Chapter 3

Evidence of Climate Change in Arabian Sea from Multi-Decadal study of SST

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EVIDENCE OF CLIMATE CHANGE IN ARABIAN SEA FROM MULTI DECADAL STUDY OF SST

3.1 INTRODUCTION

In today's era one of the greatest challenges being faced by humankind is 'global warming'. There has been a 0. 85°C increase in global temperature in the last century and it is projected to further increase by 1.8-4°C in the 21st century *(IPCC, 2007)*, posing a serious threat to the socio-economic sector worldwide. With oceans covering approximately 72% of the earth's surface, any discussion on climate change would remain incomplete without including the role of oceans. Being a fundamental part of the earth's climate system, oceans play an integral role in regulating the regional and the global climate. The rate and the spatial distribution of global warming are significantly influenced by the amount of heat and CO_2 absorbed by the oceans. However, the oceans themselves are also significantly affected by the changes in climatic conditions. Therefore, for a holistic understanding of the changing climate and its mitigation strategies, it is essential to analyze the changing state of the oceans along with their physical, chemical and biological parameters.

Sea Surface Temperature (SST) is one of the key oceanographic parameters, exerting an influential role in many of the meteorological and oceanographic processes. The IPCC assessment report *(Houghton et al., 1996)*, declared SST to be on the priority list for climate change research as its time series analysis reflects the trend of warming or cooling of the ocean. SST quantifies the energy, momentum and moisture exchanges at the ocean – atmosphere interface *(Wentz et al., 2000).* Rising SST can have many devastating consequences in the form of increase in the number and severity of tropical cyclones *(Emanuel, 2005; Webster et al., 2005)*, altered pattern of rainfall *(Goswami et al., 2006; Zhang et al., 2007),* melting of glaciers *(Oerlemans, 1994)* and sea level rise *(Church, 2001; Meehl et al., 2005)*. The increase in temperature changes the mixing and stratification of the oceans *(Sarmiento et al., 2004)* that can have a cascading effect on other physical oceanographic processes. Studies have revealed that the warming of the oceans are now penetrating into the deeper layers of the oceans *(Barnett et al., 2005)* posing a cause of much worry among the scientists and the researchers.

Arabian Sea, with it's a unique geographical location, is strongly influenced by the monsoonal winds which are controlled by the SST. SST is an important physical parameter for regulating the evolution and spatial-temporal variability of the monsoon season *(Godfrey et al., 1995; Webster et al., 1998)*. It has been reported that from 1904-1994 the Arabian Sea has warmed by $0.5^{\circ}C$ *(Kumar et al., 2002).* More recent studies have indicated that in the last decade because of the increase in the anthropogenic carbon emissions, the CO_2 driven warming has increased significantly in the Arabian Sea, resulting in warmer winters, increased frequency of cyclones and decreased rainfall *(Kumar et al., 2009)*. Arabian Sea has been reported to be one of the most productive oceanic zones *(Ryther et al., 1966)* and the occurrence of phytoplankton blooms has been a constant phenomenon over a major portion of the Northern Arabian Sea from January to late March *(Dwivedi et al., 2006).* The rising SST can even change the productivity pattern of the Arabian Sea. *Tom Schils and Simon C. Wilson (2006)* have reported SST to be the single parameter dominating the other environmental factors in the Indian Ocean such that change in the threshold SST can result in a major change of the marine flora. On one hand, the increase in

SST can strongly inhibit the growth and diversity of macro algae while on the other hand, the decrease in the SST strongly affects the coral development and their diversity *(Coles, 2003).* Recently, Hoegh-Guldberg and Bruno (2010), reported that the increasing greenhouse gases are e driving ocean systems toward conditions which did not exist millions of years ago and are leading to the risk of irreversible ecological transformation which includes decreased ocean productivity, altered food web dynamics, reduced abundance of habitat-forming species, shifting species distributions, and a greater incidence of disease.

Looking at the impact of rising SST on the overall oceanographic processes, as well as on entire marine ecosystem, it becomes essential for a comprehensive study of the spatial and temporal variability pattern of SST, its seasonal and inter-annual fluctuations. Till date, the study of SST in the Arabian Sea has been limited to specific location or region-specific analysis of a particular season or month. However, for a climate change related study, it is needed that a long time period (minimum 30 years) is taken into account. Addressing to this need, in the present study, a comprehensive assessment of SST of Arabian Sea has been done using multi decadal data sets.

3.2 DATA USED

Fig. 3.1 shows the different datasets used for the present study.

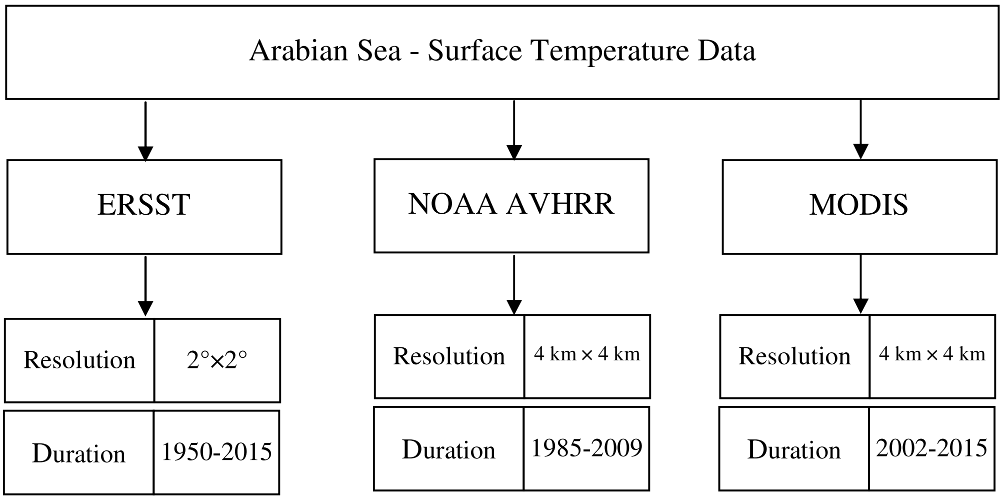

Fig. 3.1: Details of the datasets used in the present study for the SST

(a) ERSST data

As the satellite technology is a recent one and we do not have a continuity of data set from satellites for climate change related studies. For this reason, the Extended Reconstructed Sea Surface Temperature (ERSST.v3b) has been used for long term analysis of SST. This is based on the International Comprehensive Ocean-Atmosphere Data Set *(ICOADS)* release 2.4. At the end of every month, the ERSST analysis is updated with the available GTS ship and buoy data for that month. The anomalies are computed with respect to 1971-2000-month climatology *(Xue et al., 2003)*. ERSST.v3b is generated using in-situ SST data and improved statistical methods that allow stable reconstruction using sparse data. ERSST is suitable for long-term global and basin wide studies as local and short-term variations have been smoothed in ERSST. In the present study, the monthly ERSST data from 1950 to 2015 has been analyzed.

Though the ERSST data sets do give the advantage of being a long-term continuous data set, yet their coarse resolution of (which is 2° × 2°) make them unsuitable for specific local or regional studies. For this reason, the multi sensor satellite data from NOAA and MODIS were used which are discussed in (b) and (c).

(b) NOAA AVHRR Pathfinder SST data

The temporal variations of SST in different regions of the Arabian Sea has been analyzed using high resolution satellite derived SST data that gives better results than the *in situ* data in terms of their spatial coverage. For this study the monthly SST data NOAA AVHRR Pathfinder (version 5.0) of 4 km resolution were obtained from NASA'S Jet Propulsion Laboratory's Physical oceanographic centre (http://podaac.jpl.nasa.gov/) for the period 1985-2009. NOAA AVHRR uses thermal split channels to compute the SST. Multi-channel SST approach i.e. McClain split enhanced algorithm (MCSST) was used to compute the monthly SST images (McClain et al.,1985).

(c) MODIS SST data

As the NOAA AVHRR SST data sets were available only from 1985 to 2009, hence for the analysis of recent years changes in SST of the Arabian Sea, the monthly MODIS Sea Surface Temperature level 3 v2014.0 data set of 4 km resolution, from 2002 to 2015 were studied. The data set were obtained from NASA's Ocean Color Home Page (https://oceancolor.gsfc.nasa.gov/)

3.3 METHODOLOGY

For an assessment of the impact of global warming on Arabian Sea, the monthly, seasonal and annual trend of SST for the past 65 years from 1950 to 2015 was done using ERSST data. From the global data, the Arabian Sea SST data was selected and for each 2° × 2° latitude and longitude, the monthly average SST data was calculated for the months from January to December for the years 1950 to 2015.

The ERSST data with a resolution on 2° × 2° being a coarse data, the finer, 4 km resolution satellite SST data from NOAA AVHRR and MODIS Aqua were analyzed using ENVI 4.1, ERDAS 9.0 and SEADAS software. In short, for SST, three different datasets were used viz. ERSST, NOAA AVHRR and MODIS Aqua.

For ERSST, a total of 780 datasets (monthly data for of each 12 months for 65 years from 1950 to 2015), for NOAA AVHRR, a total of 300 data sets (monthly data for each 12 months for 25 years from 1985 to 2009), and for MODIS, a total of 156 datasets (monthly data for each 12 months for 13 years from 2002 to 2015) was analyzed. The study of SST was based on 1,236 datasets from three different sources viz. ERSST, NOAA AVHRR and MODIS Aqua.

The NOAA AVHRR and MODIS Aqua SST datasets were analyzed for the period from 1985 to 2009 and from 2002 to 2015, respectively. As the two data sets were from two separate sensors (NOAA AVHRR and MODIS), hence to overcome the inter-sensor temperature difference, a regression analysis was done for the overlapping period from 2002 to 2009, during which both NOAA AVHRR and MODIS datasets were available. In this, a total of 2,400 square km area of Arabian Sea, which included 1,200 square km area of the Gulfs of the Arabian Sea was taken as sample size. As the Gulfs are enclosed entities, hence, it was assured that the data points of the Gulfs were compared with those of the respective Gulfs only. Within the sample area, 150 data points of 4 km resolution of each of the two sensors were analyzed for the months of January and March for the years 2003 – 2009. The SST data from each of the two sensors were compared for pixel to pixel for every specific latitude and longitude. A regression analysis was done and a coefficient or a correction factor was calculated for the MODIS data. Hence, for the continuity of satellite data from 1985 to 2015, the MODIS SST data were corrected with the coefficient factor.

Additionally, to study the spatial variability of SST in different regions of the Arabian Sea, the entire basin was divided into 10 sub - domains, as shown in Fig. 3.2 (a), (b) and (c). These sub - domains were as follows:

Table 3.1 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

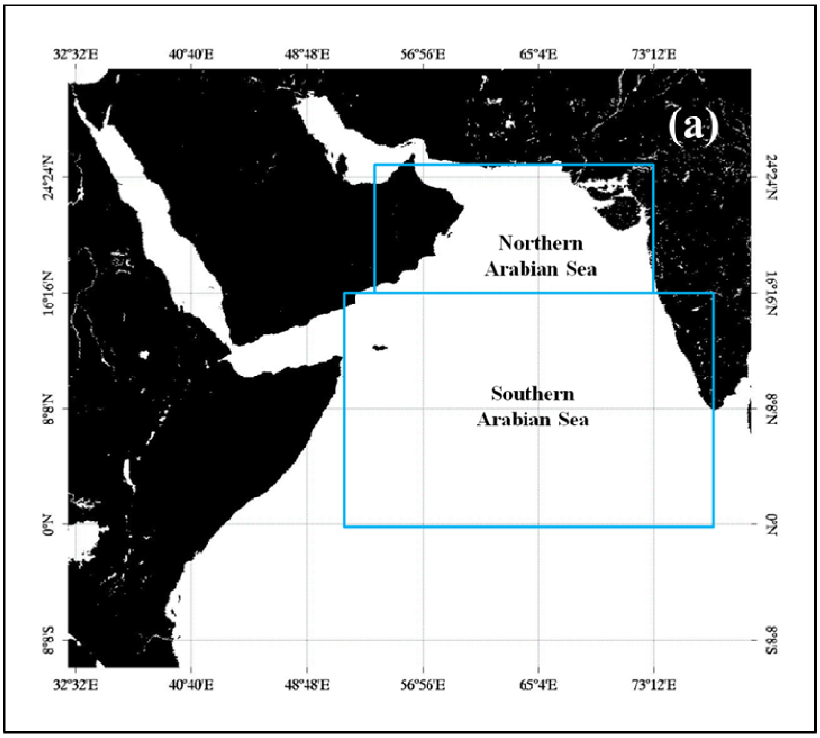

Fig. 3.2 (a): Northern and Southern subdomains of Arabian Sea

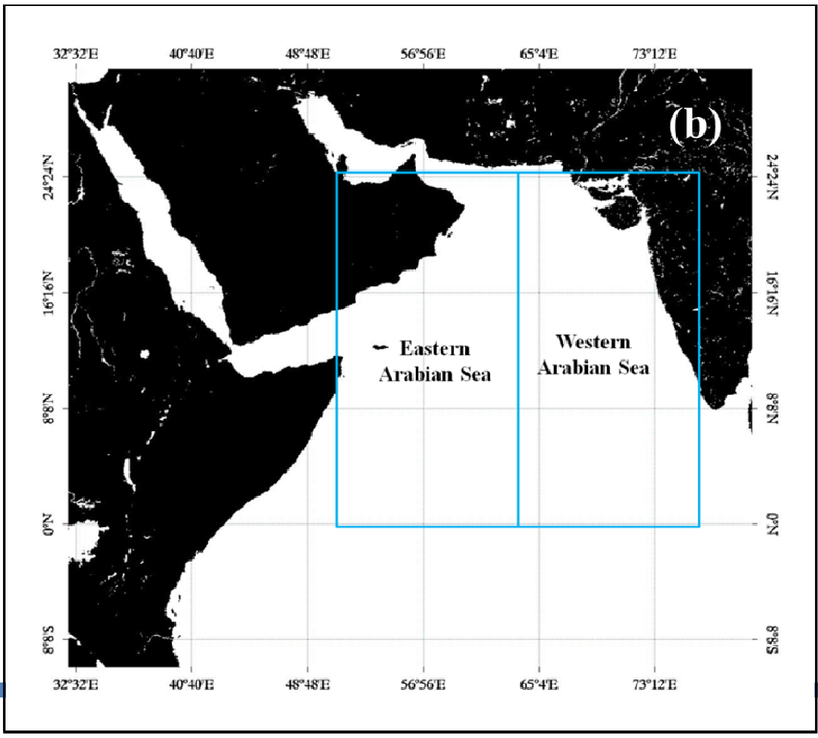

Fig. 3.2 (b): Eastern and Western subdomains of Arabian Sea

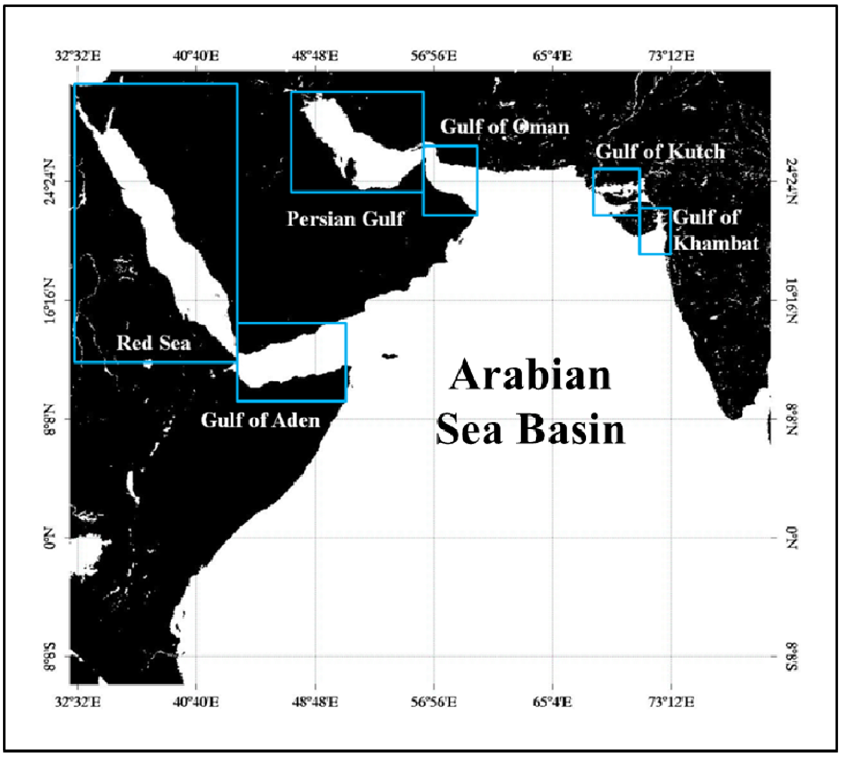

Fig. 3.2 (c): The Gulfs and the Red Sea sub -domains of the Arabian Sea

Using ENVI 4.1, SST of the respective region of interest of each of the 10 sub - domains of the Arabian Sea were extracted for each month from January to December from 1985 to 2009 (NOAA AVHRR SST) and from 2002 to 2015 (MODIS SST).

For each domain of the Arabian Sea, the monthly SST images were masked to avoid the influence of the land and clouds 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 using a Model Maker ERDAS 9.0. 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)

For ERSST data the climatological mean (CM_{65}) of 65 years (1950-2015) for each month was calculated by averaging the monthly mean ($M_{y\ (i)}$). The interannual variability was analyzed using the monthly normalized anomalies, computed by subtracting the monthly climatological mean (CM_{65}) from the monthly mean ($M_{y\ (i)}$) of each year, and normalized to the standard deviation for that month (SD_{65}) as shown in Equation 3:

$$M_{(NA)} = \frac{M_{y\,(i)} - CM_{(65)}}{SD_{65}} \qquad \text{.................. (Equation 3)}$$

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

Similarly, for the satellite retrieved SST data from NOAA AVHRR and MODIS Aqua (1985 to 2015), the monthly, seasonal and annual climatological means (CM_{31}) normalized anomalies were computed for 31 years.

Trend analysis was carried out using the nonparametric Mann-Kendall (MK) test (*Mann 1945, Kendall 1975*). This test is useful and widely used for detecting trends in climate and environment sciences. It is a rank-based test suitable for non-normally distributed data, censored data, and nonlinear trends and is robust against outliers, with a higher power than many other commonly used tests *(Hess et al. 2001)*. The Mann-Kendall rank statistics (τ) is computed, as shown in Equation 4:

$$\tau = [(4\Sigma n_i / N (N-1)] -1 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(Equation 4)}$$

Where, n_i is the number of values larger than the i^{th} value in the series subsequent to its position in the series of N values. The value of τ is tested for significance by the statistics τ_t, which is shown in Equation 5:

$$\tau_t = \pm t_g [(4N+10) / (9N (N-1)] 0.5 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(Equation 5)}$$

Where, t_g is the desired probability point of the Gaussian normal distribution appropriate to a two-tailed test.

A positive value of τ indicates an upward trend, whereas a negative value indicates a downward trend in the tested time series. In this research work, the statistically significant trends have been reported at the 95% significance level (p-value < 0.05). However, it indicates only the direction and the significance of the trend and cannot quantify the trend.

3.4 RESULTS AND DISCUSSION

3.4.1 Data Compatibility between NOAA AVHRR and MODIS Aqua SST

SST satellite data from NOAA AVHRR and MODIS Aqua were analyzed using ENVI 4.1, ERDAS 9.0 and SEADAS software. The NOAA AVHRR and MODIS Aqua data sets were analyzed for the period 1985 to 2009 and 2002 to 2015 respectively. As the two data sets were from two separate sensors (AVHRR and MODIS), hence to overcome the inter-sensor variability, a regression analysis was done for the overlapping period from 2002 to 2009, during which both NOAA and MODIS data sets were available. In this, a total of 150 data points of the study area, including 75 data points from the gulf regions of Arabian Sea were analyzed for all the 12 months for the years 2002 – 2009.

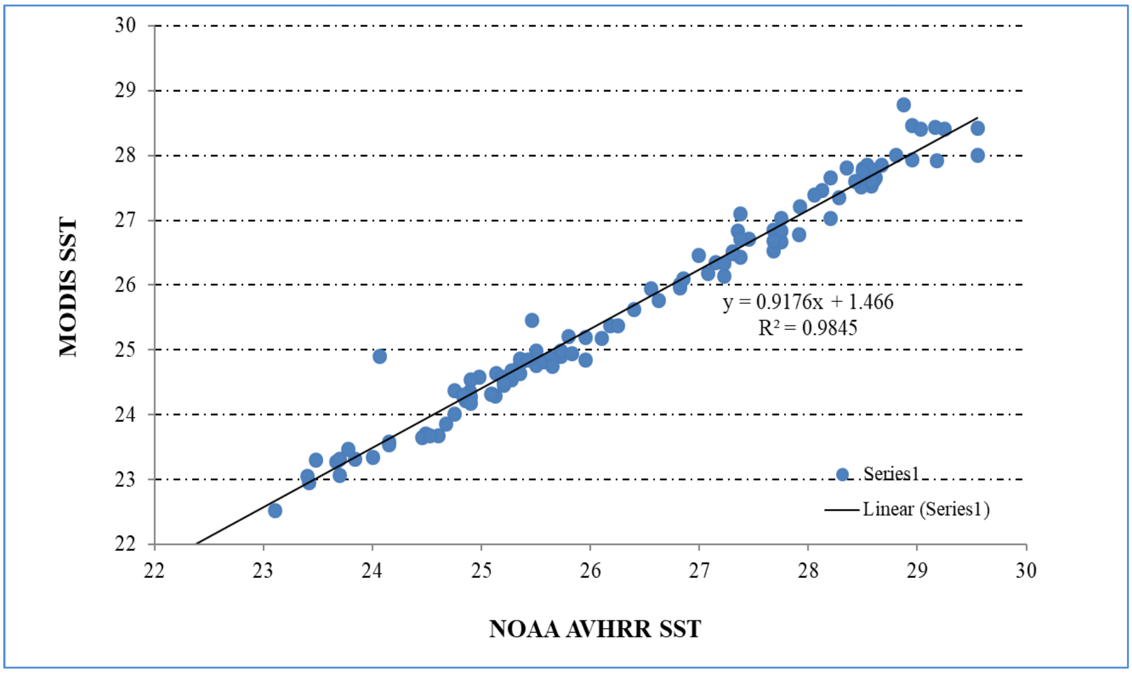

Fig. 3.3: Correlation between NOAA AVHRR and MODIS SST data

As can be seen from figure 3.3, the two data sets matched consistently across the years from 2002 to 2009. The correlation coefficient (R^2) between the NOAA AVHRR and MODIS Aqua SST data was found to be 0.984. The high value of R^2 provided ample basis for the two data sets to be combined and used for a long-term SST analysis. However, to overcome any further discrepancies in the data set of the two separate sensors, a correction factor was computed, and with this correction factor the SST data retrieved from MODIS Aqua was adjusted to cohere with the NOAA AVHRR data.

3.4.2 Interannual variability of Arabian Sea SST during the period 1950 to 2015

In the present study, the analysis of ERSST data from 1950 to 2015 was carried out and it provided much insight into climate change related impact on the Arabian Sea. The interannual variability of SST was examined. Fig. 3.4 (a) shows the mean SST of Arabian Sea across 65 years.

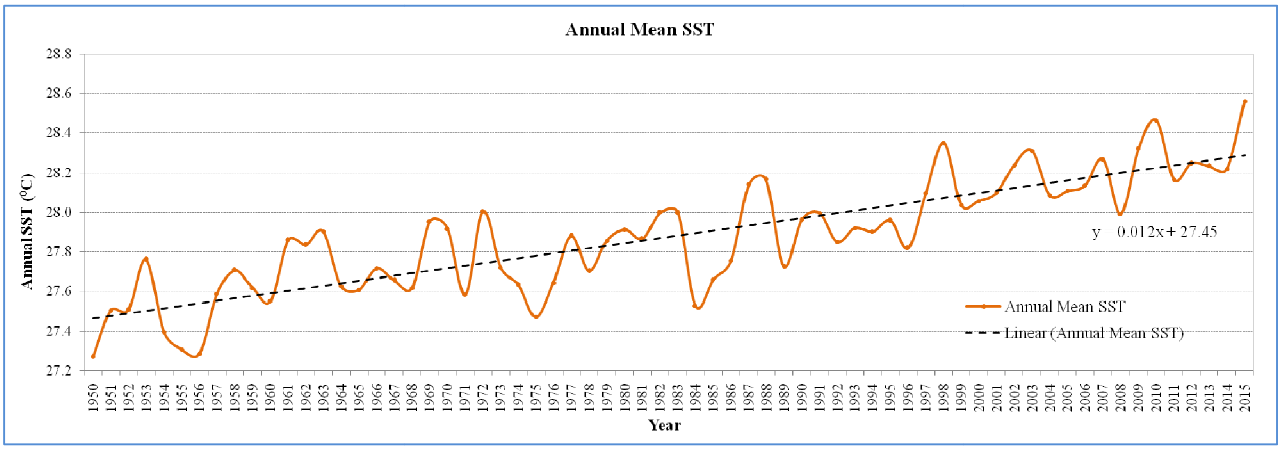

Fig. 3.4 (a): Annual Mean SST of Arabian Sea from 1950 2015

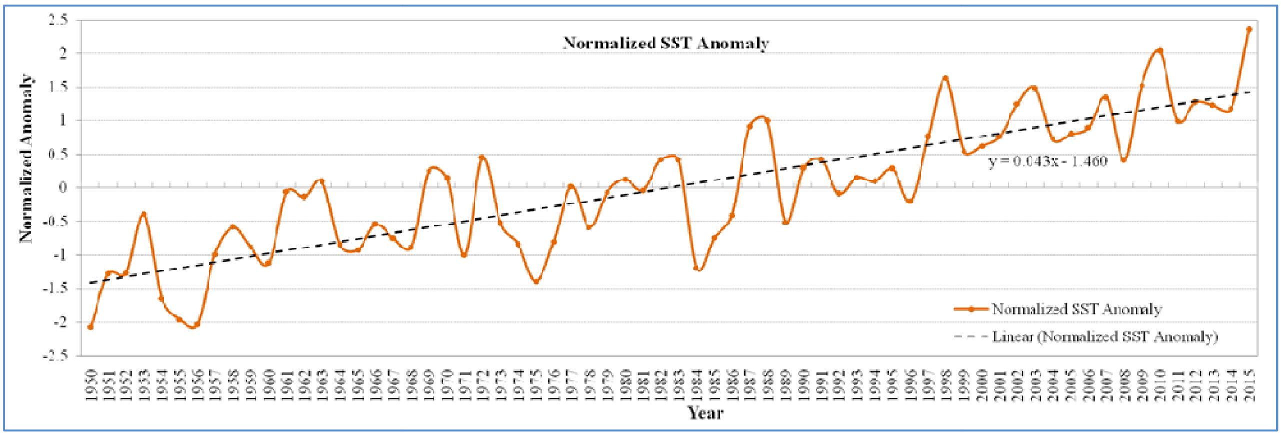

Fig. 3.4 (b): Annual Normalized SST Anomaly of Arabian Sea from 1950 2015

The climatological annual mean SST of Arabian Sea for the study period was found to be 27.9°C. As seen in Fig. 3.4 (a), it was observed that in the past 65 years, the annual SST of Arabian Sea has increased by 0.78°C (0.012°C/year). It was also noted that for most of the years prior to 1995, the annual mean SST was below the climatological mean of 27.9°C. However, post 1995 - 96 the situation was opposite with all the years having positive deviation from the climatological mean, as shown in Fig. 3.4 (b). This substantiate that, there has been a significant warming of the Arabian Sea in the past 20 years i.e. from 1995 to 2015. Hence, it was needed to analyze whether this warming was happening in all the four seasons or was confine to one or two. For this reason, the seasonal variability of SST was also carried out.

3.4.3 Seasonal variability of Arabian Sea SST during the period 1950 to 2015

Similar to the annual increase in SST, the seasonal analysis of SST also showed warming in all the four seasons, as shown in Fig. 3.5. The climatological mean SST for the NEM season was found to be 26.7°C, while during the SWM it was 27.8°C. During the two inter-monsoon seasons, the climatological mean was higher, with SST reaching 28.95°C in SIM and 28.02°C in AIM.

During the NEM season, the normalized anomalies increased substantially from -2.4 in 1950 to +1.28 in 2015, as shown in Fig. 3.5 (a). The highest positive anomaly reached was + 2.4 which was in the year 1998. It was also observed that prior to 1995, most of the years showed negative deviation from the climatological mean, while post 1995, all the years (with the only exception of 1997), had positive deviation from the climatological mean. Thus, it can be inferred that the maximum heating of the Arabian Sea during the NEM season happened in the last 20 years.

For SIM season, the normalized SST anomalies increased from -1.80 in 1950 to +1.41 in 2015, as shown in Fig. 3.5 (b). The maximum rise in SST of +2.6 was observed in 2010 followed by +2.12 which was in the year 1998. It was found that post 1995, except for the years 1997, 1999 and 2008, all the years had positive deviation from the climatological mean. Moreover, the negative deviation of SST during the year 1997 and 1999 were of the values -0.09 and -0.14, which cannot be considered as significant. Hence, it can be seen that, even for SIM season, there has been a rapid warming of the Arabian Sea post 1995.

During the SWM season also, the warming of Arabian Sea was observed, with normalized SST anomaly increasing from -1.72 in 1950 to +1.41 in 2015, as shown in Fig. 3.5 (c). Two major cooling events occurred in the year 1955-56 and 1984-85. However, post 1995, there has been a rapid and a steady increase in the SST with positive anomalies ranging from +0.43 to +1.57.

Besides, for all the years, from 2009 to 2015, the positive anomalies were more than +1, which highlights the substantial warming of the Arabian Sea in last 7 years.

The AIM season also showed a considerable increase in SST of Arabian Sea. The normalized anomaly increased from -1.6 in 1950 to +2.56 in 2015, as shown in Fig. 3.5 (d). Post 1996, a rapid increase in SST was observed, with the maximum rise in SST (of (+2.56) in the year 2015. For the years 2009 to 2015, the positive anomalies were more than +1, which provides evidence that the warming of the Arabian Sea in last 7 years has been unprecedented.

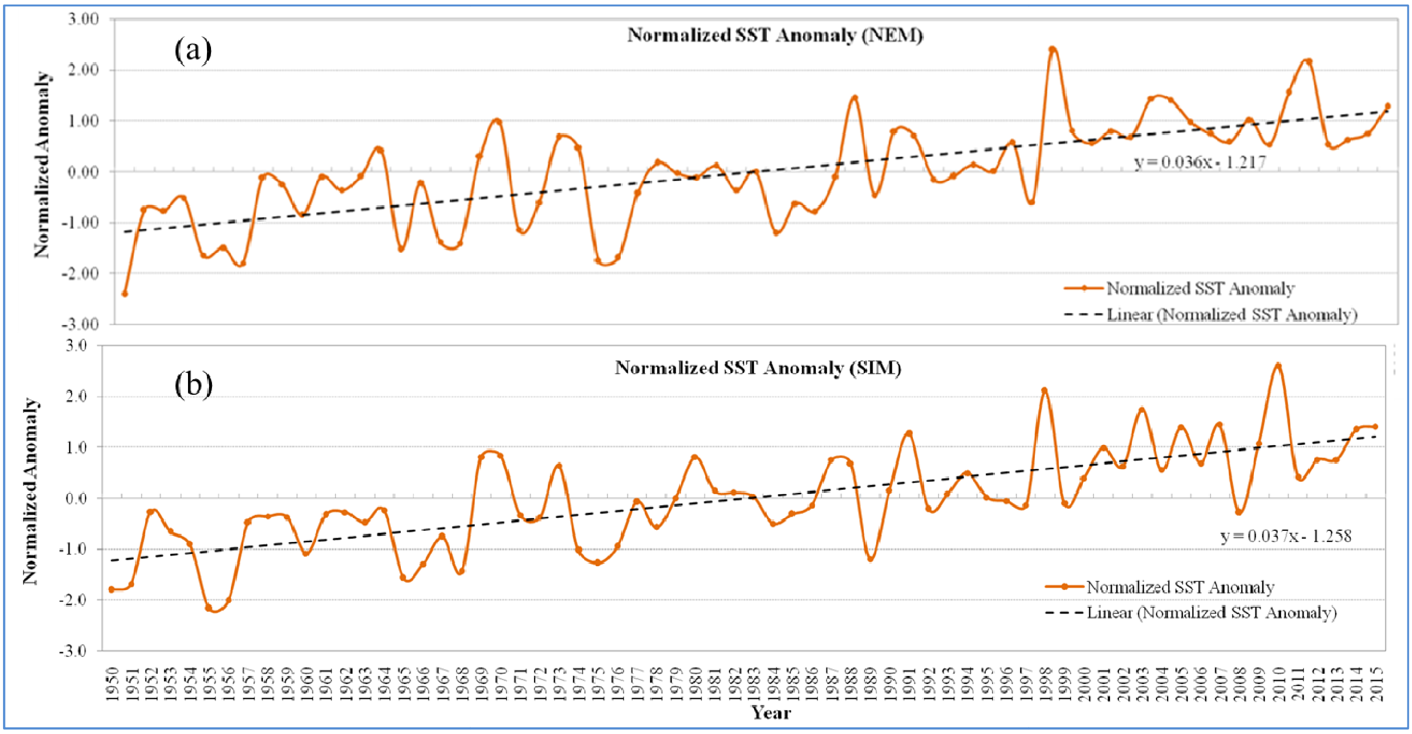

Fig. 3.5 (a -b): Seasonal Normalized SST Anomaly of Arabian Sea
(a) Northeast monsoon (NEM), (b) Spring inter monsoon (SIM)

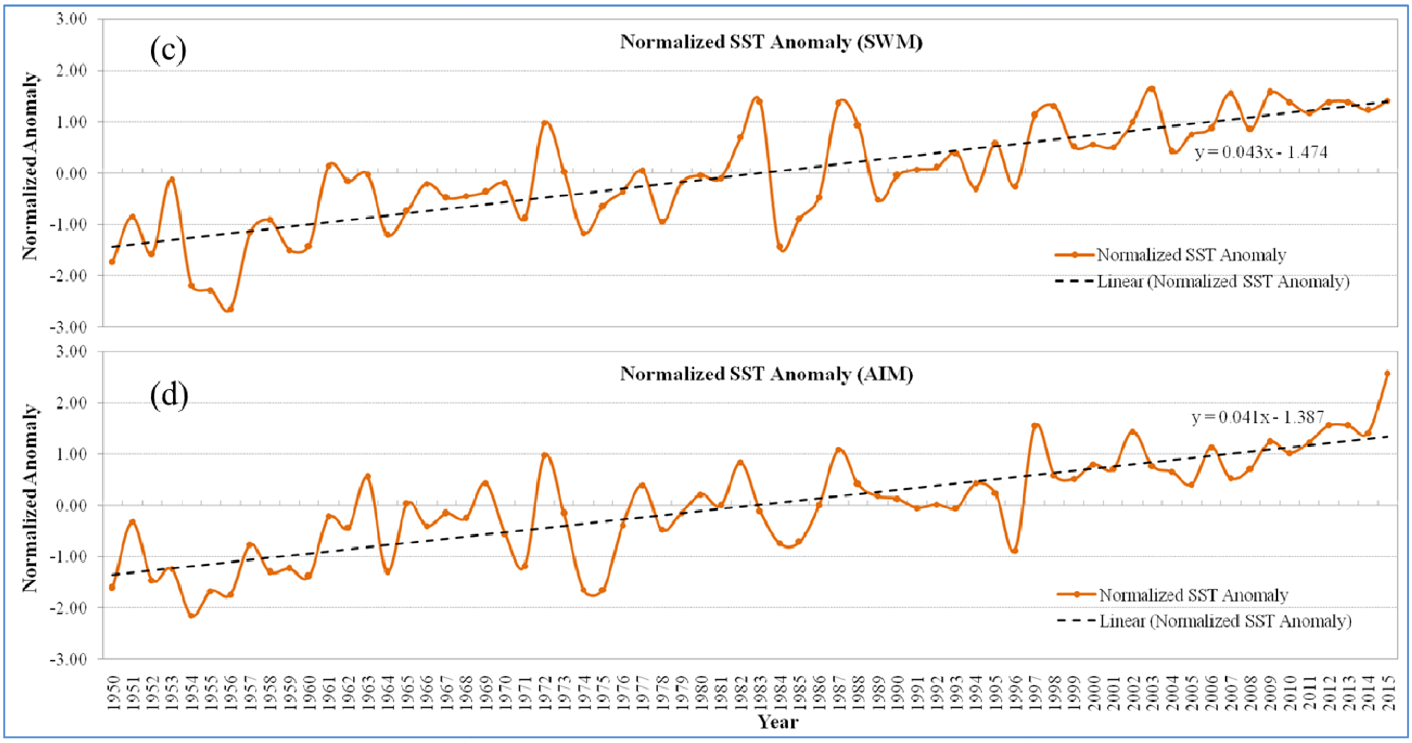

Fig. 3.5 (c -d): Seasonal Normalized SST Anomaly of Arabian Sea
(c) Southwest monsoon (SWM) & (d) Autumn inter monsoon (AIM)

3.4.4 Inter-decadal variability of Arabian Sea SST during the period 1950 to 2015

From the annual and seasonal analysis of SST, it was clear that there has been a substantial warming of the Arabian Sea in the last 65 years. However, to decipher how the warming has been taking place across the years, an inter-decadal analysis of mean SST was done, as shown in Fig. 3.6. The entire 65 years of study period was subdivided into decades of 1950s, 1960s, 1970s, 1980s, 1990s, 2000s and the last five years from 2010 to 2015 were grouped into one.

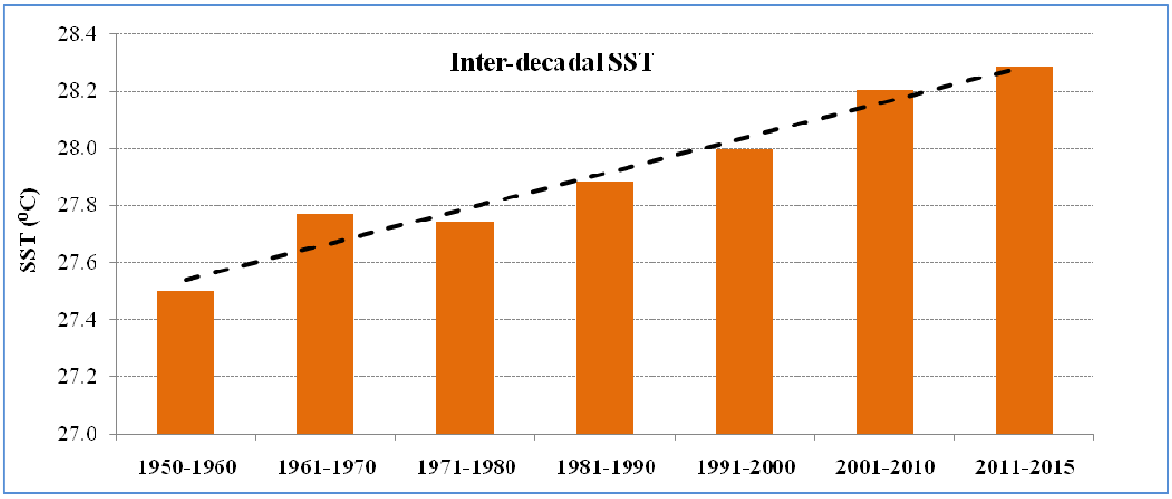

Fig. 3.6: Inter-decadal variability of Arabian Sea SST from 1950 to 2015

As seen in Fig. 3.6, there has been a rise in SST of the Arabian Sea across all the decades from 1950 to 2015. It was observed that from 1971 to 1980, there was a slight decrease in the SST as compared to the previous decade. However, post 1980 the rise in SST has been substantial. It is clear that the warming of the Arabian Sea has been the highest in the decade from 2001 onwards. But the most significant observation was that although only 5 years have been included in the decade from 2011 to 2015, yet, the mean SST for this decade is the highest of all.

3.4.5 Monthly Climatological Mean SST of Arabian Sea (1985-2015)

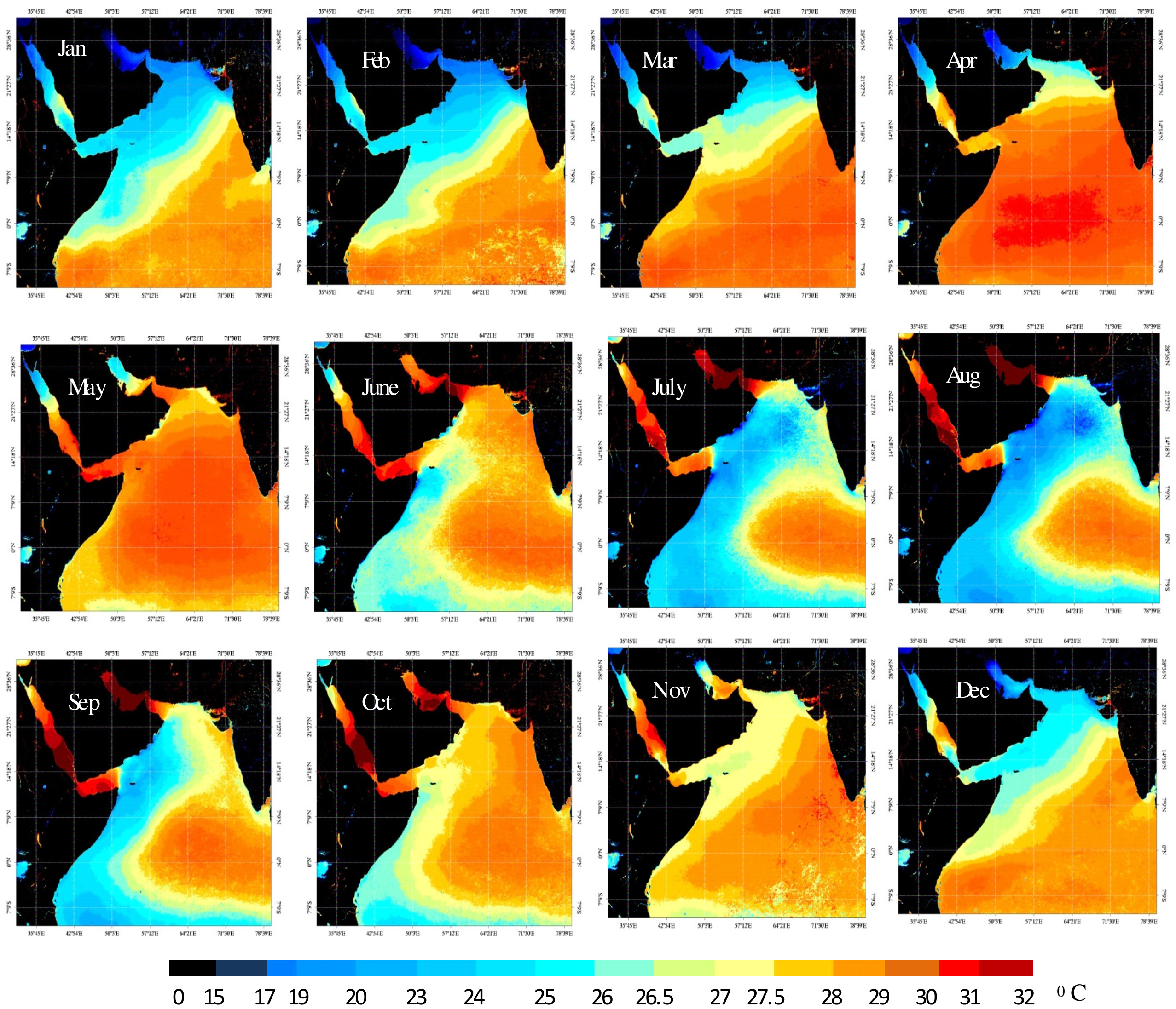

Fig. 3.7: Monthly Climatological Mean SST of Arabian Sea from 1985 to 2015 computed from NOAA AVHRR and MODIS satellite data

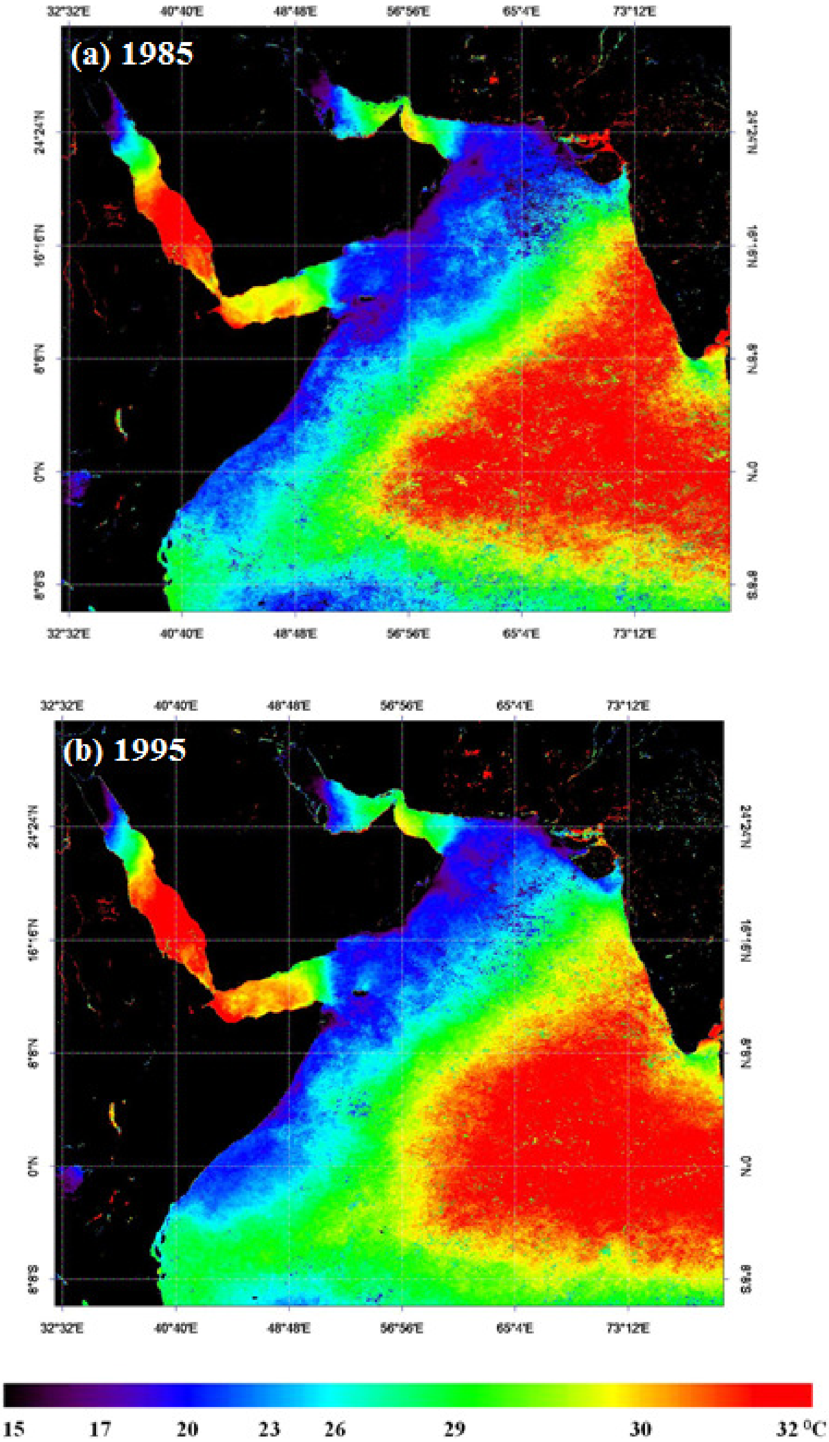

Fig. 3.8 (a -b): Annual Mean SST of Arabian Sea in (a) 1985 and (b) 1995 using NOAA AVHRR satellite data

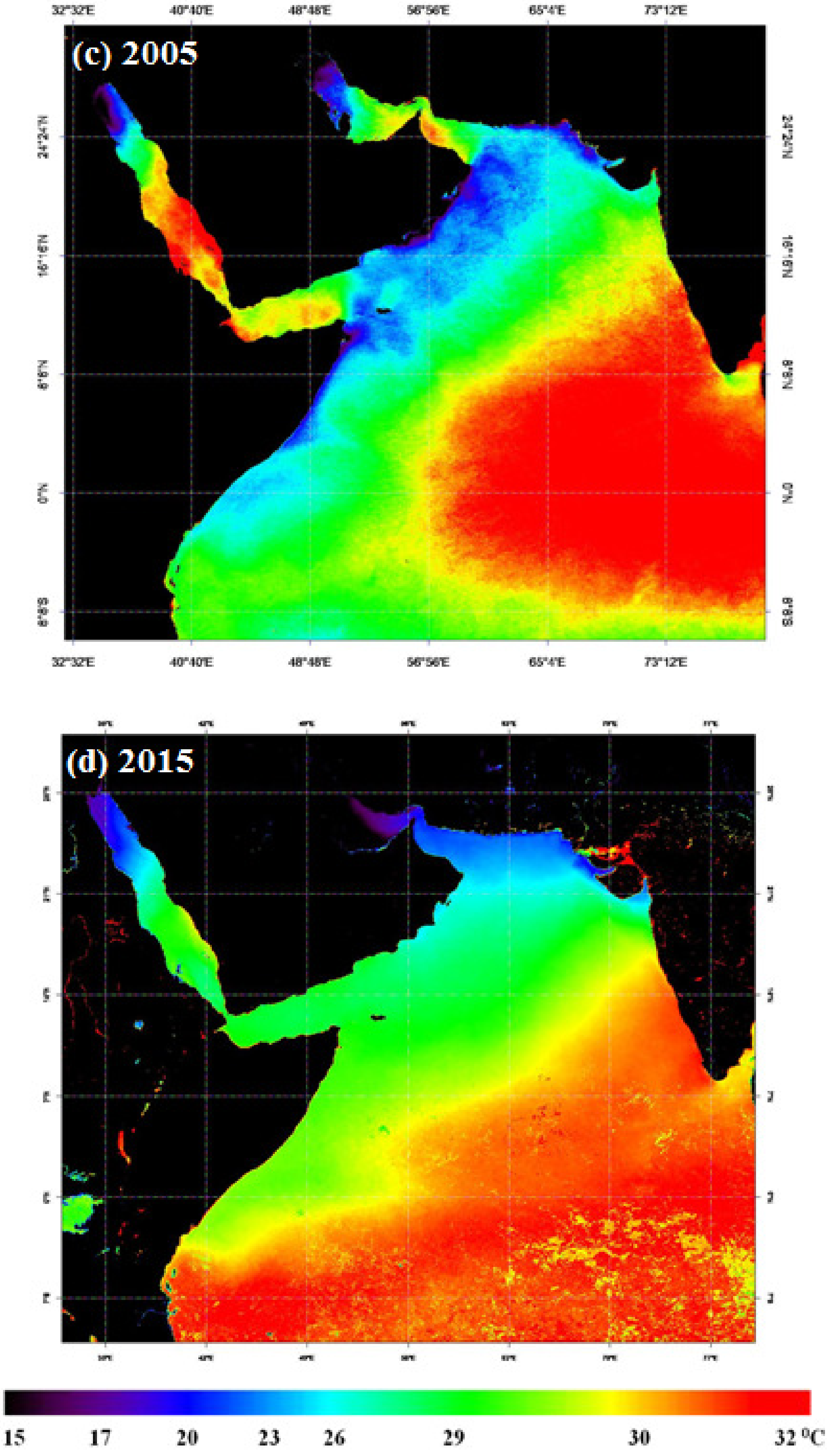

Fig. 3.8 (c -d) Annual Mean SST of Arabian Sea in 2005 (c) and 2015 (d) using MODIS satellite data

The monthly climatological mean SST of Arabian Sea, for the period from 1985 to 2015, (Fig. 3.7) was computed using NOAA AVHRR and MODIS data, and their maps were generated using ERDAS 9.0 and ENVI 4.1 software. The annual variation in SST was also studied through annual mean SST maps for the years 1985, 1995, 2005 and 2015 as shown in Fig. 3.8 (a-d)

From the maps of the climatological monthly mean SST (Fig. 3.7), different domains within the Arabian Sea basin can be identified with different pattern of SST. The northern and western domains of the Arabian Sea remain relatively cooler across the year (excluding the Gulfs), as compared to the southern and eastern domains. The southeastern domain (65°E -80°E) has been reported as the mini warm pool region of the Arabian Sea (with temperature > 30.8°C). This was observed to be the warmest from December to May. Numerous investigations have been carried out to study the role of the mini warm pool in the genesis of monsoon *(Shyte 1999; Babu et al., 2007; Shenoi et al., 2010).*

Fig. 3.8 (a-d) gives the annual mean during the years 1985, 1995, 2005 and 2015. It can be clearly seen that the SST of the Arabian Sea is increasing across the years. Though the warm waters in the range of temperature 30-32°C were limited to the southeastern domain of the basin during 1985 to 1995, it expanded towards the central domain of the basin by 2005. 2015 was one of the warmest years recorded, and the annual average SST map, gives substantial evidence that the warm waters of the Arabian Sea in the range of temperature 30-32°C, have expanded to even those domains, where annually the temperature would be in the range of 20-25°C.

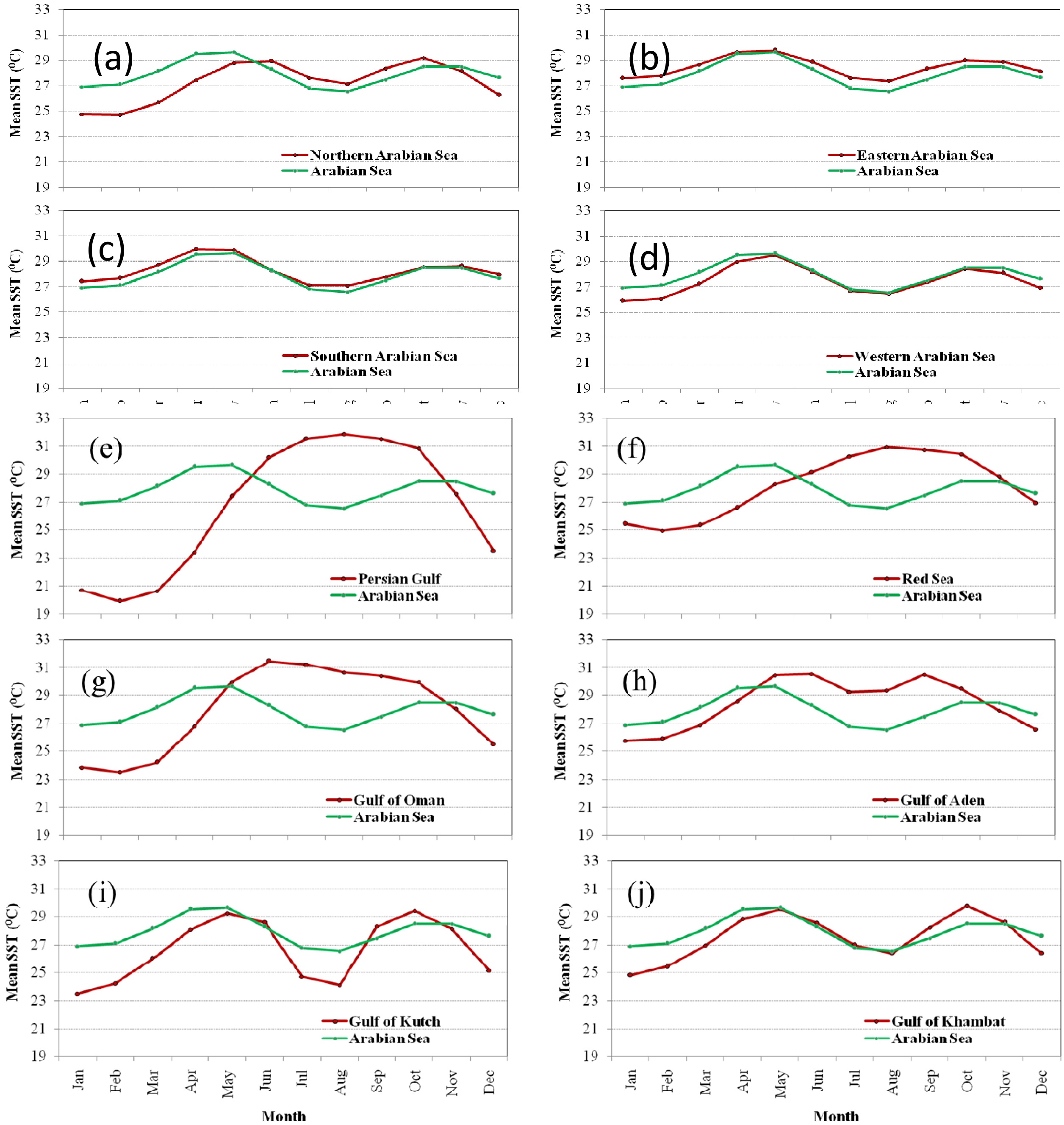

Fig. 3.9 (a-j): Comparison of Monthly Climatological Mean SST of different sub-domains of Arabian Sea (a: Northern Arabian Sea; b: Eastern Arabian Sea; c: Southern Arabian Sea; d: Western Arabian Sea; e: Persian Gulf; f: Red Sea; g: Gulf of Oman; h: Gulf of Aden; i: Gulf of Kutch; j: Gulf of Khambat)

The SST in the Arabian Sea follows a typical bimodal pattern (Fig. 3.9) with warming during Summer-Inter Monsoon (SIM) (April-May) and Autumn-Inter Monsoon (AIM) (October-November) and cooling during the South-West Monsoon (SWM) (June-September) and North-East Monsoon (NEM) (December-March) seasons (*Colborn 1975, Rao et al. 1989, Prasad and Ikeda 2002*). However, difference in the SST pattern was observed in many of the domains of the Arabian Sea, specifically the gulfs as shown in Fig. 3.9.

The northern, southern, eastern and western (Fig. 3.9 a –d) domains also followed the typical bimodal pattern of SST across the months, yet differences in the peak and the minimum values of SST could be seen. In the Eastern, Western and Southern Arabian Sea, the peak SST was observed in May where as in the Northern Arabian Sea, the maximum SST was in October. Similarly, for the months in which SST was the lowest, differed in these domains. In the Eastern and Southern Arabian Sea, SST was lowest during the months of July-August, where as in the Northern and Western Arabian Sea the lowest SST was in January - February.

Climatologically, the Northern (Fig. 3.9 a) and Western Arabian Sea (Fig. 3.9 d) domains were found to be cooler than Arabian Sea basin while the Eastern (Fig. 3.9 b) and Southern Arabian Sea (Fig. 3.9 c) was warmer than the basin. In the Western Arabian Sea, the climatological mean SST for all the months except May were observed to be lower than the basin. However, in the Northern domain, the SST during the months from November to May was lesser than the basin, while from June to October, Northern Arabian Sea was warmer than the basin.

The eastern gulfs of the Arabian Sea, viz. the Gulf of Kutch (Fig. 3.9 i) and the Gulf of Khambat (Fig. 3.9 j) followed the bimodal SST pattern as the Arabian Sea basin, but with May-June as the months with peak SST and January- February with the lowest SST.

The western gulfs of the basin, viz. The Persian Gulf (Fig. 3.9 e), Gulf of Oman (Fig. 3.9 g), and the Red Sea (Fig. 3.9 f) exhibited a distinct unimodal SST curve instead of the typical bimodal pattern as in the Arabian Sea, with minimum temperature during the Northeast Monsoon season and maximum during the Southwest Monsoon season. While the minimum temperature for these three water bodies was in the month of February, the month with the maximum temperature was found to be different. In the Persian Gulf and the Red sea, the maximum temperature was in the month of August whereas, in the Gulf of Oman, the maximum temperature was in the month of June. Climatologically from November to May, the Persian Gulf, Gulf of Oman, and the Red sea were found to be cooler than the Arabian Sea open ocean, while from June to October they were warmer than the Arabian Sea. The Red Sea and the Persian Gulf, exhibited the highest range of SST (11.97°C).

The Gulf of Aden (Fig. 3.9 h) was an exceptional to the unimodal pattern of SST found in the western Gulfs. Instead it followed the typical bimodal pattern with peak SST during May-June and the lowest SST in January –February.

3.4.6 Interannual variability of SST in different sub - domains of Arabian Sea

3.4.6.1 Northern, Southern, Eastern and Western Arabian Sea

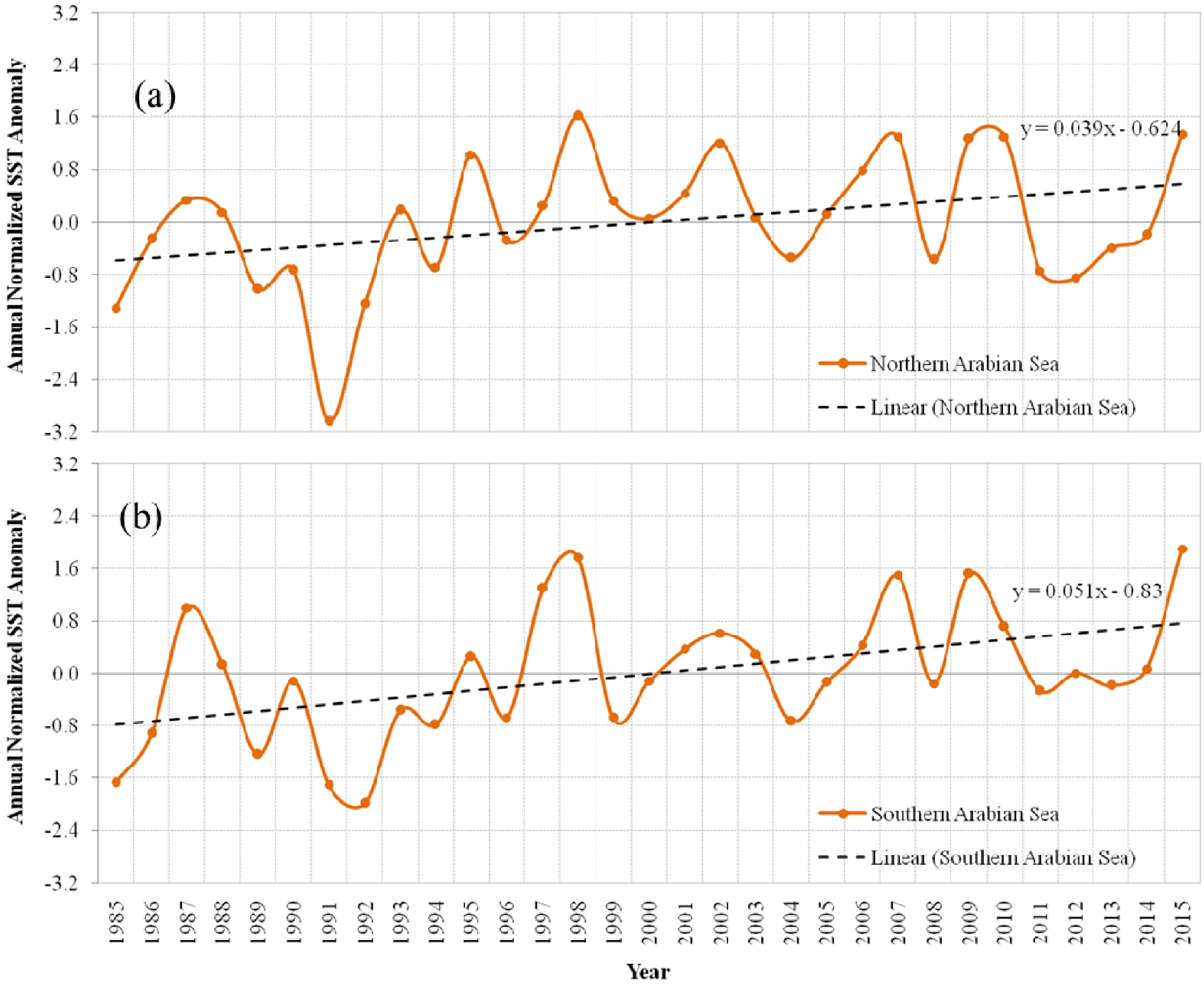

Fig. 3.10 (a-b): Interannual variability of Normalized SST Anomaly in (a) Northern and (b) Southern Arabian Sea from 1985 to 2015

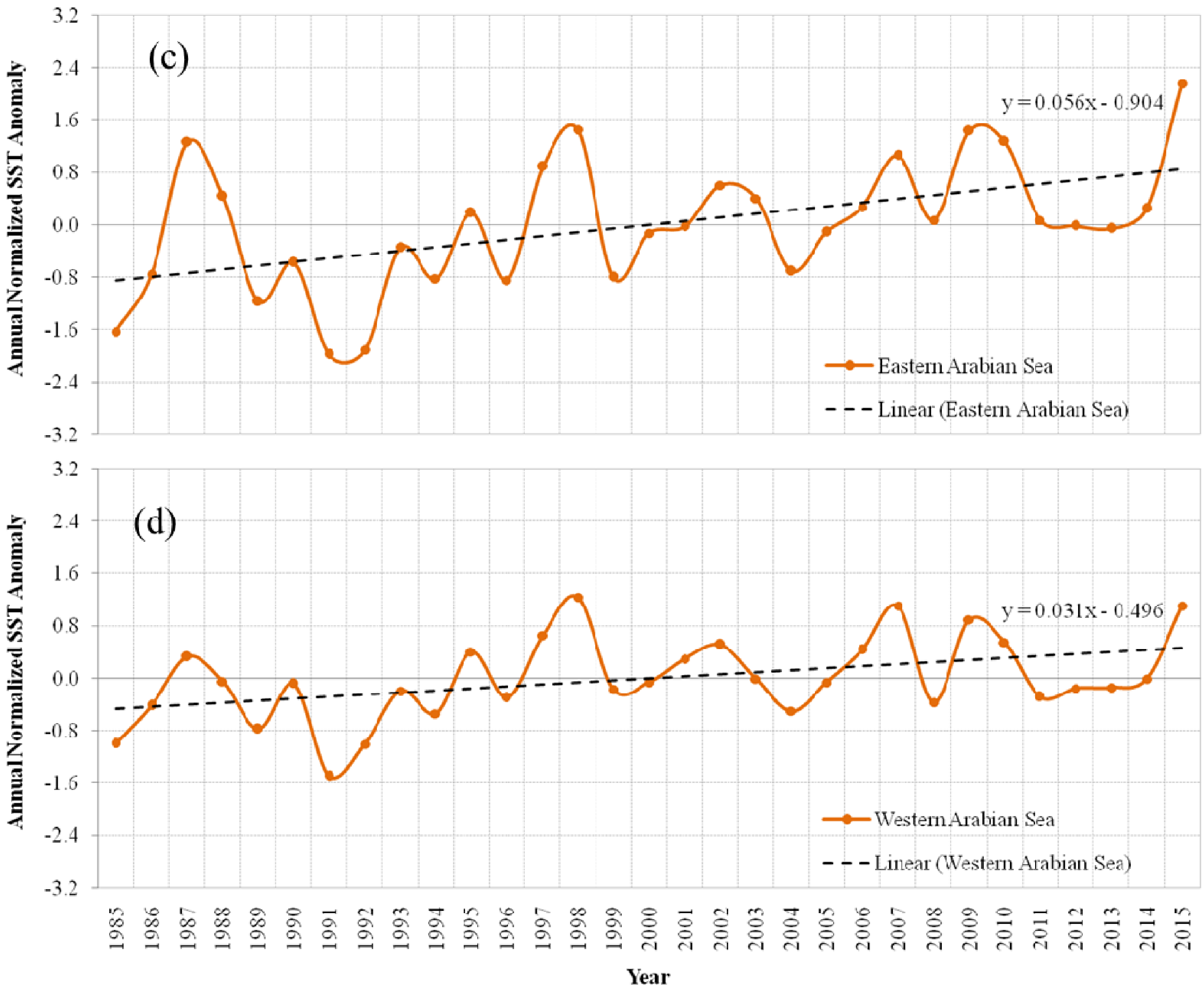

Fig. 3.10 (c - d): Interannual variability of Normalized SST Anomaly in (c) Eastern and (d) Western Arabian Sea from 1985 to 2015

As the domains of the Arabian Sea have their unique hydrographic features hence their response to the changing climatic conditions may also vary. Taking this into account, the interannual variability of SST in different domains of Arabian Sea was examined for the period 1985- 2015. As seen in Fig. 3.10 (a-d), all the four domains of the basin viz. the northern, southern, eastern and western, exhibited an increase in the annual normalized SST anomaly. However, the increase was the highest in the Eastern Arabian Sea.

In the Northern Arabian Sea (Fig. 3.10 a), the normalized anomaly increased from -1.31 in 1985 to +1.35 in 2015. The years 1998, 2007, 2009, 2010 and 2015 showed positive anomalies in the range of +1.3 to +1.62. It was observed that from 1995 to 2010 (with the exception of 1996, 2004, and 2008), all the years exhibited positive deviation from the climatological mean of Northern Arabian Sea, thereby postulating a sharp increase in the SST. However, post 2010, there has been a gradual decline in the warming, with the years 2011 to 2014 showing negative anomalies in the range of - 0.8 to -0.1. Yet, the large scale warming of the Arabian Sea in the year 2015, resulted in the sudden spike of the graph of SST with positive anomaly reaching up to +1.35 in 2015.

The climatological mean SST for the Southern Arabian Sea (Fig. 3.10 b) for the period 1985 to 2009 was found to be 28.27°C. During this period, the normalized anomaly increased from -1.67 (1985) +1.91 (2010). The years 1998, 2007, 2009, 2009 and 2015 showed positive anomalies in the range of +1.5 to +1.9. It was observed that in the last decade (from 2005 to 2015), the annual mean SST for all the years (with the exception of 2005, 2008, 2011 and 2013), exhibited positive deviation from the climatological mean. The negative deviations in the exceptional years of the decade were also in the range of -0.14 to -0.19, which could not break the increasing trend of

SST as the positive deviations were on a higher range. The year 2015, added the pace to the warming phenomena, with positive anomaly reaching up to +1.91 in 2015.

The climatological mean SST of the Western Arabian Sea (Fig. 3.10 d) for the period 1985 to 2009 was found to be 27.49. During this period, the normalized SST anomaly increased from -1.0 (1985) to +1.11 (2015). It was observed that prior to 1995 the annual mean SST of the domain was lower than the climatological mean, with all the years, except 1987, showing negative deviation in the range -0.05 to -1.48. However, from 1995 to 2010, substantial warming of the domain occurred, with 10 out of 16 years exhibiting positive anomalies in the range +0.3 to +1.24. In recent years, although the warming trend has reduced with years from 2011 to 2014 showing negative normalized anomalies, yet the +1.11 deviation in the year 2015 has resulted in the resumption of the warming of the Western domain of the Arabian Sea.

The climatological mean of Eastern Arabian Sea for the period 1985 to 2015 (Fig. 3.10 c) was observed to be 28.51°C. The annual normalized SST anomaly increased from -1.69 (1985) to +2.16 (2015). In the period from 1985 to 1995, all the years (except 1987 and 1988) showed negative deviation from the climatological mean. Though in the decade from 1995 to 2005, the SST anomalies increased but these were not substantial as the episodic cooling events like those in 1996 (-0.84), 1999 (-0.80) and 2004 (-0.71) compensated for the rising SST. However, post 2005, there has been a tremendous increase in the SST with positive anomalies reaching up to +1.06 (2007), +1.43 (2009), +1.27 (2010) and +2.16 (2015).

3.4.6.2. Eastern & Western Gulfs of Arabian Sea and Red Sea

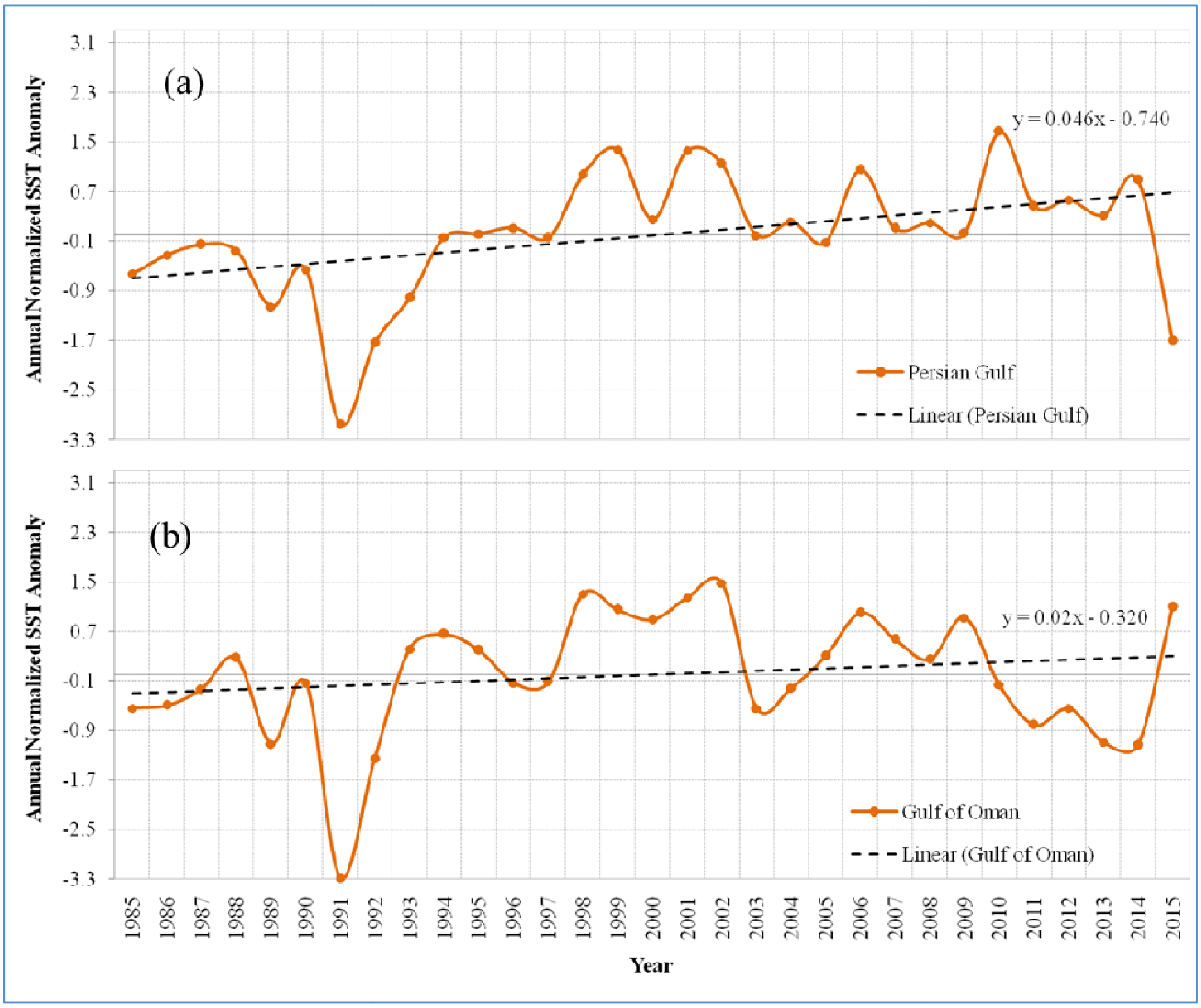

Fig. 3.11 (a –b): Interannual variability of Normalized SST Anomaly in
(a): Persian Gulf
(b): Gulf of Oman

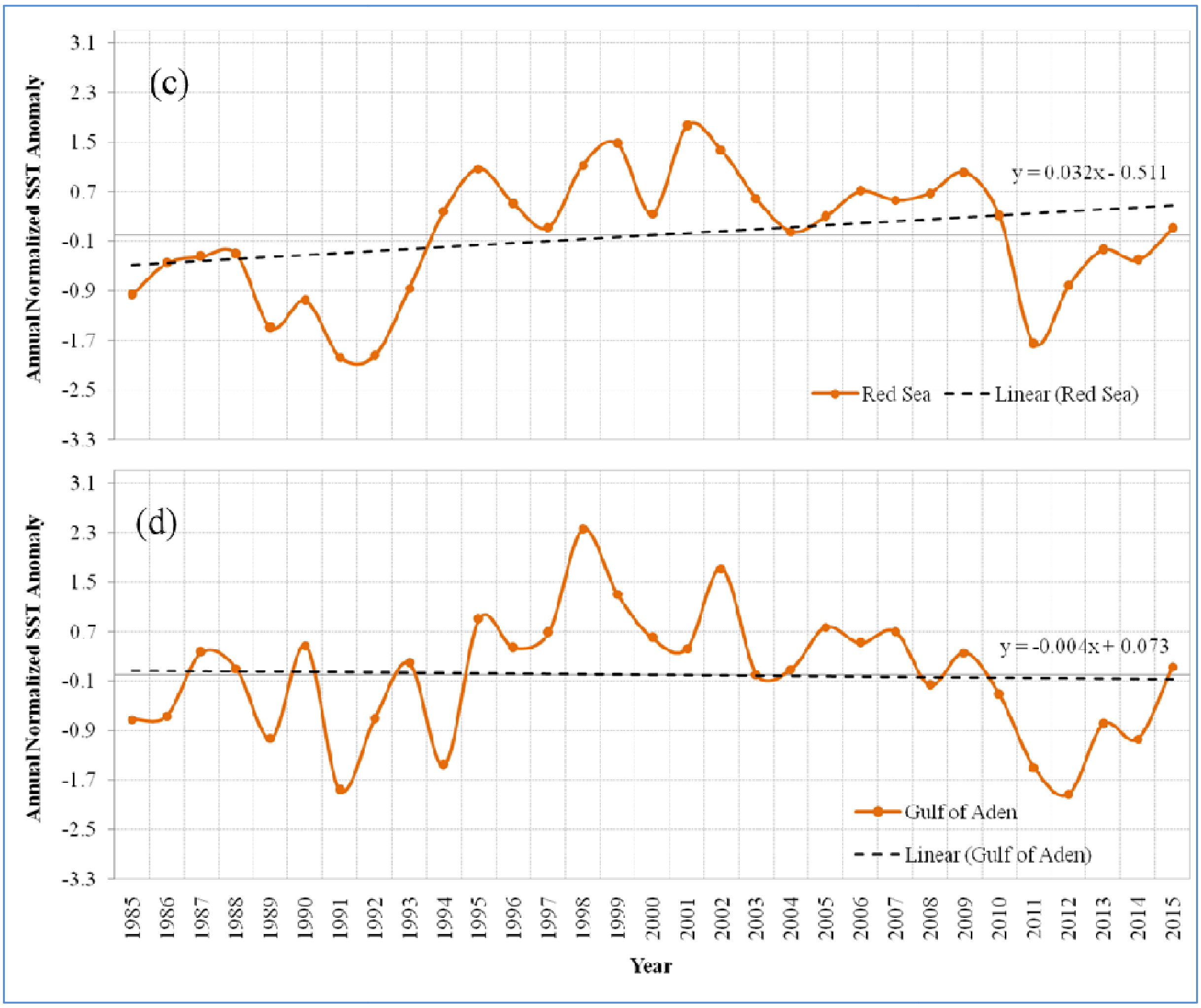

Fig. 3.11 (c –d): Interannual variability of Normalized SST Anomaly in
(c): Red Sea
(d): Gulf of Aden

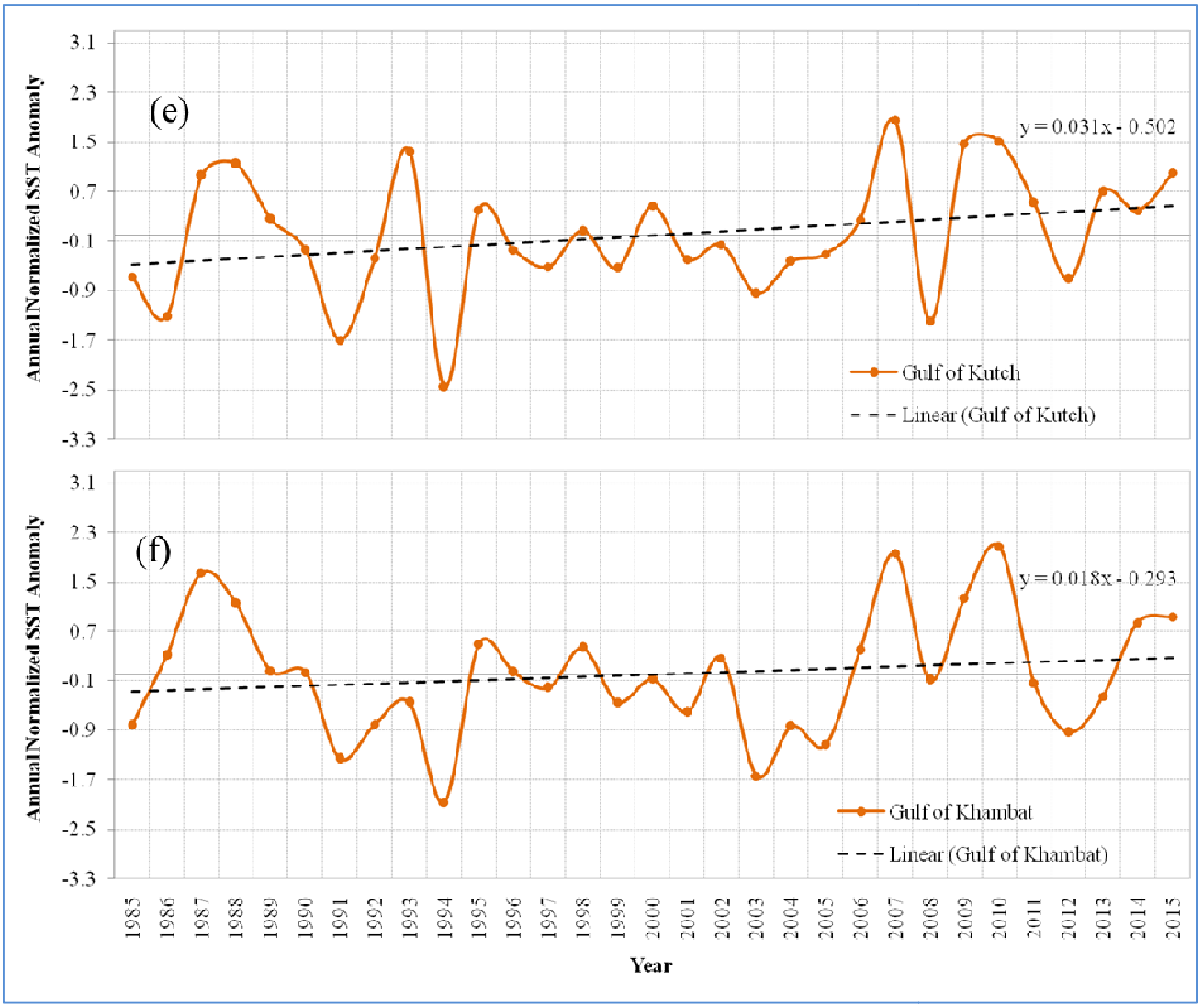

Fig. 3.11 (e –f): Interannual variability of Normalized SST Anomaly in (e): Gulf of Kutch (f): Gulf of Khambat

For a more comprehensive spatial variability of SST in the Arabian Sea across 31 years, the eastern and western Gulfs of the Arabian Sea and the Red Sea were analyzed. The interannual variability of SST in these water bodies are shown in Fig. 3.11 (a-f).

In the Persian Gulf (Fig. 3.11 a), the climatological annual mean SST was found to be 26.65°C for the period from 1985 to 2015. It was observed that the normalized anomalies increased substantially from -0.63 (1985) to +0.89 (2014). In the last decade of 2005 to 2015, only for 2005 (-0.12) and 2015 (-1.69), negative deviation of the SST anomalies from climatological mean were observed. For rest of the eight years of the decade, the normalized anomalies were found in the range of +0.2 to +1.67. The year 2010 was the warmest for Persian Gulf, as its SST anomaly reached up to +1.67 - the highest for the study period.

Similar to Persian Gulf, Red Sea (Fig. 3.11 c) also exhibited a substantial increase in its annual normalized SST anomaly. The climatological mean SST for Red Sea was found to be 28.1°C for the period from 1985 to 2015, during which its annual normalized SST anomaly increased from -0.96 to +0.11. It was observed that prior to 1995, for all the years (with exception of 1994) the SST anomalies were negative, highlighting that the Red Sea was comparatively cooler in the decade 1985 to 1995. Additionally, it was also noticed that post 1995, only in the years 2011 (-1.75), 2013 (-0.23) and 2014 (-0.40) showed negative deviation from the climatological mean SST in the Red Sea. From 1995 to 2015, the positive anomalies were of the magnitude +1.07 (1995), +1.13 (1998), +1.48 (1999), +1.76 (2001) and +1.37 (2002). This increase in the positive anomalies depicts the considerable increase in the warming up of the Red Sea.

In the Gulf of Oman (Fig. 3.11 b) also an increase in the normalized SST anomaly was observed during 1985 to 2015. The SST anomaly increased from 1985 to 2002 from -0.54 to +1.49. However, from 2003 onwards, the normalized anomalies deviated negatively from the climatological mean, and this deviation was more profound in the last 5 years from 2010 to 2014, with SST anomalies in the range -0.16 (2010), -0.81 (2011), -0.54 (2012), -1.09 (2013) and -1.14 (2014).

The annual normalized SST anomaly in the Gulf of Aden (Fig. 3.11 d) on the contrary showed a decreasing trend. It was observed that the annual SST anomalies increased from -0.72 (1985), reaching up to +2.35 (in 2002). However, from 2003 onwards a decrease in the SST anomalies was found. More importantly, from 2010 to 2015, all the years showed negative deviation from the climatological mean, with the anomalies varying in the range from -0.32 (2010) to -1.92 (2012).

In the two eastern gulfs of the Arabian Sea, viz. Gulf of Kutch (Fig. 3.11 e) and Gulf of Khambat (Fig. 3.11 f) also the normalized SST anomalies increased. However, this increase was more prominent in the Gulf of Kutch than in Gulf of Khambat. The climatological mean SST of Gulf of Kutch was observed to be 26.67°C while those of Gulf of Khambat was 27.56°C for the period 1985-2015. The annual normalized SST anomaly in Gulf of Kutch increased from –0.68 (1985) to +1.0 (2015), where as in the Gulf of Khambat it increased from –0.82 (1985) to +0.94 (2015). In the Gulf of Kutch (Fig. 3.11 e), it was noticed that post 2005, for all the years (except 2008 and 2012), the SST anomaly deviated positively from the climatological mean with normalized anomalies reaching up to +1.85 (2007), +1.47 (2009), +1.51 (2010) and +1.0 (2015). In the Gulf of Khambat (Fig. 3.11 f), from 1985 to 1995, the annual SST decreased with the normalized anomalies reaching up to -2.06 (1994). However, post 1995 there has been considerable warming, which continued till 2010, with the normalized anomalies reaching to +1.97 (2007), +1.24 (2009) and +2.07 (2010). From 2011 to 2013, although there was cooling observed in the Gulf of Khambat, as the anomalies deviated negatively from the climatological mean for three consecutive years. But the pace of warming resumed in 2014 and 2015 with normalized anomaly at +0.84 and +0.94 respectively.

3.4.7 Trend Analysis of Monthly & Annual Mean SST of Arabian Sea

The satellite SST data retrieved from NOAA AVHRR and MODIS Aqua, provide a comparatively longer, continuous 31 years of data (1985 to 2015), required for climate change studies. As these data are at 4 km resolution, they help in regional analysis of the different domains within the vast oceans. In the present study, monthly and annual SST trend for different domains of Arabian Sea was carried out using the standard Mann-Kendall test at 95% significance level.

Table 3.2 gives the statistical z-value of the trend analysis of the Mann-Kendall test and table 3.3 summarizes the resulting trend.

Table 3.2: Z-value (Mann-Kendall Trend Test statistics) for the Monthly and Annual Mean SST for different domains of Arabian Sea

	ASB	NAS	SAS	EAS	WAS	PG	GO	RS	GA	GKTCH	GKMBT
Jan	0.99	1.05	0.08	0.99	0.14	1.16	0.58	1.46	0.48	**-2.55***	**-2.69***
Feb	1.12	0.88	0.51	0.88	0.58	1.16	0.88	**2.40***	-0.2	-1.46	**-2.65***
Mar	1	**1.73***	-0.49	0.82	0.31	**3.03***	**2.46***	**1.85***	-1.38	-0.99	-0.95
Apr	0.65	0.95	0.12	0.48	0.82	**3.20***	**2.35***	1.16	-0.48	0.48	0.76
May	**1.67***	0.29	1.02	0.99	1.09	**2.41***	0.71	0.85	-0.85	0.82	**1.77***
Jun	**1.99***	0.42	**1.82***	**1.78***	1.58	**2.60***	**-1.65***	-0.19	-0.32	0.61	1.22
Jul	**1.67***	-0.1	**1.63***	**1.62***	0.37	**4.20***	**-1.73***	0.92	**-2.11***	1.53	0.75
Aug	**4.08***	**2.35***	**3.01***	**3.60***	**2.80***	**3.19***	-0.85	0.71	0.37	**1.73***	1.63
Sep	**3.69***	**1.87***	**3.71***	**3.26***	**3.06***	**2.43***	-0.24	-0.17	-0.44	0.44	1.46
Oct	**3.50***	1.5	**3.04***	**3.09***	**2.69***	-0.17	0.44	0.58	0.24	1.43	**1.70***
Nov	**3.60***	1.02	**3.25***	**2.72***	**2.65***	0	1.16	1.5	0.99	0.75	0.58
Dec	**2.41***	**1.70***	**1.97***	**2.48***	1.53	-0.34	1.46	1.5	**2.28***	0.24	-0.07
Annual	**4.45***	**1.84***	**2.41***	**2.79***	**2.35***	**3.20***	0.71	1.39	-0.41	1.39	0.51

**trend significant at 95% confidence level*

Table 3.3: Mann-Kendall Trend Test results for the Monthly and Annual Mean SST for different domains of Arabian Sea during 1985-2015

	ASB	NAS	SAS	EAS	WAS	PG	GO	RS	GA	GKTCH	GKMBT
Jan	U	U	U	U	U	U	U	U	U	D*	D*
Feb	U	U	U	U	U	U	U	U*	D	D	D*
Mar	U	U*	NT	U	U	U*	U*	U*	D	D	D
Apr	U	U	U	U	U	U*	U*	U	D	U	U
May	U*	U	U	U	U	U*	U	U	D	U	U*
Jun	U*	U	U*	U*	U	U*	D*	D	D	U	U
Jul	U*	NT	U*	NT	U	U*	D*	U	D*	U	U
Aug	U*	U*	U*	U*	U	U*	D	U	U	U*	U
Sep	U*	U*	U*	U*	U*	U*	D	D	D	U	U
Oct	U*	U	U*	U*	U*	D	U	U	U	U	U*
Nov	U*	U	U*	U*	U*	U	NT	U	U	U	U
Dec	U*	U*	U*	U*	U	D	U	U	U*	U	D
Annual	U*	U*	U*	U*	U*	U*	U	U	D	U	U

(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)*

From Table 3.2 and Table 3.3, it can be seen that the z-values of SST for all the months from January to December of Arabian Sea, and its northern, southern, eastern as well as western domains are positive, indicating an increasing trend. However, statistically significant upward trend was observed for all the months from May to December in the Arabian Sea basin. In the Southern and Eastern domains, significant warming has taken place in the months from June to December, while the Western domain showed substantial warming during the peak monsoon months of August-September and the subsequent months of October-November. The Northern Arabian Sea, which is also the domain for the occurrence of phytoplankton blooms during the NEM season, exhibited significant warming trend during the months of December and March as well as August and September. A major finding of the trend analysis was that there has been a statistically significant warming of the Arabian Sea on an annual scale.

In case of the gulfs and the marginal sea of Arabian Sea, the trend analysis of monthly and annual mean SST was distinct from the northern, southern, eastern and western domains. In the eastern gulfs of Arabian Sea, i.e. the Gulf of Kutch and Gulf of Khambat, cooling was observed for the months from January – March, though this cooling was significant only for January and February. For the rest of the months, warming was observed with an upward trend, which was significant only during August in Gulf of Kutch and May and October in Gulf of Khambat. In the Red Sea, February and March were the months during which significant warming was found, where as in Gulf of Aden significant warming was only during December. A unique trend was observed for monthly SST of Gulf of Aden, as unlike the rest of the domains of Arabian Sea, downward trend of SST was observed for the months from February to July and September, and this was also reflected in the annual mean SST trend. However, this cooling in different months of the Gulf of Aden was found to be significant only during the month of July.
Among the western gulfs of the Arabian Sea, the Persian Gulf, owing to its unique hydrographic features, depicted a different trend of SST from the rest of gulfs of the basin. Significant upward trend of SST was observed for the months from March to September. Besides, among the rest of the gulfs and the Red Sea, it was only the Persian Gulf in which that annual mean SST showed a statistically significant upward trend. The Gulf of Oman, although adjacent to the Persian Gulf,

yet it exhibited a downward trend of SST during the South West Monsoon season from June to September.

3.5 CONCLUSIONS

Sea-surface temperature (SST) is one of the key physical parameters, exerting an influential role in many of the oceanographic processes. The warming of the oceans across months, years and seasons, helps in investigating the impact of climate change and also in quantifying the rate of the change. In the present work, a detailed examination of the seasonal and annual changes in the SST of the Arabian Sea was done using two different data sets, viz. the ERSST data which was a coarse data of 2° x 2° spatial resolutions. This data set was able to provide sufficient evidence that there has been a substantial warming of the Arabian Sea Basin since 1950 to 2015. However, for the analysis of the changing trend in different domains of the Arabian Sea, the 4 km NOAA SST and MODIS Aqua SST data sets were analyzed. From the results obtained, the following conclusions can be drawn:

1. **Annual and Seasonal variability of SST of Arabian Sea during from 1950 to 2015**
   (a) There has been a rapid warming of the Arabian Sea, with the annual SST increasing by 0.78 °C in past 65 years.
   (b) From 1950 to 1995, for most of the years, the annual SST anomalies were negative. However, post 1995-96, all the years had positive SST anomalies, implying that in the last 20 years from 1995 to 2015, the basin has warmed up significantly.
   (c) The warming of the Arabian Sea was also evident from the seasonal analysis of SST, with increasing SST in all the four seasons.

(d) The highest rise in SST was observed during the SWM season, with the normalized SST anomalies increasing at the rate of +0.43 units/ decade, followed by those during the AIM (+0.41 units /decade).

(e) The occurrence of positive SST anomalies in almost all the years post 1995, was also seen for all the four seasons as well. This strongly provides the evidence that an unprecedented warming of the basin has occurred in the last 20 years.

(f) It was also found that post 2010, for all the years, the positive normalized anomalies were higher with their units being > +1.0, making it evident that in the last 5 years, there has been a more rapid warming of the Arabian Sea than the preceding years.

2. Inter-decadal variability of Arabian Sea SST during the period 1950 to 2015

(a) There has been a rise in SST of the Arabian Sea across all the decades from 1950 to 2015.

(b) The rise in SST was the highest in the last two decades from 2001 onwards.

(c) Though the SST data for only 5 years for the decade 2010 was analyzed, yet the SST for this period was the highest of all. This further proves that there the warming in last 5 years has been most significant and rapid.

3. Monthly Climatologically Mean SST of Arabian Sea from 1985 to 2015

(a) The satellite images of SST provided evidence for different warming pattern in different domains of the Arabian Sea.

(b) The SST maps of the period 1985, 1995, 2005 and 2010, showed rise in SST across the years.

(c) There has been an expansion of the warm waters of the Arabian Sea in the range of 30-32°C, from the southeast domain to the central domain of the Arabian Sea.

(d) Differences were observed in the bimodal pattern of SST across the months, in different domains of the Arabian Sea, with the western gulfs viz. the Persian Gulf, Gulf of Oman, and the Red Sea exhibiting a distinct unimodal SST curve with minimum temperature during the Northeast Monsoon season and maximum during the Southwest Monsoon season.

4. Interannual variability of SST in different domains of Arabian Sea from 1985 to 2015

(a) Increase in SST was observed in all the domains of the Arabian Sea, with the exception of the Gulf of Aden.

(b) The warming eastern and southern domains was higher, with their normalized SST anomalies increasing at the rates of +0.56 units /decade and +0.51 units /decade, respectively.

(c) In the western gulfs of the Arabian Sea, the warming in the Persian Gulf and the Red Sea has been more than those of the Gulf of Oman and Gulf of Aden.

(d) Amongst the eastern gulfs of the basin, the rise in SST was more prominent in the Gulf of Kutch than in Gulf of Khambat.

5. SST Trend in Arabian Sea and its domains

(a) From 1985 to 2015, there has been an upward trend of annual SST in all the domains of the Arabian Sea, except for the Gulf of Aden, and these trends was statistically significant for the Arabian Sea basin, its northern, southern, eastern and western domains along with the Persian Gulf.

(b) Significant warming has occurred during the months from June to December in Eastern and Southern domains.

(c) Whereas in the northern domain, significant warming has happened during the months of March, August, September and December; whereas the western domain showed significant warming during September, October and November.

The climatological monthly, seasonal and annual study of the different domains revealed that, like the Arabian Sea basin, the sub domains, viz. the northern, southern, eastern and western domains of the Arabian Sea as well the eastern and western gulfs and the Red Sea are warming up speedily. The only exception to this trend was the Gulf of Aden, where substantial cooling has been observed. Moreover, the results are in coherence with those of *Kumar et al. (2009)*, who reported about the increasing SST of the Arabian Sea and concluded that the anthropogenic induced global warming is disrupting the decadal cycle of SST of Arabian Sea after 1995. In the present study, also a clear demarcation of the interannual SST variability is seen for the pre 1995 and post 1995 period.

In most of the domains, the normalized SST anomalies for most of the years from 1985 to 1995 were found to be negative implying the mean SST to be below the climatological mean. While the normalized SST anomalies for most of the years from 1995 to 2010 were found to be positive. The positive anomalies post 1995 ranged from +0.8 to at times even +2. This highlights the alarming rate at which the surface water of the Arabian Sea in different domains are warming up. However, a major cause of concern was the warming up of the northern and western domains of the Arabian Sea which have been known to be the regions for phytoplankton bloom and higher productivity.