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Research Article

Comparative Analysis of Sea Surface Temperature Pattern in the Eastern and Western Gulfs of Arabian Sea and the Red Sea in Recent Past Using Satellite Data

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With unprecedented rate of development in the countries surrounding the gulfs of the Arabian Sea, there has been a rapid warming of these gulfs. In this regard, using Advanced Very High Resolution Radiometer (AVHRR) data from 1985 to 2009, a climatological study of Sea Surface Temperature (SST) and its inter annual variability in the Persian Gulf (PG), Gulf of Oman (GO), Gulf of Aden (GA), Gulf of Kutch (KTCH), Gulf of Khambhat (KMBT), and Red Sea (RS) was carried out using the normalized SST anomaly index. KTCH, KMBT, and GA pursued the typical Arabian Sea basin bimodal SST pattern, whereas PG, GO, and RS followed unimodal SST curve. In the western gulfs and RS, from 1985 to 1991-1992, cooling was observed followed by rapid warming phase from 1993 onwards, whereas in the eastern gulfs, the phase of sharp rise of SST was observed from 1995 onwards. Strong influence of the El Niño and La Niña and the Indian Ocean Dipole on interannual variability of SST of gulfs was observed. Annual and seasonal increase of SST was lower in the eastern gulfs than the western gulfs. RS showed the highest annual increase of normalized SST anomaly (+0.64/decade) followed by PG (+0.4/decade).

1. Introduction

In today's era, one of the greatest challenges faced by humankind is "global warming." There has been a 0.6°C increase in global temperature in the last century, and it is projected to further increase by 1.8°C to 4°C in the 21st century [1], posing a serious threat to the socioeconomic sector worldwide. With oceans covering approximately 72% of the earth's surface, any discussion on climate change and global warming would remain incomplete without including the role of the oceans. Studies have revealed that because of the increase in greenhouse gases, the oceans are warming significantly, which is affecting the marine ecosystem [2–5], resulting in shifting of habitats and dwindling of marine biota. Most of the studies with respect to climate change have focussed on global scale changes [5–15]. However, an exhaustive analysis at the regional and local levels is needed for framing adaptive and mitigative strategies to alleviate the effect of global warming.

In the Indian context, the recent finding, that amongst the oceans, the warming of the Indian Ocean is second highest [15], is a cause of worry and calls for immediate attention. Even though climatological studies have been done in the past in the Indian Ocean encompassing the Arabian Sea and the Bay of Bengal [16–20], a comparative analysis of the changing Sea Surface Temperature (SST) pattern the gulfs of Arabian Sea (Persian Gulf, Gulf of Oman, Gulf of Aden, Gulf of Kutch, and Gulf of Khambhat) and the Red sea has not been done. The gulfs of the Arabian Sea are not just strategically important with rich sources of oil and natural gas but are also the hot spots of the marine biodiversity [21–28]. However, in the recent years, there has been an expeditious change in the marine ecosystem of the eastern and western gulfs of the Arabian Sea and the Red Sea, owing to anthropogenic interference [29–32]. Since 1990s, 40% of the coasts of the Persian Gulf have been modified [33]. The Persian Gulf and the Red

Sea areas have been reported to be warming rapidly owing to the developmental projects undertaken in the surrounding coastal countries [30–32]. The Gulf of Kutch on the Indian coast is being aggressively developed as oil importing bases because of its proximity to the Middle East countries [29]. In general, the issues of common concern in the eastern and western gulfs of the Arabian Sea and the Red Sea include various anthropogenic activities like industrialization, coastal infrastructure development projects, setting up of new ports and oil terminals, oil pollution from shipping industry, overfishing, dredging, and increase in tourism and recreational activities. [29–32, 34], resulting in habitat destruction, changes in temperature and salinity profile, and causing a significant loss of biodiversity [35].

In this regard, the present work was taken up to study the monthly, seasonal, and annual pattern of Sea Surface Temperature (SST) and to analyse its changing pattern with emphasis on interannual variability in the eastern (Gulf of Kutch and Gulf of Khambhat) and the western gulfs (Persian Gulf, Gulf of Oman, and Gulf of Aden) of the Arabian Sea and the Red sea.

2. Materials and Methods

2.1. Area of Study. The gulfs of the Arabian Sea basin (Figure 1(a)) can be grouped into the eastern and the western branches. The eastern branch includes the Gulf of Kutch and the Gulf of Khambhat on the Indian coast, whereas the western branch includes the Gulf of Oman and the Persian Gulf in the northwestern part of Arabian Sea, and the Gulf of Aden in the southwestern part of Arabian Sea, connecting it with the Red Sea.

2.1.1. Persian Gulf. The Persian Gulf (24–3°N; 48–56.5°E), (Figure 1(b)) located in an arid subtropical zone, is a semienclosed shallow, marginal sea with an average water depth of 36 m. It is spread over an area of 239,000 km^2 and is 990 km in length. It is connected to the Gulf of Oman through the 56 km wide Strait of Hormuz [36].

In the Persian Gulf, the seasonal differences of insolation, along with cold winds from the nearby highlands, result in extreme temperature (ranging from 16°C to 35°C) [36] and salinity (ranging from 36 to 43 parts per thousand) conditions [37]. However, despite the extreme conditions, the offshore waters of the Persian Gulf are rich in nutrients and support a variety of marine photoautotroph like the macroalgae, phytoplankton, mangroves, sea grass beds, and intertidal vegetation [25].

2.1.2. Gulf of Oman. The Gulf of Oman (22°3–26°5′N; 56.5–61°43′E) is a strait connecting the Arabian Sea with the Persian Gulf (Figure 1(c)). The Gulf of Oman is 320 km wide and 560 km long.

Some of the most powerful eddy currents of the Arabian Sea are located close to the Omani coast. The coastal areas of the Gulf of Oman support varied habitats including mangrove swamps, lagoons, and mudflats.

2.1.3. Gulf of Aden. The Gulf of Aden (GA) (10°–15°N; 43°–52°E), connecting the Red Sea with the Arabian Sea, is part of the Suez Canal shipping route between the Mediterranean Sea and the Indian Ocean (Figure 1(d)). It is about 900 km long, with average depth of 1800 m, and covers an area of about 220×10^3 km^2. Its importance lies in the fact that it provides an outlet to the saline water masses of the Red Sea into the Arabian Sea [38].

2.1.4. Red Sea. The Red Sea (RS) (12°29′N–27°57′N; 34°36′E–43°30′E) is approximately 2,100 km long and 280 km wide (Figure 1(e)). The average depth is about 500 m, but at places it is more than 2,000 m deep. The Red Sea is linked to the Mediterranean Sea by the Suez Canal in the north, whereas in the south, it is connected to the Arabian Sea through the Gulf of Aden.

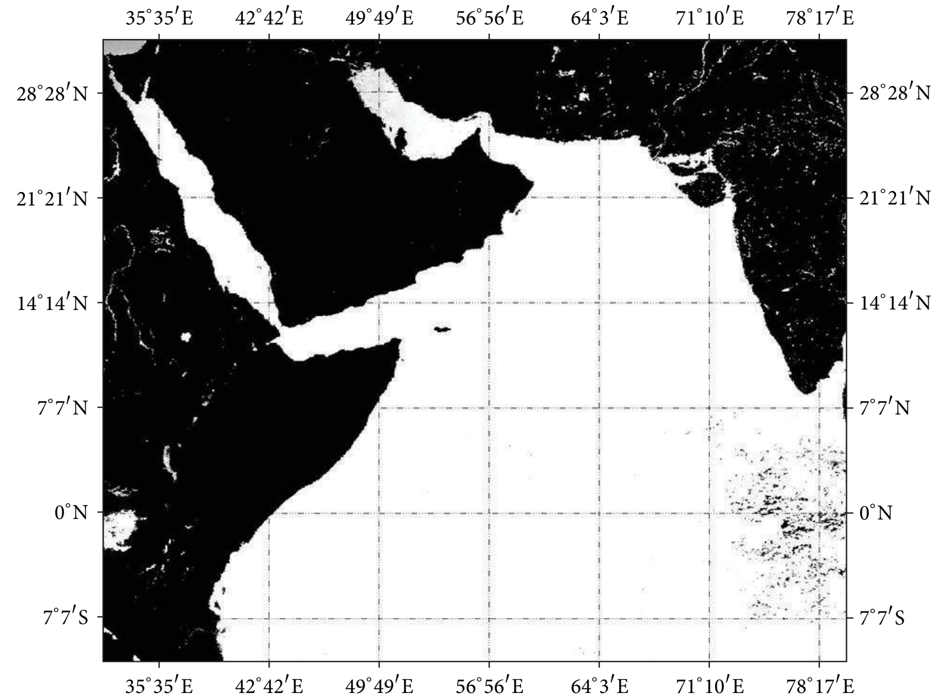
The waters of the Red Sea are warm and saline. The temperature ranges from 21°C–28°C in the north and 26°C to 32°C in the south. Salinities in the Red Sea range from 37% in the south to 42% in the north. A consequence of these extreme conditions is that some species within the Red Sea (like mangroves, shallow sea grasses, etc.) probably exist at the limits of their physiological tolerance [30].

2.1.5. Gulf of Kutch. The Gulf of Kutch (22°15′–23°4′N; 68°20′–70°40′E) encloses an area of 7350 km^2 (Figure 1(f)). Towards the western end, the Gulf is about 75 km wide and 60 m deep, while in the eastern end it is 18 km wide and less than 20 m deep. It is under the influence of strong tidal currents. High rate of evaporation, along with the release of salty water from the adjoining saltpans of Rann of Kutch, makes the eastern part of the Gulf of Kutch more saline (40%) than the western part (35%). The temperature of the Gulf waters varies between 24°C to 30°C.

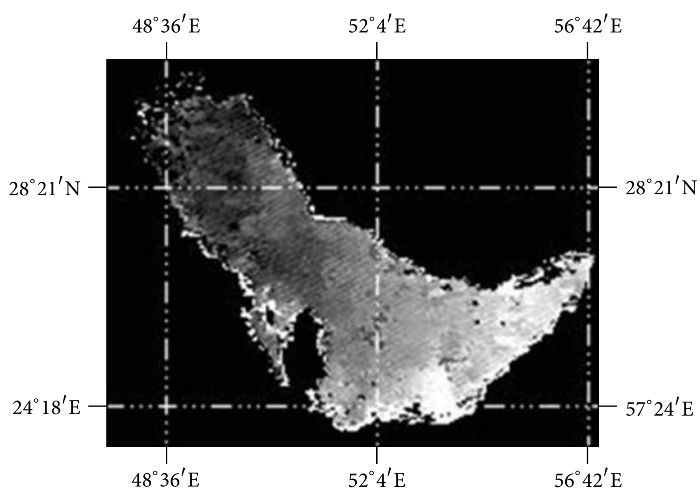
The Gulf of Kutch is one of India's only coastal areas endowed with coral reefs. It provides a platform for different habitats like coral reefs, mangroves, creeks, mud flats, islands, rocky shore, sandy shore, and so forth and hence is enriched in biodiversity [29].

2.1.6. Gulf of Khambhat. Gulf of Khambhat (between 72°2′E to 72°6′E and 21° to 22°2′N) is one of the major fishing areas along western coast of India (Figure 1(f)). It is about 80 km wide at mouth and tapers to 25 km along the coast. It is about 140 km in length and is characterised by several inlets and creeks formed by the confluence of rivers. The Gulf of Khambhat is shallow with about 30 m average depth and abounds in shoals and sandbanks. It is known for its extreme tides. The tidal range at Gulf of Khambhat is known to be one of the largest along the Indian coastline [39].

2.2. Data Used. The regional effect of the global warming in the oceanic water masses needs to be assessed and quantified. However, the lack of uniform data and methodology hampers such regional analysis [1]. With the availability of National Oceanic and Atmospheric Administration's (NOAA) Advanced Very High Resolution Radiometer



(a)



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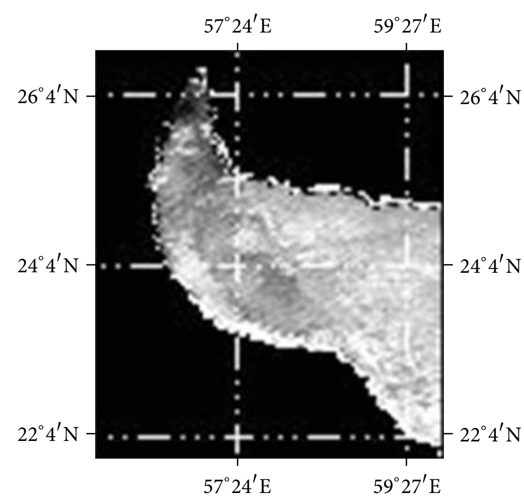

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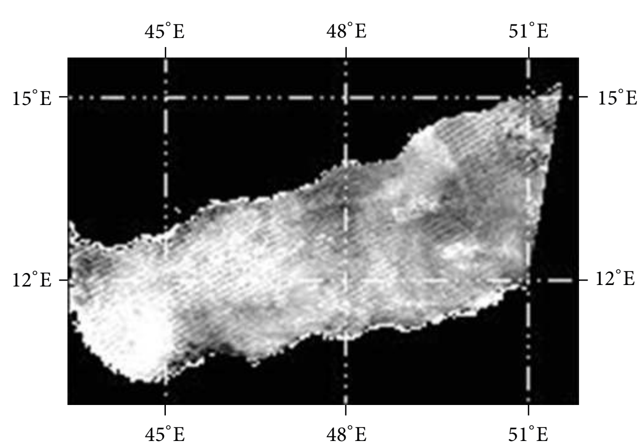

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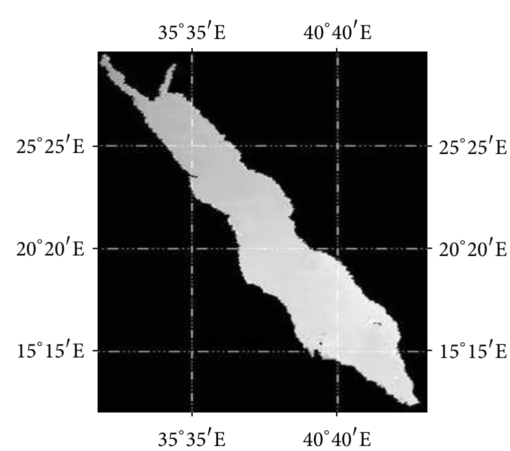
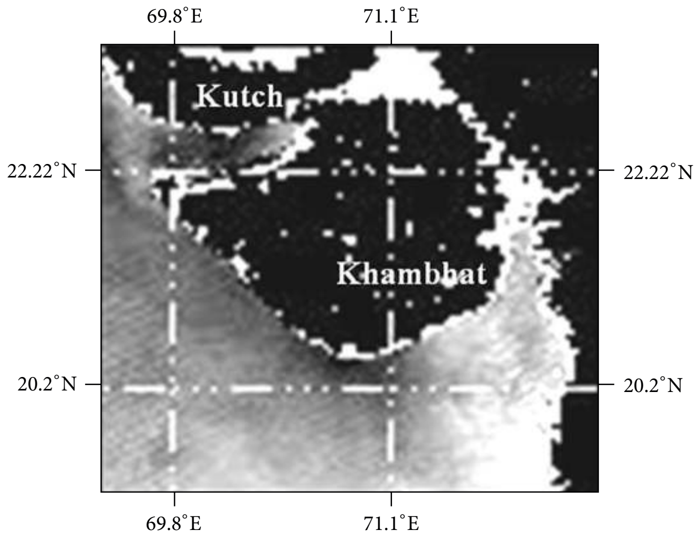


(e)

Figure 1: Continued.



(f)

Figure 1: (a) Area of Study showing Arabian Sea basin. (b) Persian Gulf. (c) Gulf of Oman. (d) Gulf of Aden. (e) Red Sea. (f) Gulf of Kutch and Gulf of Khambhat.

(AVHRR) satellite data set, for 25 years of span (1985–2009), to some extent the problem of uniformity of data has been solved. Besides, the high resolution satellite derived SST data gives better results than *in situ* data in terms of its continuity and spatial coverage. Even though Reynolds SST and National Center for Environmental Prediction (NCEP) reanalyzed data sets [40] are available for longer periods, but their low spatial resolution (1° and 2.5°, resp.) and interpolation and reanalysis methods do not accurately capture the coastal areas and the upwelling regions [41].

In this study the monthly NOAA AVHRR Pathfinder (version 5.0) SST data at 4 km resolution was obtained from NASA'S Jet Propulsion Laboratory's Physical Oceanographic Centre (http://podaac.jpl.nasa.gov/), for the period 1985–2009, for climatological study of the eastern and western gulfs of the Arabian Sea and the Red Sea. SST fields were derived through the Multichannel Sea Surface Temperature (MCSST) algorithm, as given by McClain [42].

2.3. Methodology. For each of the defined areas of study, the monthly 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. Following Joint Global Ocean Flux Study (JGOFS) [43], the four climatological seasons described here are

(a) northeast monsoon (December–March) (NEM),

(b) spring intermonsoon (April-May) (SIM),

(c) southwest monsoon (June–September) (SWM), and

(d) fall intermonsoon (October-November) (FIM).

The climatological mean (CM_{25}) of 25 years (1985–2009) 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_{25}) from the monthly mean ($M_{y(i)}$) of each year, and normalized to the standard deviation for that month (SD_{25}) and given as

$$M_{(\mathrm{NA})} = \frac{M_{y(i)} - \mathrm{CM}_{25}}{\mathrm{SD}_{25}}. \quad (1)$$

The seasonal and annual normalized anomalies were computed by averaging the monthly normalized anomalies over appropriate seasons and years. Coefficient of variation (CV) was used to express the magnitude of interannual variability in the annual and the seasonal SST for the eastern and the western gulfs of the Arabian Sea and the Red sea [44] and is calculated as

$$\mathrm{CV} = \frac{\text{Standard Deviation}}{\text{Mean}} \times 100. \quad (2)$$

To study the effect of El Niño and La Niña, comparison with ENSO (El Niño-Southern Oscillation) was carried out using the multivariate ENSO index, that is, MEI index, provided by the climate diagnostic centre (http://www.cdc.noaa.gov/).

3. Results

3.1. Comparison of the Monthly Climatological Mean SST (1985–2009). Figure 2 shows the comparative analysis of the monthly climatological mean SST (1985–2009) of the eastern and western gulfs of the Arabian Sea and the Red Sea. The SST in the Arabian Sea open ocean varies in a typical bimodal pattern with warming during spring inter monsoon (SIM) (April-May) and fall intermonsoon (FIM) (October-November) and cooling during the southwest monsoon (SWM) (June–September) and northeast monsoon (NEM) (December–March) seasons [45–47].

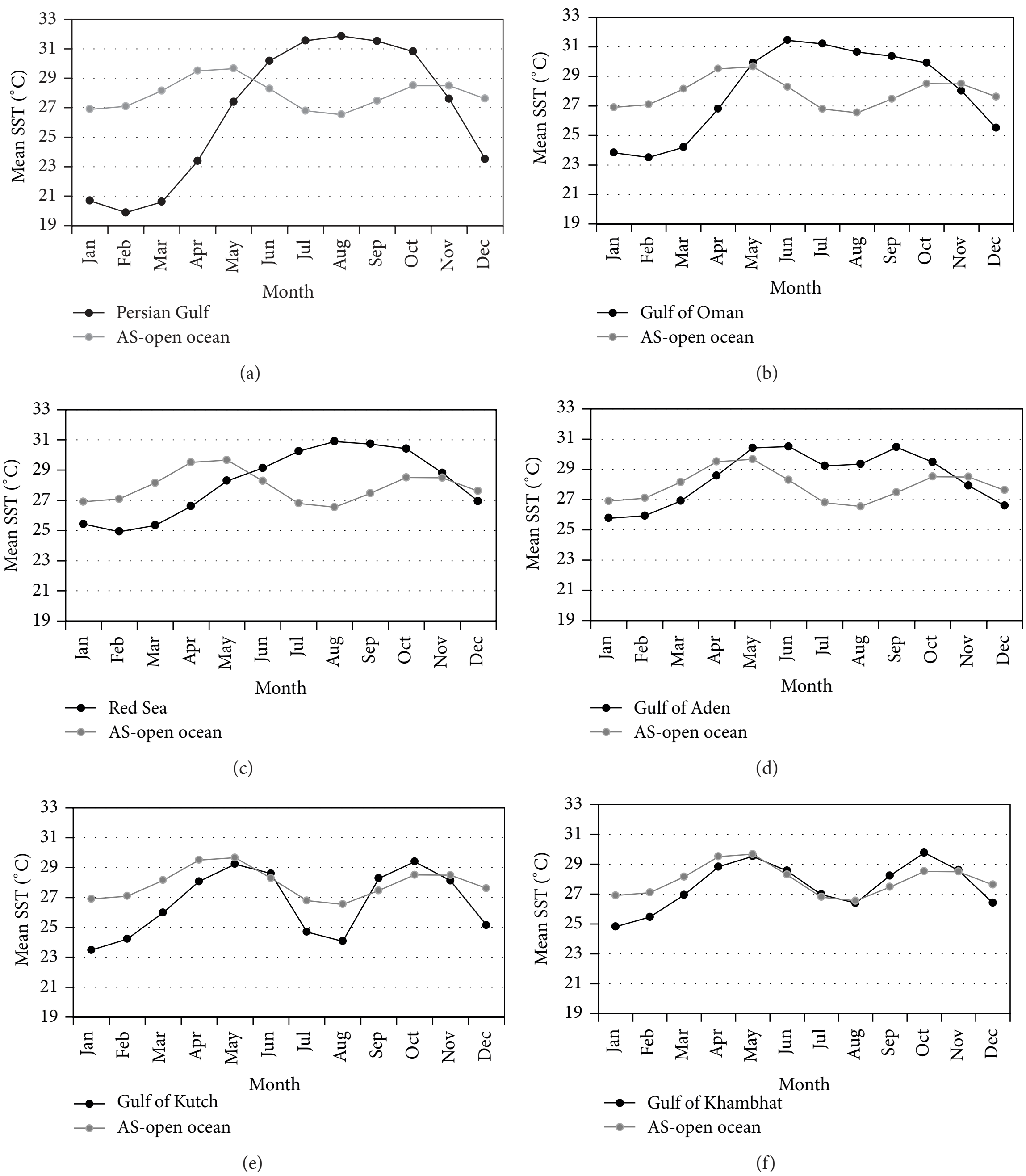


Figure 2: Comparison of the monthly climatological mean SST (1985–2009) of the Persian Gulf, Gulf of Oman, Red Sea, Gulf of Aden, Gulf of Kutch, and Gulf of Khambhat with Arabian Sea open ocean.

The Gulf of Aden and the eastern gulfs of the Arabian Sea, namely, Gulf of Kutch and Gulf of Khambhat followed the typical bimodal SST pattern as in the Arabian Sea. However, unlike the Arabian Sea open ocean where the minimum SST is observed during the months of July-August (SWM season), the minimum SST in these gulfs was found in the month of January (NEM season). In the bimodal pattern, the observed second peak of SST in the Gulf of Kutch and Gulf of Khambhat was in the month of October, similar to the Arabian Sea open ocean pattern, but in the Gulf of Aden, the second peak of SST was observed in the month of September. Climatologically, from November to April, Gulf of Aden was cooler than the Arabian Sea open ocean (by an average 1°C), while from May to October, it was warmer than the Arabian Sea open ocean (by an average 2.02°C). Climatologically, both the eastern gulfs were cooler than the Arabian Sea open ocean (by an average difference of 1.32°C and 0.38°C, resp.), for all the months, except for September and October. Besides, in the months of July and August Gulf of Kutch was found to be cooler than Arabian Sea open ocean months by more than 2°C, whereas in Gulf of Khambhat no such significant difference was found.

The Persian Gulf, Gulf of Oman, and the Red Sea exhibited a distinct unimodal SST curve instead of the typical bimodal pattern as in the Arabian Sea open ocean, with minimum temperature during the NEM season and maximum temperature during the SWM season. Whereas the minimum temperature for these three water bodies was in February, the maximum temperature in the Persian Gulf and the Red sea was in 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 (by an average 4.9°C, 2.2°C, and 1.9°C, resp.), while from June to October they were warmer than the Arabian Sea open ocean (by an average 3.7°C, 2.7°C and 2.08°C, resp.). Amongst the eastern and western gulfs of the Arabian Sea and the Red Sea, the Persian Gulf exhibited the highest range of SST (11.97°C).

3.2. Interannual Variability of SST in the Eastern and Western Gulfs of Arabian Sea and Red Sea from 1985 to 2009

3.2.1. Comparison of the Annual Normalized SST Anomaly from 1985 to 2009. A time series study of the interannual variability of SST can be seen from Figure 3. A warming trend was observed in all the gulfs of the Arabian Sea in terms of the increasing annual normalized SST anomalies from 1985 to 2009. Whereas in the eastern gulfs of the Arabian Sea, the annual increase of normalised SST anomaly from 1985 to 2009 was insignificant with the Gulf of Kutch and Gulf of Khambhat showing an increase of 0.19/decade and 0.1/decade, respectively, in the western gulfs of the Arabian Sea and the Red sea, a sharp increase in SST was observed with the maximum rate of increase of normalized SST anomaly in the Red Sea (0.64/decade) followed by the Persian Gulf (0.4/decade).

A remarkable time lag in the rise of annual SST was found between the eastern and the western gulfs of the Arabian Sea and the Red Sea. For the western gulfs of the Arabian Sea and the Red Sea, a sharp increase in the annual SST was observed from 1992-1993 to 2009. However, for the eastern gulfs, the warming was delayed till 1995, and hence instead of 1992-1993, the sharp rise of annual SST was found from 1995 onwards.

For the Persian Gulf, Gulf of Oman, and Gulf of Aden, a decrease in annual normalized anomaly (cooling) was observed from 1985 to 1991, and thereafter from 1992 to 2009, a sharp increase (warming) was found. In the Persian Gulf, the normalized anomaly decreased (by −1.61), from −0.25 in the 1985 to −1.36 in 1991 and thereafter increased (by +1.48) to +0.12 in 2009. In the Gulf of Oman normalized anomaly decreased (by −1.0) from −0.44 (1985) to −1.44 (1991) and later increased (by +1.0) to +0.45 (2009). However, in the Red Sea, the normalized anomaly decreased from 1985 to 1992, (instead of 1991), from −0.76 (1985) to −1.53 (1992), and thereafter increased to +0.64 (2009).

In the Gulf of Kutch and Gulf of Khambhat (eastern gulfs of the A rabian Sea), a significant decrease in normalized anomaly (cooling) was observed from 1985 to 1994, and thereafter from 1995 to 2009 a sharp increase in normalized anomaly (warming) was found. In the Gulf of Kutch and Gulf of Khambhat, the normalized anomaly decreased from −0.10 in 1985 to −0.92 in 1994 and subsequently increased to +0.75 in 2009. Similarly, in the Gulf of Khambhat the normalized anomaly decreased from −0.22 in 1985 to −0.75 in 1994 and later increased to +0.58 in 2009.

In the three western gulfs of the Arabian Sea, namely, Persian Gulf, Gulf of Oman, and Gulf of Aden, the maximum negative normalized SST anomaly was observed in 1991 (−1.36, −1.44, and −1.16, resp.). In the Red Sea the maximum negative normalized SST anomaly was found in 1992 (−1.5). On the other hand in both the eastern gulfs of the Arabian Sea, maximum negative normalized SST anomaly was observed in 1994 (−0.93 in Gulf of Kutch and −0.75 in Gulf of Khambhat). The maximum positive normalized SST anomaly was found to be in 1998 in Gulf of Aden (+1.54), in 1999 in Persian Gulf (+1.1), in 2001 in Red Sea (+1.1), and in 2002 in Gulf of Gulf of Oman, whereas in both the eastern gulfs of the Arabian Sea, maximum positive normalized anomaly was observed in 2007.

In the western gulfs of Arabian Sea and the Red Sea, the influence of the El Niño and the La Niña events can be seen from the crest and the troughs of the graph depicting the annual SST anomaly. For instance the La Niña years like 1985, 1986, 1989, 1996, 1999, 2000, and 2008 were found to have a high negative anomalies (cooling), and the El Niño years like 1986, 1988, 1991–1995, 1997-1998, 2002, 2006, and 2009 were observed to have a high positive normalized anomalies (warming). However, the influence of the El Niño and La Niña varied in terms of the difference in magnitude of the positive and negative anomalies. Besides, in the eastern gulfs of the Arabian Sea, only few of the El Niño (namely, 1987, 1988, 2002, and 2006) or La Niña (namely, 1989 and 2008) events influenced the warming or cooling of the gulfs.

3.2.2. Comparison of Seasonal Normalized SST Anomaly from 1985–2009. The interannual variation of SST during the four seasons, namely, northeast monsoon (NEM) (December–March), spring intermonsoon (SIM) (April-May), southwest Monsoon (SWM) (June–September), and fall inter Monsoon (FIM) (October-November), affecting the gulfs of Arabian Sea and the Red sea, was analyzed using the normalized SST anomaly indices as in Figure 4.

As seen from Figures 4(a), 4(b), 4(c), and 4(d), a similar interannual variation of SST pattern for the western gulfs of the Arabian Sea (namely, Persian Gulf, Gulf of Oman, and Gulf of Aden) and the Red Sea was observed with an increasing trend of SST in all the four seasons. However, in the eastern gulfs (Gulf of Kutch and Gulf of Khambhat), an increasing pattern of SST was found during the NEM, SIM, and FIM, but during the SWM season, cooling was observed.

During the northeast monsoon (NEM) (December–March), (Figure 4(a)), the normalized SST anomaly increased (warming) in all eastern and western gulfs of the Arabian

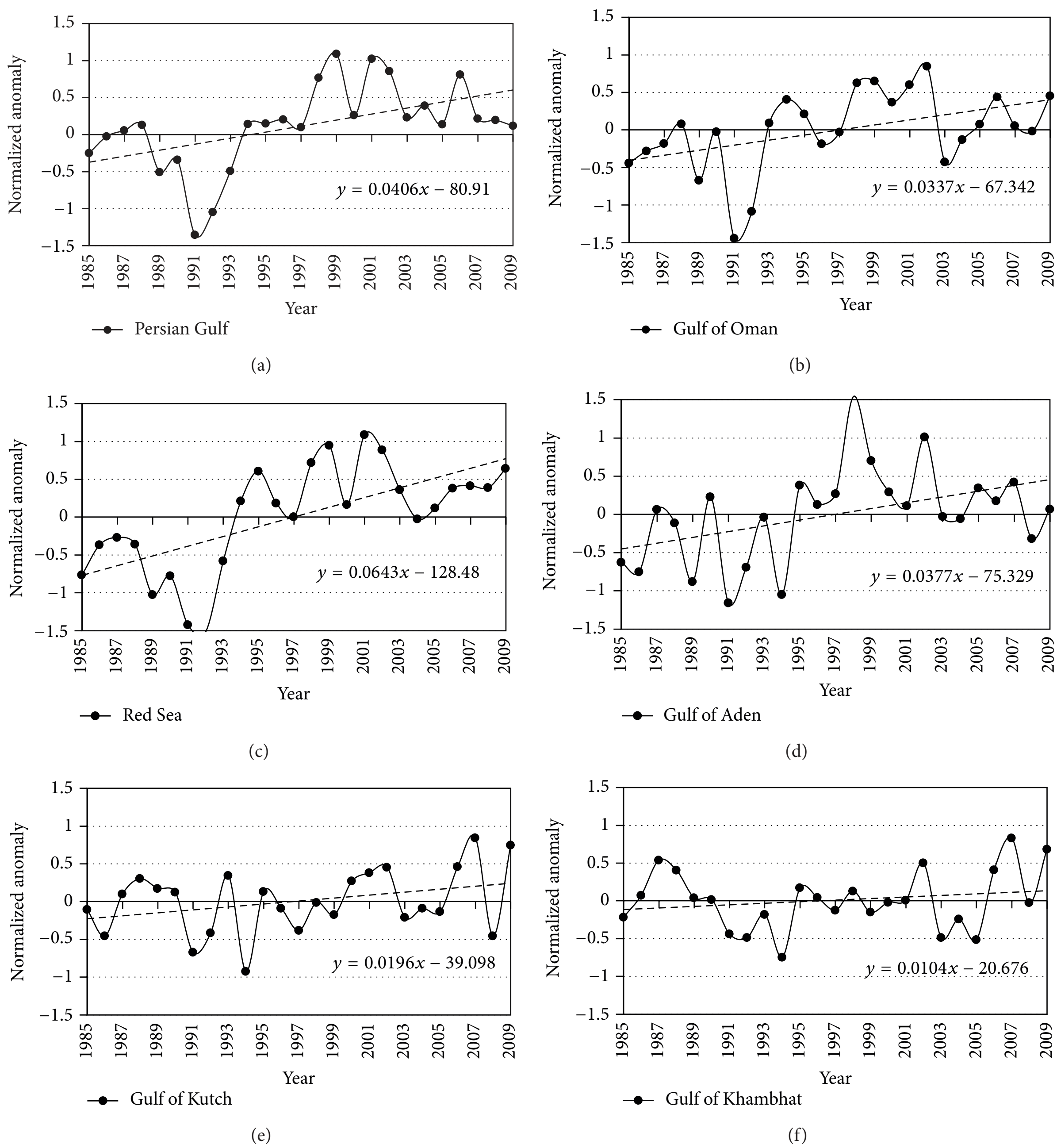
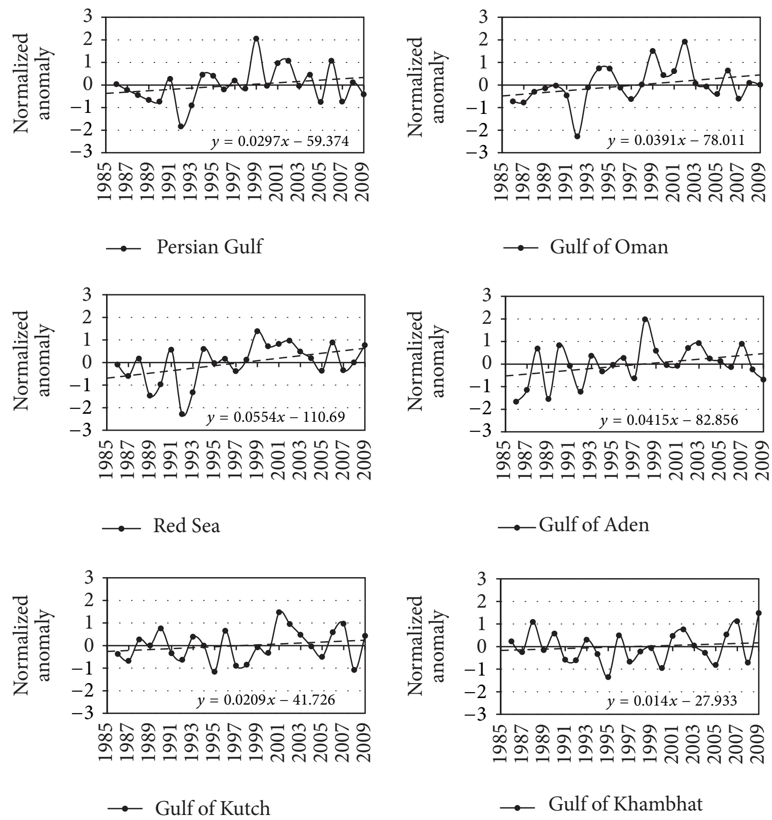
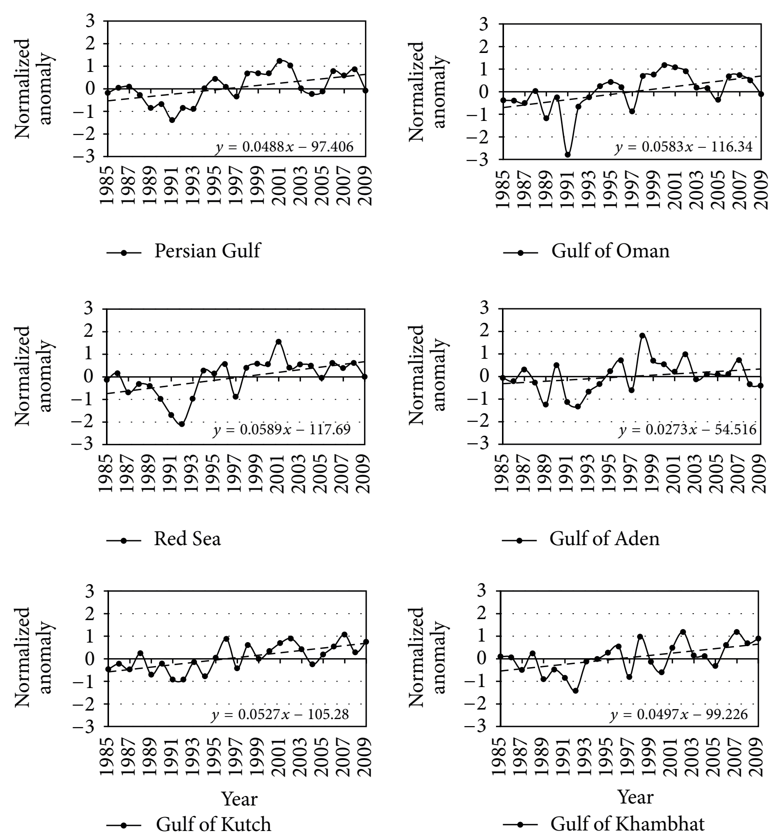


Figure 3: Comparison of the annual normalised SST anomaly from 1985 to 2009 of the Persian Gulf, Gulf of Oman, Red Sea, Gulf of Aden, Gulf of Kutch, and Gulf of Khambhat.

Sea and the Red Sea, but the increase was more in the western gulfs and the Red Sea as compared to the eastern gulfs, with the maximum rate of increase of SST in the Red Sea (0.55/decade). A similar interannual variability pattern during the NEM season was observed in the Persian Gulf, Gulf of Oman, and the Red Sea on one hand and Gulf of Aden, Gulf of Kutch, and Gulf of Khambhat on the other. From 1986 to 1992, in the Persian Gulf, Gulf of Oman, and the Red Sea, a decrease in SST anomaly was observed (cooling), which was followed by a phase of increasing SST anomaly (warming) from 1992 to 1999. From 1999 to 2005, the SST anomaly decreased substantially. However, from 2005 to 2009, again a warming phase with increasing SST anomaly was observed. In the year 1998-1999, an El Niño year, a very high positive SST anomaly was observed in the western gulfs of the Arabian Sea and the Red Sea. The warming was remarkable, as in the Persian Gulf and the Red Sea, the positive anomaly reached up to +2.05 and +1.38, respectively. Even though the Gulf of Oman showed a high positive deviation of +1.5 from the climatological mean in 1999, but its maximum positive anomaly (i.e., maximum warming) was observed during 2002 (+1.92), which was again an El Niño year. Amongst the eastern gulfs



(a) NEM



(b) SIM

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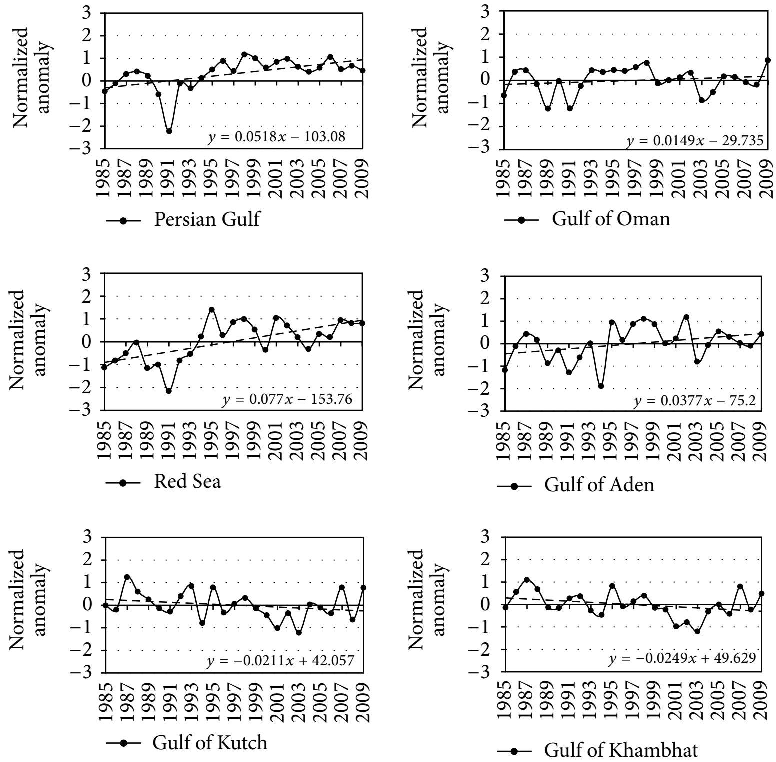
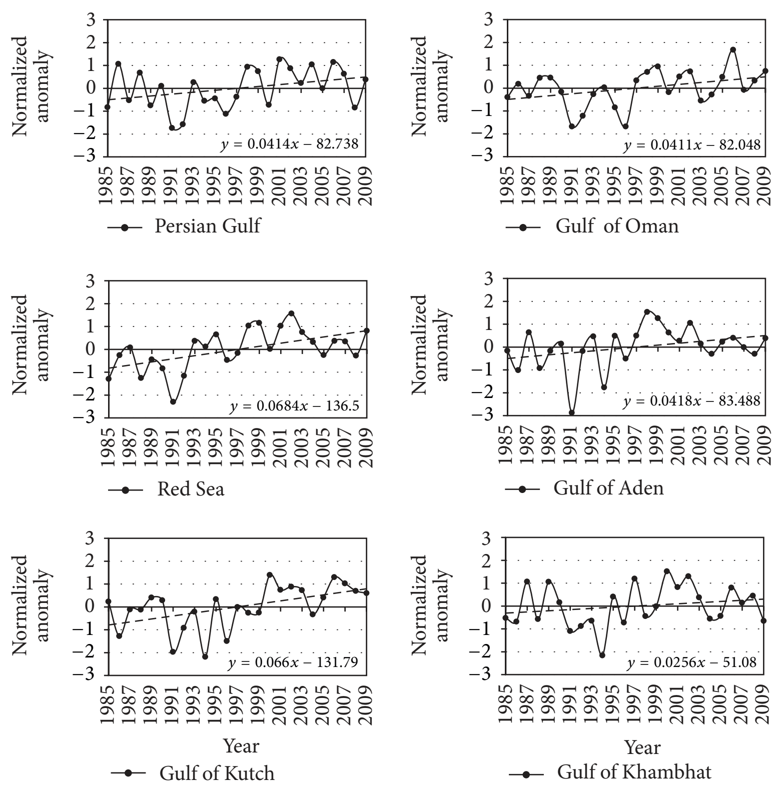


(c) SWM



(d) FIM

FIGURE 4: Comparison of the seasonal normalised SST anomaly from 1985 to 2009 of the Persian Gulf, Gulf of Oman, Red Sea, Gulf of Aden, Gulf of Kutch, and Gulf of Khambhat. (a) Northeast monsoon (NEM) (December–March), (b) spring intermonsoon (SIM) (April-May), (c) southwest monsoon (SWM) (June–September), and (d) fall intermonsoon (FIM) (October-November).

of the Arabian Sea and the Gulf of Aden, a similar pattern of interannual variation was observed, wherein from 1986 to 1990, the SST anomaly increased remarkably, followed by a phase of decreasing SST anomaly from 1990 to 1995. However, this cooling phase got extended in the Gulf of Aden up to 1997. From 1995 to 2001-2002, the SST anomaly increased in the two eastern gulfs, whereas in the Gulf of Aden, the increase was noticed up to 2003. From 2001-2002 (2003 in case of Gulf of Aden) to 2005, the SST anomaly again decreased, resulting in a cooling phase. However, from 2005 onwards, like the rest of the western gulfs of the Arabian Sea and the Red Sea, a remarkable increase in SST anomaly was observed in the Gulf of Aden and the two eastern gulfs of the Arabian Sea. In the Gulf of Aden the maximum positive SST anomaly was in 1998 (+1.98). However, in Gulf of Kutch, the maximum positive deviation from the climatological mean was noted during 2001 (+1.47), whereas in Gulf of Khambhat it was observed to be during 2009 (+1.48). During NEM, the Persian Gulf, Gulf of Oman, and the Red Sea exhibited the maximum negative deviation of SST from the climatological mean (i.e., maximum cooling) during 1992 (−1.8, −2.28, and −2.29, resp.), whereas Gulf of Kutch, and Khambhat showed the maximum negative deviation observed during 1995 (−1.15 and −1.36, resp.).

During the spring intermonsoon (SIM) (April-May) (Figure 4(b)), the normalized SST anomaly increased (warming) in all the eastern and the western gulfs of the Arabian Sea and the Red Sea, with maximum increase in the Gulf of Oman and the Red Sea (at the rate of 0.58/decade). It was observed that from 2005 onwards, during the SIM, the normalized SST anomalies increased substantially in the Persian Gulf, Gulf of Oman, Red Sea, Gulf of Kutch, and Gulf of Khambhat. The interannual variability pattern of the eastern gulfs of the Arabian Sea and the Gulf of Aden was found to be similar, beginning with a cooling phase (decreasing SST anomaly) from 1985 to 1991-1992, followed by a warming phase (increasing SST anomaly) which continued up to 1998. Whereas in the Gulf of Aden, the next phase of cooling was noticed from 1998 till 2003, in the eastern gulfs, a time lag of a year was found, with Gulf of Kutch extending the period of cooling from 1998 to 2004 and Gulf of Khambhat extending the period from 1998 to 2005. In the eastern gulfs of the Arabian Sea, the maximum positive deviation of SST from the climatological mean (i.e., maximum warming) during SIM was in 2002. Amongst the rest of the western gulfs of the Arabian Sea and the Red Sea, the pattern of interannual variability of SST was observed to be similar during the SIM. In the Persian Gulf, Gulf of Oman, and the Red Sea, from 1985 to 1991-1992, a cooling phase (with decreasing SST anomaly) was found. It was followed by a decade of warming from 1991-1992 to 2001, when the SST anomaly increased significantly. In these gulfs and the Red Sea, from 2001 onwards till 2005, another cooling phase was observed. However, in the last 5 years, that is, from 2005 to 2009 a substantial warming was noticed with significant increase in the SST anomaly during this period. Whereas the maximum positive deviation of SST from the climatological mean in the Red Sea and the Persian Gulf was during 2001 (+1.23 and +1.55, resp.), in the Gulf of Aden, it was in 1998 (+1.8) and in the Gulf of Oman in 2000 (+1.15). The maximum negative deviation of SST from the climatological mean (i.e., maximum cooling) in the Persian Gulf and the Gulf of Oman was in 1991 (−1.4 and −2.8, resp.), whereas in the Red Sea, Gulf of Aden, Gulf of Kutch, and Gulf of Khambhat, it was in 1992 (−2.1, −1.32, −0.92, and −1.41, resp.).

During the southwest monsoon season (SWM) (June–September) (Figure 4(c)), a cooling trend was observed in the eastern gulfs of the Arabian Sea, whereas in the western gulfs a warming trend was found in the last 25 years, with the maximum increase of SST anomaly in the Red Sea (0.77/decade). A similar pattern of SST anomaly was observed in the eastern gulfs of Arabian Sea on one hand and the western gulfs of Arabian Sea and the Red Sea on the other hand. However, a careful examination revealed that in the last 6 years (2003–2009) a substantial warming has been taking place in both the eastern and western gulfs of the Arabian Sea during the SWM season. In the eastern and western gulfs of Arabian Sea and the Red Sea, the SST anomaly increased from 1985 to 1987-1988, followed by a phase of decreasing anomaly, which continued until 1990-1991. During the extended El Niño period of 1991–1995, a sharp rise in SST anomaly was observed in the eastern gulfs of the Arabian Sea, after which SST decreased till 2003. On the other hand in the western gulfs of the Arabian Sea and the Red Sea, the SST anomaly increased substantially from 1991 till 1998 (with maximum positive anomaly in 1998). However, similar to the eastern gulfs, the SST anomalies again decreased from 1998 to 2003. But from 2003 onwards, a sharp rise of SST was observed till 2009, in both the eastern gulfs and the western gulfs of the Arabian Sea and the Red sea, with the maximum positive deviation of SST anomaly in the year 2007. The Persian Gulf showed positive SST anomalies in all the years from 1993 to 2009. Even in the Red Sea from 1993 onwards the anomalies have been positive, except for the years 2000 and 2004. The years with strong positive SST anomaly (more than +1.0) during SWM season were 1995, 1997, 1998, and 2002 in the Gulf of Aden; 1995, 1997, 1998, 2001, 2007, and 2009 in the Red Sea; 1998, 2002, and 2006 in the Persian Gulf; 1987 and 1993 in the Gulf of Kutch; and 1987 in the Gulf of Khambhat. None of the years showed strong positive SST anomalies (more than +1.0) in the Gulf of Oman. On the other hand, the years with strong negative SST anomaly (more than −1.0) during SWM season were 1985, 1991, and 1994 in the Gulf of Aden; 1985, 1989, 1990, and 1991 in the Red Sea; 1991 in the Persian Gulf; 1989, 1991, and 2003 in the Gulf of Oman; 2001 and 2003 in the Gulf of Kutch and the Gulf of Khambhat.

During the fall intermonsoon (FIM) (October-November), an increasing trend of the normalized anomalies for the eastern and the western gulfs of the Arabian Sea and the Red sea (Figure 4(d)) was observed. The Red Sea and the Gulf of Kutch had a much sharper increase in positive SST anomalies (0.68/decade and 0.66/decade, resp.) than the rest of the gulfs. For both the eastern gulfs of the Arabian Sea a similar interannual variability pattern was observed. In the Gulf of Kutch and Gulf of Khambhat, the SST anomaly increased from 1985-1986 to 1989-90 followed by a substantial cooling, which continued until 1994 (with maximum negative anomaly in 1994). From 1994 to 2000, a warming phase was followed by a cooling phase, which continued up to the year

2004 in the two eastern gulfs. However, in the last 4 years, that is, from 2004 till 2008, the SST anomaly again increased, with 2006 showing a high SST anomaly. Overall in the Gulf of Kutch and Gulf of Khambhat, a sharp rise of normalized anomalies (warming) was found from 1994 onwards, though the rise was more pronounced in the Gulf of Kutch, in which, from 1997 onwards, (except for 2004) none of the years showed negative departure from the climatological mean during this season. On the other hand, in the western gulfs of the Arabian Sea and the Red Sea, even though the pattern of interannual variability during the FIM season was similar, a significant difference in the magnitude of variability was noticed especially in the Persian Gulf and the Red Sea, owing to their enclosed locations. In the Persian Gulf, Gulf of Oman, Red sea, and Gulf of Aden the normalized SST anomalies decreased from 1985 to 1991 (cooling) and thereafter increased (warming) remarkably until 1998-1999. Eventually from 1998-1999 to 2003-2004, the SST anomalies again decreased significantly. However, similar to the eastern gulfs of the Arabian Sea, the western gulfs and the Red Sea also exhibited warming from 2003-2004 to 2009. During the FIM, in the Persian Gulf and the Gulf of Oman, apart from 1991, 1996 also showed intense cooling with negative SST anomaly reaching up to −1.67.

The influence of El Niño and La Niña on the interannual SST pattern during different seasons was observed. However, not all the warming and cooling events had similar effect on the SST anomaly. Besides, the geographical location of the particular gulf also played a crucial role in determining the impact of the ENSO.

3.2.3. Coefficient of Variation of Annual and Seasonal SST of the Eastern and Western Gulfs of Arabian Sea and Red Sea from 1985 to 2009. The coefficient of variation (CV) gives the magnitude of the interannual variability. CV values of the annual and seasonal SST of the eastern and the western gulfs of the Arabian Sea and the Red Sea showed large variation amongst these water bodies as seen in Table 1.

The largest variation in annual SST was found in the Persian Gulf (mean CV of 18.02%), followed by the Gulf of Oman (mean CV of 11.1%), whereas Gulf of Aden was least variable (mean CV of 6.37%). The interannual variability in seasonal mean SST was highest in the Persian Gulf in all the seasons except for the SWM season. During SWM season, the maximum variability was observed to be in the Gulf of Kutch (mean CV of 10.07%) followed by Gulf of Khambhat (mean CV of 4.9%). Gulf of Aden and Gulf of Oman were least variable during the NEM and SWM seasons, whereas Gulf of Khambhat was least variable during SIM and FIM seasons.

Table 1: % Coefficient of variation for annual and seasonal SST.

Gulf/Sea	Annual	NEM	SIM	SWM	FIM
Persian Gulf	18.02%	7.88%	11.77%	2.68%	7.77%
Gulf of Oman	11.1%	3.85%	8.37%	1.93%	4.61%
Red Sea	8.02%	3.56%	4.65%	2.76%	3.83%
Gulf of Aden	6.37%	2.20%	4.68%	2.63%	3.84%
Gulf of Kutch	9.35%	5.06%	3.63%	10.07%	3.14%
Gulf of Khambhat	6.5%	4%	2.13%	4.90%	2.83%

3.3. Comparison of Normalised SST Anomaly of the Eastern and Western Gulfs of Arabian Sea and Red Sea with Multivariate ENSO Index and Role of Indian Ocean Dipole. The El Niño/Southern Oscillation (ENSO) is a phenomenon that integrates both atmospheric and oceanic parameters and is measured by various indices like the Southern Oscillation Index (SOI), Multivariate ENSO Index (MEI), Nino 3.4, and so forth. [48–51]. El Niño and La Niña result from interaction between the ocean and the atmosphere in the tropical Pacific. The warm El Niño to cold La Niña conditions oscillate on an average of every three to five years. Of all these indices, MEI, a representative of SST, sea surface pressure, zonal and meridional components of the surface wind, air temperature and cloudiness of the sky, gives more structured information about ENSO phenomena and its correlation with surface temperature [52]. Hence, in this study, MEI was used to find the relationship between ENSO events and the change in the SST pattern in the gulfs of the Arabian Sea as seen in Figure 5.

Besides ENSO, the Indian Ocean Dipole (IOD) is also known to be affecting the interannual SST anomalies. One phase of the IOD (positive IOD or PIOD) causes a cooling of SST in the eastern tropical Indian Ocean, while the western tropical Indian Ocean (western Arabian Sea) tends to experience a warming of sea surface temperatures. The other phase (negative IOD or NIOD) in contrast involves high SST in the eastern Indian Ocean and low in the west [49, 53, 54]. Some dipole events occur without ENSO events, and some ENSO events do not accompany the dipole events. When an ENSO event occurs, the dipole tends to be positive during El Niño and negative during La Niña. However, the amplitude of the dipole varies greatly from year to year. 1991, 1994, 1997-1998 are reported to be the positive IOD years, whereas 1992, 1996, and 1998 are reported to be negative IOD years [55].

The major El Niño events of 1986-1987, 1991-1992, 1997-1998, 2002-2003, 2006-2007, and 2009-2010 and the La Niña events of 1988-1989, 1998-1999, 2000-2001, and 2007-2008 are evident from the peaks and troughs of the MEI values, with positive MEI values indicating a warming event (El Niño) and the negative MEI value indicating a cooling event (La Niña). The influence of the ENSO on SST of the Gulfs of the Arabian Sea can be clearly seen. However, one to one connection was not found. Besides, not all the El Niño or La Niña events had similar impact in the eastern and the western gulfs of the Arabian Sea. For example, the El Niño of 1991-1992 and 1994-1995 did not influence the eastern gulfs of the Arabian Sea as compared with the one of 1997-1998. The year 1997-1998 was also a positive IOD year. Hence, the extent of warming especially in the western gulfs of the Arabian Sea and the Red Sea was high. Besides, in 1992, a high negative anomaly in the western gulfs and the Red Sea was observed, owing to the influence of the negative IOD. Moreover, the impact of an IOD was seen more in the western domains of the Arabian Sea. During the extended El Niño of 1991–1995, the normalized positive SST anomaly increased remarkably in all the gulfs except the Gulf of Kutch and

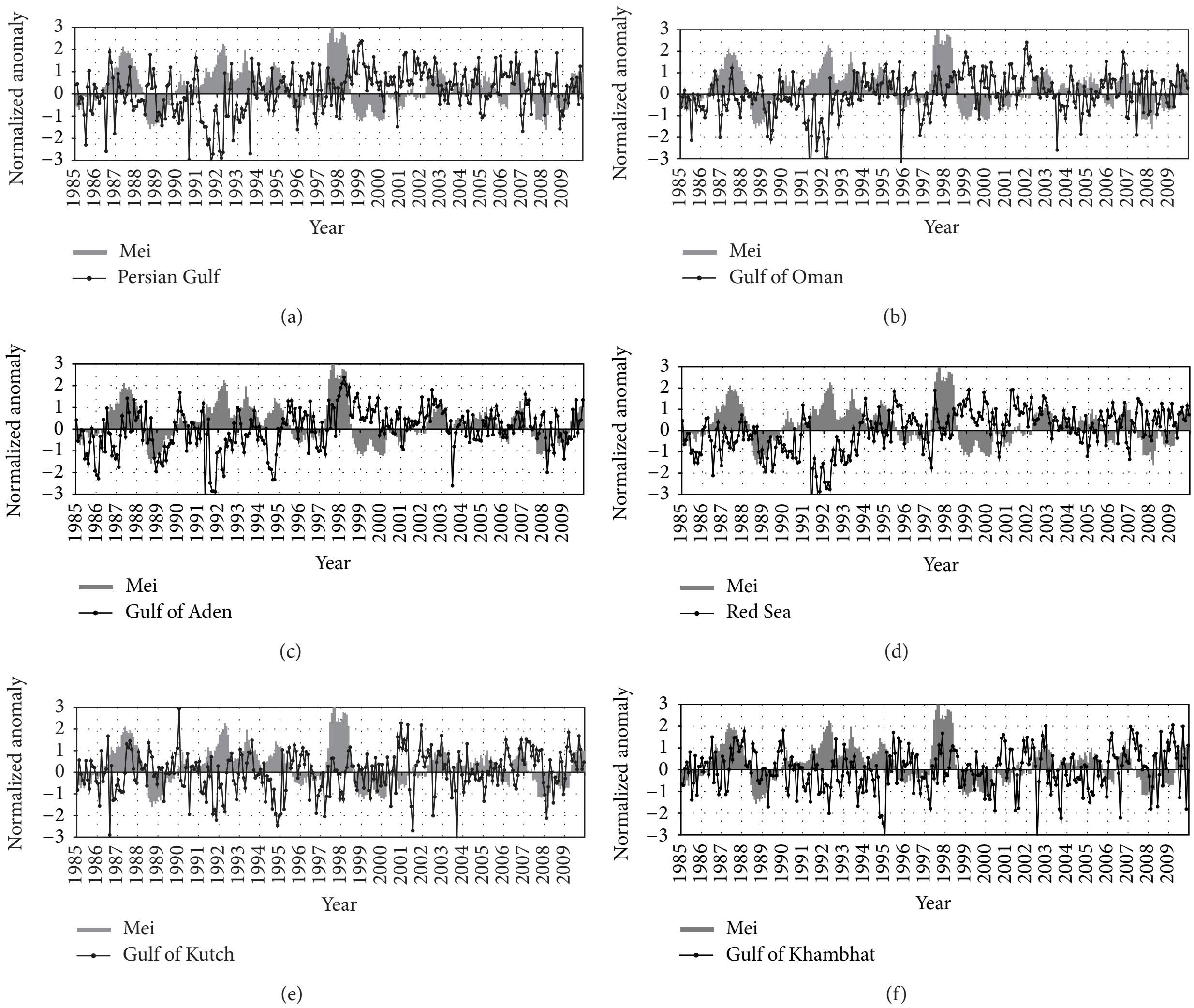


Figure 5: Comparison of normalised SST anomaly of (a) Persian Gulf, (b) Gulf of Oman, (c) Gulf of Aden, (d) Red Sea, (e) Gulf of Kutch, and (f) Gulf of Khambhat, from 1985 to 2009 along with Multivariate ENSO Index (MEI).

Gulf of Khambhat. Similarly, the stronger El Niño of 1997-1998 had a major impact on all gulfs except for the Gulf of Kutch. However, a delayed effect was observed in the Persian Gulf, Gulf of Oman, and Red Sea with peaks of normalised anomalies in 1998-1999. The La Niña of 1988-1989 resulted in cooling of Gulf of Oman, Red Sea, and Gulf of Aden but had no influence in the Gulfs of Kutch and Khambhat, whereas the La Niña of 2008 affected all the gulfs except for the Red Sea.

4. Discussion

Time series studies of the oceanographic parameters are useful for understanding seasonal, interannual, and decadal impact of climate change. Numerous investigations have been conducted in the Arabian Sea basin to study the effect of global warming. Rupa Kumar et al. [17] reported that from 1904 to 1994 the Arabian Sea has warmed by 0.5°C. Recent studies have also confirmed about the warming of the Arabian Sea by 0.16°C/decade from 1971 to 2002 [18] and 0.10°C/decade from 1982 to 2006 [56]. Kailasam and Rao [20] using GISS Surface Temperature observed that there has been an increasing trend of SST, with strong positive SST anomalies (0.8°C) during the period of 1981–2009 over the Northern Indian Ocean.

However, as the gulfs of the Arabian Sea have unique oceanographic features and are quite distinct from the open ocean, it becomes essential to study them individually. These gulfs are single water masses, and therefore studies conducted in few of the coastal areas cannot be generalized for the whole of the gulfs. In the present study, a comparative analysis of SST in different months and seasons was carried out for the eastern and western gulfs of the Arabian Sea and the Red Sea from 1985 to 2009 to study the regional effect of the warming of the Arabian Sea. Annually the SST has increased significantly in all the western gulfs of the Arabian Sea and the Red sea, with maximum increase of normalized SST anomaly in the Red sea (0.64/decade) and the Persian Gulf (0.40/decade).

However, the increase was not significant for the eastern gulfs of the Arabian Sea (Gulf of Kutch and Gulf of Khambhat).

The analysis by Kumar et al. [19] about the anthropogenic induced global warming disrupting the decadal cycle of SST of Arabian Sea after 1995 was also observed in the present study in the eastern gulfs of the Arabian Sea (Gulf of Kutch and Gulf of Khambhat), where the annual SST increased rapidly from 1995 onwards. However, in the western gulfs (Persian Gulf, Gulf of Oman, and Gulf of Aden) and the Red Sea, the disruption of the decadal cycle of SST resulting in a sharp rise of SST was observed from the year 1991-1992. Therefore, a remarkable time lag of (3 years) between the eastern and the western gulfs of the Arabian Sea and the Red sea was observed in the annual increase of SST. There was similarity in the interannual variability pattern of SST amongst the western gulfs and the Red sea on one hand and the eastern gulfs on the other.

Annually for western gulfs of the Arabian Sea, that is, the Persian Gulf, Gulf of Oman, and Gulf of Aden, cooling was observed from 1985 to 1991, and thereafter from 1992 to 2009, warming was found. Whereas in the eastern gulfs of the Arabian Sea, that is, the Gulf of Kutch and Gulf of Khambhat, a significant cooling was observed from 1985 to 1994, and thereafter from 1995 to 2009, a sharp increase in normalized anomaly was found. In the three western gulfs of the Arabian Sea, (Persian Gulf, Gulf of Oman, and Gulf of Aden), the maximum negative normalized SST anomaly was observed in 1991. In the Red Sea the maximum negative normalized SST anomaly was found in 1992 (negative IOD). On the other hand in both the eastern gulfs of the Arabian Sea, maximum negative normalized SST anomaly was observed in 1994. In the western gulfs of Arabian Sea and the Red Sea, 1997-1998, 1999, 2001, 2002, 2006, 2007, and 2009 were the years with high positive normalized SST anomalies, whereas in the eastern gulfs of the Arabian Sea, the years 2002, 2007, and 2009 showed strong positive SST anomalies. Most of these years are reported to be the El Niño years like 1997-98, 2002, 2006, and 2009 which affected the SST variability pattern.

The seasonal SST analysis for the western gulfs of the Arabian Sea and the Red Sea showed an increasing trend of SST in all the four seasons. However, in the eastern gulfs of the Arabian Sea during the SWM season, cooling was observed. During the NEM and the SIM seasons, similar interannual SST variability pattern was observed in the Persian Gulf, Gulf of Oman, and the Red Sea on one hand and Gulf of Aden, Gulf of Kutch and Gulf of Khambhat on the other. During the SWM and FIM seasons similar interannual SST variability pattern was in the eastern gulfs of Arabian Sea on one hand and the western gulfs of Arabian Sea and the Red Sea on the other.

During the NEM season, in the Persian Gulf, Gulf of Oman, and the Red Sea, an alternate cycle of cooling and warming phases was observed from 1986 to 1992, 1992 to 1999, 1999 to 2005, and 2005 to 2009, whereas in the eastern gulfs of the Arabian Sea and the Gulf of Aden, the alternate cycle of cooling and warming phases was observed from 1986 to 1990, 1990 to 1995 (1997 in Gulf of Aden), 1995 to 2001-2002 (2003 in Gulf of Aden), 2001-2002 to 2005, and 2005 to 2009. The Persian Gulf, Gulf of Oman, and the Red Sea exhibited maximum cooling during 1992, owing to the negative IOD. During the NEM season, the years 1987, 1989, and 2008 showed the influence of La Niña, with high negative SST anomalies in the western gulfs of the Arabian Sea and the Red Sea. But in the eastern gulfs of the Arabian Sea, only the influence of La Niña of 2008 was visible. Similarly of all the El Niño years, 1991–1995, 2002, and 2006 resulted in a higher positive SST anomaly in the eastern and the western gulfs of the Arabian Sea and the Red sea.

Similarly, during the SIM season, alternate warming and cooling phases were noticed in the eastern gulfs of the Arabian Sea and the Gulf of Aden from 1985 to 1991-1992, 1991-1992 to 1998, 1998 to 2004-2005 (2003 for Gulf of Aden) and 2004-2005 to 2009. In the eastern gulfs of the Arabian Sea, the maximum positive SST anomaly during SIM was in 2002 that was an El Niño year. Amongst the rest of the western gulfs of the Arabian Sea and the Red Sea, the alternate phases of warming and cooling were observed from 1985 to 1991-1992, 1991-1992 to 2001, 2001 to 2005, and 2005 to 2009. The maximum negative deviation of SST from the climatological mean in the Red Sea, Gulf of Aden, Gulf of Kutch, and Gulf of Khambhat was in 1992, owing to the negative IOD. During the SIM, the influence of El Niño of 1991–1995, 1997-1998, 2002 and 2009 and La Niña of 1987 and 1989 could be seen on the SST anomalies of the eastern and the western gulfs and the Red Sea.

In the SWM season, the periods of warming and cooling included 1985 to 1987-1988, 1987-1988 to 1990-1991, 1991 to 1995 (1998 for the western gulfs and the Red Sea), 1995 to 2003, and 2003 to 2009. The Persian Gulf and the Red Sea showed positive SST anomalies in all the years from 1993 to 2009. The years with strong positive SST anomaly were 1995, 1997, 1998, and 2002 in the Gulf of Aden; 1995, 1997, 1998, 2001, 2007, and 2009 in the Red Sea; 1998, 2002 and 2006 in the Persian Gulf; and 1987 and 1993 in the Gulf of Kutch; and 1987 in the Gulf of Khambhat, of which most of the years like 1995, 1997, 1998, 2002, 2006, and 2009 were the El Niño years. However the influence of La Niña was not seen during SWM season. The years with negative SST anomalies included 1985, 1991, and 1994 in the Gulf of Aden; 1985, 1989, 1990, and 1991 in the Red Sea; 1991 in the Persian Gulf; 1989, 1991, and 2003 in the Gulf of Oman; 2001 and 2003 in the Gulf of Kutch and the Gulf of Khambhat.

During the FIM season, an increasing trend of the normalized anomalies for the eastern and the western gulfs of the Arabian Sea and the Red sea was observed. In the eastern gulfs, the alternate phases of increasing and decreasing SST anomaly included 1985-1986 to 1989-1990, 1989-1990 to 1994, 1994 to 2000, 2000 to 2004, and 2004 to 2009. In the western gulfs of the Arabian Sea and the Red Sea the phases of warming and cooling included 1985 to 1991, 1991 to 1998-1999, 1998-99 to 2003-2004, and 2003-2004 to 2009. The years with high negative SST anomalies during the FIM were 1986, 1988, 1991, and 1994 in the Gulf of Aden, whereas in the Red Sea, these were 1985, 1988, and 1991. Of these 1985 and 1988 were the La Niña years. The years with strong positive SST anomalies during the FIM were 1986, 1998, 2001, 2004, and 2006 in the Persian Gulf; 1999 and 2006 in Gulf of Oman; 1998 and 2002 in Gulf of Aden; and 1998, 2001, and 2002 in the Red Sea. Of these 1986, 1988, 2002, and 2006 were the El Niño years.

The contrasting features between the eastern and western gulfs of the Arabian Sea could be attributed to their difference in oceanographic features, current systems, and also anthropogenic impact. Being enclosed in semiarid surroundings in the northern edges of the Indian subtropical zone, the western gulfs of the Arabian Sea come under the direct influence of multiple atmospheric pressure systems like the impact of the Siberian high pressure system, the El Niño, Southern Oscillation, the North Atlantic Oscillation, and the IOD [57]. The influence of the ENSO and the IOD affecting the interannual variability of SST was found. However, one to one connection was not found. Besides, not all the El Niño or La Niña events had similar impact in the eastern and the western gulfs of the Arabian Sea. The year 1997-1998 was an ENSO dipole year. Hence the extent of warming especially in the western gulfs of the Arabian Sea and the Red Sea was high. Besides, in 1992, a high negative anomaly in the western gulfs and the Red Sea was observed, owing to the strong influence of the negative IOD. During the extended El Niño of 1991–1995, the normalized positive SST anomaly increased drastically in all the gulfs except the Gulf of Kutch and Gulf of Khambhat. Similarly, the stronger El Niño of 1997-1998 had a major impact on all gulfs except for the Gulf of Kutch. The atmospheric temperature over the Persian Gulf including the Gulf of Oman has been reported to be increasing rapidly and is projected to further increase up to 4°C by the end of the century [58]. There are reports of the weakening of the Siberian high pressure system resulting in a decline in the zonal component of wind and hence an increase in surface temperature [59]. Besides, the regional orography of the surrounding land masses which includes deserts and mountains also affects the physical oceanographic processes of the western gulfs of the Arabian Sea. However, the most significant contributor for the sharp rise of SST in the western gulfs of the Arabian Sea that has resulted in disruption of the decadal SST cycle much ahead of that of the Arabian Sea basin and the eastern Gulf is the increasing anthropogenic induced warming. There has been tremendous increase in human activities in the countries surrounding the western gulfs of the Arabian Sea which have contributed to the higher rate of warming along these western gulfs of the Arabian Sea as compared to the Arabian Sea basin and its eastern gulfs.

5. Conclusion

Sea surface Temperature (SST) is one of the key oceanographic parameters, exerting an influential role in many of the meteorological and oceanographic processes. From 1985 to 2009, the SST of the eastern and western gulfs of the Arabian Sea and the Red sea showed a clear cut signal of warming. The rate of increase of SST was highest in the Persian Gulf followed by the Red Sea. From 1991-1992 onwards, the western gulfs of the Arabian Sea and the Red sea exhibited a sharp increase in SST, whereas in the eastern gulfs of the Arabian Sea, the warming was more pronounced from 1995 onwards. Seasonal differences were also found with respect to increasing temperature. Interannual variability pattern was found to be similar in the annual and seasonal SST amongst the western gulfs and the Red Sea. Similarity in SST variability was also found in the two of the eastern gulfs of the Arabian Sea. Red Sea was found to be warming significantly across all the seasons and months. The largest variation in annual SST was found in the Persian Gulf (CV of 18.02%). The interannual variability in seasonal mean SST was highest in the Persian Gulf in all the seasons except for the SWM season. During SWM season, the maximum variability was observed in the Gulf of Kutch (CV of 10.07%) followed by Gulf of Khambhat (CV of 4.9%). The influence of ENSO and IOD on the SST variability pattern was also found. The impact of rising temperature on other physical and biological parameters of the gulfs of the Arabian Sea and the Red Sea needs to be scrutinized further.

The difference in the oceanographic features of the eastern and western gulfs of the Arabian Sea and the Red Sea, from the open oceans, makes them unique ecosystem. Hence, caution is needed to analyze them individually and not to generalize the findings of the entire basin upon them.

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