

# Interannual and Interdecadal Variations in Tropical Cyclone Activity over the Arabian Sea and the Impacts over Pakistan

Wash Dev Khatri, Zhi Xiefei, and Zhang Ling

## 1 Introduction

This study is to investigate the tropical cyclone (TC) activity over the Arabian Sea (AS). The idea of the topic rose from the work done by Chan (2005) on interannual and interdecadal variations of TC activity over the western North Pacific (WNP). In his study, Chan (2005) reviewed the Interannual and Interdecadal variations in tropical cyclone (TC) activity over the WNP and emphasized that the Interannual variations could largely be explained by changes in the planetary-scale flow patterns. Sea-surface temperatures (SSTs) in the WNP, however, did not contribute to such variations. Rather, SSTs in the central and eastern equatorial Pacific were significantly correlated with TC activity over the WNP. Changes in the SST in the equatorial Pacific were found to be in relation with the El Nino-Southern Oscillation (ENSO) phenomenon, and modifications of the planetary-scale flow associated with ENSO altered the conditions over the WNP and hence TC activity there.

The nature of TC activity over AS is different from TC activity over WNP, as the former has the lowest and latter has the highest yearly TC occurrence frequency. The work on the AS started in 1970s. Shukla and Misra (1977) computed the correlation coefficients among time series of SST, wind speed and rainfall. They used the data prior to 1960 and after that the TC activity over AS has more decreasing trend in contrast to previous years. Evans (1993) gave total credit to the underlying

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W.D. Khatri

Pakistan Meteorological Department, Headquarter Office,  
Sector H-8/2, Islamabad, Pakistan

SAARC Meteorological Research Center (SMRC), Dhaka 1207, Bangladesh

Z. Xiefei (✉) • Z. Ling

Nanjing University of Information Science and Technology,  
5 Panxin Rd, Pukou, Nanjing, Jiangsu, China

e-mail: [zhi@nuist.edu.cn](mailto:zhi@nuist.edu.cn)

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water temperature for the intensity of the TCs in different oceans, and suggested that the other factors may also have their roles in the intensity of TC activity like pressure troughs. Ramsay et al. (2008) have related the TC activity with large scale environmental factors with emphasis on SST. They have also found the correlations between the TC activity and Nino 3.4 and Nino 4. Chen et al. (2006) find out that any mechanism that can modulate the location and intensity of the monsoon trough affects the genesis location and frequency of TC. They divided the TCs into three groups, namely, low, high and very high according to their intensity. In response to tropical Pacific SST anomalies, a short wave train consisting of east-west oriented cells emanates from the tropics and progresses along the WNP rim. Population of the Group 1 TCs varies interannually in phase with the oscillation of the anomalous circulation cell northeast of Taiwan and south of Japan in this short wave train, while that of Group 3 fluctuates coherently with the tropical cell of this short wave train. Because these two anomalous circulation cells exhibit opposite polarity, the out-of-phase interannual oscillation between these two cells results in the opposite interannual variation of genesis frequency between TC of Groups 1 and 3 (Chen et al. 2006). Wu et al. (2010) found that the SST suppressed the TC activity in Indian and Pacific Oceans and similar results are obtained in case of TC activity over AS. They indicated the close relationship between the Atlantic SST and TC activity over the past 30 years, including basin-wise increases in the average lifetime, annual frequency and proportion of intense hurricanes (Wu et al. 2010).

The response of the Arabian Sea to global warming is the disruption in the natural decadal cycle in the SST after 1995, followed by a secular warming. The Arabian Sea is experiencing a regional climate-shift after 1995, which is accompanied by an increase in the occurrence of “most intense cyclones”. Signatures of this climate-shift are also perceptible over the adjacent landmass of India and Pakistan (Kumar et al. 2009). Krishna (2009) found that the frequency of tropical cyclones in the north Indian Ocean has registered increasing trends during summer monsoon, which accounts for maximum number of intense cyclones. The increasing trend has been primarily due to decrease in the vertical wind shear. Thus, the future evolution of north Indian Ocean storm activity will critically depend on the warming of the sea surface waters and also the vertical wind shear. Likewise changes in ENSO statistics in the tropical Pacific may become important, as they affect the SSTs in all three tropical oceans. The stronger warming of tropical NIO during recent years drove reduced vertical wind shear over the NIO and is thus responsible for the strong TC activity observed.

In the past few years Pakistan's coastal areas received a lot of economic damages due to the TC activities over AS. The coastal line of Pakistan is almost 1,200 km long along the Arabian Sea. Three main seaports of Pakistan i.e. Kaemari Karachi, Bin Qasim Karachi and Gawadar lie along this coastal belt along with large and small fish harbours and the ship breaking industry near Gadani. The coastal areas of Pakistan were frequently influenced by TC activities over AS in the past. The area in the north of the eastern coast of Pakistan is the cotton growing area and the TC activity near the area during pre-monsoon period vigorously affects the crop in case

of violent rains or winds. In the same manner, during post-monsoon, the TC activity affects the wheat crop and the farmers get a big financial loss in both cases.

Although the frequency of TC landfall is much less in the coastal area of Pakistan than in other regions, the TCs near Pakistan's coastal region may have significant impact on the human life and agriculture in Pakistan. This study focusses on the analysis of tropical cyclone activity over AS, and discusses more about the impact of TC activities on Pakistan.

## 2 Data and Methodology

The TC data used in this study are taken from the website of Unisys weather, in which the data has been extracted from the warnings of the Joint Typhoon Warning Centre. Though the data was available from the year 1945, in this study the data used is from 1960 keeping in mind the study focussing the coastal belt of Pakistan, where the data of temperatures is generally available from this period and also various reading material suggest to use data of this period because of missing events in the past and also due to lack of proper observations and the remoteness of the region.

The data of TC are also available on the website of India Meteorological Department through RSMC, New Delhi but the problem arises for the tracks, which are only available for last 10 years.

The data for monthly rain, monthly average maximum and minimum temperatures are obtained from Pakistan Meteorological Department.

The data of Sea Surface Temperature (SST), geopotential heights, and upper atmosphere winds have been downloaded from NOAA website.

### 2.1 Statistical Analysis

The analysis of data is generally based on simple statistical methods, which are mostly the graphical representation of the data to find the trends in the changing frequency of the TC over the region.

The analysis has been done with two formats: (1) the actual occurrence of TCs and (2) 9 years running mean of TCs.

The first is studied under "Interannual Variations" and the later as "Inter Decadal Variations" of the TC activity over AS.

The data of TC activity is also checked in various parts of AS to find out the active region in the basin. The same has been done by dividing the area into two parts spanned in East-West directions with an imaginary line over 65°E longitude that divides the study area in almost two halves.

The monthly data of 'occurrence frequency' of TCs over the Arabian Sea is used to check the active seasons of the activity over the region and then it is examined with the SST of various months in the area.

## 2.2 Correlation

The data of frequency of occurrence of TCs over Arabian Sea is correlated with the precipitation, maximum temperatures and minimum temperatures of the stations in the vicinity of coastal region of Pakistan, ENSO index and SST of the key area through Correlation Matrix in accordance with Pearson's formula of correlation of product moment, which is as follows

$$r_{xy} = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{(n-1)s_x s_y}$$

$$= \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2 \sum_{i=1}^n (y_i - \bar{y})^2}}$$

where  $x$  and  $y$  are the samples of  $X$  and  $Y$ , and  $s_x$  and  $s_y$  are the sample means standard deviations of  $X$  and  $Y$ .

This can also be written as:

$$r_{xy} = \frac{\sum_{i=1}^n x_i y_i - n \bar{x} \bar{y}}{(n-1)s_x s_y}$$

$$= \frac{n \sum_{i=1}^n x_i y_i - \sum x_i \sum y_i}{\sqrt{\left( n \sum_{i=1}^n x_i^2 - \left( \sum_{i=1}^n x_i \right)^2 \right) \left( n \sum_{i=1}^n y_i^2 - \left( \sum_{i=1}^n y_i \right)^2 \right)}}$$

The TC activity is also correlated with the geopotential heights at 500 hPa and 850 hPa level.

## 2.3 Wavelet Analysis

Wavelet transform is a powerful way to characterise the frequency, the intensity, the time position, and the duration of variations in a climate data series (Jiang et al. 1997; Zhi 2001; Zhang et al. 2006) which reveals the localized time and frequency information without requiring the time series to be stationary as required by the Fourier transform and other spectral methods. The advantage of wavelet transform in time-frequency

analysis in comparison with conventional Fourier transform can be found in many literatures. Usage of the wavelet transform in the study of climatic changes and hydrological changes and other fields is receiving an increasing attention. Nakkan (1999) applied the continuous wavelet transforms (CWTs) to detect the temporal changing characteristics of the precipitation and the runoff processes, and their correlations and separating roles of climatic changes caused by human activities on stream flow changes. Other scholars used CWTs for analyzing stream discharge data and flood levels. In this paper, the CWT following Torrence and Compo (1998) is used. We assume that  $x_n$  is a time series with equal time spacing  $\delta t$  and  $n=0, \dots, N-1$ .  $\Psi_0(\eta)$  is a wavelet function which depends on a non-dimensional ‘time’ parameter  $\eta$ , with zero mean and is localized in both frequency and time (Farge 1992; Torrence and Compo 1998). Because Morlet wavelet provides a good balance between time and frequency localization, here we applied the Morlet wavelet defined as

$$\psi_0(\eta) = \pi^{-1/4} e^{i\omega_0\eta} e^{-\eta^2/2}$$

where  $\omega_0$  is the non-dimensional frequency, here taken to be 6 to satisfy the admissibility condition (Farge 1992; Torrence and Compo 1998). The continuous wavelet transform of a discrete sequence  $x_n$  is defined as the convolution of  $x_n$  with a scaled and translated version of  $\psi_0(\eta)$ :

$$W_n(S) = \sum_n^{N-1} X_n \cdot \psi^* \left[ \frac{(n' - n)\delta t}{s} \right]$$

where the asterisk (\*) indicates the complex conjugate.

To ignore the edge effects because the wavelet is not completely localized in time, the cone of influence (COI) was introduced. Here the COI is the area where the edge effect becomes important and the wavelet power spectrum may not be regarded as real. The statistical significance of wavelet power can be assessed under the null hypotheses that the signal is generated by a stationary process by being given the background power spectrum ( $P_k$ ), many geophysical series have their noise characteristics which can be modeled by a first order autoregressive (AR1) process. The Fourier power spectrum of an AR1 process with lag-1 autocorrelation  $\alpha$  (estimated from the observed time series e.g. Allen and Smith 1996) is given by Grinsted et al. (2004) as

$$P_k = \frac{1 - \alpha^2}{|1 - \alpha e^{-2i\pi k}|^2}$$

where  $k$  is the Fourier frequency index.

In this study, the Morlet wavelets have been used to determine the significance in the cyclic periods in the TC activity over the period of this study.

### 3 Results and Discussions

#### 3.1 Interannual Variations of the TC Activities over the Arabian Sea

Figure 1 shows the interannual variations of TC activity over AS for 50 years. It reveals a significant decreasing linear trend. Figure 2 shows that the SST has an increasing trend. The ENSO index reflects the oceanic properties in tropical central and eastern Pacific, while the IOD index reflects the oceanic properties in the east and west of Indian Ocean. Compared with the increasing trend of the SST over AS, the linear trend of the ENSO and IOD indices are not significant.

As far as the violent nature of the TC activity is concerned, the maximum sustained winds of the TCs available from 1975 till 2009 was used as an indicator. Figure 3 reveals that the duration of TC activity over AS has a decreasing trend and the violence of TCs has an increasing trend in terms of its wind speed. The increasing TC intensity may be associated with the increasing trend of the SST in the region where the TC activity occurs. Kumar et al. (2009) indicated that the Arabian Sea is experiencing a regional climate-shift after 1995, which is accompanied by a fivefold increase in the occurrence of “most intense cyclones”. In general, our findings are in agreement with their result.

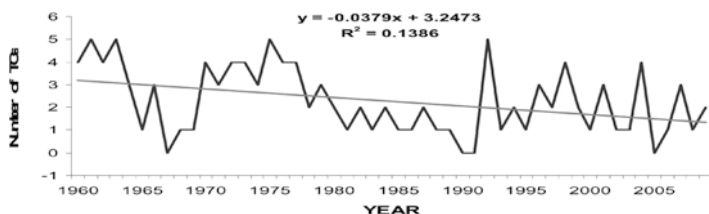


Fig. 1 Interannual variations and the trend of TC activities during the period from 1960 to 2009

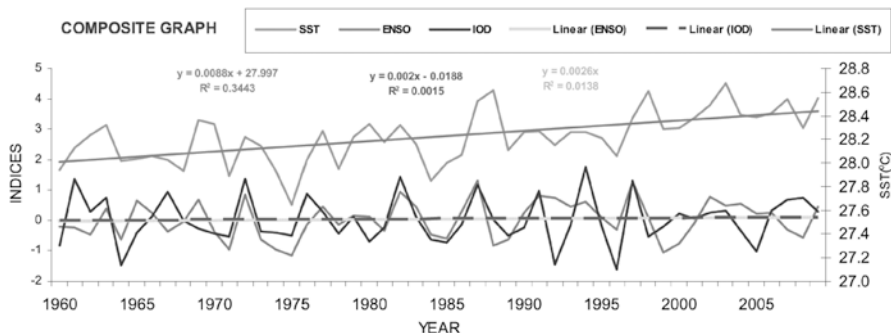
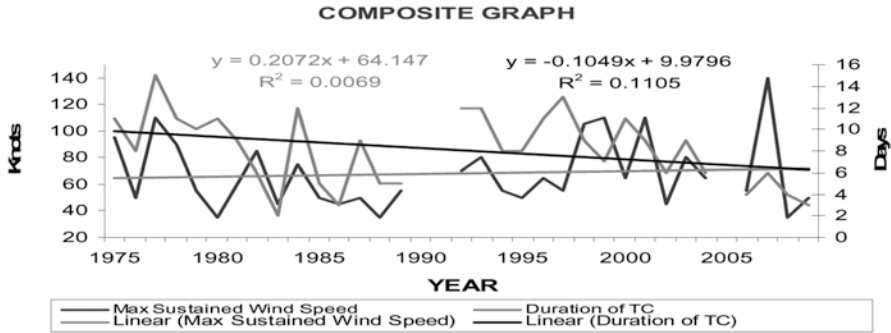
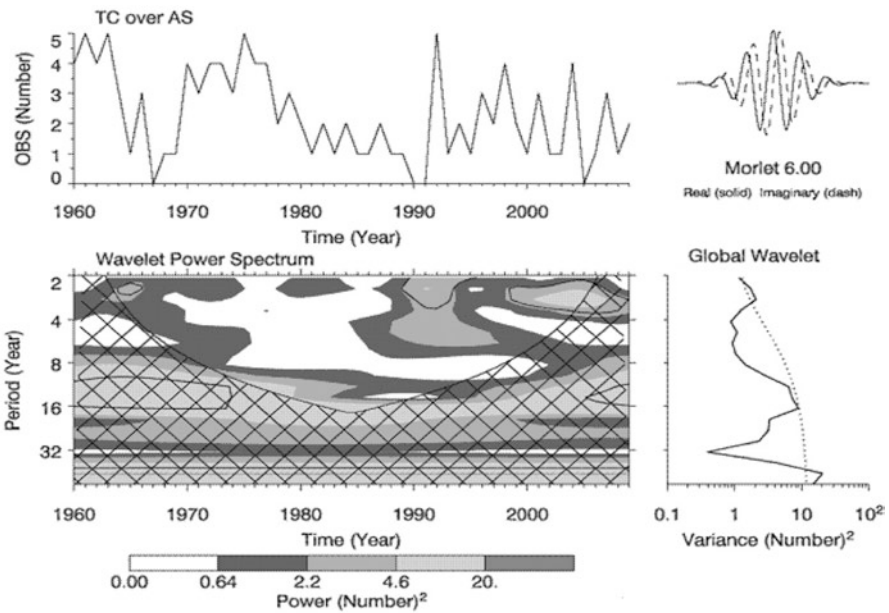


Fig. 2 SST, IOD and ENSO indices with linear trends during the period from 1960 to 2009



**Fig. 3** Maximum sustained wind and TC duration with linear trends (*Broken lines* represent no TC activity in that year)



**Fig. 4** The local power spectrum of the occurrence frequency of the TC activity over AS by using Morlet wavelet analysis. The *thick contour* encloses regions of greater than 90 % confidence for a red-noise process. Cross-hatched regions on either end indicate the “cone of influence,” where edge effects become important

The spectral analysis of the TC occurrence frequency is done to see its power spectrum and significant period of its variations. As shown in Fig. 4, the occurrence frequency of the TC over the Arabian Sea has a significant period of 2–3 years during the periods 1962–1965, 1989–1996 and 1998–2006. The quasi-biennial oscillation (period of 2–3 years) was observed in both surface elements and upper-level

fields as well as in the monsoon system in the troposphere in addition to its significant presence in the stratosphere (Walsh and Mostek 1980; Wang and Zhao 1981; Mooley and Parthasarathy 1983; Huang 1988; Zhu and Zhi 1991; Zhi 1997, 2001). Originally, the tropospheric biennial oscillation (TBO) was defined as the oscillation tendency of monsoon with the transitions occurring in the season prior to the monsoon involving coupled land–atmosphere–ocean processes over Indo-Pacific region (Meehl 1994; Meehl and Arblaster 2001). An important part of any biennial mechanism is anomalous heat storage in the ocean and the associated SST anomalies that can occur in certain regions (Meehl et al. 2003). Thus, the ocean retains the “memory” of ocean–atmosphere interaction over the course of a year to affect the atmosphere the following year (Brier 1978; Nicholls 1978; Chang and Li 2000; Li et al. 2001; Meehl 1987, 1993). Several studies have suggested that coupled ocean dynamics plays a role in the formation and maintenance of these heat content and SST anomalies associated with the TBO (Meehl 1993; Clarke et al. 1998; Webster et al. 1999, 2003; Saji et al. 1999; Meehl and Arblaster 2002a; Loschnigg and Webster 2000).

As the formation of the TCs is closely associated with the SST, it is not surprising that the occurrence frequency of the TC activity has an interannual variation with a significant period of 2–3 years.

### 3.2 Interdecadal Variations of the TC Activities over the Arabian Sea

The data used for discussing interdecadal variations have been processed by taking 9 years running average. Figure 5 shows the trend and the interdecadal variations of TC activity over AS for 50 years. It reveals a significant decreasing linear trend with three major peaks in 1964, 1978 and 2000. As shown in Figs. 4 and 6, the wavelet spectral analysis shows a significant period of around 16 years during the period from middle 1970s to 1989 in terms of the interdecadal variations of the TC activities over AS.

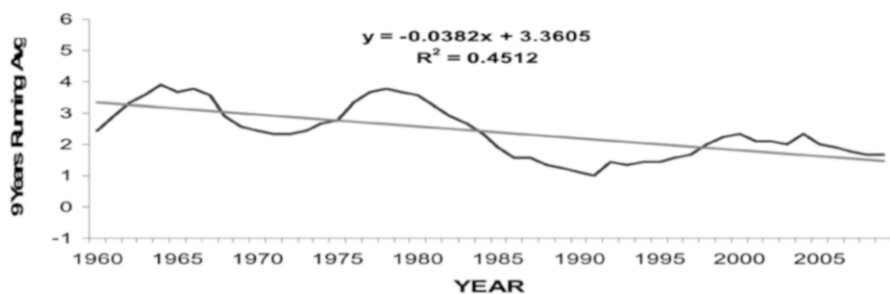
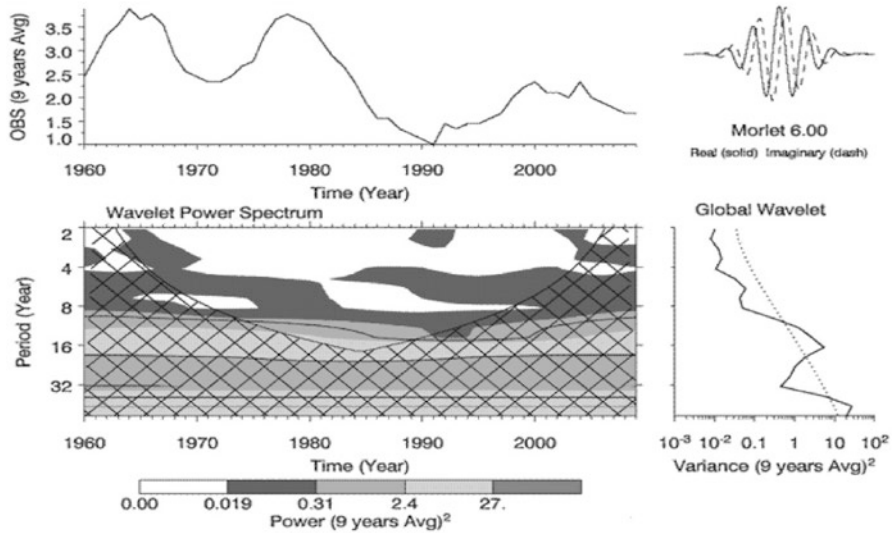
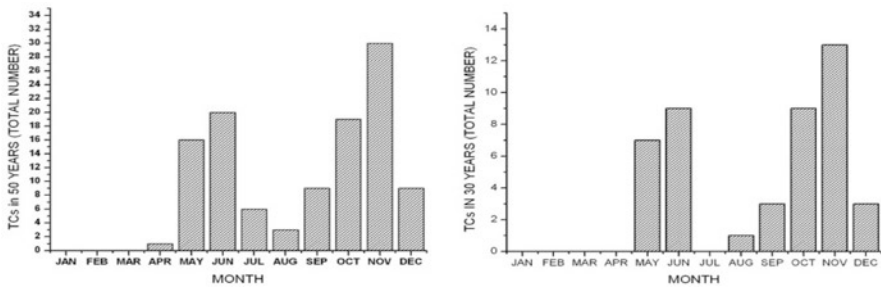


Fig. 5 Interdecadal variations and the trend of TC activities during the period from 1960 to 2009





**Fig. 6** The local power spectrum of the 9-year running mean occurrence frequency of the TC activity over AS by using Morlet wavelet analysis. The *thick contour* encloses regions of greater than 90 % confidence for a red-noise process. Cross-hatched regions on either end indicate the “cone of influence,” where edge effects become important



**Fig. 7** Total number of the TCs in different months of a year for the period from 1960 to 2009 (*left*) and from 1980 to 2009 (*right*)

### 3.3 Seasonal Variation of the TC Activity over AS

Figure 7 shows that the occurrence frequency of the TCs over AS in pre-monsoon (May–June) and post-monsoon (October–November) are much higher than the rest of the months. During the past 50 years, no TC occurred in January, February and March. However, during past 30 years, there are 5 months without TC over AS.

In conclusion, there are two dominant seasons of the TC activities over AS, namely pre-monsoon season (May and June) and post-monsoon season (October and November). In other 5 months (April, July, August, September and December) there are much fewer occurrence of TCs over AS.

As shown in Figs. 7 and 8, the average monthly SST reveals that the temperatures during the two seasons are higher as compared to the months with less TC activity in the area. During TC active seasons the SST is higher than 27 °C in most areas of the Arabian Sea (Fig. 8), while the SST is lower than 27 °C in most areas of the north Arabian Sea during TC inactive season (Fig. 8). Palmen (1948) observed that tropical cyclones required ocean temperatures of at least 26.5 °C for their formation and growth. Gray (1979) also pointed out the need for this warm water to be present through a relatively deep layer (50 m) of the ocean. This 26.5 °C value is closely linked to the instability of the atmosphere in the tropical and subtropical latitudes. Above this temperature deep convection can occur, but below this value the atmosphere is too stable and little to no thunderstorm activity can be found (Graham and Barnett 1987). This indicates that the TC activity is strongly modulated by the SST underneath. If the SST in the region is lower than 27 °C, no TC or much fewer TCs will be formed there.

Figure 9 demonstrates the monthly TC activities every 10 years during the past 50 years (1960–2009). As shown in the figure, during the first two decades, there are 8 months in a year with TC activities. During last three decades, there are only 6 months with TC activities. This result coincides with the decreasing trend of the TC activity over AS during the past 50 years. In addition, it was seen that the largest occurrence frequency of TCs over the AS is in November.

### ***3.4 Spatial Distribution of TC Activity***

The TC activity over AS is checked for its variation in east-west and north-south directions to find the key region of pronounced activity. For this purpose, the study area is divided into grids of 5° × 5° and the genesis point of TCs is marked as shown in Fig. 10. Figure 10 reveals that there are much more TCs on the eastern side of 65°E than its western counterpart, and the key area for TC genesis is 5°N–25°N, 65°E–75°E. The yearly occurrence frequency of TCs over AS in the east and west of 65°E is shown graphically in Fig. 11.

Figure 11 describes the yearly distributions of TCs on the eastern and western side of 65°E. Almost 90 % of TC activity occurred in the eastern part. As can be seen in Figs. 11 and 12, the SST is generally higher on the eastern side of the Arabian Sea than the western side. This can also be seen in Fig. 12 that the mean SST during the past 50 years is higher in the eastern side of the Arabian Sea than its western side.

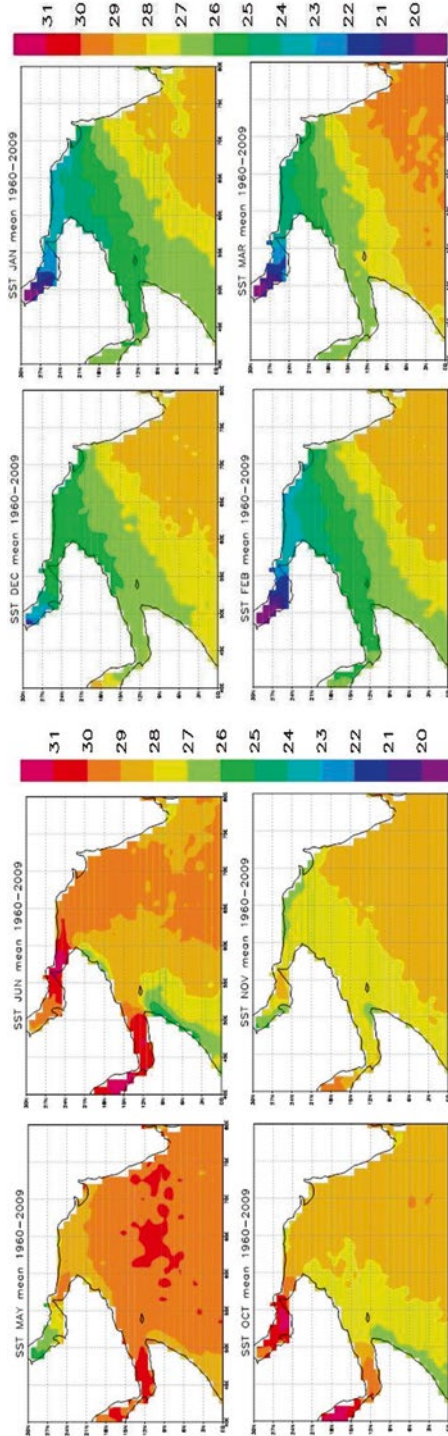
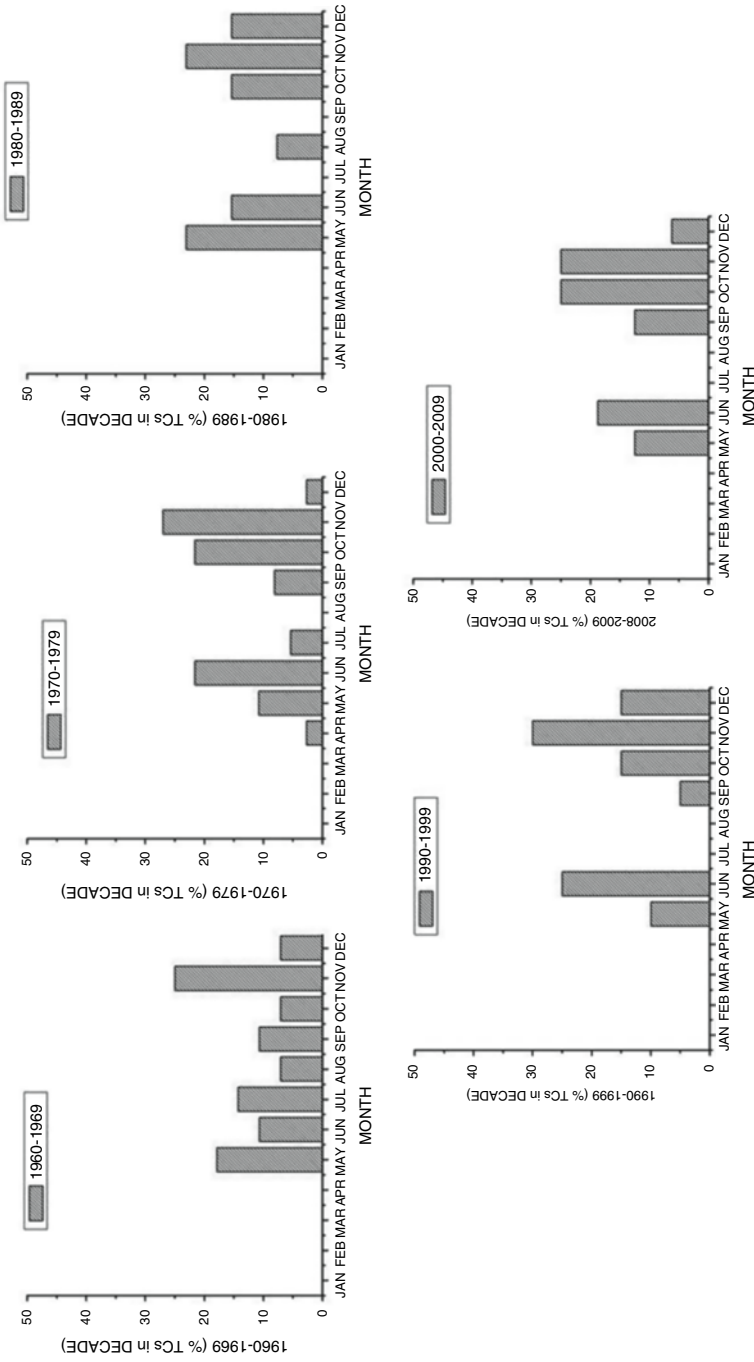


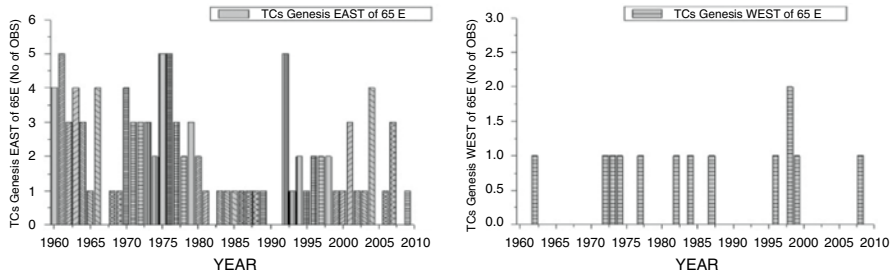
Fig. 8 Mean monthly SST averaged for the period 1960-2009 in TC active months (left) and inactive months (right)



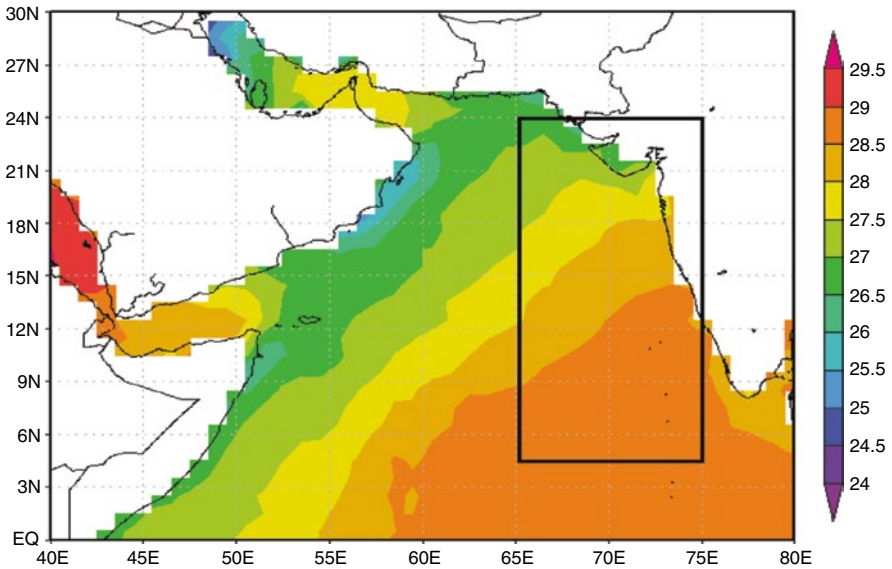
**Fig. 9** Interdecadal variations of the monthly TC activities during the period from 1960 to 2009

**Fig. 10** Spatial distribution of TC activity over AS (Shaded rectangle is the key area of TC genesis)

	45°E	50°E	55°E	60°E	65°E	70°E	75°E	80°E
25°N	0	0	0	0	0	9	4	0
20°N	0	0	0	5	9	18	0	0
15°N	0	1	2	3	8	32	4	4
10°N	0	0	0	1	7	9	4	4
5°N	0	0	0	0	1	1	2	2



**Fig. 11** Yearly distribution of TC activity over east (left) and west (right) of 65°E



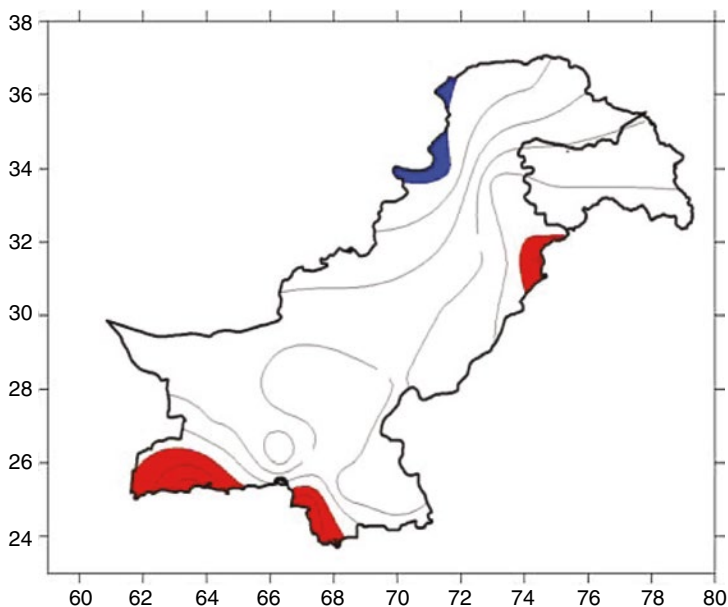
**Fig. 12** The average of SST during the period from 1960 to 2009 (Note: Rectangle defines the key area of TC genesis)

### 3.5 TC Activity over AS and Rainfall Anomaly in Southern Pakistan

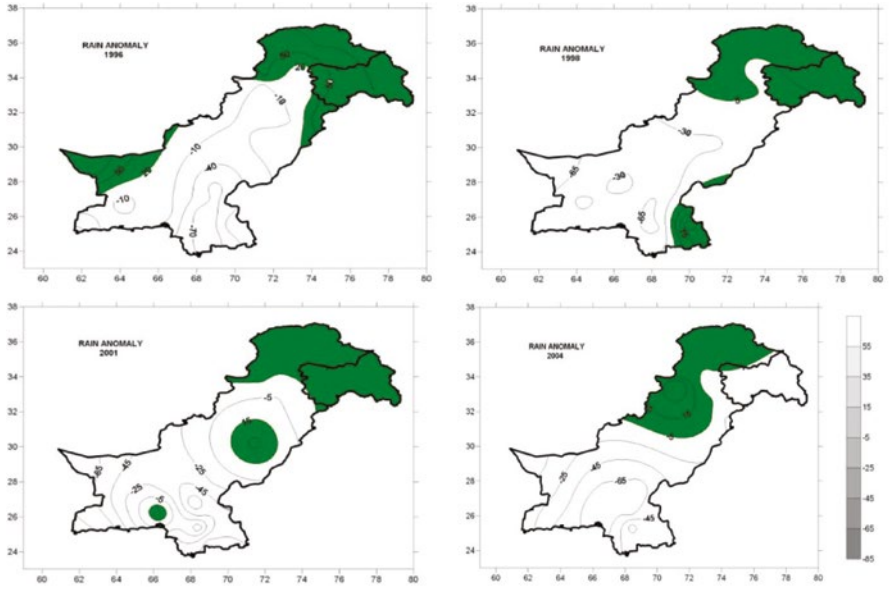
The TC activity over AS has a negative correlation with the rainfall anomaly in the southern region of Pakistan (Fig. 13); in other words, in case of more activity the rainfall anomaly will be negative, and vice versa. In the following, we shall give some examples as mentioned below to elaborate it.

Figure 14 shows rain anomalies of years 1996, 1998, 2001 and 2004 when there are more TC activities. It reveals that there are negative anomalies of rainfall in coastal regions of Pakistan and positive anomalies in the north of Pakistan in these years. There are 3, 4, 3 and 4 TCs, respectively in these years. The average number of TCs is 2.28 during past 50 years.

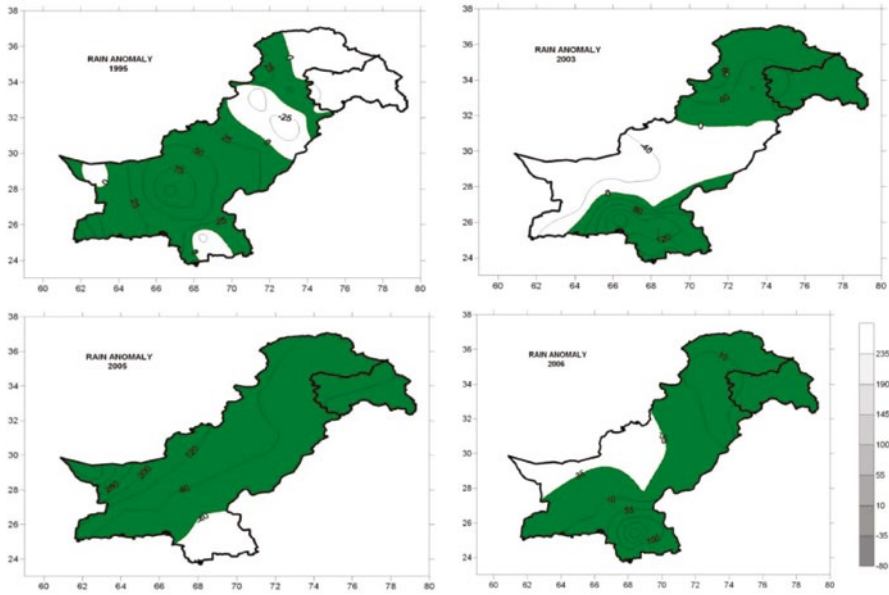
Figure 15 shows rain anomalies of years 1995, 2003, 2005 and 2006 when there are less TC activities. It reveals that there are positive anomalies of rainfall in large part of coastal regions of Pakistan. In these years the frequency of TC activity is 1, 1, 0 and 1, respectively, which is less than the average number (2.28) of TC activity during the past 50 years.



**Fig. 13** Correlation coefficients between the number of TCs after removing linear trend and the rainfall anomaly in Pakistan and adjoining areas. The correlation coefficients are significant at 90 % confidence level. Significant negative (positive) correlation coefficients are shaded in red (blue)



**Fig. 14** Rainfall anomaly in case of more TC activities for Pakistan and adjoining areas (*shaded region is positive anomaly*)



**Fig. 15** Rainfall anomaly in case of less TC activity for Pakistan and adjoining areas (*shaded region is positive anomaly*)



## Conclusions

The TC activity over AS during study period is found to have decreasing tendency in its frequency with a slope of  $-0.04$  in interannual as well as interdecadal variations. It is more frequent in two spells, pre-monsoon and post-monsoon seasons, of the region of emphasis i.e. Pakistan. It is supported by the sea surface temperatures of AS, which in active seasons remain higher than the other months with less or no TC activity. The TC activity over AS is more pronounced in the region bounded by four vortices ( $5^{\circ}\text{N}$ ,  $65^{\circ}\text{E}$ ), ( $25^{\circ}\text{N}$ ,  $65^{\circ}\text{E}$ ), ( $25^{\circ}\text{N}$ ,  $75^{\circ}\text{E}$ ) and ( $5^{\circ}\text{N}$ ,  $75^{\circ}\text{E}$ ). In this region 80 % of the TCs have their point of genesis and the area is regarded as key area of AS for generation of TCs. The higher TC activity in the eastern side of  $65^{\circ}\text{E}$  longitude than the western part is in relation with the SST of open sea area. According to Morlet wavelet analysis, yearly TC activity has cyclic behaviour of 2–3 years period.

The TC activity over AS has negative impacts on the rainfall over the areas around coast or in general southern part of Pakistan. The rainfall of the area is suppressed in case of more TC activity over AS whereas in case of less TC activity the area gets more precipitation.

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