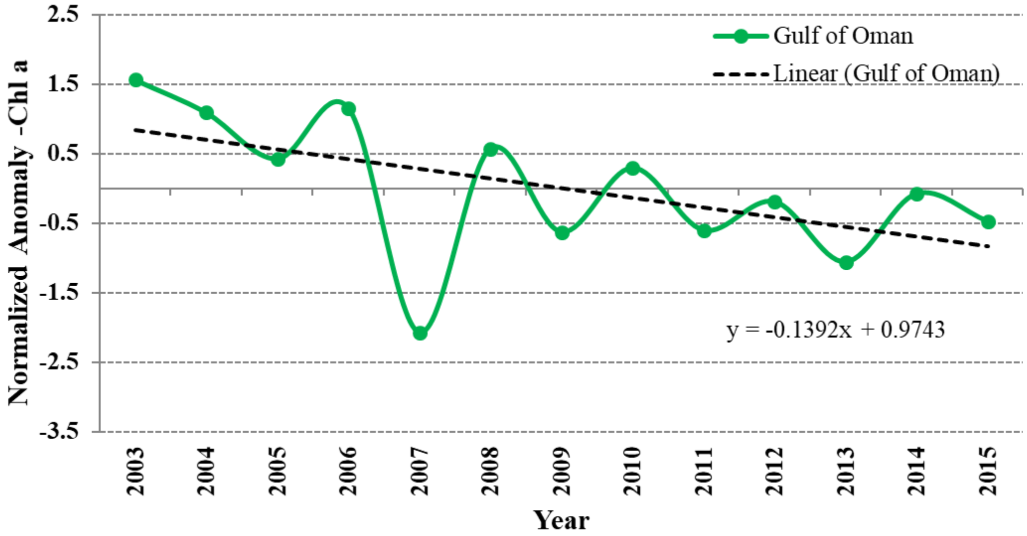


Fig. 5.12 (b): Interannual variability of Phytoplankton Biomass in the Gulf of Oman from 2003 to 2015

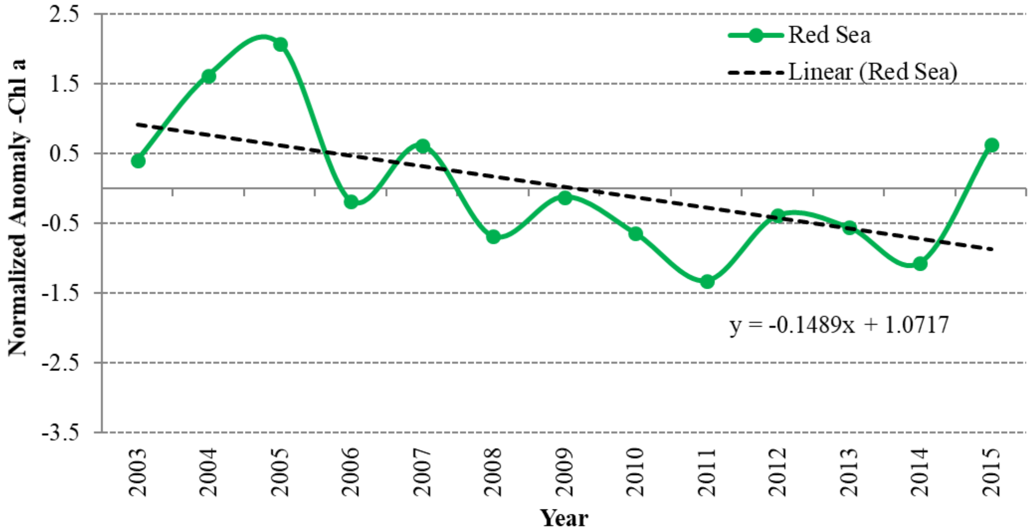


Fig. 5.12 (c): Interannual variability of Phytoplankton Biomass in the Red Sea from 2003 to 2015

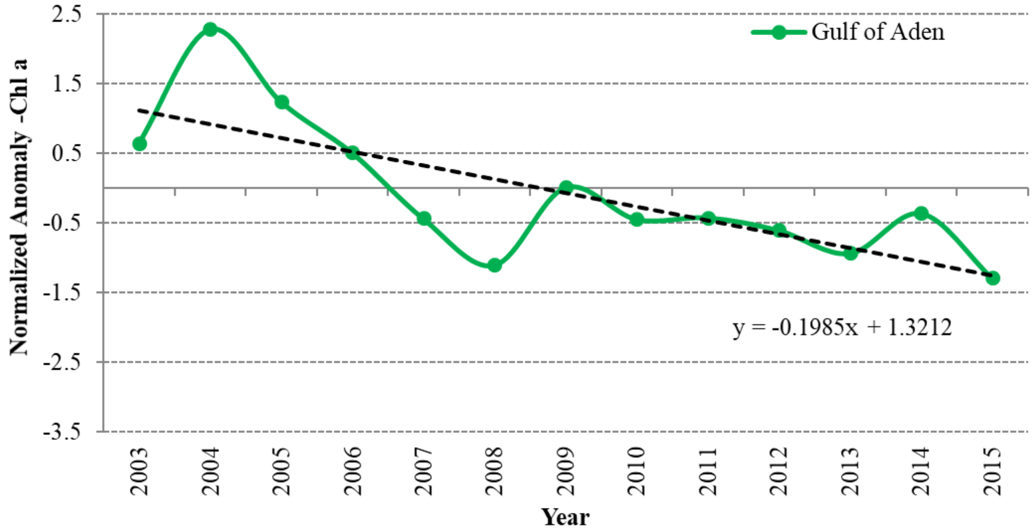


Fig. 5.12 (d): Interannual variability of Phytoplankton Biomass in the Gulf of Aden from 2003 to 2015

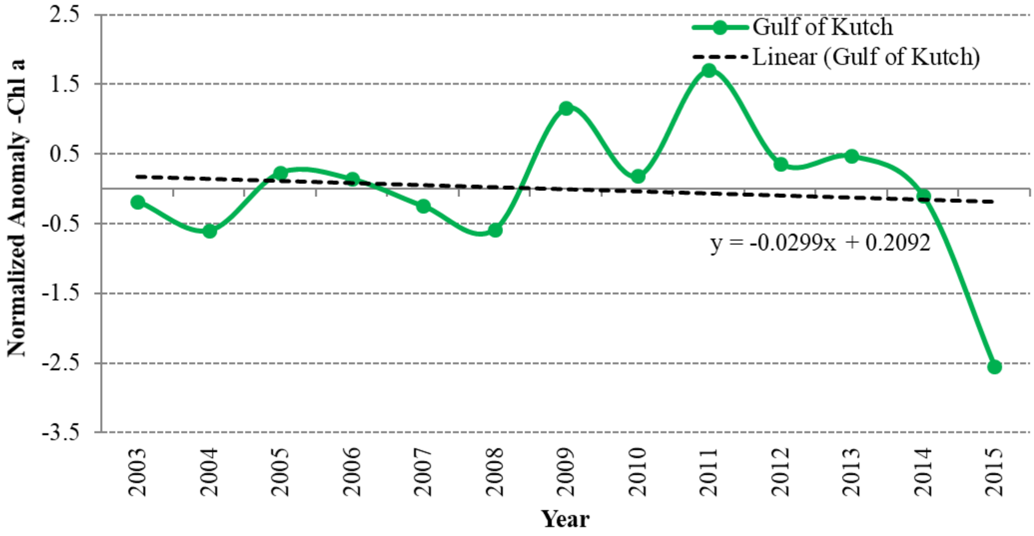


Fig. 5.12 (e): Interannual variability of Phytoplankton Biomass in the Gulf of Kutch from 2003 to 2015

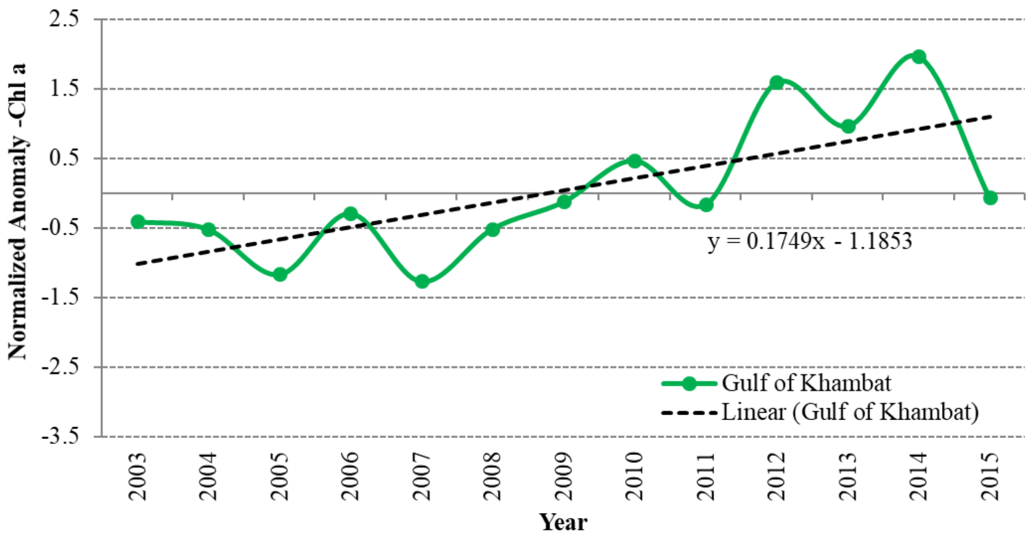


Fig. 5.12 (f): Interannual variability of Phytoplankton Biomass in the Gulf of Khambat from 2003 to 2015

The annual variability of phytoplankton biomass in the eastern and western gulf of the Arabian Sea and the Red Sea are given in fig.5.12 (a -f). It can be clearly noticed that amongst these 6 sub-domains, except for the Gulf of Khambat, rest all the sub domains have been experiencing a sharp decline in phytoplankton biomass. While in the Persian Gulf, the normalized chlorophyll -a anomaly decreased at the rate of -0.08/year, the adjoining Gulf of Oman had a much sharper decline at the rate of -0.2/year with the anomaly decreasing from +1.56 (2003) to -0.47 (2015), with it reaching its lowest value of -2.0 in 2007.

In the Red Sea and the Gulf of Aden also the decreasing pattern of phytoplankton biomass was observed. It was found that in the Red Sea the anomaly decreased at the rate of -0.15/year, from +0.4 in 2003 to -1.07 in 2014 but increased to +0.63 in 2015. On the contrary, in the Gulf of Aden, the anomaly decreased at a much higher rate of -0.2/year, from +0.65 in 2003 to -1.28 in 2015.

Amongst the eastern Gulfs of the Arabian Sea, two opposite trends were observed. Where as in the Gulf of Kutch, the decreasing pattern of phytoplankton biomass (at the rate of 0.03/unit), as observed in the rest of the basin was prevalent, the Gulf of Khambat showed an overall annual increase in phytoplankton biomass across the years from 2003 to 2015. In the Gulf of Khmabat, the normalized anomaly increased from -0.40 in 2003 to +1.97 in 2014. Though the anomaly decreased from 2014 to 2015, yet the rate of increase was high with the rate being +0.18/year.

The overall decreasing pattern of the phytoplankton biomass that was observed in the Arabian Sea basin as well as in the Northern, Southern, Eastern and Western sub-domains was also seen in the Western Gulfs and the Red Sea. However, the decrease in the Gulfs was at a much higher rate. In the Eastern Gulfs, while the decrease in the anomaly of Gulf of Kutch was similar to the pattern observed in the Arabian Sea Basin, Gulf of Khambat was an exception, where an annual increase in the phytoplankton biomass was observed.

5.4.5 Trend Analysis of Phytoplankton Biomass

The satellite derived monthly chlorophyll–a concentration data from SeaWiFS for the period from 1998 to 2010 (13 years) and MODIS Aqua for the period from 2003 to 2015 (13 years), provide a comparatively longer, continuous of data set needed for trend analysis. Although it falls short of the 30 years data required for climate change studies, yet being the most continuous data sets, with a good spatial resolution makes them the best suited data for the study of changing phytoplankton biomass across the oceans. In the present study, the monthly, seasonal and annual chl.-a conc. trend for different domains of Arabian Sea was carried out using the standard Mann-Kendall test at 95% significance level. Table 5.2 gives the statistical z-value of the trend analysis of the Mann-Kendall test and Table 5.3 summarizes the resulting trend.

It can be clearly seen from Table 5.2 and Table 5.3 that, there has been a decrease in the phytoplankton biomass in the Arabian Sea on an annual basis during both the study periods i.e. from 1998 to 2010 and from 2003 to 2015. However, the decreasing trend is statistically significant for the period from 2003 to 2015, emphasizing that the decrease observed during 1998 to 2010 continued even after 2009 and became more prominent in recent years, i.e. from 2010 to 2015. The seasonal trend was found to be similar for the SWM and AIM seasons, with decreasing trend during both the study periods, yet the decreasing trend was statistically significant for the period from 2003 to 2015, further confirming that there has been a substantial decrease in phytoplankton biomass in these two seasons in recent past. For SIM season, it was found that the phytoplankton biomass decreased significantly during 1998 to 2010, yet for the period from 2003 to 2015, an increase in trend was observed. However, this increase was not significant. No trend was observed for NEM season for the period from 1998 to 2010. However, from 2003 to 2009, an increasing trend was found, though it was again statistically not significant. The monthly trend analysis for chlorophyll-a concentration from 1998 to 2010 depicted an overall decreasing trend for all the months, except January, September and October. Nevertheless, this decrease was significant only for May and August months. On the other hand, for the period from 2003 to 2015, it was noticed that there was an increasing trend in the phytoplankton biomass for the months from February to May, though not statistically significant. Whereas for the months from June to December, a decreasing trend in phytoplankton biomass was noticed, with the decrease being significant for June, September, October and November, which eventually affected the overall annual trend leading to a significant downward trend.

Amongst the Northern, Southern, Eastern and Western domains, it was observed that annually, in all the domains, for both the study periods, there was decreasing trend in the phytoplankton biomass. However, it was found to be statistically significant in the Eastern Arabian Sea for the period from 1998 to 2010 and Western and Southern Arabian Sea for the period from 2003 to 2015.

The seasonal trend analysis for these four domains revealed that during the SWM season, there has been a significant decrease in the phytoplankton biomass in the Northern, Southern and Western domains for both the periods from 1998 to 2010 and 2003 to 2015. Though, a similar trend was observed for the Eastern domain as well, but it was found to be statistically non-significant.

AIM was another season for which decreasing trend in chlorophyll-a concentration was observed for all the domains, yet it was significant only for Northern, Southern and Western domains and that too only in the period from 2003 to 2015.

For the NEM season, a similarity was observed in the trend of phytoplankton biomass in the Northern and Eastern domains on one hand and Southern and Western domains on the other. While in the Northern and Eastern domains, a decreasing trend was observed for the period from 1998 to 2010. However, for the period from 2003 to 2015, the trend got reversed, and an increase was noticed. Similarly, for the Southern and Western domains, there was an upwards trend for the period from 1998 to 2010, but it was found to be downward for the period from 2003 to 2015. Though, these trends were not statistically significant, yet, they give an overall view of the inter-domain variability and changing pattern of phytoplankton biomass.

The monthly trend analysis of chlorophyll–a concentration for the different domains of the Arabian Sea, revealed that it was only in the Western domain that a significant increase in phytoplankton biomass during the month of January, during the period from 1998 to 2010. This trend did not continue for the period from 2003 to 2015. For all the rest of the months either a decreasing trend was observed or even if the increase was there, it was not significant. It was also observed that in all the four domains, there has been a significant decrease in the phytoplankton biomass in the months of September, October and November from 2003 to 2015. This can be interpreted as a threat to the overall productivity of the Arabian Sea, as September being peak season for biological productivity; a decrease in the phytoplankton biomass will affect the other organisms of the trophic level, disrupting the entire food chain. Besides, the

Northern and Western domains have been the high productive areas of the Arabian Sea, hence, the dwindling phytoplankton in these domains may affect their productivity pattern.

	ASB		NAS		SAS		EAS		WAS	
	1998-2009	**2003-2015**	**1998-2009**	**2003-2015**	**1998-2009**	**2003-2015**	**1998-2009**	**2003-2015**	**1998-2009**	**2003-2015**
Jan	+1.56	-0.06	-0.48	+0.42	+0.78	-0.91	-0.15	+0.30	**+2.49***	-0.30
Feb	0	+1.22	-0.15	+0.42	+0.31	+0.48	-1.24	+1.40	+0.46	+0.30
Mar	-0.62	+1.03	-0.46	+1.16	+0.15	+0.67	**-1.87***	+1.28	-0.15	+0.42
Apr	-0.62	+1.04	-0.89	+1.40	0	0	-0.89	+0.67	-0.20	+0.30
May	**-1.71***	+0.37	-0.63	+0.79	-0.54	0	**-1.79***	-0.42	-0.70	+0.54
June	-1.30	-0.67	-0.34	0	-0.62	0	-0.27	-0.12	-0.96	-1.10
July	-1.09	**-2.44***	**-1.64***	+0.67	-0.93	**-2.93***	-1.55	-1.52	-0.93	**-2.13***
Aug	**-2.58***	-0.91	**-2.12***	-1.16	-1.16	-0.79	-0.89	0	**-2.26***	-0.79
Sep	+0.15	**-2.25***	+0.47	**-2.25***	0.31	**-2.37***	-0.15	**-1.76***	+0.155	**-2.74***
Oct	+0.93	**-2.98***	+1.17	**-2.50***	+1.09	**-2.44***	-0.93	**-1.83***	+1.09	**-2.98***
Nov	-1.3	**-3.30***	-1.30	**-2.74***	**-1.99***	**-2.62***	-0.48	**-2.32***	-0.75	**-3.11***
Dec	0.48	-1.15	-0.96	-0.79	-1.57	**-1.95***	-1.58	-0.73	-0.69	-1.52
Annual	-1.02	**-1.76***	-0.20	-0.54	-1.03	**-2.13***	**-2.13***	-0.91	-0.20	**-1.64***
NEM	0	+0.67	-0.06	+0.48	+0.34	-0.18	-1.30	+1.40	+1.30	-0.18
SIM	**-1.79***	+0.30	-1.03	+1.03	-1.16	-0.06	**-1.65***	-0.30	-0.89	+0.06
SWM	-1.3	**-2.13***	**-1.71***	**-1.89***	**-1.78***	**-2.13***	-0.48	-1.52	**-1.78***	**-2.37***
AIM	-0.48	**-3.47***	0.07	**-2.74***	0.20	**-2.86***	-0.41	-2.13	-0.07	**-2.98***

Table 5.2 Z-value (Mann-Kendall Trend Test statistics) for Monthly, Seasonal and Annual chlorophyll- a conc. in different domains of the Arabian Sea

**trend significant at 95% confidence level*

Table 5.3 **Mann-Kendall Trend Test results for Monthly, Seasonal and Annual chlorophyll- a conc. in different domains of the Arabian Sea**

	ASB		NAS		SAS		EAS		WAS	
	1998-2009	2003-2015	1998-2009	2003-2015	1998-2009	2003-2015	1998-2009	2003-2015	1998-2009	2003-2015
Jan	U	D	D	U	U	D	D	U	U *	D
Feb	NT	U	D	U	U	U	D	U	U	U
Mar	D	U	D	U	U	U	D*	U	D	U
Apr	D	U	D	U	NT	NT	D	U	D	U
May	D*	U	D	U	D	NT	D*	D	D	U
June	D	D	D	NT	D	NT	D	D	D	D
July	D	D*	D*	U	D	D*	D	D	D	D*
Aug	D*	D	D*	D	D	D	D	NT	D*	D
Sep	U	D*	U	D*	U	D*	D	D*	U	D*
Oct	U	D*	U	D*	U	D*	D	D*	U	D*
Nov	D	D*	D	D*	D*	D*	D	D*	D	D*
Dec	U	D	D	D	D	D*	D	D	D	D
Annual	D	D*	D	D	D	D*	D*	D	D	D*
NEM	NT	U	D	U	U	D	D	U	U	D
SIM	D*	U	D	U	D	D	D*	D	D	U
SWM	D	D*	D*	D*	D*	D*	D	D	D*	D*
AIM	D	D*	U	D*	U	D*	D	D	D	D*

(U = Upward trend, U = Upward trend significant at 95% confidence level, D = Downward Trend, D* = Downward trend significant at 95% confidence level, NT = No trend)*

5.5 CONCLUSIONS

Arabian Sea, being one of the most productive oceanic zones of the world has attracted numerous investigators attention and several studies have been done in the past to estimate its biological productivity. An assessment of phytoplankton biomass and its seasonal variations in Arabian Sea has also been extensively studied. *Bhattathiri et al. (1996)* studied the phytoplankton distribution in the Eastern and Central Arabian Sea during different seasons. Variability of Chlorophyll-a in Eastern and Western Arabian Sea has been studied by *Tang et al., (2002; 2005)* and *Mudgal et al., (2009)*. *Nair et al. (1999)* and *Kumar et al. (2000)* reported that the biological productivity of the Arabian Sea is tightly coupled with the physical forcing mediated through nutrient availability. *Pillai et al. (2000)* studied the seasonal variations in physico-chemical and biological characteristics of the Eastern Arabian Sea. *Ravichandran et al. (2012)* evaluated the chlorophyll a variability in the southeastern Arabian Sea using Argo profiling.

In the present study an assessment of the standing stock or biomass of the phytoplankton of the Arabian Sea, using chlorophyll–a concentration, as an index and a proxy for inferring about its productivity has been done using satellite data.

The phytoplankton biomass (indexed from chlorophyll–a concentration) in the Arabian Sea was observed to follow a typical bimodal pattern, with peaks during the NEM and SWM seasons. For the period from 1998 to 2009, it was observed that September was the month with peak chlorophyll–a concentration. This is similar to the findings of *Piontkovski and Nezlin (2012).* However, for the period from 2010 to 2015, a deviation from the pattern which was followed during 1998 to 2009 was observed. It was found, that from 2010 onwards, a distinct shift in the peak was observed, with February turning out to be the month with the maximum productivity instead of September. It was an interesting observation, as it depicts a change in the phenology of the phytoplankton of the Arabian Sea, and this has been one of the anticipated impacts of climate change in the oceans *(Rubao Ji et al., 2010; Sheridan C et al., 2004).* Moreover, this shift was not an episodic one, instead it continued for all the successive years from 2010 to 2015, making it evident that it was a phenological change of the phytoplankton of the Arabian Sea.

The decadal analysis of chlorophyll–a concentration in the present study revealed that there has been a substantial decrease in the extent of the productive areas of the Arabian Sea basin especially the Northern, Western and Eastern domains from 1998 to 2008 and from 2005 to 2015. This is coherent with the findings of *Prakash and Ramesh (2007) and Piontkovski and Claereboudt (2012)*, who analyzed the SeaWiFS data from 1997 to 2009. Yet, the decadal change observed from 2005 to 2015, is a recent finding about the decrease in phytoplankton biomass and the productivity of the Arabian Sea, and fits into the trend set during 1997 to 2009.

The present study highlights that the phytoplankton biomass of the Arabian Sea basin has been decreasing at a statistically significant rate annually as well as seasonally. From the MODIS Aqua data, it was found that from 2007 to 2015, only one year (2014) showed positive deviation from the climatological mean, making it evident that the decrease in phytoplankton biomass has been occurring on a continuous basis, annually and that too more rapidly in recent years.

However, the most notable observation was the decrease in the phytoplankton biomass of the Arabian Sea, during the SWM season, which considered as the season with highest productivity. It was found that amongst all the seasons the highest decrease in phytoplankton biomass was during the SWM season. This poses a serious issue of concern, as rate at which the phytoplankton are dwindling during SWM, it will affect the overall productivity of the Arabian Sea basin. The absence of the primary producers would result in the subsequent mismatch between the primary producers, and secondary and tertiary consumers *(Cushing, 1990)* which would eventually disrupt the trophic structure and its balance.

Amongst the Northern, Southern, Eastern and Western domains, it was observed that annually, in all the domains, there was decreasing trend in the phytoplankton biomass. The seasonal trend analysis for these four domains revealed that during the SWM season, there has been a significant decrease of the phytoplankton biomass in the Northern, Southern and Western domains. The overall decreasing pattern of the phytoplankton biomass that was observed in the Arabian Sea basin as well as in the Northern, Southern, Eastern and Western sub-domains was also seen in the Western Gulfs and the Red Sea. However, the decrease in the Gulfs was at a much higher rate. In the Eastern Gulfs, while the decrease in the anomaly of Gulf of Kutch was similar to the pattern observed in the Arabian Sea Basin, Gulf of Khambat was an exception, where an annual increase in the phytoplankton biomass was observed.

The monthly trend analysis of chlorophyll–a concentration. for the different domains of the Arabian Sea, revealed that it was only in the Western domain in which a significant increase in phytoplankton biomass has happened, but limited to the month of January, from 1998 to 2009. This trend did not continue for the period from 2003 to 2015. For all the rest of the months either a decreasing trend was observed or even if the increase was there, it was not significant. It was also observed that in all the four domains, there has been a significant decrease in the phytoplankton biomass in the months of September, October and November from 2003 to 2015. This can be interpreted as a threat to the overall productivity of the Arabian Sea, as September being peak season for biological productivity; a decrease in the phytoplankton biomass will affect the other organisms of the trophic level, disrupting the entire food chain. Besides, the Northern and Western domains have been the high productive areas of the Arabian Sea, hence, the dwindling phytoplankton in these domains may affect their productivity pattern.

The satellite chlorophyll-a concentration. data from SeaWiFS for the period from 1998 to 2010 (13 years) and MODIS Aqua for the period from 2003 to 2015 (13 years), provide a comparatively longer, continuous of data set needed for trend analysis. Although it falls short of the 30 years data required for climate change studies, yet being the most continuous data sets, with a good spatial resolution makes them the best suited data for the study of changing phytoplankton biomass across the oceans.