Chapter 6

Correlation of the Changing Climate on the Biological productivity of the Arabian Sea

⑥ CORRELATION OF THE CHANGING CLIMATE ON THE BIOLOGICAL PRODUCTIVITY OF THE ARABIAN SEA

6.1 INTRODUCTION

In recent times, one of the biggest challenges for the existence of life on earth is the unequivocal rate of changing climatic conditions. The unprecedented rate of increasing global temperature, including the SST, is posing a threat to the existence of life on earth. The most direct impact of changing climate is the rising SST *(Bindoff et al. 2007).* The increase in the SST leads to a cascade of events like rising sea level *(Church, 2001; Meehl et al., 2005)*, decreased sea-ice extent, altered pattern of ocean currents, wind circulation and precipitation *(Goswami et al., 2006; Zhang et al., 2007)*. Warmer SSTs may affect the frequency and strength of tropical storms *(Emanuel, 2005; Webster et al., 2005),* increasing the vulnerability of coastal habitats. Additionally, the rise in temperature and altered wind patterns, can adversely affect the mixing and stratification of the surface ocean *(Sarmiento et al., 2004)*, limiting the supply of nutrients.

The physical and biological processes in the marine ecosystem are balanced in an intricate manner with the physical factors like SST, wind speed, wind direction, salinity, and ocean currents, etc. having a pronounced effect on the marine organisms, especially the phytoplankton. The growth and abundance of the phytoplankton as well as their productivity are dependent on the availability of light and nutrients, which are regulated by highly complex processes like ocean circulation and upwelling. These physical oceanographic processes are in turn driven by climate factors like SST, surface winds, surface air temperature etc. *(Behrenfeld et al., 2006).*

Hence, any change in these variables may disrupt the bio-physical coupling in the oceans and may lead to catastrophic effects, with shifts in habitats, alteration in marine food chain, and decrease in the biomass or abundance etc. of the marine organisms. (*Ji et al., 2007*)

Behrenfeld et al. (2006), using satellite data assessed that from 1999 to 2004, the warming of the oceanic waters, resulted in a decline in the global phytoplankton biomass as well as their growth, which caused a decrease in the net primary productivity of the oceans. They gave an insight on the effect of warming of oceans (which is an outcome of climate change) on the biological productivity of the oceans across the globe.

Recently, *Boyce et al. (2010)* came up with an alarming report that on an average the global phytoplankton population has declined by 40%, since 1950. They attributed this decline to the climate change induced warming of the sea waters, that has resulted in a relatively stable thermally stratified surface layers, which prevents mixing of the deeper nutrient rich layers of the ocean. As a result, due to lack of nutrients, the phytoplankton growth gets limited and eventually, in the absence of nutrients they do not survive.

In addition to SST, wind is another factor on which the growth and abundance of phytoplankton is dependent. This factor is more applicable in case of the Arabian Sea, as it is strongly affected by the semi-annual seasonal reversal of winds during the Southwest Monsoon and Northeast Monsoon seasons, which lead to specific seasonal cycle of phytoplankton *(Banse, 1987).* These monsoonal winds affect the circulation pattern and lead to mixing of the oceanic layers through the process of upwelling and downwelling (*Lee et al., 2000; Schott and McCreary, 2001)*, which ultimately affect the availability of nutrients for the growth of the phytoplankton. *Kahru et al. (2010)* brought out correlation between satellite-derived winds and surface chlorophyll concentration across the oceans. They reported a high positive correlation in most of the oceans, where increased winds deepened the mixed layer and entrained additional nutrients into surface water.

In context of climate change, it is well known that the increase in global temperatures will disrupt the thermal stratification and gradient of the earth, adversely affecting the air circulation. This will impact the wind speed as well. Numerous investigations using different climate models have reported that in the last 30 years, the wind speed across the globe has decreased by 5–15% *(Vautard et al., 2010; McVicar et al., 2012)*. It is anticipated that with the decrease in the wind speed, the subsequent oceanic circulation pattern and the processes of upwelling and downwelling would be affected, resulting in the decrease in the growth and the productivity of the phytoplankton.

In case of the Arabian Sea, *Kumar et al. (2001)* studied the physical factors including SST and wind speed and their coupled physical forcing on primary productivity of the central and eastern Arabian Sea. Using ocean colour sensors viz. CZCS (Coastal Zone Colour Scanner) and SeaWiFS (Sea viewing Wide Field-of-view Sensor) data, *Gregg et al. (2003)* were the first to report on the increase in the productivity of the northern Indian Ocean (including Arabian Sea) since the 1980s. *Goes et al. (2005)* also reported the increase in phytoplankton biomass (by over 350%) from 1997-2003 off Somalia coast owing to a decline in the winter and spring snow cover over Eurasia causing an intensified up welling. However, *Kumar et al. (2009)* analyzed the trend of SST and wind speed and chlorophyll- a concentration using satellite data and concluded that along with a gradual secular increase in SST, the phytoplankton biomass increased from 1998 to 2006. However, the increase in productivity was not linked with the intensification of monsoonal winds, as there was a decrease in the wind speed over Arabian Sea. Recently, *Prakash and Ramesh (2007),* found no secular trend in winter-time chlorophyll- a distribution between 1997 and 2005 in the eastern Arabian Sea. Even the study by *Naqvi et al. (2010) u*sing *in situ* and reanalysed satellite data for western Arabian Sea did not support the increase in biological productivity of the Arabian Sea. *Piontkovski and Claereboudt (2011)* also reported on decrease in the productivity of the eastern Arabian Sea from 1997 to 2009, and linked it with rising SST and decreasing wind speed.

Keeping in line with the above findings, in the present work, it was aimed at analyzing the changing trend of the productivity of the Arabian Sea in recent past and its correlation with the physical parameters like SST and wind speed. Further, the bio-physical coupling and its trend was analyzed for northern, southern, eastern and western domains of the Arabian Sea, to conclude about the changing productivity pattern and the reason thereof in these domains as well.

6.2 DATA USED

(a) Sea Surface Temperature Data:

For this study, the monthly SST data from NOAA AVHRR Pathfinder (version 5.0) of 4 km resolution was obtained from NASA'S Jet Propulsion Laboratory's Physical oceanographic centre (http://podaac.jpl.nasa.gov.) for the period 1998-2009. Additionally, for analysis of the SST in recent years, the monthly, MODIS Aqua SST data (R.2014.0) of 4 km resolution was obtained from NASA Ocean Colour Home (http://oceandata.sci.gsfc.nasa.gov) for the period 2003 to 2015.

(b) Surface Wind Speed Data:

The monthly (level 3.5) gridded cross calibrated multiplatform (CCMP) ocean surface wind speed of 25 km spatial resolution, derived through cross calibration and assimilation of data from SSM/I, TMI, AMSRE, SeaWinds on QuikSCAT, and SeaWinds on ADEOSII was used for analysis of wind speed for the period 1998 -2009.

(c) Chlorophyll-a Data:

Surface-ocean chlorophyll-a measured from the SeaWiFS (Sea viewing Wide Field-of-view Sensor) was used for analysing the spatial and temporal distribution for the period 1998–2010. The monthly 9 km data were accessed from NASA Ocean Colour Home (http://oceandata.sci.gsfc.nasa.gov). Additionally, monthly, chlorophyll-a data of 4 km resolution, from MODIS Aqua (R.2014.0) was also obtained, from NASA Ocean Colour Home (http://oceandata.sci.gsfc.nasa.gov) for the period 2003 to 2015.

6.3 METHODOLOGY

For the present study the Arabian Sea basin (ASB) (32°N-10°S; 32°W-80°E) was divided into Northern Arabian Sea (NAS), Southern Arabian Sea (SAS), Eastern Arabian Sea (EAS) and Western Arabian Sea (WAS).

For each of the defined domains of the Arabian Sea, the monthly chl.-a and SST images were masked to avoid the influence of the land and clouds using ENVI 4.1 and ERDAS 9.0 software. For chlorophyll-a, 50 meters bathymetric influence were removed to avoid the influence of the coastal waters. The monthly, seasonal and annual climatological mean of NOAA AVHRR SST and CCMP wind speed for 10 years for the period 1999-2009 corresponding to chl.-a data from the SeaWiFs were calculated. Similarly, for the study of changes in recent past, the climatological mean of SST and chlorophyll- a, for 13 years from 2003 to 2015, corresponding to MODIS Aqua were calculated. The inter annual variability for each month was analyzed using the monthly anomalies computed by subtracting the climatological mean from the monthly mean, which was then normalized to the standard deviation for that month. A regression analysis was done to know about the trend.

Additionally, see the impact of climate change with rising SST and diminishing wind speed on the biological productivity of the Arabian Sea, a respective correlation analysis was done using the statistical software tool MINITAB 14.1.

6.4 RESULTS & DISCUSSION

The physical forcing of SST and Wind speed on phytoplankton biomass and their productivity follows a typical relationship, with rising SST inhibiting the growth and productivity of the phytoplankton. The increase in wind speed helps in the mixing of the nutrients, which in turn promotes the growth and productivity of the phytoplankton. However, this relationship between wind speed and phytoplankton biomass does not follow a direct correlation. In fact, there is a lag period between the increase in wind speed and the growth and productivity of phytoplankton because it takes some time for the mixing of the nutrients which would then be easily available for the microscopic phytoplankton to promote their growth. Hence, as compared to SST where an inverse correlation exists between the rise in temperature and growth of phytoplankton biomass, the relationship between wind speed and phytoplankton growth is direct but with a lag phase. This feature was observed in all the domains of the Arabian Sea for both the periods of study i.e. from 1999 to 2009 and from 2003 to 2015. However, few variations were also noticed that were found to be domain specific, which are discussed below.

6.4.1 Intra-annual variability of SST, Wind Speed and phytoplankton biomass in Northern Arabian Sea

The Northern Arabian Sea is a biologically significant domain because of the occurrence of phytoplankton bloom in the monsoon season, which leads to an increase in the productivity. As shown in Fig. 6.1 (a), (c), the intra annual variability of SST and phytoplankton biomass, follow a typical bimodal pattern for different months of the year. However, the wind speed as shown in Fig.6.1 (b) follows a unimodal pattern with the maximum wind speed in the month of July during the SWM season. For the period from 1999 to 2009, the Northern Arabian Sea exhibited lowest temperature in the range of 23.8 - 25.3°C during the NEM season (January-February), while the maximum temperature was observed during the AIM season, with SST in the range of 28.0 - 30.05°C. This was found to be a deviation from other domains of the Arabian Sea, as in the rest of the domains, the highest temperature was noted during SIM and the lowest during the SWM season. The wind speed also followed the unimodal pattern, with maximum wind speed during SWM season (July). Even the pattern for phytoplankton biomass was observed to be similar to the basin, with maximum abundance during in September (chlorophyll–a concentration of 1.196 mg/m^3), yet the spike in their growth during the NEM season (chlorophyll–a concentration) of 1.01 mg/m^3), comparable to that of the SWM season, was a distinct feature observed in the Northern sub-domain.

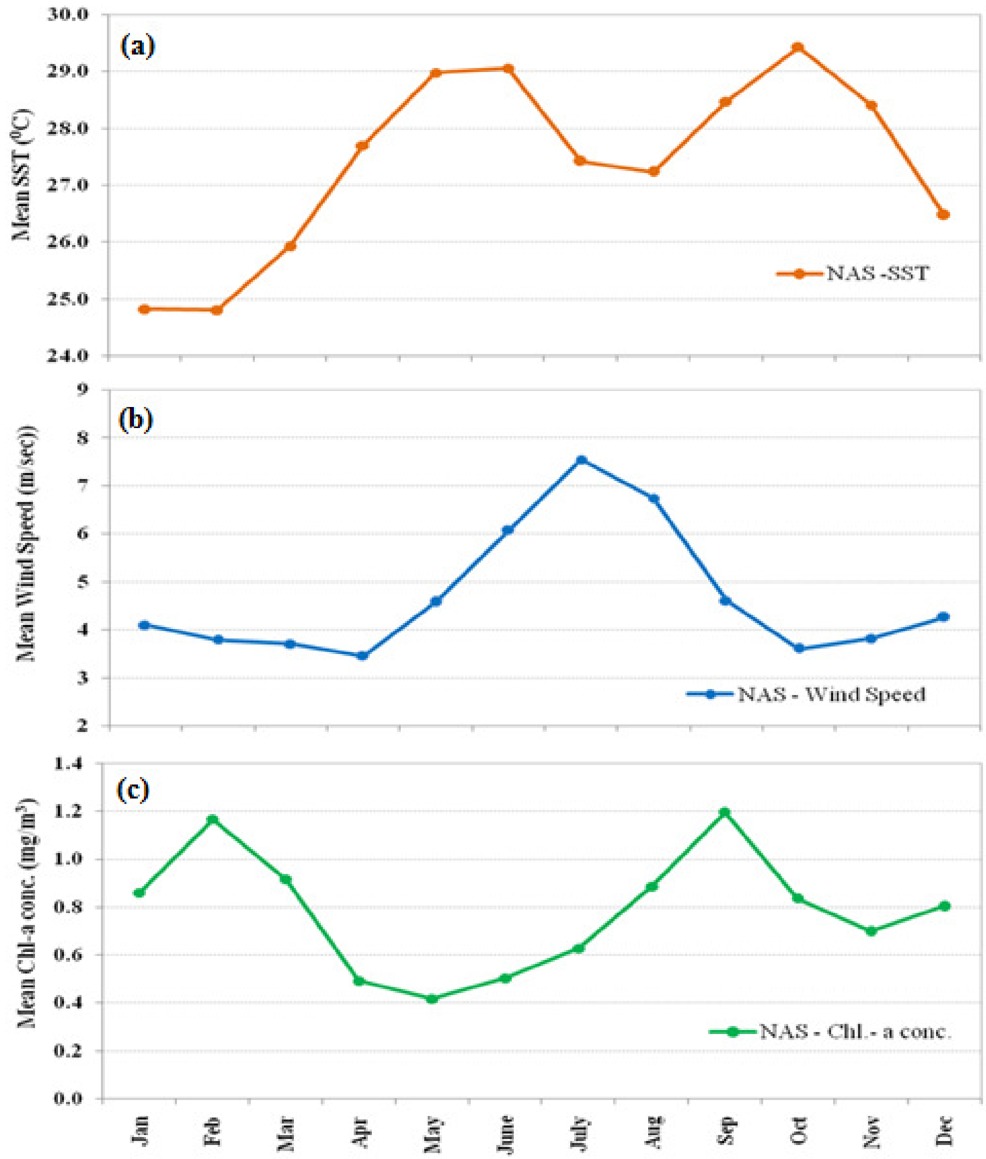

Fig. 6.1 (a-c): Intra-annual variability of (a) SST, (b) Wind speed, (c) Chl.-a over Northern Arabian Sea from 1999 to 2009

For the change in the recent years, the analysis of MODIS Aqua SST and chlorophyll–a concentration for the period from 2003 to 2015 was done, as shown in Fig. 6.2 (a-b).

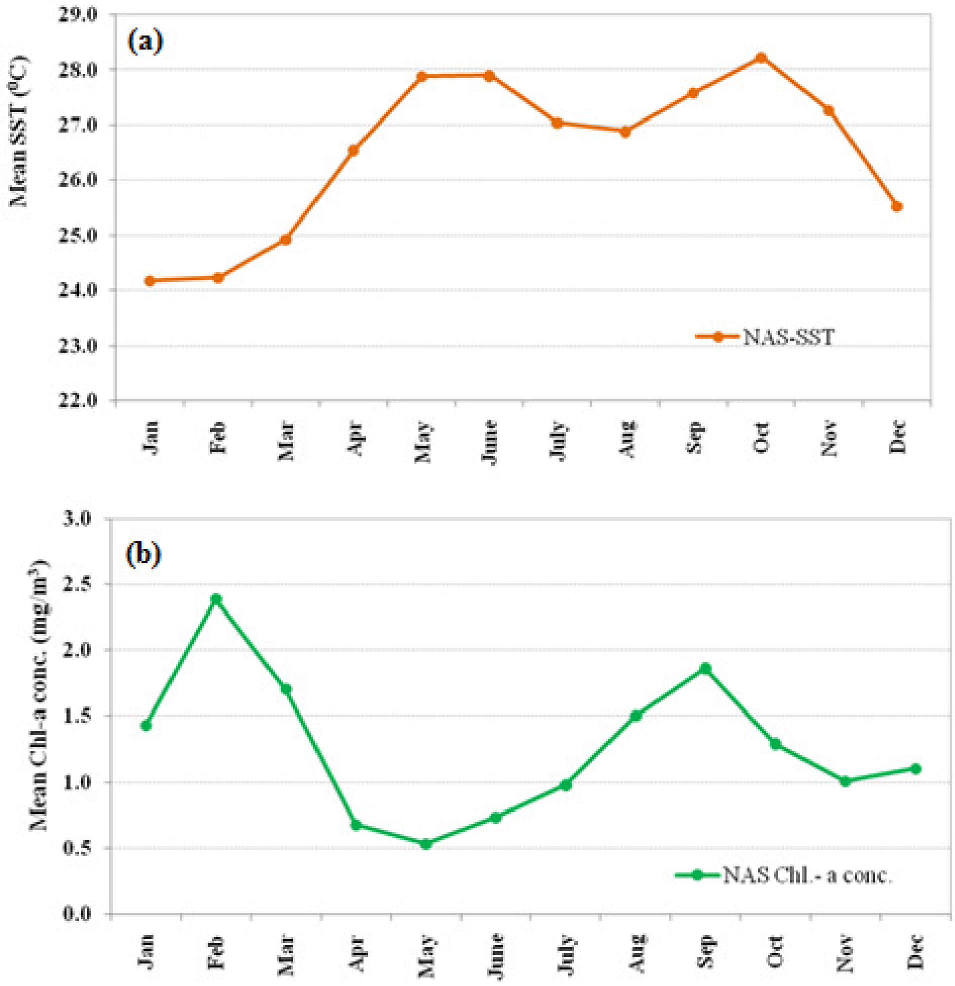

Fig. 6.2 (a-b): Intra-annual variability of (a) SST and (b) Chlorophyll-a concentration over Northern Arabian Sea from 2003 to 2015

It was observed that for SST, the pattern followed during the decade 1999 to 2009 continued during 2003 to 2015, with maximum cooling during the NEM season and maximum warming during the AIM season, although the magnitude differed. However, as the data for the two periods were obtained from two different sensors, viz. NOAA AVHRR for the period from 1999 to 2009 and MODIS for the period from 2003 to 2015, hence the magnitude cannot be compared.

The analysis of the chlorophyll–a concentration from MODIS data (2003 to 2015), as shown in Fig. 6.2 (b), depicts a major deviation from those observed for the period from 1999 to 2009. It was found that the phytoplankton achieved their maximum growth during the NEM season instead of the usual SWM season. The values of chlorophyll–a concentration in February, the month with the peak, ranged from 1.9 - 3.8 mg/m^3 with the decadal average of 2.5 mg/m^3. On the other hand, September turned out to be the month with the second peak, with chlorophyll–a concentration values ranging 1.2 to 2.7 mg/m^3. However, the inverse relationship between SST and phytoplankton biomass can easily be seen in fig. 6.2 (a) and (b).

6.4.2 Inter-annual variability of SST, Wind Speed and phytoplankton biomass in Northern Arabian Sea

The inter-annual variability of SST, Wind speed and phytoplankton biomass was analyzed by computing the normalized anomalies for each of the variables for the period from 1999 to 2009, as shown in Fig. 6.3 (a, b and c) and 2003 to 2015 (Fig. 6.4), for the northern domain.

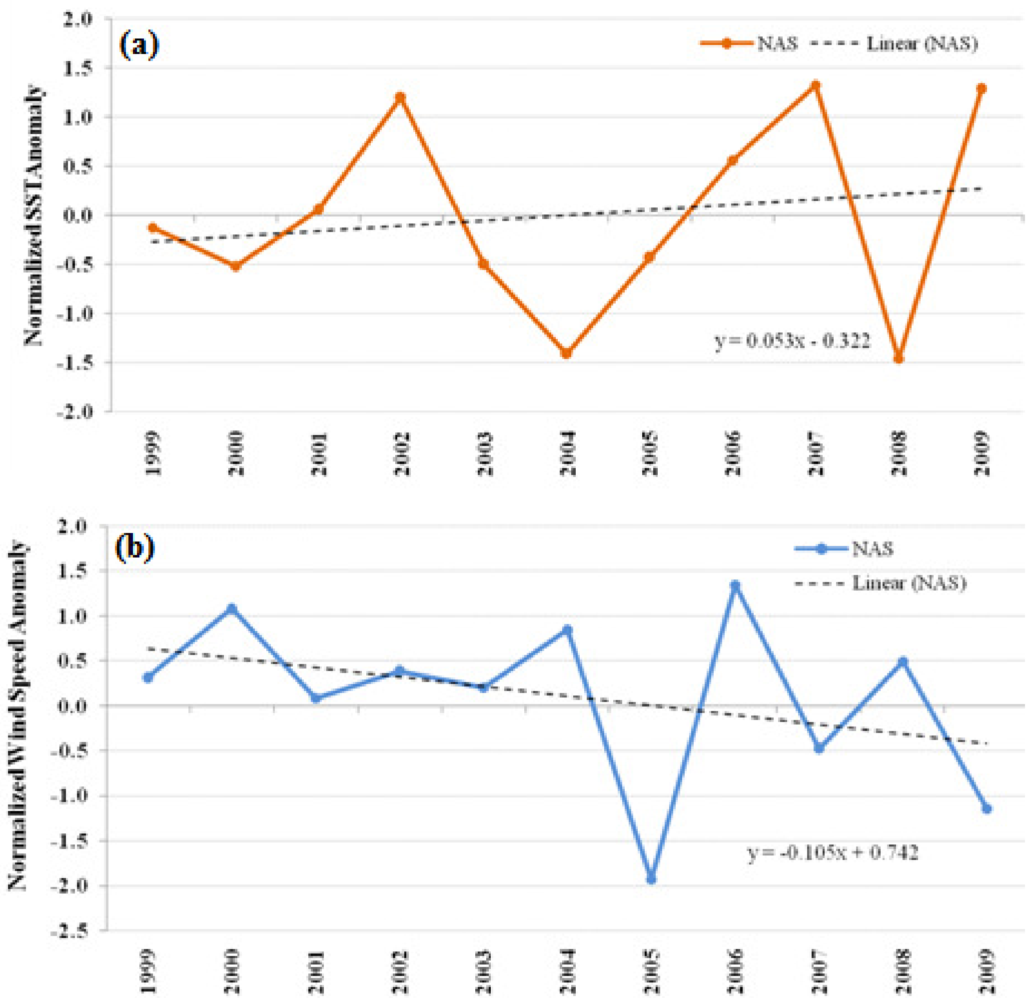

Fig. 6.3 (a-b): Interannual variability of (a) SST & (b) Wind speed over Northern Arabian Sea from 1999 to 2009

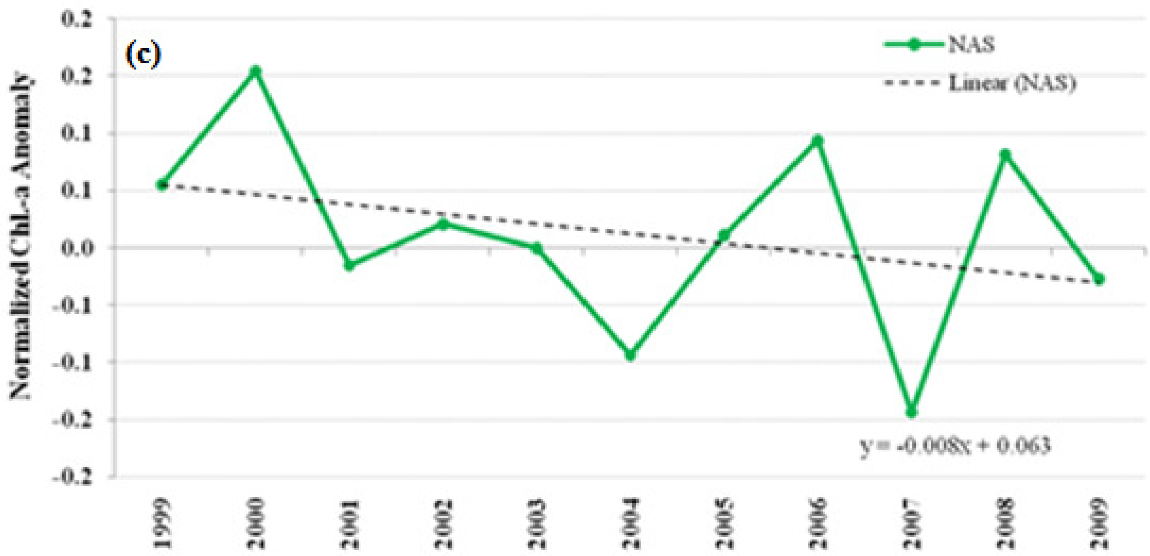

Fig. 6.3 (c): Interannual variability of Chlorophyll-a concentration over Northern Arabian Sea from 1999 to 2009

As shown in Fig. 6.3 (a), the warming of the northern domain for the period from 1999 to 2009, is clearly visible, with the anomalies increasing at the rate of +0.53 unit/decade. It was observed that the SST increased drastically from -0.12 in 1999 reaching up to +1.2 in 2002. With only the years 2003 and 2004 being comparatively below the climatological mean, the warming of the Northern sub-domain proceeded again from 2004 to 2007, with SST anomaly reaching up to +1.32 in 2007. 2008 was the year during which cooling occurred and the anomalies reached their minimum value for the decade (-1.4), but it may be considered that 2008 was an anomalous year during which the cooling occurred due to the effect of strong La Nina. However, in the very next year, i.e. 2009, once again SST was high with its anomaly reaching up to +1.3. Though this decadal study may be a short period of time to analyze the impact of climate change, yet the SST results obtained are consistent with those of the analysis of 65 years of ERSST data as concluded in chapter 4.

In contrast to SST, the average wind speed over the northern domain was observed to be decreasing, with its anomalies declining at the rate of -1.05 unit/decade, as shown in Fig. 6.3 (b). The maximum positive deviation from the decadal mean wind speed was observed for the year 2006 with its anomalies reaching up to +1.34. Although, the negative anomalies were observed in only 3 years (2005, 2007 and 2009), yet the positive deviations were of smaller magnitude and couldn't offset the declining trend.

The normalized anomalies of phytoplankton biomass, which can be taken as a proxy for the estimation of productivity pattern of Arabian Sea in shown in Fig. 6.3 (c). It can be clearly seen that the pattern observed in SST and wind speed justifies for the chlorophyll- a anomalies pattern. As expected, with the rising SST and decreasing wind speed, the growth of the phytoplankton is bound to get hampered and the phytoplankton biomass anomalies were observed to be decreasing at the rate of -0.8/decade for the Northern sub-domain of the Arabian Sea. The decrease in the SST and increase in the wind speed over the domain in the year 2000 and 2008, resulted in a higher growth and productivity of the phytoplankton with positive anomalies for chlorophyll-a reaching up to +0.15 (2000) and +0.08 (2008). For the year 2006, though SST was high, yet the substantially increased wind speed with anomaly reaching +1.34, resulted in an increased growth of the phytoplankton and their biomass showing positive deviation. However, an overall analysis of the phytoplankton biomass revealed that during the decade 1999 to 2009, there has been a considerable decrease in their abundance and hence there has been a reduced productivity of the phytoplankton in the Northern Arabian Sea.

For the period from 2003 to 2015, SST and phytoplankton biomass over the Northern Arabian Sea was analyzed using MODIS Aqua data and the results are shown in Fig 6.4 (a-b).

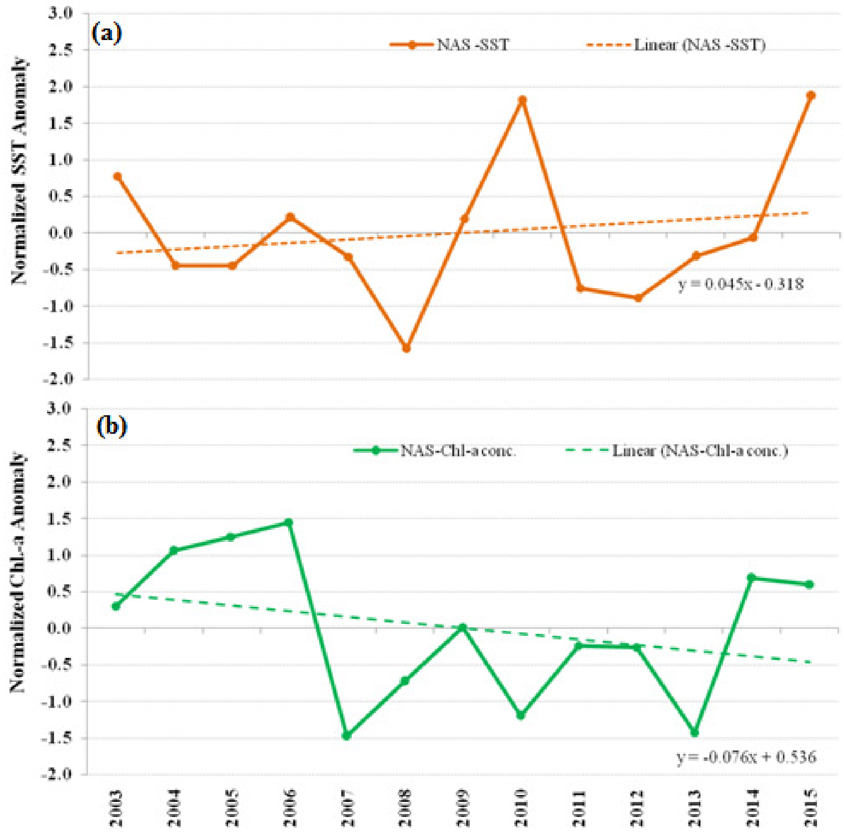

Fig. 6.4 (a-b): Interannual variability of (a) SST & (b) Chlorophyll-a concentration over Northern Arabian Sea from 2003 to 2015

From these figures (figure 6.4 a & b) it can be clearly seen that the increasing trend of SST and the decreasing trend of phytoplankton biomass continued in the period from 2003 to 2015 as well. While the normalized SST anomaly increased at the rate of +0.45 /decade; the decrease in the chlorophyll-a concentration was more prominent with the normalized anomaly declining at the rate of -0.76/decade. The inverse relationship between SST and productivity was clearly seen, with the negative anomalies of SST during 2004 and 2005 correlating with positive anomalies of chlorophyll-a during the same period. Besides, the high positive anomaly of 2010 and 2015 can be correlated with low chlorophyll-a values of the same years.

6.4.3 Intra-annual variability of SST, Wind Speed and Phytoplankton biomass in Southern Arabian Sea

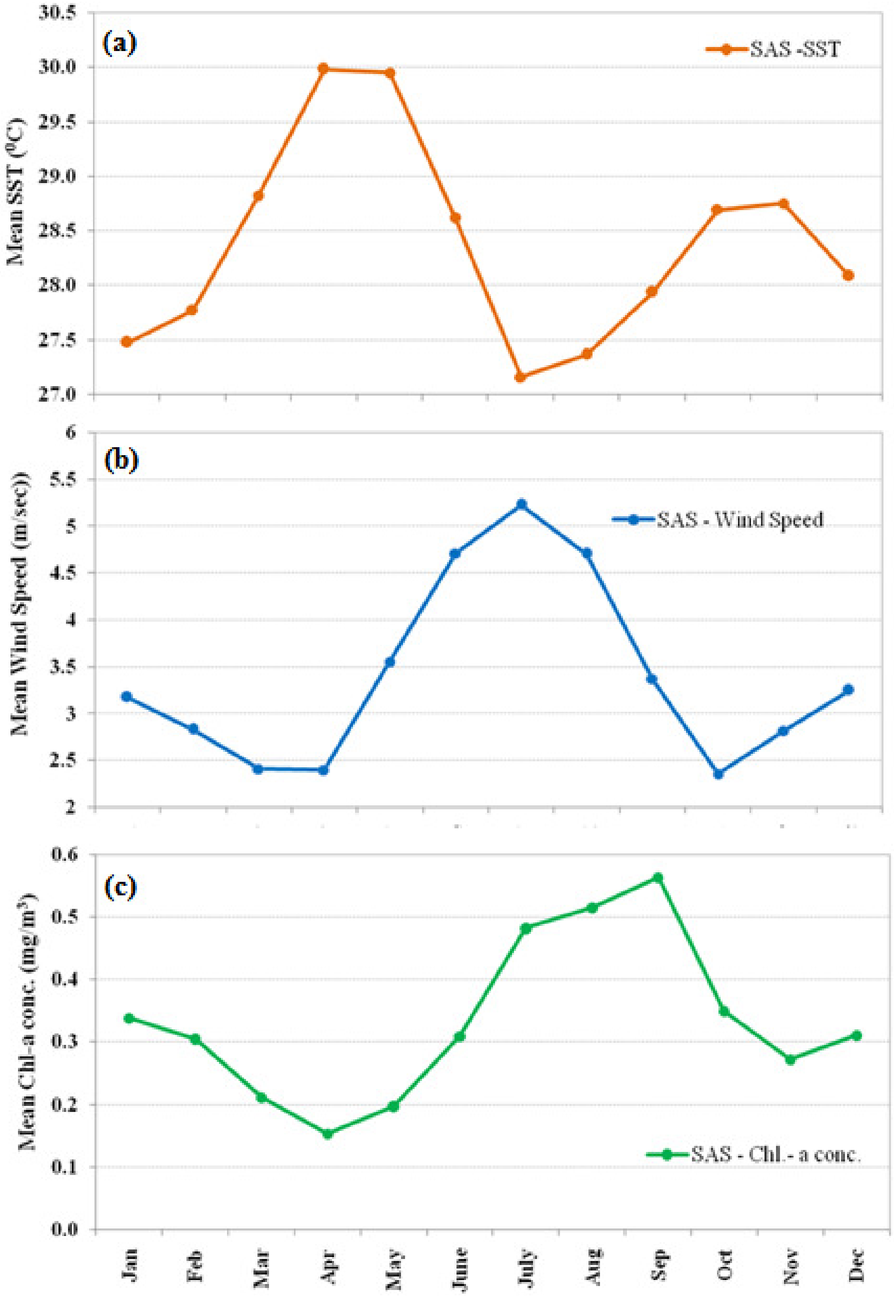

Fig. 6.5 (a-c): Intra-annual variability of (a) SST, (b) Wind speed, and (c) Chlorophyll-a concentration over Southern Arabian Sea from 1999 to 2009

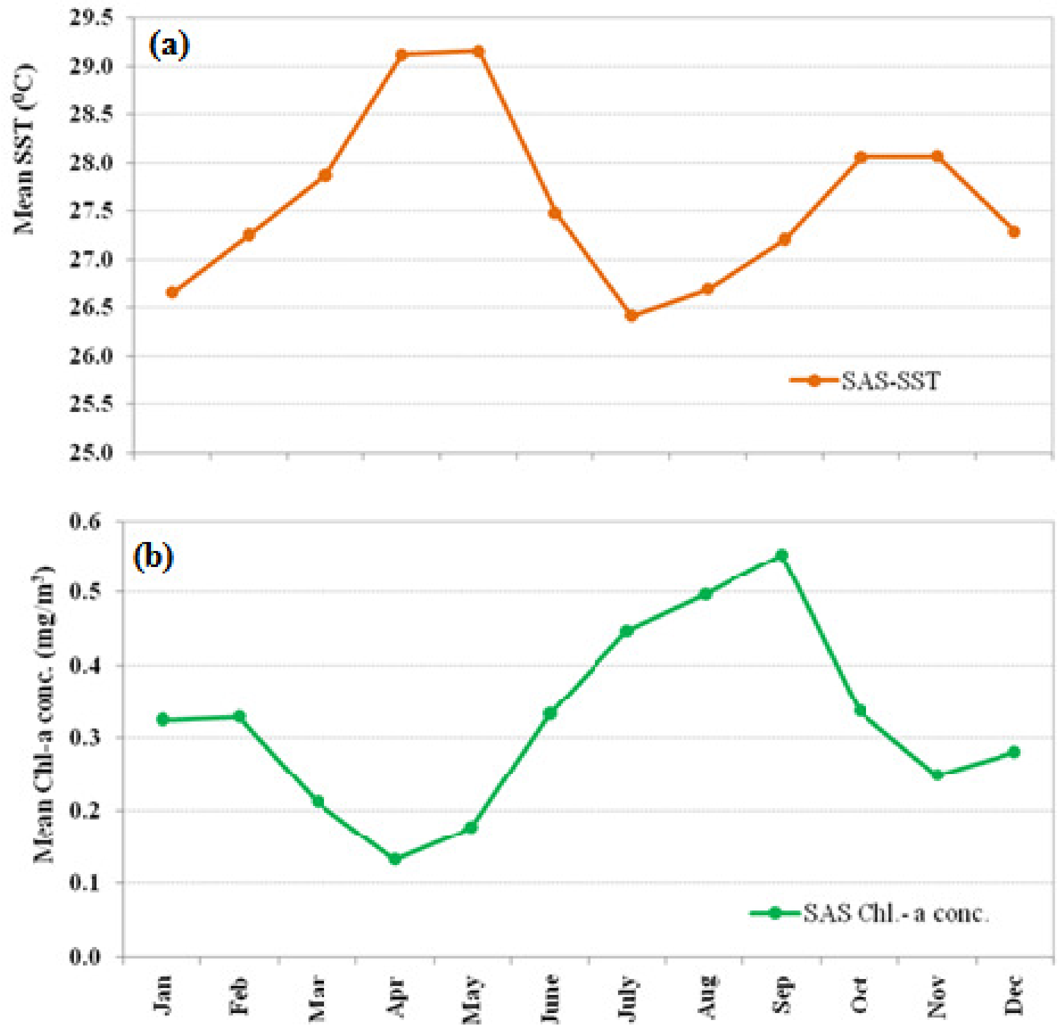

Fig. 6.6 (a-b): Intra-annual variability of (a) SST and (b) Chlorophyll-a concentration over Southern Arabian Sea from 2003 to 2015

In the Southern Arabian Sea, the intra- annual variability of SST, Wind Speed and phytoplankton biomass followed a similar pattern as the Arabian Sea basin which is shown in Fig. 6.5 and Fig. 6.6. The SST of the southern domain for the periods from 1999 to 2009 and 2003 to 2015, are shown in Fig. 6.5 (a) and Fig. 6.6 (a). It can be clearly seen that the SST exhibits a bimodal pattern with peak during SIM season (April –May) and the secondary peak during AIM season

(October –November), while the SWM season (June –September) is the period when the cooling occurs in the southern domain of the Arabian Sea.

From the Fig. 6.5 (b) it can be seen that the wind speed also follows a unimodal pattern with the maximum values during the SWM season (July) followed by NEM season. SIM and AIM seasons are the period when the wind over the Southern Arabian Sea are relatively calmer and slower.

Productivity wise, again the SWM season are the most favorable phase for phytoplankton to grow during both the study periods i.e. 1999 to 2009, as shown in Fig. 6.5 (c), and 2003 to 2015, as shown in Fig. 6.6 (c), with their biomass reaching the maximum values during the month of September. Although during the NEM season also the productivity increased, but its quantum was much lesser than those during the SWM season. SIM season was observed to be the least productive months for both the periods. It was noticed that the intra-annual variability of phytoplankton biomass in the Southern domain did not show any deviation with the shift in its peak values for the period 2003 to 2015 as what was observed for the Arabian Sea basin and the Northern domain.

6.4.4 Inter-annual variability of SST, Wind Speed and phytoplankton biomass in Southern Arabian Sea

Fig. 6.7 (a-c) shows the interannual variability of SST, Wind speed and phytoplankton biomass in Southern Arabian Sea for the period 1999-2009.

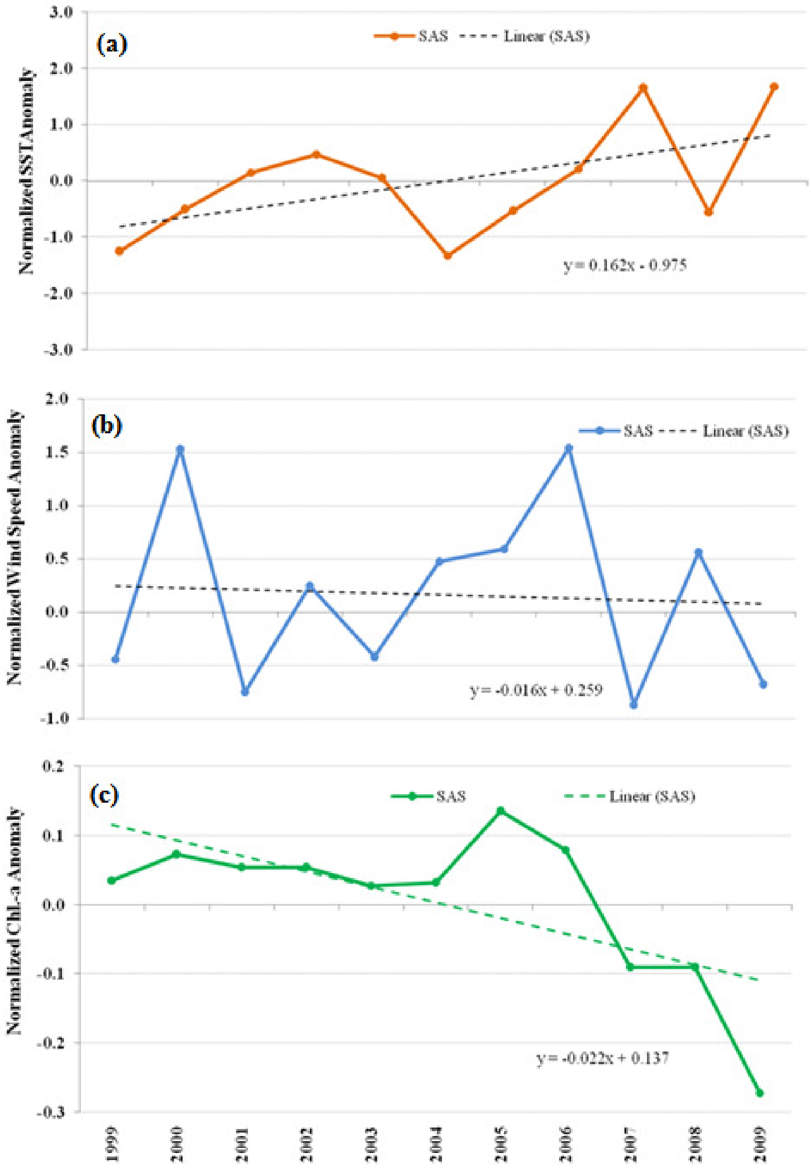

Fig. 6.7(a-c): Interannual variability of (a) SST, (b) Wind speed and (c) Chlorophyll-a concentration over Southern Arabian Sea during 1999 to 2009

As seen in Fig. 6.7 (a), there has been a rapid warming of the southern Arabian Sea in the decade from 1999 to 2009, with its anomalies increasing at the rate of +1.62 units /decade, which is a substantial increase. The SST anomalies increased from -1.26 in 1999 to +1.7 in 2009. Although, an episodic cooling event occurred during the year 2004, when the anomaly decreased to – 1.32, yet positive anomalies of the years 2001, 2002, 2003, 2006, 2007 and 2009 dominated the overall trend resulting in the warming of the southern domain. On the other hand, from the Fig. 6.7(b) it can be seen that the wind speed over the southern Arabian Sea is decreasing at the rate of -0.16 units / year.

However, the most prominent change that was observed was in the productivity pattern of the southern Arabian Sea in the period from 1999 to 2009, as shown in Fig. 6.7 (c). It was found that there has been a drastic decrease in the phytoplankton biomass over southern domain with the Chlorophyll-a concentration anomalies decreasing at the rate of - 0.22 units/ decade, from +0.03 in 1999 to -0.27 in 2009. More so, the decrease has been more rapid in the later part of the decade from 2005 to 2009. This may be attributed to the sharp rise in SST during the same period.

Figure 6.8 (a-b) shows the interannual variability of SST and phytoplankton biomass for the period from 2003 to 2015. From the Fig 6.7 (a) and 6.8 (a), it can be very much emphasized that the increasing trend of SST which was seen during 1999-2009 continued for the period 2003-2015, however the increase was not that prominent. During the period 1999-2009, the increase was at the rate of +1.62/decade which was reduced to +0.37/decade for the period 2003-2015.

On the contrary, the productivity of the southern domain decreased at a much faster rate during 2003-2015 in comparison to the duration 1999-2009. The Chlorophyll-a concentration anomalies decreased at the rate of -1.56/decade during 2003-2015, while the decrease that was observed during 1999 to 2009 was at the rate of -0.2/decade during 1999-2009. This may be attributed to the effect of any other physical variable like reduced wind speed or depleted oxygen level or reduction in nutrients that may have caused the decrease in phytoplankton biomass.

Fig. 6.8 (a-b): Interannual variability of (a) SST and (b) Chlorophyll-a concentration over Southern Arabian Sea from 2003 to 2015

6.4.5 Intra-annual variability of SST, Wind Speed and phytoplankton biomass in Eastern Arabian Sea

Similar to the southern sub-domain, the Eastern Arabian Sea also exhibited a bimodal pattern of SST, and phytoplankton biomass which can be seen in the Fig. 6.9 and Fig. 6.10, whereas the wind speed followed unimodal pattern for different months of an year, The SST of the Eastern sub-domain for the periods from 1999 to 2009 and 2003 to 2015, are shown in Fig. 6.9 (a) and 6.10 (a). It can be clearly seen that the SST exhibits a bimodal pattern with peak during SIM season (April –May) and the secondary peak during AIM season (October –November), while SWM season (June –September) and NEM season (December – March) are the period when the oceanic waters become relatively cooler.

From the Fig. 6.9 (b), it can be seen that the wind speed follows unimodal pattern but with the maximum values during the SWM season (July) followed by NEM season. SIM and AIM seasons are the period when the winds over the eastern Arabian Sea are relatively calmer.

With respect to the productivity pattern, the Eastern sub-domain of the Arabian Sea exhibits similarity with both Southern as well as Northern domains. Fig. 6.9 (c) shows that for the period 1999 - 2009, the productivity was higher during the SWM season, with September showing the maximum values for Chlorophyll-a concentration, ranging from 0.4 to 0.73 mg/m^3, which is comparable with those observed for the Southern sub-domain. Nevertheless, it was observed that for the period from 2003 to 2015, as shown in Fig. 6.10 (b), the peak values were observed during the NEM season, instead of the SWM season – a feature found similar in the Northern sub-domain, and the Arabian Sea basin for the same period.

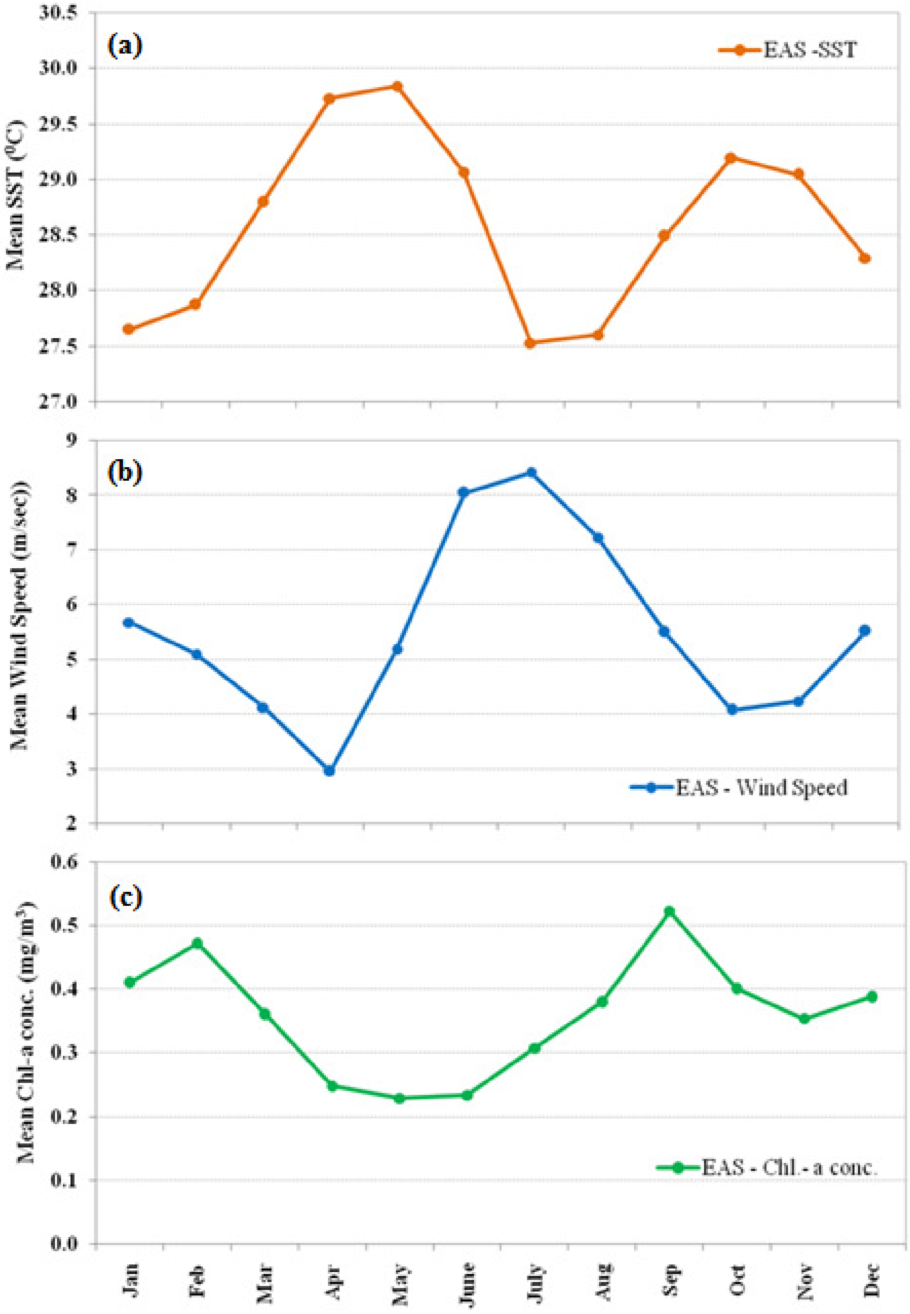

Fig 6.9 (a-c): Intra-annual variability of (a) SST, (b) Wind speed and (c) Chlorophyll-a concentration over Eastern Arabian Sea from 1999 to 2009

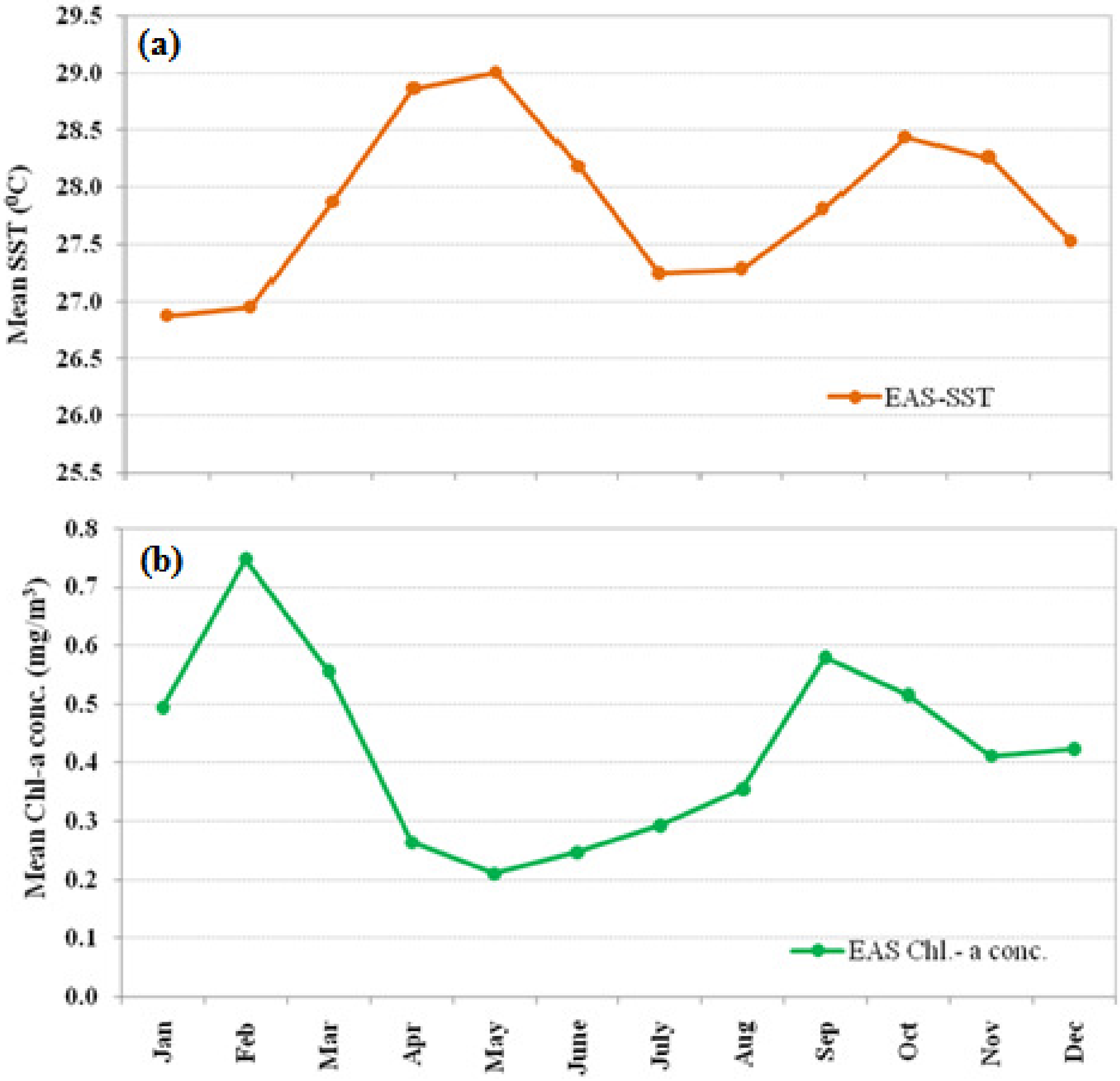

Fig. 6.10 (a-b): Intra-annual variability of (a) SST and (b) Chlorophyll-a concentration over Eastern Arabian Sea from 2003 to 2015

6.4.6 Inter-annual variability of SST, Wind Speed and phytoplankton biomass in Eastern Arabian Sea

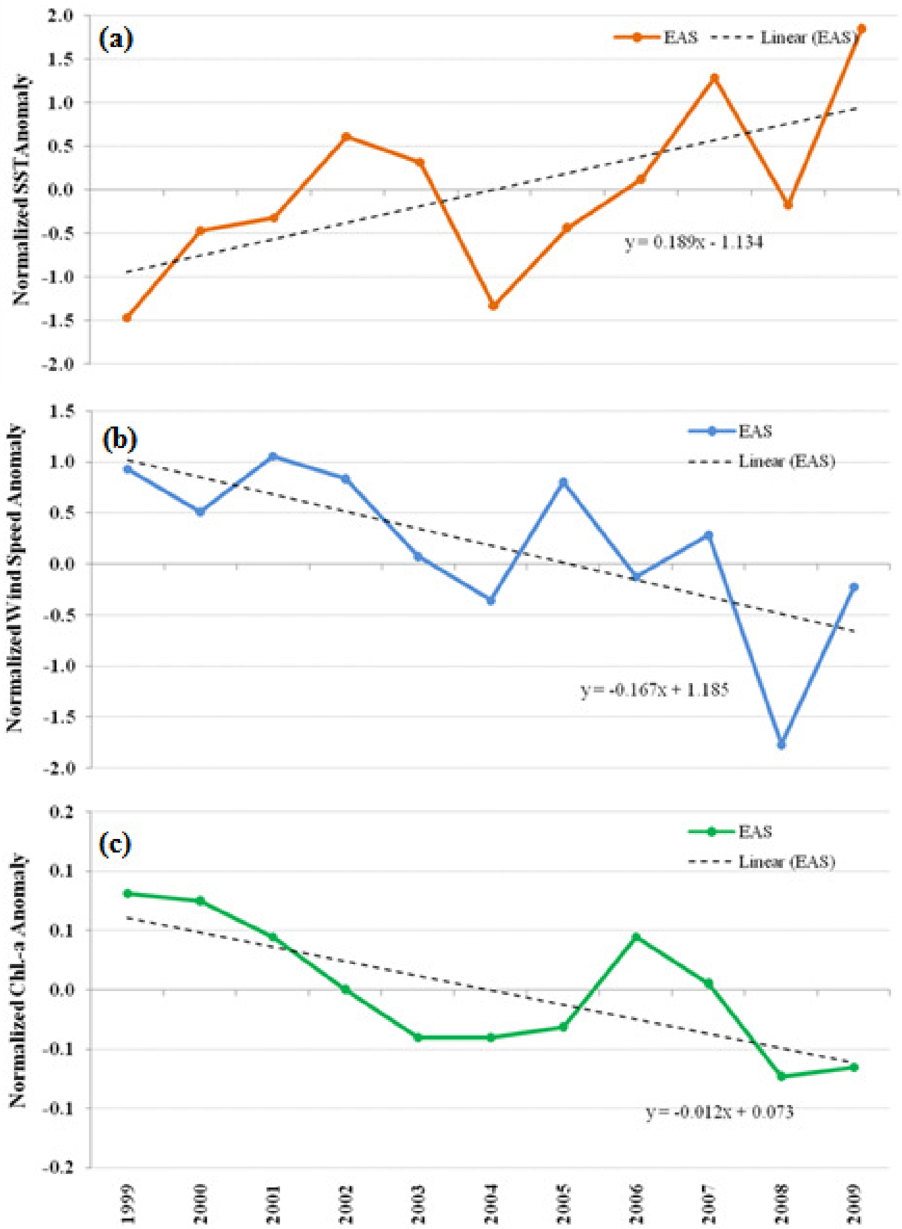

Fig. 6.11 (a-c): Interannual variability of (a) SST, (b) Wind speed and (c) Chlorophyll-a concentration over Eastern Arabian Sea from 1999 to 2009

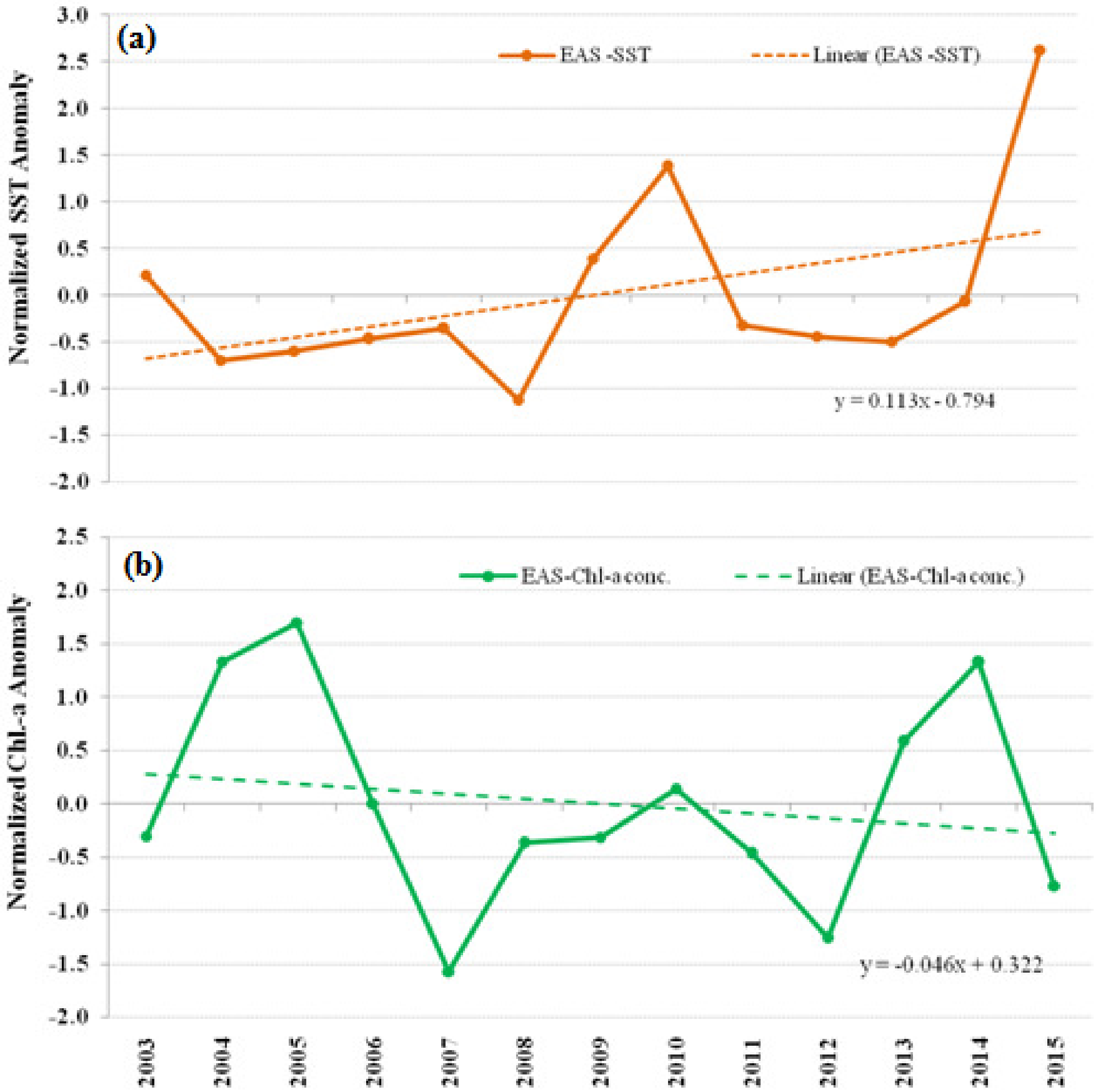

Fig. 6.12 (a-b): Interannual variability of (a) SST and (b) Chlorophyll-a concentration over Eastern Arabian Sea from 2003 to 2015

Like the previous two sub-domains, the interannual variability of SST, for both the periods from 1999 to 2009 and from 2003 to 2015 was found to have an increasing trend as shown in Fig. 6.11 (a) and Fig. 6.12 (a) respectively. During the decade 1999 to 2009, as seen in fig. 6.11 (a), the normalized SST anomaly increased at a very rapid rate of +1.9/decade, from -1.5 in 1999 to +1.84 in 2009. The warming of the Eastern sub-domain was equally high during the period from 2003 to 2015 (fig.6.12 a), with the SST anomaly increasing at the rate of +1.1/ decade. The year 2015 was exceptional with the positive anomaly reaching up to +2.5 units, as shown in Fig. 6.12 (b).

The decreasing wind speed that was observed for the Northern and Southern sub-domains was also noticed over the Eastern sub-domain of the Arabian Sea, as shown in Fig. 6.11 (b. It was found that the normalized anomaly of the wind speed over Eastern Arabian Sea, decreased at the rate of -1.6/ decade, from +0.93 in 1999 to -1.77 in 2008. Though, a slight increase in the value was noticed in 2009, but still the anomaly was -0.22, showing the negative deviation from the decadal mean.

With the rapid increase in SST and a considerable decrease in wind speed, it was expected that the phytoplankton biomass in the Eastern sub-domain should have also shown a rapid decrease, but it was not so. Though the Chlorophyll-a concentration values decreased during the decade from 1999 to 2009, yet the rate of decrease was not so significant. The normalized Chlorophyll-a concentration anomaly decreased from +0.08 in 1999 to -0.06 in 2009, showing the rate of decrease at -0.12/ decade, as shown in Fig. 6.11 (c). However, for the period from 2003 to 2015, a rapid decrease of in phytoplankton biomass was observed, with the chlorophyll-a anomaly decreasing at the rate of -0.46/ decade, as shown in Fig. 6.12 (b). This was an interesting observation as the Eastern sub-domain also encompasses the region with high productivity. Hence, in the recent years i.e. from 2003 to 2015, the rapid decrease in the phytoplankton biomass of this region is resulting in the dwindling of its high productive zones.

6.4.7 Intra-annual variability of SST, Wind Speed and Phytoplankton biomass in Western Arabian Sea

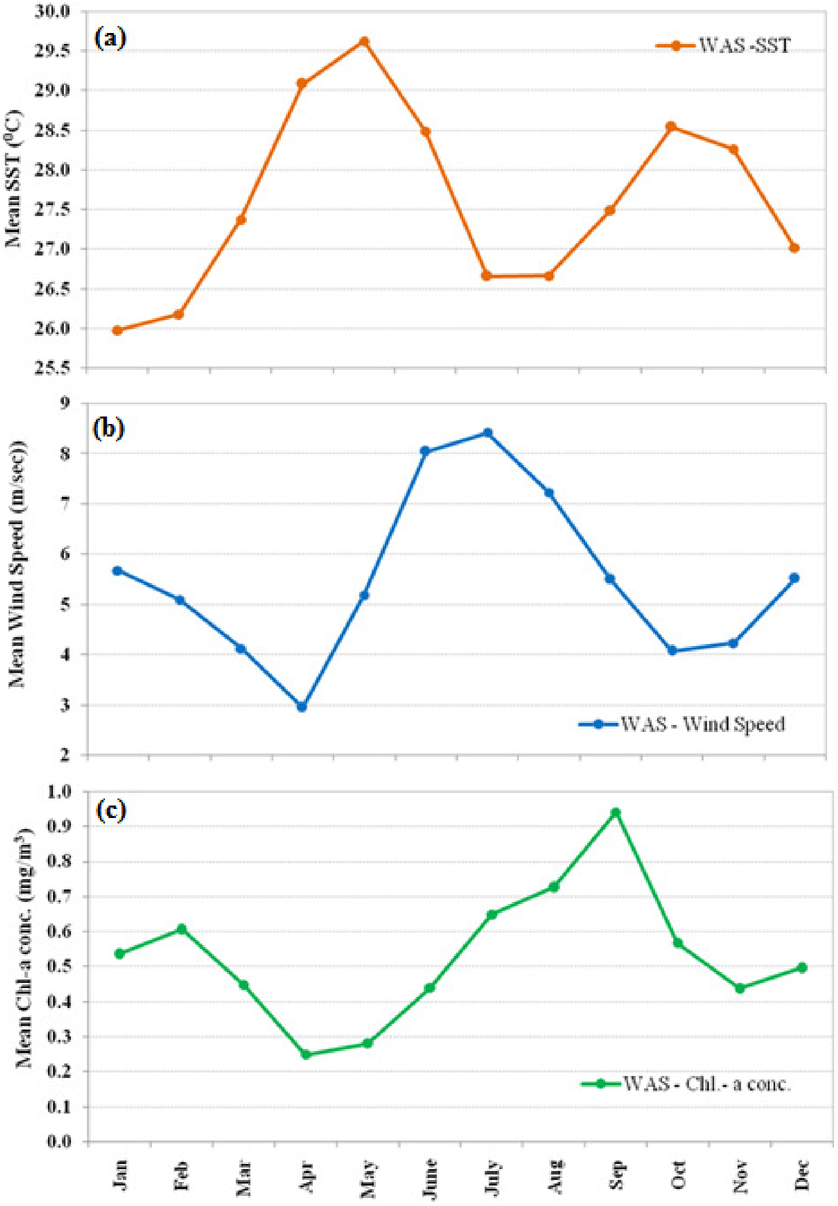

Fig. 6.13 (a-c): Intra-annual variability of (a) SST, (b) Wind speed and (c) Chlorophyll-a concentration over Western Arabian Sea from 1999 to 2009

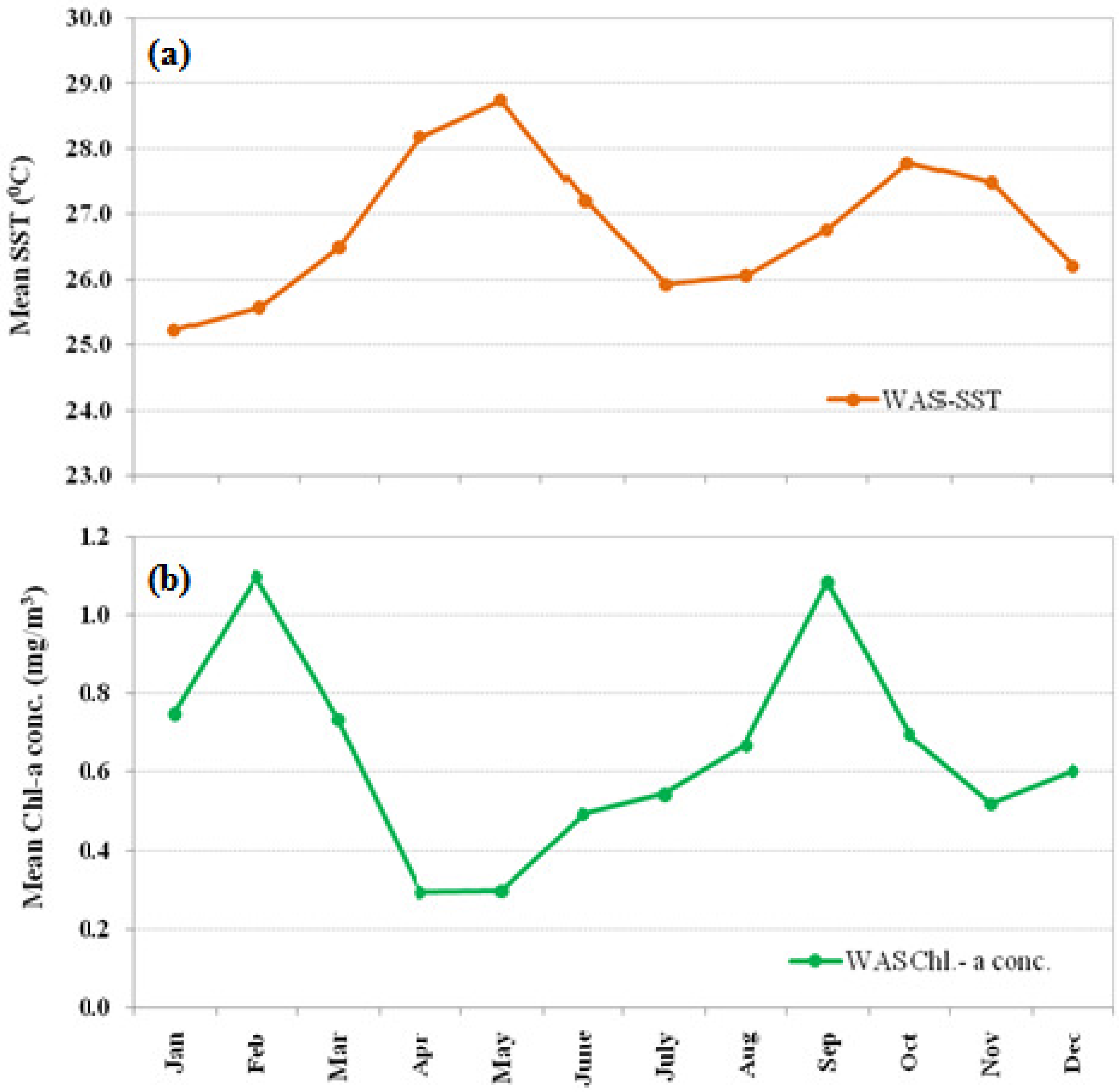

Fig. 6.14 (a-b): Intra-annual variability of (a) SST and (b) Chlorophyll-a concentration over Western Arabian Sea from 2003 to 2015

The Western Arabian Sea is again one of the most biologically significant domains with high productivity during the SWM and NEM seasons. The SST, and phytoplankton biomass in this domain also follows the characteristic bimodal pattern as exhibited in the rest of the domains

(Fig. 6.13 and 6.14), while the wind speed follows the typical unimodal pattern. The peak for SST occurs during the SIM season (April –May), with its the secondary peak during AIM season (October –November). However, unlike the other domains, the cooling during the NEM (December – March) season is more than those of the SWM season, (June –September) as shown in Fig. 6.13 (a). Besides, the entire domain was also observed to be comparatively cooler than the Arabian Sea basin.

The wind speed over the western domain was observed to be similar to the rest of the domains (Fig. 6.13 b), with the maximum values during the SWM season (July) and lowest during the SIM season (April).

Even the productivity pattern of the Western sub-domain for the period from 1999 to 2009 was similar to those observed in the Eastern, Southern and Northern domains, yet the magnitude was much higher than the rest. Of all the seasons, the productivity was observed to be higher during the SWM season, with September showing the maximum values for Chlorophyll-a concentration, ranging from 0.75 to 1.24 mg/m^3 (Fig. 6.13 c), while February was the month with the second peak. However, for the period from 2003 to 2015 (Fig. 6.14 b), the peaks during the SWM and NEM seasons were equal with Chlorophyll-a concentration values ranging from 0.7 to 1.7 mg/m^3 in February and from 0.77 to 1.5 mg/m^3 in September. This was a distinguishing feature observed for Western domain with high and almost equal productivity during both the monsoonal seasons.

6.4.8 Inter-annual variability of SST, Wind Speed and phytoplankton biomass in Western Arabian Sea

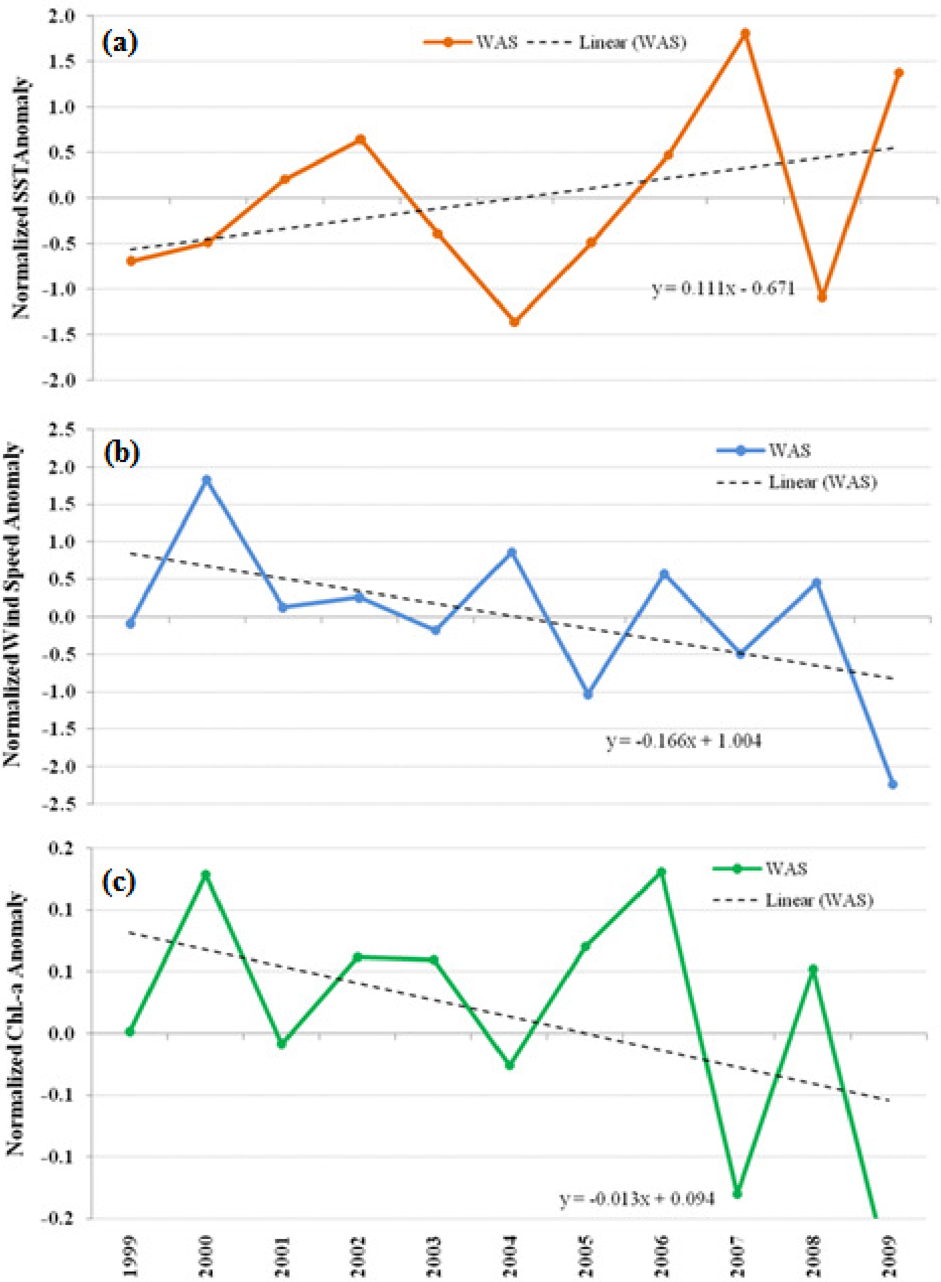

Fig. 6.15 (a-c): Interannual variability of (a) SST, (b) Wind speed and (c) Chlorophyll-a concentration over Western Arabian Sea from 1999 to 2009

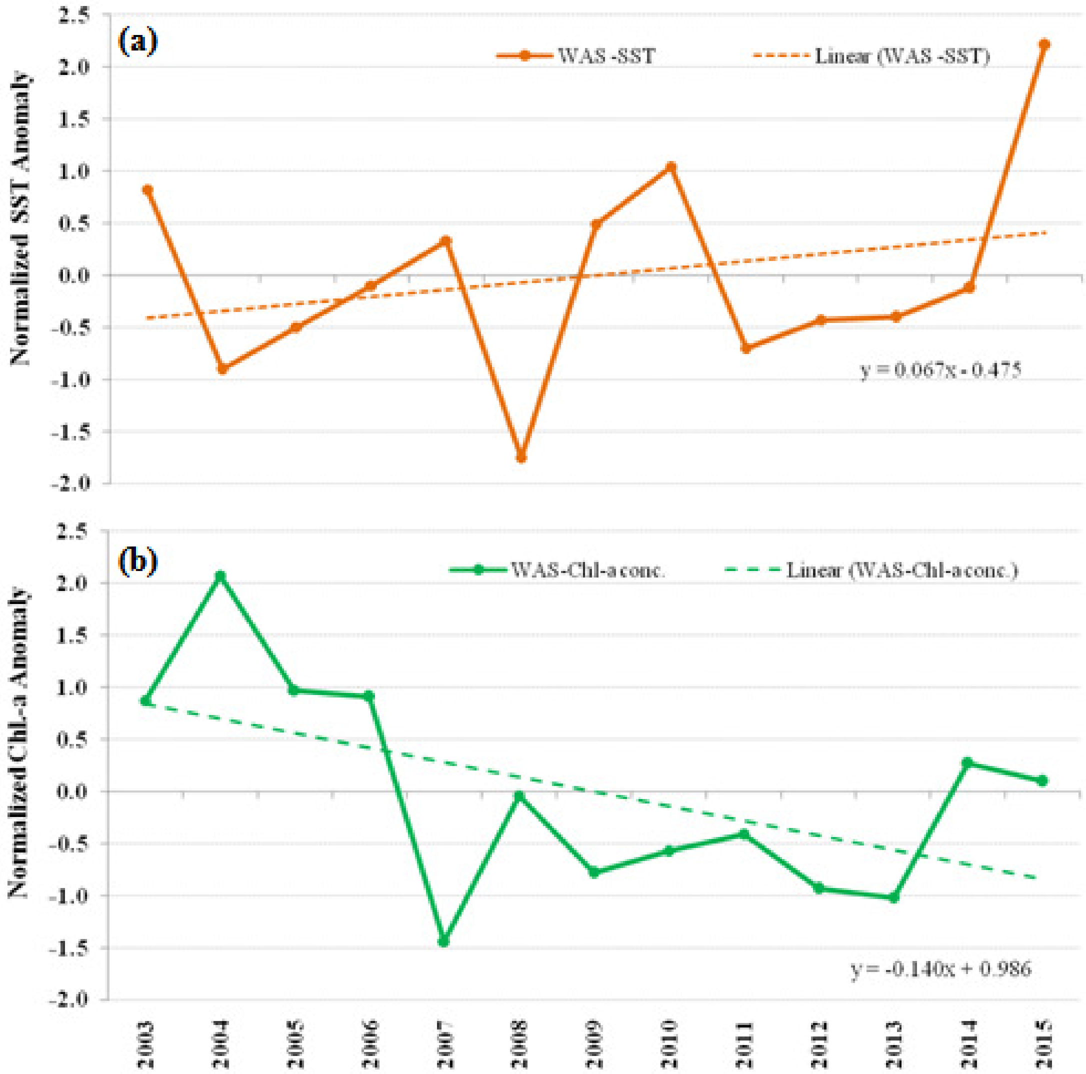

Fig. 6. 16 (a-b): Interannual variability of (a) SST and (b) Chlorophyll-a concentration over Western Arabian Sea from 2003 to 2015

In the Western sub-domain of the Arabian Sea, once again the impact of climate change with rapid warming of the oceanic water was observed for the periods from 1999 to 2009 as well as from 2003 to 2015 as shown in Fig. 6.15 (a) & Fig. 6.16 (a) respectively. The normalized SST anomaly for the decade from 1999 to 2009 increased at the rate of +1.1 /decade from -0.69 in

1999 to +1.38 in 2009. Even for the period from 2003 to 2015, the increase in the SST anomaly was substantial with the rise at the rate of + 0.67/decade. This increase in the SST was noteworthy as it was happening in one of the most biologically productive areas of the Arabian Sea.

The Western domain, off the coast of Somalia, is known for its upwelling areas. Hence, wind plays a major role in making this area productive. However, the inter annual variability of wind speed during the 1999 to 2009 showed a considerable decrease over this domain, as shown in Fig. 6.15 (b). It was found that the wind speed decreased substantially on an annual scale, with wind speed normalized anomaly decreasing at a high rate of -1.6/ decade (from -0.08 in 1999 to +2.2 in 2009).

The productivity of the Western sub-domain was observed to be decreasing at a considerable rate during both the study periods with a much higher and rapid diminishing of the phytoplankton biomass in recent years. During 1999 to 2009, the rate of decrease of the normalized chlorophyll-a anomaly was -0.13/decade, as shown in Fig. 6.15 (c), which further decreased during 2003 to 2015 to -1.4/decade, as shown in Fig. 6.16 (b). This poses a serious challenge as the rate at which the phytoplankton biomass is diminishing, would ultimately hamper the productivity of this zone, turning it to be another oceanic desert in the making.

6.4.9 Intra-annual variability of SST, Wind Speed and Phytoplankton biomass in Arabian Sea Basin

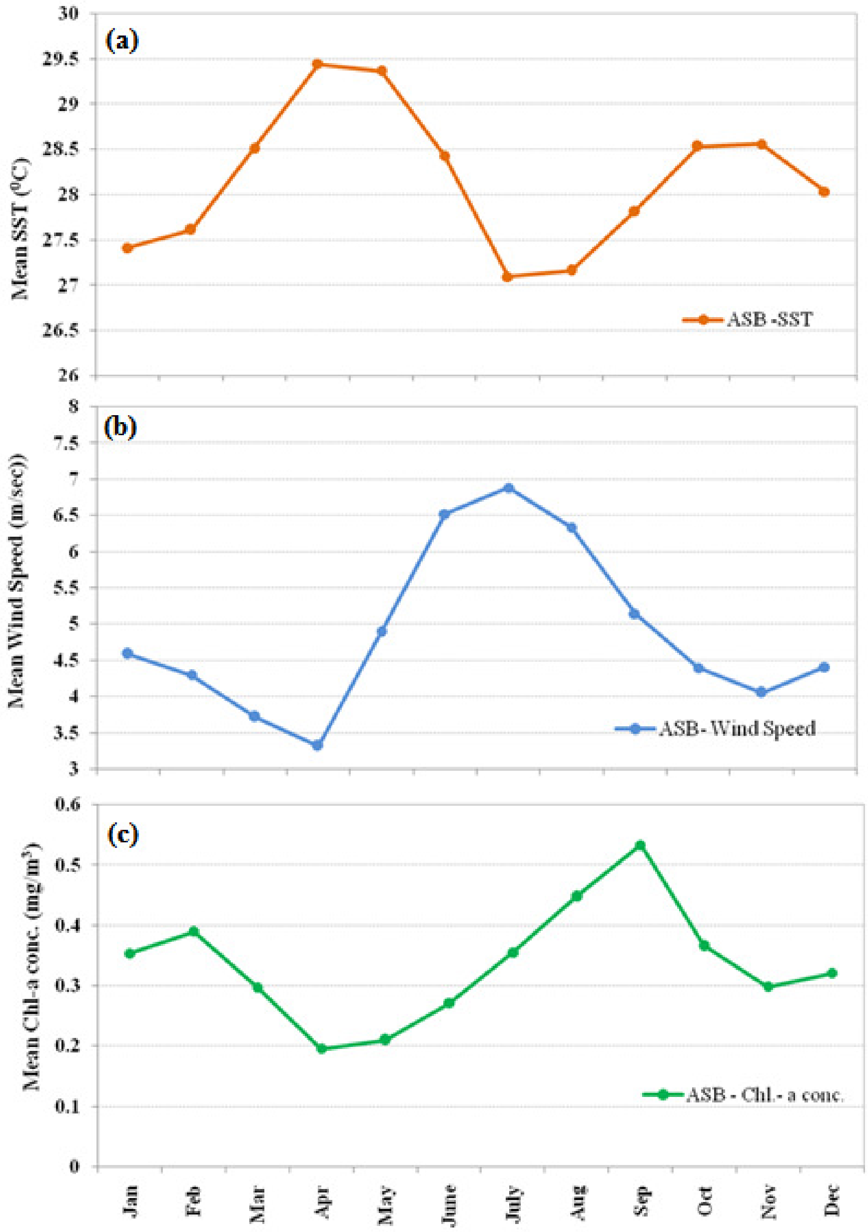

Fig. 6.17 (a-c): Intra-annual variability of (a) SST, (b)Wind speed and (c) Chlorophyll-a concentration over Arabian Sea from 1999 to 2009

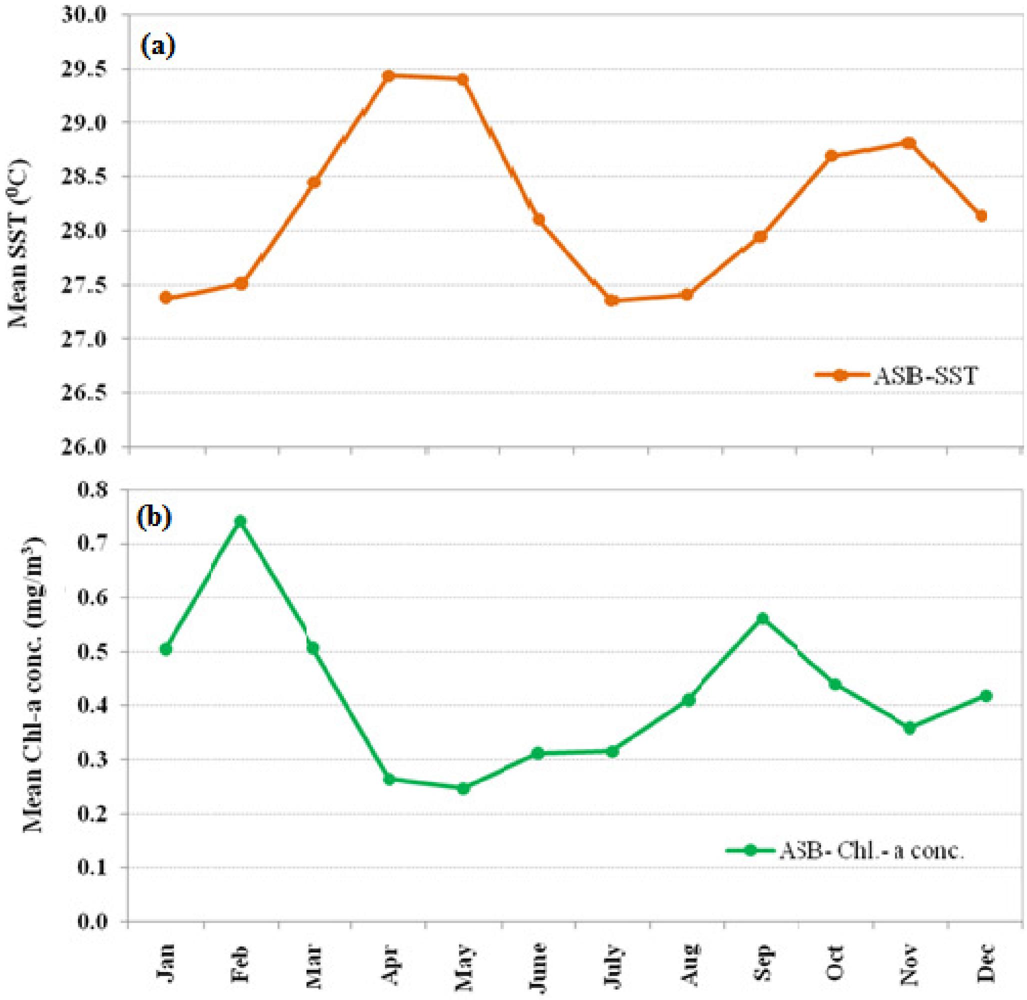

Fig. 6.18 (a-b): Intra-annual variability of (a) SST and (b) Chlorophyll-a concentration over Arabian Sea from 2003 to 2015

Most of the studies done in the Arabian Sea, either generalizes the feature of the basin to all its sub- domains, or else, even if domain wise analysis is also done, it is limited to either one or two sub-domains and lastly the domain specific scenarios are not compared with the basin wide scenario. The Arabian Sea basin, similar to its other sub-domains, also exhibits bimodal variation of SST and Phytoplankton biomass and a unimodal pattern of wind speed as shown in Fig. 6.17 and 6.18.

While the SST showed peak during SIM season, as shown in Fig. 6.17 (a) & Fig 6.18 (b), the wind speed was the highest during the SWM season, as shown in Fig. 6.17 (b). This pattern was found during both the study periods. However, the phytoplankton biomass of the Arabian Sea for the period 2003 to 2015 exhibited a marked departure from the pattern observed from 1999 to 2009, as shown in Fig. 6.17 (c) & Fig. 6.18 (b). Similar to the observation made for the Northern and Eastern sub-domains, the phytoplankton showed their maximum growth during the NEM season instead of the usual SWM season, with February turning out to the most productive month. The climatological average chlorophyll-a concentration for February month was found to be 0.74 mg/m^3 while that of September was 0.56 mg/m^3.

The year wise analysis of chlorophyll-a concentration (Refer Chapter 5) reveled that it was post 2010 that the shift in peak occurred making it one of the most prominent impact of climate change in recent years in the Arabian Sea. It may be inferred that due to the rise in SST specially during the SWM season, the microflora of the oceans are experiencing tremendous physiological pressure and hence to adapt to the new circumstances might be getting shifted either in their phenological aspect or there may be an altogether change in the species composition. This would be an interesting future scope of work.

6.4.10 Inter-annual variability of SST, Wind Speed and phytoplankton biomass in Arabian Sea Basin

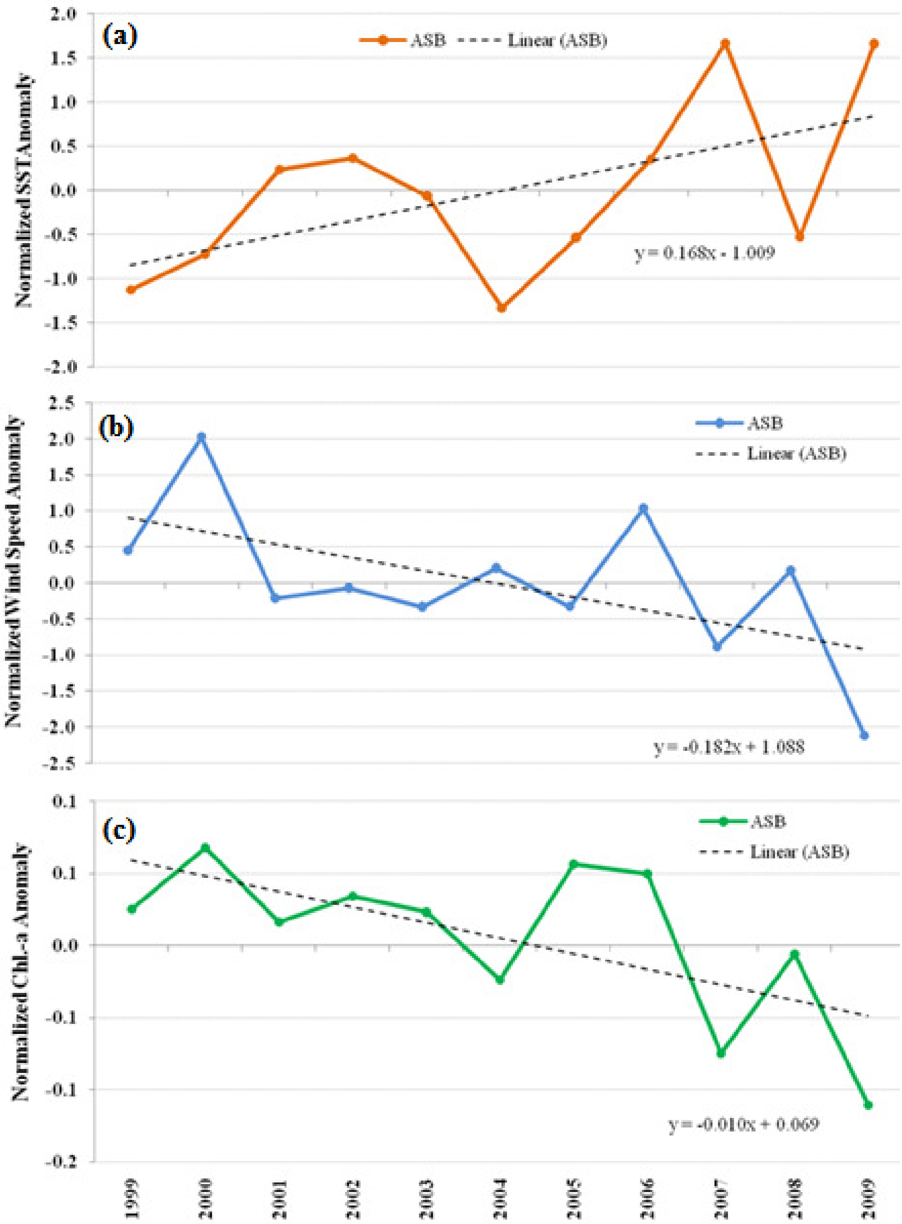

Fig. 6.19 (a-c): Interannual variability of (a) SST, (b) Wind speed and (c) Chlorophyll-a concentration over Arabian Sea from 1999 to 2009

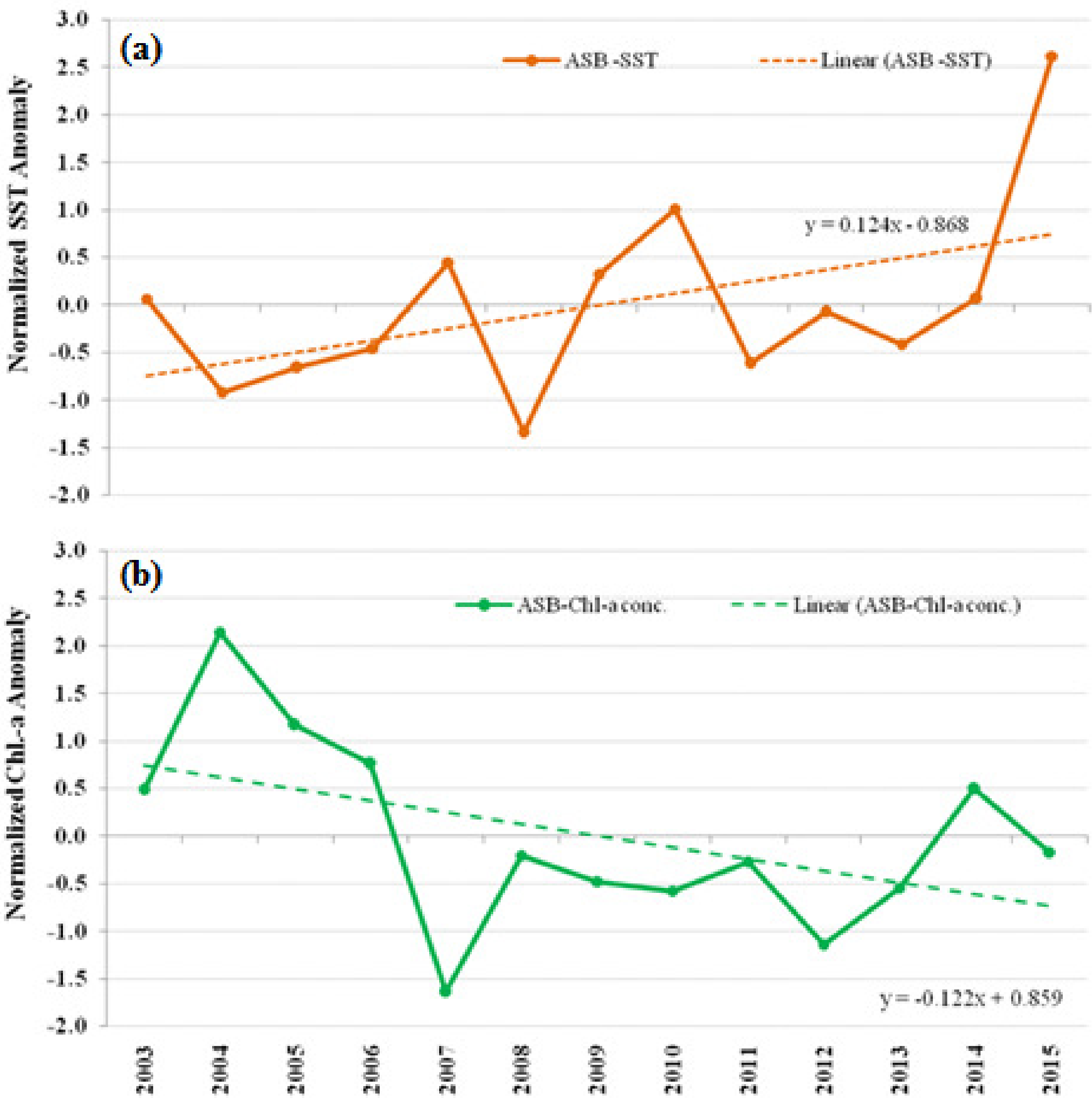

Fig. 6.20 (a-b): Interannual variability of (a) SST and (b) Chlorophyll-a concentration over Arabian Sea from 2003 to 2015

Basin wide analysis of SST revealed that the trend of warming observed in its different sub-domains remains applicable for the basin as well. While during 1999 to 2009, the normalized SST anomaly increased at the rate of +1.68 /decade, the rate of increase was +1.24 for the period from 2003 to 2015, as shown in Fig. 6.19 (a) & Fig. 6.20 (a). This reveals that a rapid warming of the Arabian Sea has been happening in the recent past which could be the impact of global warming. Though the study period is short of the 30 year requirement for a conclusive remark on effect of climate change, but as we have already seen in the ERSST analysis (Chapter 3), That there has been an unprecedented warming of the Arabian Sea in the last 65 years from 1950 to 2015, which also encompasses the current period of study from 1999 to 2009 and 2003 and 2015, it can be said that the warming in these last 13 years is the impact of global warming and this warming of the Sea will be detrimental for the productivity of the Arabian Sea as SST is the driving force with which different physical and biological processes are associated.

The wind speed over the Arabian Sea has also decreased significantly during 1999 to 2009, as shown in Fig. 6.19 (b). The rate of decrease of wind speed anomaly was much higher (-1.82/decade) than any of the other four domains analyzed in the present study.

The phytoplankton biomass in the Arabian Sea basin was also found to be decreasing steadily in both the periods. During 1999 to 2009, the normalized anomaly of chlorophyll-a concentration decreased at the rate of -0.1/decade, as shown in Fig. 6.19 (c), the rate of decrease during 2003 to 2015 was much higher at -1.22/decade, as shown in Fig. 6.20 (b). This reveals that in recent past there has been a higher rate of decrease in the productivity as compared to the previous decade. Linking it with higher warming and decreasing wind speed, it can be clearly said that the Arabian Sea is surely showing up the signatures of the regional impact of climate change and global warming.

6.4.11 Monthly variability of SST, Wind Speed and phytoplankton biomass in Arabian Sea Basin

To further investigate whether the impact of climate change with rising SST and diminishing productivity was confined to annual scale or was spread across the months of the years, the normalized anomalies for each month from January to December for the periods from 1999 to 2009 and from 2003 to 2015 were computed. From Fig. 6.21, it can be clearly seen that there has been an increase in the SST for all the months of the years from 1999 to 2009. On the other hand, the abundance of phytoplankton diminished substantially during the same period, as seen from the decreasing trend of the monthly anomalies of chlorophyll-a concentration. Besides, the inverse relationship between SST and phytoplankton biomass is also seen. The rise in SST during 2002 – 2003, 2007 and 2009 hampered the growth of the phytoplankton, which is evident from the negative anomalies of chlorophyll-a concentration during the same period. Besides, the cooling events during 1999, 2000, 2004 and 2006 promoted the growth of the phytoplankton resulting in higher positive anomalies of chlorophyll-a concentration.

The effect of wind in facilitating the growth of the phytoplankton can be seen from Fig. 6.22. The increase in the monthly wind speed during 1999, 2000, 2004, 2006 and 2008, resulted in the increase in phytoplankton biomass. However, this increase was not a direct relation but had an effect of a lag phase, where the effect of increasing wind speed on increasing phytoplankton biomass could be seen with a lag phase of one-two months. On an annual scale from 1999 to 2009, there has been a decreasing trend of monthly wind speed, which in combination with the rise in SST (Fig. 6.23) is the reason for diminishing phytoplankton biomass and productivity of the Arabian Sea.

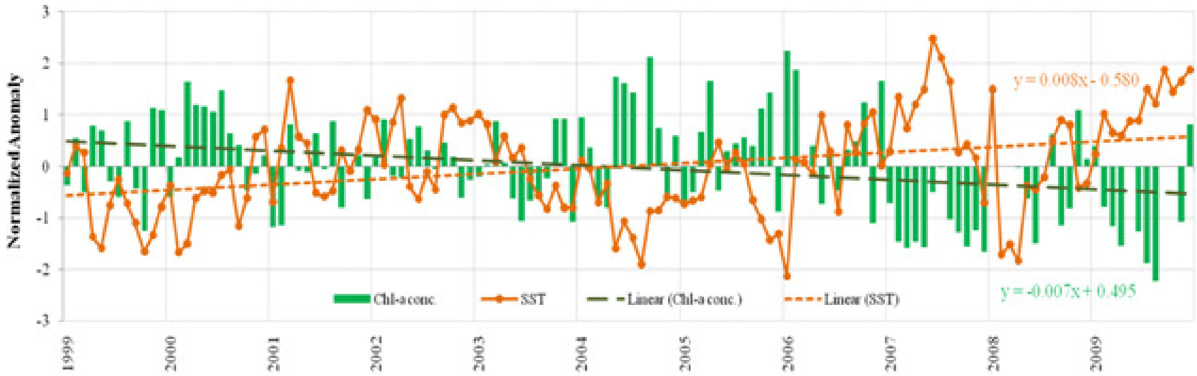

Fig. 6.21: Monthly variability of SST and Chlorophyll-a concentration over Arabian Sea from 1999 to 2009

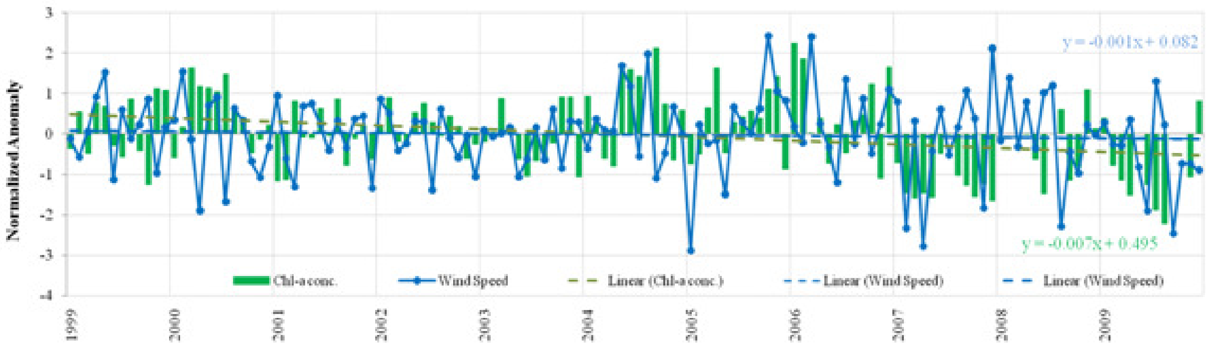

Fig. 6.22: Monthly variability of Wind Speed and Chlorophyll-a concentration over Arabian Sea from 1999 to 2009

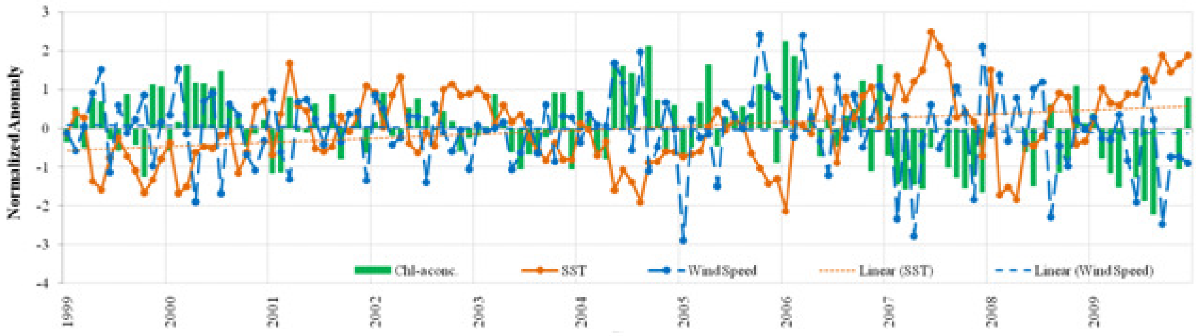

Fig. 6.23: Monthly variability of SST, Wind Speed and Chlorophyll-a concentration over Arabian Sea from 1999 to 2009

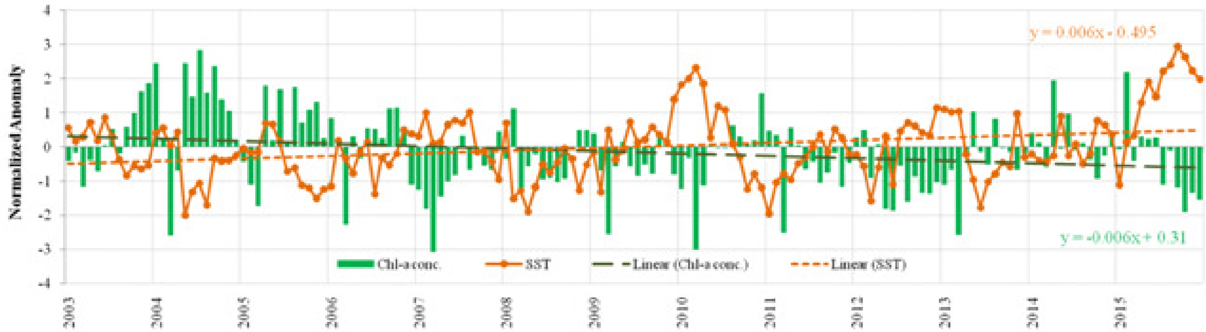

Fig. 6.24: Monthly variability of SST and Chlorophyll-a over Arabian Sea from 2003 to 2015

The monthly SST and chlorophyll-a anomalies for the period from 2003 to 2015 were also analyzed to observe the relation between the two in the recent years. As shown in Fig. 6.24, there has been a rapid warming of the Arabian Sea in recent past which is evident from the strong positive anomalies of SST. More so, from 2013 to 2015, the rise has been sharper with SST anomalies increasing from -2.0 in 2013 to almost +3.0 in 2015. This increase in the SST anomaly by 5 units is massive a rise and that took over a very short period of time of 2 years only. On the other hand, the phytoplankton biomass of the Arabian Sea was found to be diminishing across the months from 2003 to 2015. This decrease is all the more alarming as since the year 2006, almost for all months, the chlorophyll-a anomalies were negative. This makes it more than evident, that the phytoplankton biomasses of the Arabian Sea are diminishing rapidly and this decrease has happened at a faster rate in recent past.

6.4.12 Interannual variability of SST and Phytoplankton biomass in the Eastern and Western Gulfs and the Red Sea

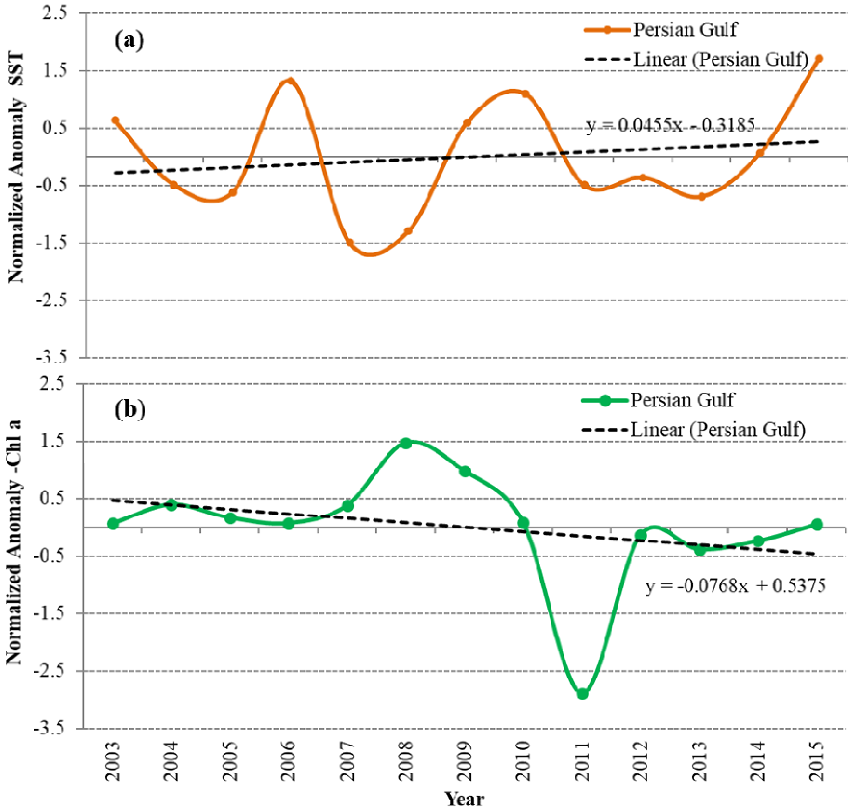

Fig. 6.25 (a-b): Interannual variability of (a) SST and (b) Chlorophyll-a over Persian Gulf from 2003 to 2015

Amongst the gulfs of the Arabian Sea, the Persian Gulf has an altogether different hydrographic features and has been a zone of high productivity, However, as can be seen from fig. 6.25 (a) and (b), there has been warming of the Gulf which was noted to be at the rate of +0.45/decade and the phytoplankton biomass was observed to be decreasing in recent past at a very high rate of -0.7/decade). However, as they have a different oceanographic feature, there is no linear direct relationship between the rise in SST and the decrease in phytoplankton biomass.

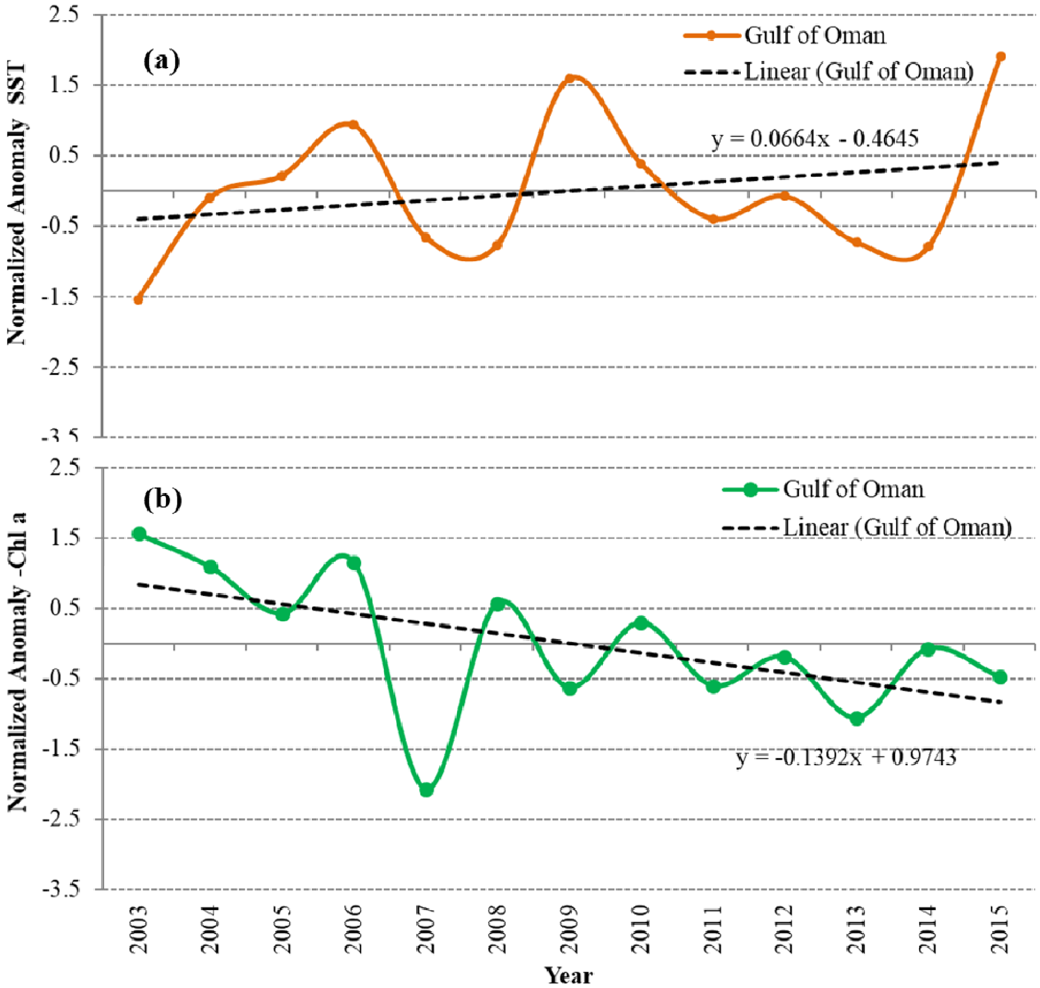

Fig. 6.26 (a-b): Interannual variability of (a) SST and (b) Chlorophyll-a over Gulf of Oman from 2003 to 2015

Similar to the Persian Gulf, its adjoining water body, i.e. the Gulf of Oman also experienced a sharp increase in its SST from 2003 to 2015. The warming of this comparatively smaller water body occurred at a higher rate with SST normalized anomaly increasing at the rate of 0.66/decade as shown in fig.6.26 (a). However, the reduction in chlorophyll-a concentration at the rate of -1.39/decade across the years was worth noticing (fig.6.26 b), as Gulf of Oman is also known to be a high productive zone of the Arabian Sea.

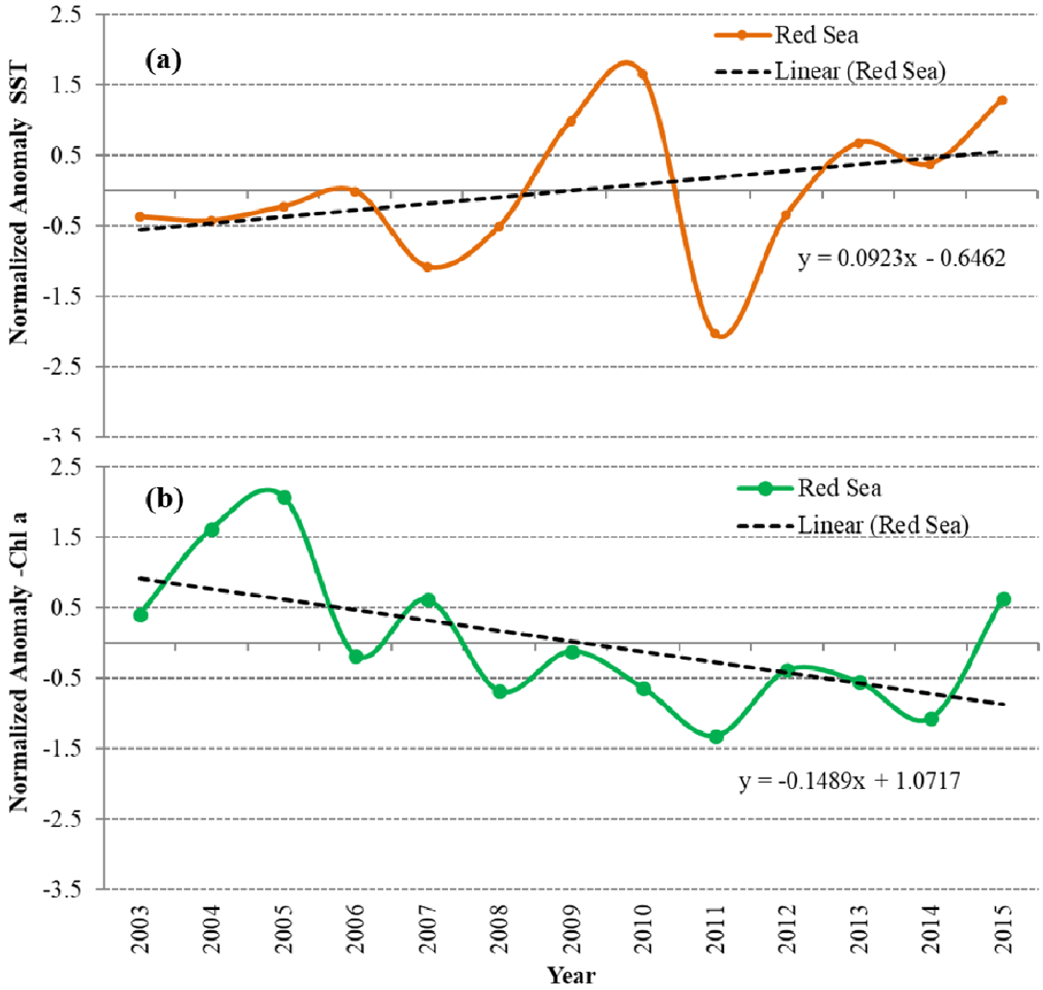

Fig. 6.27 (a-b): Interannual variability of (a) SST and (b) Chlorophyll-a over Red Sea from 2003 to 2015

Red Sea is one of the marginalized seas of the Arabian Sea. As it is land-locked from the three sides, it has unique oceanographic features. As seen in fig.6.27 (a-b), during the period from 2003 to 2015, the SST of the Red Sea increased at an alarming rate with its normalized anomaly increasing at the rate of 0.92/decade. On the other hand, the chlorophyll-a concentration also decreased at a comparatively very high rate with its anomaly decreasing at the rate of -1.49/decade.

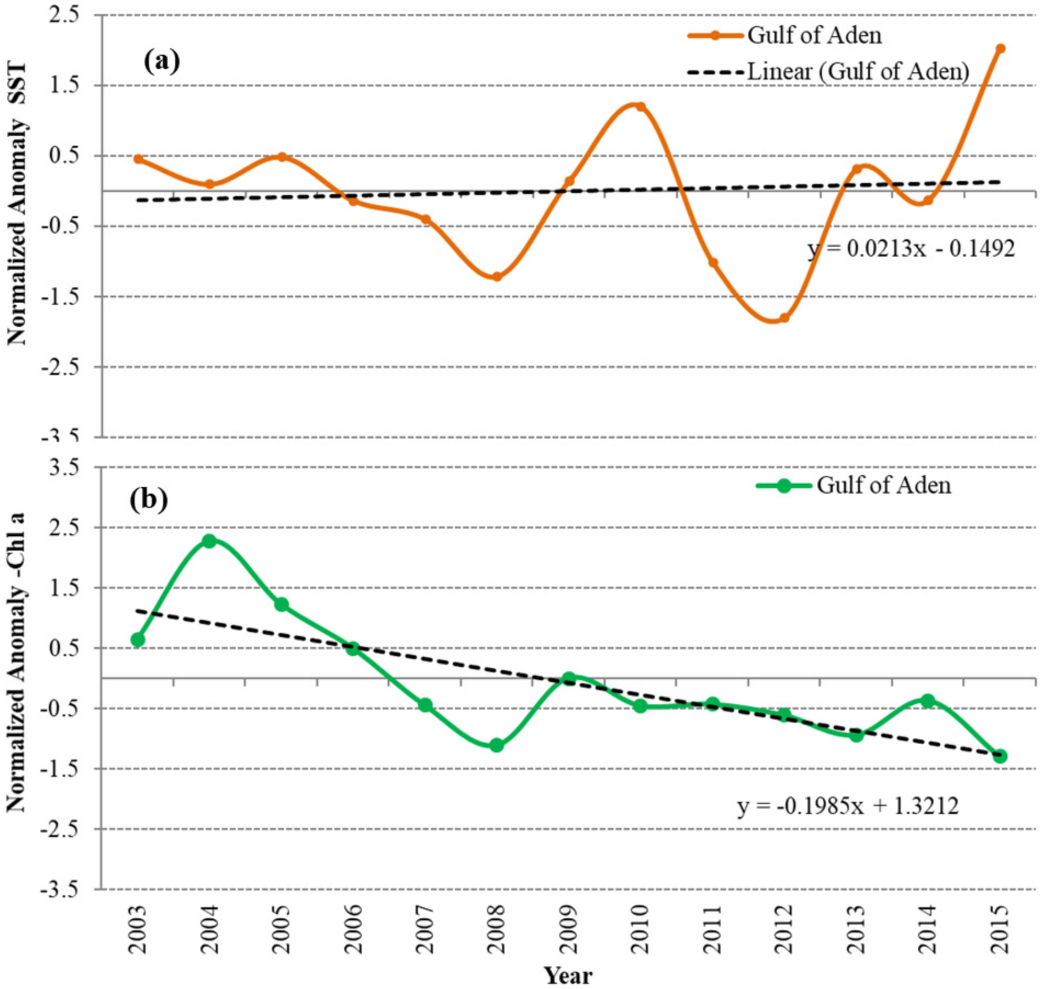

Fig. 6.28 (a-b): Interannual variability of (a) SST and (b) Chlorophyll-a over Gulf of Aden from 2003 to 2015

Gulf of Aden is the water body connecting the Arabian Sea with the Red Sea and is known to be a region of high productivity. As seen in fig. 6.28 (a), the SST in this Gulf did increase during the period 2003 to 2015, but no clear trend was observed. However, the phytoplankton biomass during the same period reduced at an alarming rate with chlorophyll-a normalized anomaly decreasing at the rate of -1.98/decade.

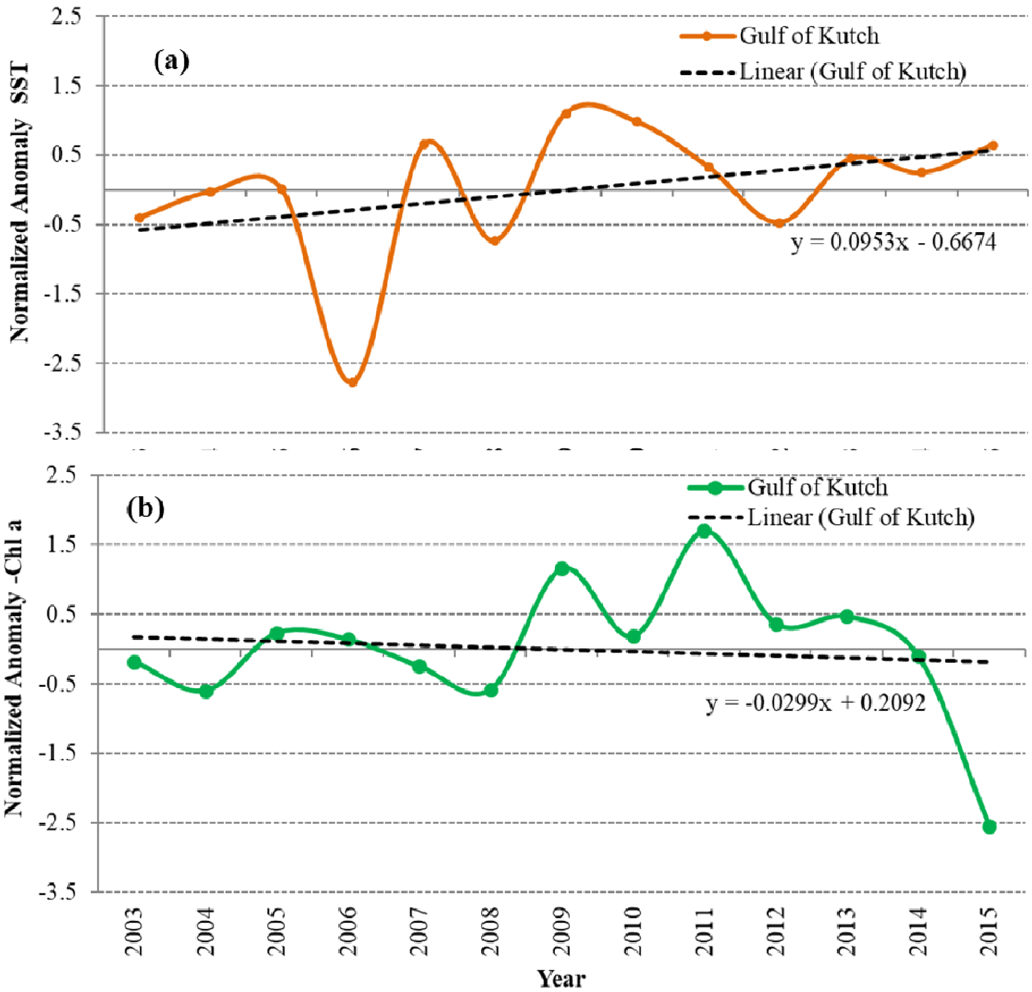

Fig. 6.29 (a-b): Interannual variability of (a) SST and (b) Chlorophyll-a over Gulf of Kutch from 2003 to 2015

Amongst the eastern gulfs of the Arabian Sea, it was observed that in the Gulf of Kutch, the rise in SST was sharp (fig.6.29 a) with SST anomaly increasing at the rate of +0.9/decade. However, the phytoplankton biomass did not show equal or matching decrease (fig. 6.29 b). Instead, the normalized anomaly of chlorophyll-a concentration decreased at a very miniscule rate. It was also noticed that in the year 2015, chlorophyll-a concentration was the lowest with normalized anomaly reaching up to -2.5.

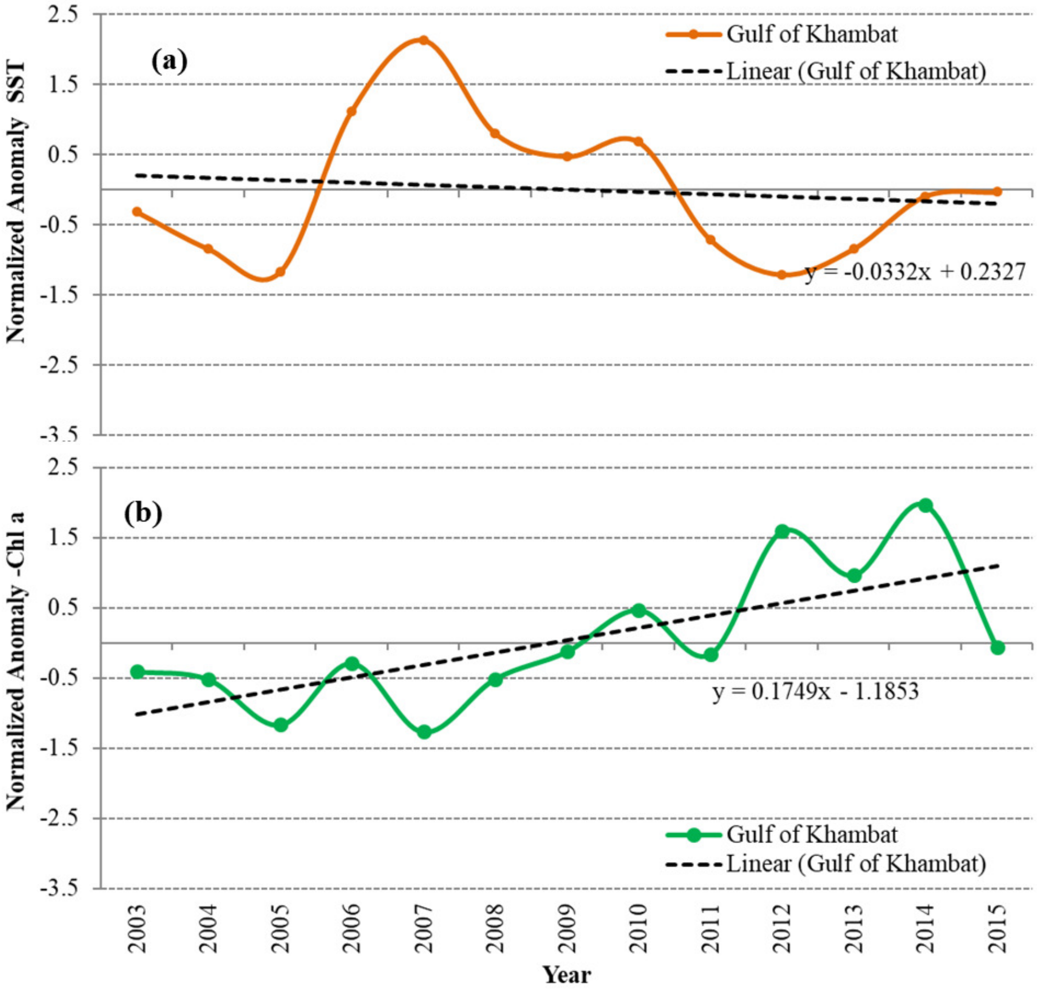

Fig. 6.30 (a-b): Interannual variability of (a) SST and (b) Chlorophyll-a over Gulf of Khambat from 2003 to 2015

An interesting feature was observed in the Gulf of Khambat (fig.6.30 a and b), where the chlorophyll-a concentration was found to increase from 2003 to 2015 and this increase was quite sharp with chlorophyll-a normalized anomaly increasing at the rate of +1.7/decade. It was also unique amongst all the rest of the sub-domains, as though SST in this Gulf did increase but there was no clear trend.

6.4.13 Statistical Analysis of the Correlation between SST, Wind Speed and Phytoplankton Biomass

To understand the impact the impact of the climate change with rising SST and diminishing wind speed on the biological productivity of the Arabian Sea, a correlation analysis was done between SST, wind speed and chlorophyll-a using the statistical software tool MINITAB 14.1.

(a) Correlation between SST and Phytoplankton Biomass

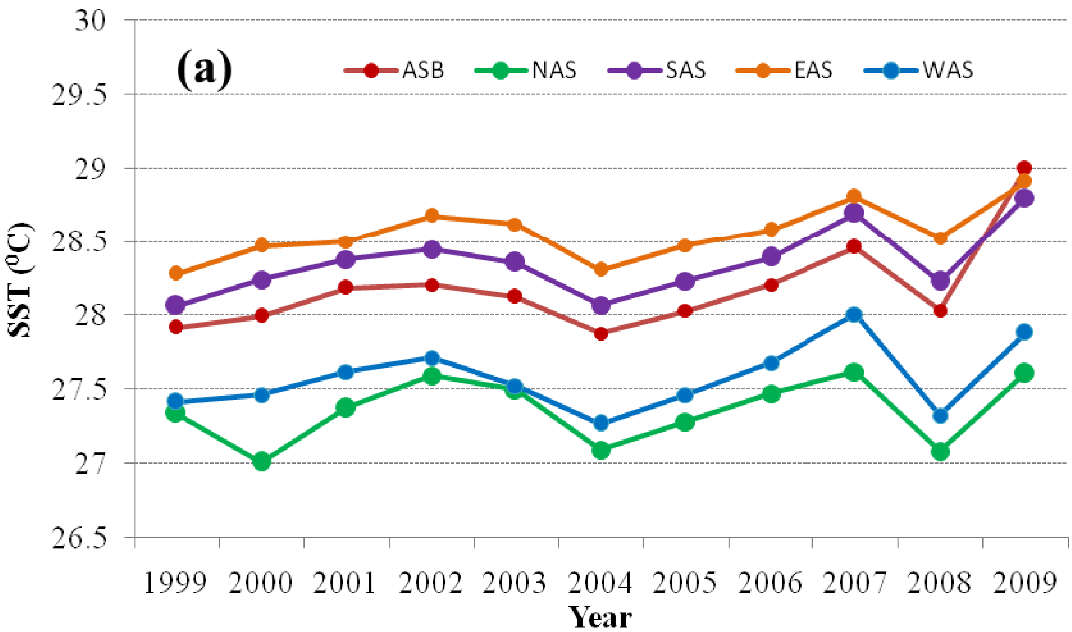

Fig. 6.31 (a): Interannual variability of SST in different domains of the Arabian Sea

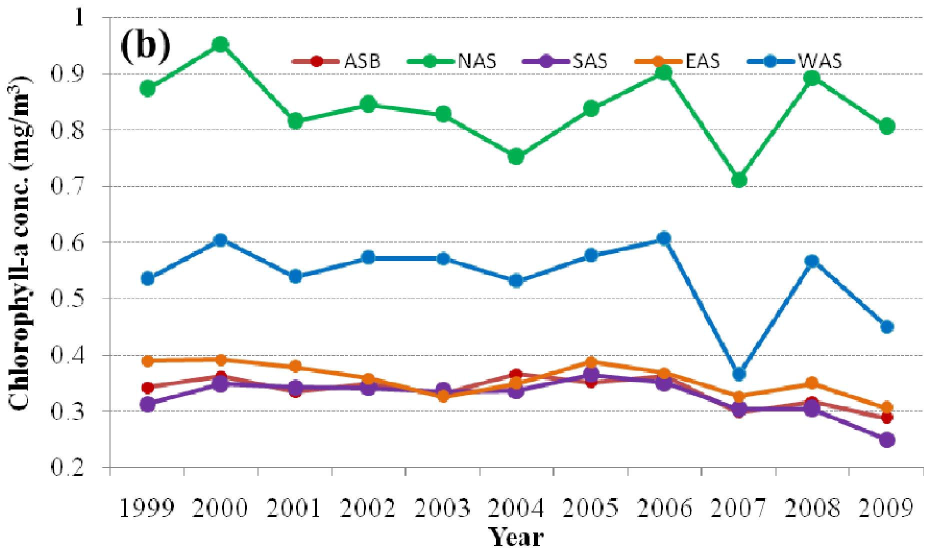

Fig. 6.31 (b): Interannual variability of chlorophyll -a conc. in different domains of the Arabian Sea

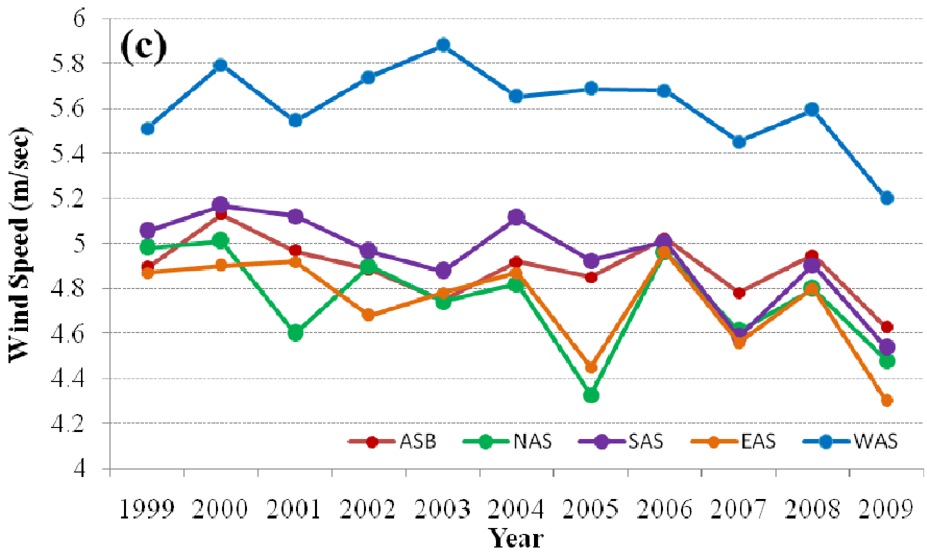

Fig. 6.31 (c): Interannual variability of wind speed in different domains of the Arabian Sea

Figure 6.31 (a, b and c), shows the annual mean SST, chlorophyll-a concentration and wind speed in different sub-domains of the Arabian Sea. Based on these data a correlation analysis between the three parameters were carried out.

Table 6.1 gives the correlation analysis between SST and chlorophyll -a, for different domains of the Arabian Sea Basin. As can be seen, for all the domains the correlation coefficient was negative, confirming that the rise in SST has been one of the reasons for the decrease in the phytoplankton biomass. The correlation coefficient was found to be statistically significant for the Arabian Sea basin, Eastern and the Western sub-domains.

Table 6.1 Correlation Coefficient between SST and phytoplankton biomass over Arabian Sea and its domains

Domain	Pearson Correlation Coefficient
Arabian Sea Basin	-0.77
Northern Arabian Sea	-0.43
Southern Arabian Sea	-0.57
Eastern Arabian Sea	-0.73
Western Arabian Sea	-0.65

(b) Correlation between Wind Speed and Phytoplankton Biomass

Table 6.2 Correlation Coefficient between Wind speed and phytoplankton biomass over Arabian Sea and its domains

Domain	Pearson Correlation Coefficient
Arabian Sea Basin	+0.73
Northern Arabian Sea	+0.52
Southern Arabian Sea	+0.45
Eastern Arabian Sea	+0.52
Western Arabian Sea	+0.72

The correlation between Wind Speed and Phytoplankton biomass over different domains of the Arabian Sea is given in Table 6.3. As can be seen, there exists a positive correlation between the wind speed and phytoplankton biomass over all the domains of the Arabian Sea. The correlation coefficient was found to be higher and even statistically significant for the Arabian Sea Basin and the Western sub-domain of the Arabian Sea.

6.5 CONCLUSION

In the present work, the analysis of the monthly SST, Wind Speed and Phytoplankton Biomass, which is take as a proxy for the estimation of the pattern and trend of the biological productivity of the Arabian Sea was done to find out the correlation between these parameters. From the results obtained, the following conclusions can be drawn:

1. **The intra- annual variability of SST, Wind Speed and Phytoplankton Biomass**

(a) The Intra annual variability of SST, Wind Speed and phytoplankton biomass in Northern, Southern, Eastern and Western domains of the Arabian Sea followed the typical bimodal pattern which is the characteristic of the Arabian Sea basin during the period from 1999 to 2009.

(b) However, for the period from 2003 to 2015, a marked variation in the bimodal pattern of the phytoplankton biomass was observed. It was noticed that in the Arabian Sea basin, as well as the northern and eastern domains, the peak productive season shifted from SWM season to NEM season with February being the most productive month instead of July. It is an important finding, as it could be because of the change in phytoplankton species composition or because of a change in the phenology, both of which are the anticipated outcome of the impact of climate change on marine phytoplankton.

(c) Though, this shift in the productivity pattern was not observed for the southern domain, the western domain did exhibit a similarity, with its higher productivity during February, which came to be comparable to that of July.

(d) The wind speed, and SST over the domains did not exhibit any marked deviation during the two study periods corresponding to 1999 to 2009 and 2003 to 2015.

2. **The inter- annual variability of SST, Wind Speed and Phytoplankton Biomass**

(a) The inter annual variability of SST, Wind Speed and phytoplankton biomass in Northern, Southern, Eastern and Western domains of the Arabian Sea showed a similar pattern of increasing SST, decreasing wind speed and diminishing phytoplankton biomass.

(b) Except for the Gulf of Khambat, none of the sub-domains showed any increase in productivity.

(c) The warming of the Arabian Sea and its sub-domains was found to be more prominent during the decade from 1999 to 2009 than the period from 2003 to 2015. However, a sharp increase in the SST was noticed in all the sub-domains post 2010.

(d) The wind speed decreased substantially over all the domains of the Arabian Sea during the decade 1999 to 2009. However, this decrease was more for the Arabian Sea basin and the Eastern and Western sub-domains.

(e) The phytoplankton biomass and the resulting productivity decreased substantially across both the periods of study. However, the decrease was sharper during the period from 2003 to 2015. While the basin wide decrease in the normalized anomalies of chlorophyll--a was at the rate of -1.22/decade, the rate was high for the western (-1.4/ decade) and southern domain (1.56/decade) as well.

3. **The Correlation of SST, Wind Speed and Phytoplankton Biomass**

The statistical analysis of the correlation of SST, Wind Speed and Phytoplankton Biomass was done to conclude that the decrease in productivity as observed was because of the rise in SST and the decrease in wind speed.

(a) A very strong negative correlation was found between SST and phytoplankton biomass over all the domains, implying that the rise in SST was indeed hampering the growth of the phytoplankton in the Arabian Sea.

(b) A positive correlation was found between wind speed and phytoplankton biomass, asserting that the winds play an important role in promoting the growth of the phytoplankton. However, as the wind speed have decreased across the years in all the domains, the growth and the productivity of the phytoplankton have been hampered resulting in a substantial decrease in the biomass of the phytoplankton and their productivity.