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Changes in the frequency of tropical cyclones over the North Indian Ocean

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With 6 Figures

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Summary

Changes in the frequency of tropical cyclones developing over the Arabian Sea and the Bay of Bengal have been studied utilizing 122 year (1877–1998) data of tropical cyclone frequency. There have been significant increasing trends in the cyclone frequency over the Bay of Bengal during November and May which are main cyclone months. During transitional monsoon months; June and September however, the frequency has decreased. The results have been presented for five months, i.e., May-November which are relevant as far as tropical cyclone frequency over the Arabian Sea and the Bay of Bengal are concerned. The tropical cyclone frequency in the Arabian Sea has not shown any significant trend, probably due to small normal frequency.

The frequency time series has been subjected to the spectral analysis to obtain the significant periods. The cyclone frequency over the Bay of Bengal during May has shown a 29 year cycle. A significant 44 year cycle has been found during November. Over the Arabian Sea significant cycles of 13 and 10 years have been observed during May-June and November, respectively. The tropical cyclone frequency in the North Indian Ocean has a prominent El Niño-Southern Oscillation (ENSO) scale cycle (2–5 years) during all above five months. The annual cyclone frequency exhibits 29 year and ENSO scale (2–4 years) oscillations. There is a reduction in tropical cyclone activity over the Bay of Bengal in severe cyclone months May and November during warm phases of ENSO.

Examination of the frequencies of severe cyclones with maximum sustained winds ≥ 48 knots has revealed that these cyclones have become more frequent in the North Indian Ocean during intense cyclone period of the year. The rate of intensification of tropical disturbances to severe cyclone stage has registered an upward trend.

1. Introduction

Tropical cyclones are most fascinating weather events of the tropics. They have significant impact on the weather and climate of tropical countries (Riehl, 1979). Thus, the trends in their frequency and intensity in the North Indian Ocean are very important for the maritime regions of South Asia.

Most of the severe cyclones of North Indian Ocean form during November and May and strike coasts of India and Bangladesh. These cyclones cause considerable loss of life and property every year in this region. There is a growing feeling that increase of sea level in response to global warming may enhance the risks of coastal flooding due to increased frequency of tropical cyclones. Most of the studies pertaining to the tropical cyclones of the North Indian Ocean have dealt with the prediction of their intensity and movement (e.g., Sikka and Suryanarayana, 1968; Neumann, 1981). Although there have been some climatological studies (e.g., Mandal and Neumann, 1976) but none of these have looked into the long term changes in the monthly frequencies of

* South Asian Association for Regional Cooperation

tropical cyclones forming over the Arabian Sea and the Bay of Bengal.

The main objective of the present study is to find out the trends and oscillations in the monthly frequencies of tropical cyclones of the Arabian Sea and the Bay of Bengal during past century. The trends and cycles would certainly provide long-range indications of the expected frequencies of occurrence of tropical cyclones in the North Indian Ocean.

The trends in the intensity of cyclones during intense cyclone seasons have been obtained by computing the changes in the intensification rates of tropical disturbances to severe cyclone stage. As maximum number of North Indian Ocean intense cyclones form in pre- and post-monsoon seasons during May, October and November the trends in the frequency of severe cyclones with maximum sustained wind $\geq$48 knots have been obtained separately for these months.

2. Data and method of analysis

The frequencies of tropical cyclones forming over the Arabian Sea and the Bay of Bengal during the period 1877 to 1989 have been obtained from the storm atlas published by the India Meteorological Department (IMD, 1979). The data for recent years 1990–1998 has been obtained from IMD records.

The monthly linear trend coefficients for the cyclone frequencies have been calculated for the Arabian Sea and the Bay of Bengal separately. The correlation coefficients have been computed between the cyclone frequencies and the years. Obviously the linear correlation coefficients should be significant, if a time series has to have any trend. The significance of correlations has been tested using two-tailed t-test. The trend analysis has been performed using method of least squares. The power spectrum analysis (Blackman and Tukey, 1958; Panofsky and Brier, 1985; Jenkins, 1961) has been applied with different lags to find out the significant periods in the frequencies of tropical cyclones. The significance of periods has been tested using χ^2-test.

3. Results

The results of trend analysis have been presented in Table 1. The significance level of correlation coefficients (CCs) pertaining to Bay of Bengal range from 90% to 99% during the months May, June, September and November. The CC for October is not significant. It may be remarked that due to very high degree of freedom (N-2, N being the number of years in the time-series, which is 122 in this case) even smaller CCs become highly significant. Further, linear CCs in such long time-series of cyclone frequency are not expected to be very high as the time-series contains the periodical oscillations in addition to the linear trend. Generally, the CCs with 90% level of significance should draw attention. The highest positive trend of cyclone frequency, e.g., +0.67 per hundred years has been observed during November followed by +0.27 per hundred years during May. The highest negative trend of −0.31 per hundred years was found during June followed by −0.24 per hundred years during September.

The tropical cyclone frequency over the Arabian Sea has not shown any significant trend

Table 1. Results of trend analysis performed on the monthly frequencies of tropical cyclones over the Bay of Bengal and Arabian Sea for the period of 1877–1998

	Bay of Bengal					Arabian Sea					North Indian Ocean
	May	June	September	October	November	May	June	September	October	November	Annual
Correlation coefficient	+0.168	−0.207	−0.157	−0.025	+0.244	−0.098	+0.009	+0.076	+0.11	+0.091	−0.112
Level of significance	0.90	0.975	0.90	NS	0.99	NS	NS	NS	NS	NS	NS
Trend per 100 Years	+0.27	−0.31	−0.24	−0.05	+0.67	−0.11	+0.01	+0.04	+0.14	+0.11	−0.82

Table 2. Results of spectral analysis performed on the monthly frequencies of tropical cyclones over the Bay of Bengal and Arabian Sea for the period of 1877–1998

	Significant periods in years (Parenthesis value indicate level of significance)				
	May	**June**	**September**	**October**	**November**
Tropical cyclone frequency over Bay of Bengal	4.1, 29 (0.95) (0.90)	2.2, 3.5 (0.95) (0.975) 87 (0.95)	2.2, 2.5 (0.90) (0.95) 2.6, 3.6 (0.95) (0.90)	4.6, 4.8 (0.95) (0.90) 5.4, 17.4 (0.90) (0.99)	2.8, 3.3 (0.95) (0.90) 3.5, 43.5 (0.90) (0.95)
Tropical cyclone frequency over Arabian sea	5.1, 13.4 (0.90) (0.975)	2.0, 2.1, 2.5 (0.90) (0.95) (0.975) 4.3, 13.4 (0.90) (0.99)	2.3, 2.5 2.6 (0.90) (0.90) (0.90) 2.8, 34.8 (0.90) (0.90)	3.9, 4.6 (0.90) (0.90) 29 (0.90)	2.6, 3.0 (0.95) (0.90) 5.8, 10.2 (0.90) (0.95)
Annual frequency over the North Indian Ocean (Bay of Bengal and Arabian Sea)			2.2, 2.3, 3.4, 3.6, 29 (0.975) (0.90) (0.90) (0.975) (0.995)		

in any month. When we consider the annual frequency of tropical cyclones over the Bay of Bengal and the Arabian Sea together it has shown slight decreasing trend of −0.8/100 years. It may be noted that slight decline in the annual frequency is primarily due to the decreasing trend in the frequency of weaker cyclones of monsoon season. We have presented the monsoon results for June and September only. Substantial number of marginal cyclones form over the Bay of Bengal during July and August also. The cyclones of transitional monsoon months June and September are relatively stronger. When we consider the overall trend during important cyclone months May, June, September, October and the November, it is certainly positive. Similarly, when we consider the net trend during intense cyclone months May, October and November, it is significantly positive. Thus slight decreasing trend (statistically not significant) of −0.8/100 years in the annual tropical cyclone frequency over the North Indian Ocean does not undermine the significance of increasing trends in the frequencies of severe cyclones over the Bay of Bengal during intense cyclone months May, October and November. The annual trend in the frequency of all cyclones, weaker as well as severe has been given for the sake of completeness only.

The authors have noticed significant decreasing trends in the frequencies of monsoonal systems over the Bay of Bengal. As the emphasis of present study is on intense tropical cyclones, the details about monsoonal systems are omitted which is being documented separately. If the trends in the frequencies of cyclones and depressions over the North Indian Ocean could be linked to the global warming then certainly the global warming does not have the same impact on the cyclogenesis during intense cyclone period and the monsoon. Has it something to do with warm-core pre- and post-monsoon cyclone and cold-core monsoon depression? It would be surely an interesting area of investigation because a study by Dugam (1997) suggests that there may be a reduction in the frequency of monsoon depressions/cyclones due to global warming.

The results of power spectrum analysis with different lags have been presented in Table 2. The most common period of 2–5 years has been found in the cyclone frequency in all the months under consideration. Other significant periods for the Arabian Sea are: 13 years during May-June, 35 years during September, 29 years during October, and 10 years during November. For the Bay of Bengal also cyclone frequency exhibits prominent ENSO-scale oscillation of 2–5 years in different months. In May frequency a 29 year cycle has also been noticed. Interestingly, a long periodicity of 87 years has been observed during June. Some other important periods in the cyclone frequency over the Bay of Bengal are: 17 years during October and 44 years during November. The annual frequency of tropical

cyclones over the North Indian Ocean area covered by the Bay of Bengal and the Arabian Sea exhibits prominent 29 year and ENSO scale (2–4 years) oscillations.

An effort has been made to settle the question whether the severe cyclones have become more frequent over the North Indian Ocean or not. Majority of severe cyclones (maximum sustained winds 48 knots or more) over the North Indian Ocean develops during November followed by May. Figure 3a,b depicts the trends in the intensification rates of tropical depressions (maximum sustained winds 33 knots or less) to severe cyclones. There has been a 17% increase in the intensification rate to cyclone stage and a 25% increase to severe cyclone stage over the North Indian Ocean in November during the entire period of 122 years under study. These trends in the intensification rates are significant at 99% level. It shows that the frequency of severe cyclones has increased at a faster rate. The intensification rate to severe cyclones has registered increasing trend in May also but the trend is lower than that observed during November. This implies that more number of tropical disturbances are intensifying into severe cyclones during November and May which matter most as far as intense tropical cyclones over the North Indian Ocean are considered.

The spectral analysis revealed the existence of an ENSO-scale (2–5 years) cycle in the tropical cyclone frequency over the North Indian Ocean showing the impact of ENSO on the cyclogenesis over this part of the world ocean. In order to investigate the possible impact of ENSO on the tropical cyclone frequency over the North Indian Ocean the correlations between the tropical cyclone frequency and the Southern Oscillation Index (SOI) were computed. Significant correlations were found for May, July, August and November over the Bay of Bengal. The results for May, October and November have been presented in Fig. 5. There is a significant reduction in the tropical cyclone frequency over the Bay of Bengal in May and November during ENSO epochs. The CC for May is +0.3 and for November is +0.2. The CC for October is also positive but not significant. Standardized anomalies of tropical cyclone frequencies over the Bay of Bengal and SOI have been presented in Figs. 6a,b.

4. Discussion

Severe tropical cyclones form over the Bay of Bengal and the Arabian Sea during pre-monsoon (especially during May) and post-monsoon (October and November). During the pre-monsoon period cyclones of Bay of Bengal generally move northward and cross northeastern coast of India or Bangladesh after recurvature. A pronounced shift towards west central Bay of Bengal occurs during the post-monsoon period due to which most of the cyclones strike southeastern coast of India and some of them even cross east coast of Sri Lanka. The months of November and May account for highest number of severe cyclones over the North Indian Ocean.

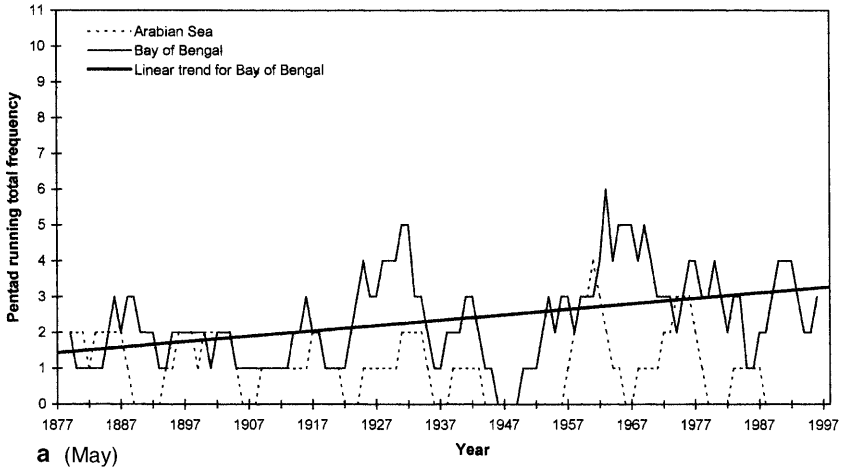
The cyclone frequency shows variations of different time scales. For instance interannual variations in the frequency has been documented by Shapiro, 1982; Gray, 1984; Nicholls, 1984 and Chan, 1985. El Niño-Southern Oscillation seems to influence the tropical cyclone frequency. For example, Sadler 1984 found that 1982–83 cyclone season in the Central and Eastern South Pacific was significantly different in terms of cyclone frequency, extended season and eastward longitude of formation. Over the North Indian Ocean lesser number of cyclones tend to form during post-monsoon season of ENSO years, whereas during winter their frequency is slightly higher.

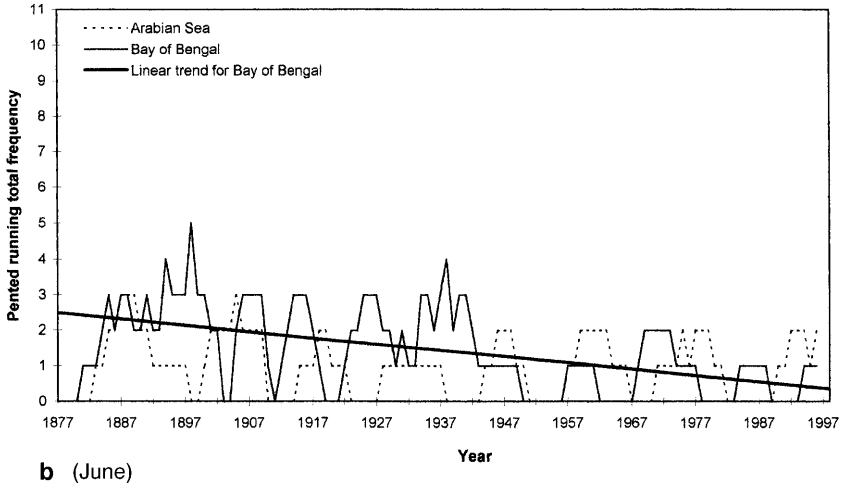
Other than interannual variations there are variations of higher time scales. If these long-term variations of cyclone frequency are properly documented then the epochs of higher and lower frequencies could be foreshadowed much in advance.

Long-term trends in the cyclone frequency can provide insight into various changes that are taking place in the ocean-atmosphere system. It is with these views that the present study is undertaken.

4.1. Trend

As revealed by the trends presented in Fig. 1a–e and Table 1 the cyclone frequency over the Bay of Bengal has shown different trends in different months. During November and May (which matter most as far as severe cyclones over the Bay are concerned) the cyclone frequency has





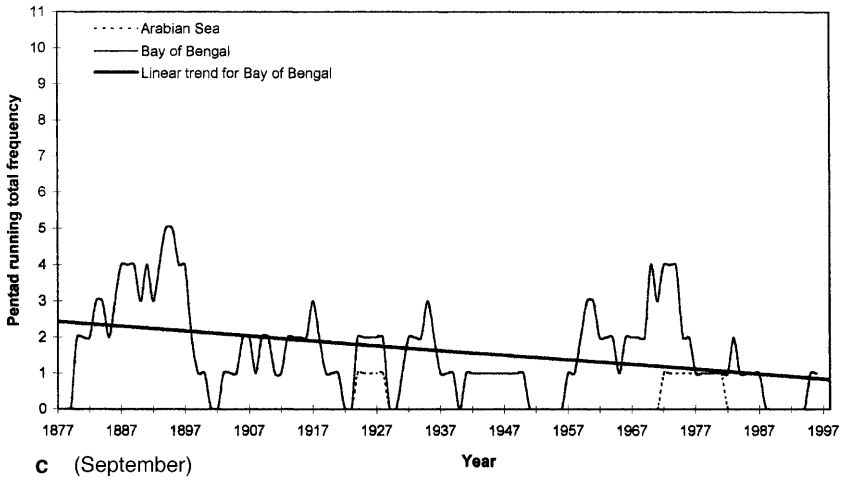
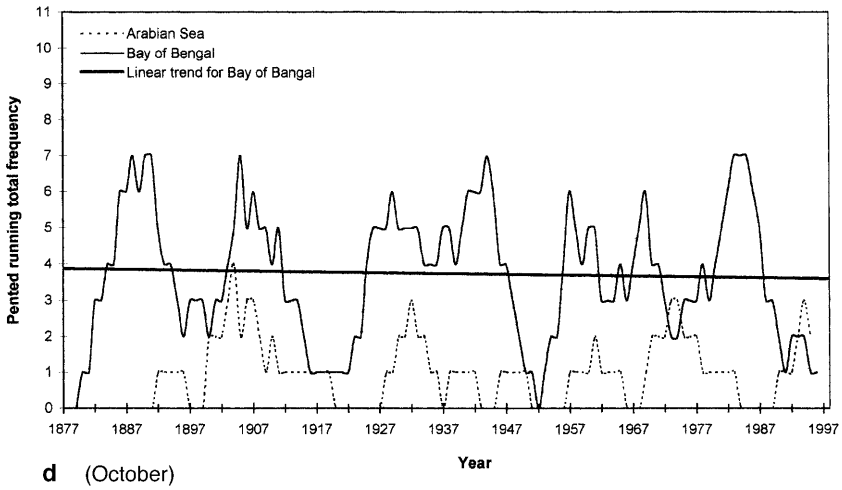
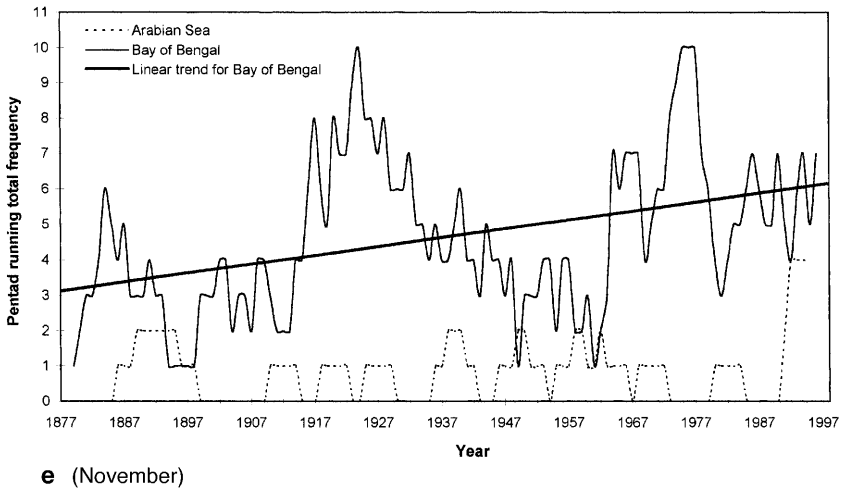


Fig. 1a–e. Pentad running total frequencies and linear trend for May, June, September, October and November (trend line has been shown for Bay of Bengal only)

shown significant increasing trend. For instance, during November it is +0.67/100 years, which is statistically significant at 99% level. Keeping in view the average frequency during November (about 0.87 per year) this increase is highly significant. The frequency has almost doubled during last 122 years. If this type of trend in the November cyclone frequency over the Bay continues then it might lead to far reaching implications in the affected regions.



d (October)



e (November)

Fig. 1 (continued)

The trend of +0.27/100 years during May is also significant. The average May frequency of tropical cyclones over the Bay of Bengal is about one cyclone in two years. Thus there has been a substantial increase in the May frequency over past century.

It may be remarked that over the Bay of Bengal highest sea-surface temperatures (SSTs) are recorded during May and November. The long-term trends in SST over the Bay of Bengal will have to be looked into in order to establish probable linkages between the observed cyclone frequency trend and the SST trend.

It is interesting to note that cyclone frequencies over the Bay have exhibited marked negative trends during the monsoonal months June and September. During other two monsoon months as well, (e.g., July and August) the frequencies have decreased. As a matter of fact the seasonal frequency of monsoonal depressions and cyclones has shown remarkable decrease of about 5 disturbances per hundred years. In other words the number of depressions and cyclones has been almost halved over the Bay of Bengal during past hundred years. As the trends and the periodicities in the monsoonal system frequency over the Bay are being studied separately the details are omitted here. But the scenario that emerges is the following: there has been a distinct increasing trend in the cyclone frequency in pre-monsoon (May) and significant decreasing trend in the monsoon months.

After the monsoon the reversal in the trend starts again. Consequently, the cyclone frequency during October does not show any significant trend. But by November the trend becomes significantly positive. The reversal in trend pattern has been depicted in Fig. 2.

There is a striking difference between the trend patterns observed in the cyclone frequen-

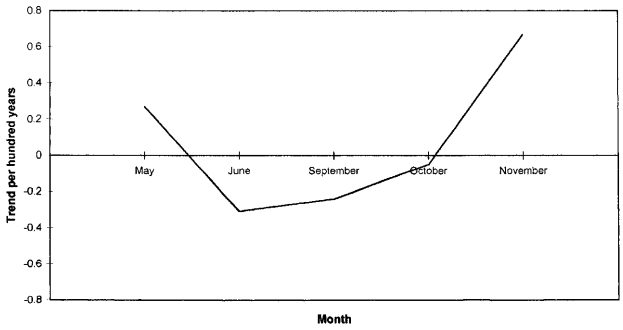


Fig. 2. Reversal of trend over the Bay of Bengal during different months

cies over the Bay of Bengal and the Arabian Sea. The Bay of Bengal seems to be very responsive but the Arabian Sea has not shown any trend in the cyclone frequency. It is also important to note that any change in the cyclone frequency over the Bay has more impact on the neighboring region as compared to the change over the Arabian Sea, since the cyclone frequency over the Bay is substantially higher.

Due to different trend patterns observed in different seasons the trend in the annual frequency of tropical cyclones over the Bay of Bengal and the Arabian Sea is not very high but can not be ignored. The overall trend is negative, e.g., −0.8/100 years. This is mainly due to the decrease in frequency during monsoon.

4.2. Periodicity

As discussed earlier interannual fluctuation in the cyclone frequency is a common feature. But the oscillations of decadal or higher time scales are required to be documented. It is interesting that – although the long-term trends in the cyclone frequencies over the Bay of Bengal and the Arabian Sea have been entirely different – the observed periodicities have been more or less similar.

The power spectrum analysis performed on the cyclone frequency has provided a quantitative footing to the influence of ENSO on the frequency of tropical cyclones forming over the North Indian Ocean. Significant ENSO scale cycles have been found in all the months. The periods have ranged from 2–5 years over the Bay of Bengal and 2–7 years over the Arabian Sea.

Prominent decadal scale cycles of about 13 and 10 years have been observed in the cyclone frequency over the Arabian Sea during May-June and November, respectively.

Table 2 shows that the annual frequency of tropical cyclones over the North Indian Ocean is characterized by the ENSO scale oscillations. The annual frequency of cyclones also possesses a strong 29 year cycle. Thus first decade of 21st century may witness more number of tropical cyclones over the Bay of Bengal and the Arabian Sea as the rising leg of the cycle has commenced during early 1990's.

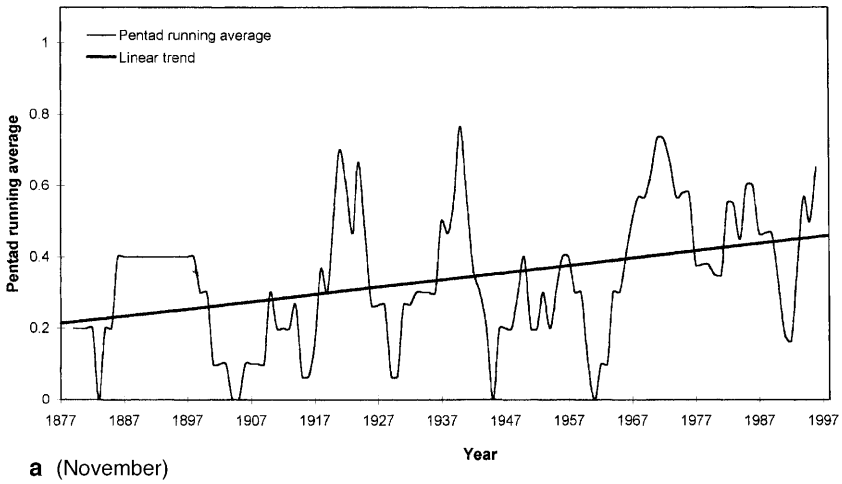
4.3. Trends in the intensification rate of tropical disturbances to severe cyclones

As revealed by Fig. 3a more tropical disturbances are now intensifying into severe cyclones during November. The intensification rate to severe cyclone stage in November has registered an increasing trend of 20% per hundred years, which is significant at 99% level.

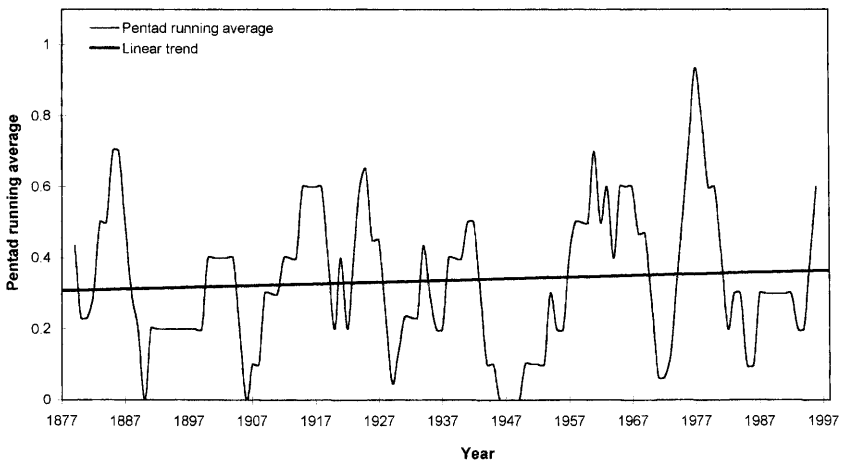
May accounts for second highest number of severe cyclones over the North Indian Ocean after November. Tropical disturbances that develop during May have high probability of reaching to severe cyclone stage. Therefore, any change in the intensification rate has important implications for the affected regions. Figure 3b shows that the intensification rate to severe cyclone stage has registered an increasing tendency during May also but the rate is lower than that observed during November.

4.4. Trends in the frequency of severe cyclones (with maximum sustained winds ≥48 knots) during intense cyclone seasons

In order to bring out the trends in the frequency of severe cyclones of North Indian Ocean during past decades separately, all intense cyclones having maximum sustained winds ≥48 knots that formed over the Bay of Bengal and the Arabian Sea during intense cyclone period of the year, i.e., October-November (post-monsoon) and May (pre-monsoon) were clubbed together. Figure 4 depicts the linear trend in the frequency of severe cyclones of North Indian Ocean during intense cyclonic period of the year. It is interesting to note that the severe cyclones in the North Indian Ocean have registered more than two-fold increase during 122 years period under considera-



a (November)



b (May)

Fig. 3a,b. Five year running average of intensification rate to severe cyclonic storm stage over the North Indian Ocean for November and May

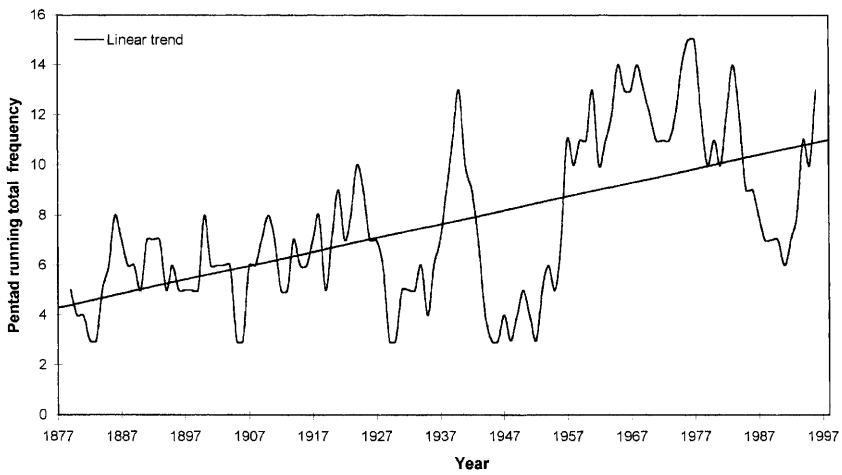


Fig. 4. Pentad running total frequency of severe cyclonic storms and linear trend over the North Indian Ocean during intense cyclone period of the year, i.e. May, October and November

tion. Therefore, the diminishing frequency of weaker cyclones of monsoon season does not undermine the importance of the fact that the hazardous potential of North Indian Ocean tropical cyclones has shown an upward trend due to steep rising trends in the frequency of severe cyclones. As a matter of fact the intense cyclones which mostly form in the Bay of Bengal during May, October and November have registered significant rising trends in their frequencies

in each individual month. Corresponding figures are not being presented here to avoid congestion.

4.5. Impact of ENSO on tropical cyclone frequency in the North Indian Ocean

ENSO is known to cause world wide weather anomalies. There is a substantial reduction in the cyclone frequency over the North Atlantic Ocean during the negative phase of SO (Gray, 1984). According to Chan (1985) the frequency of cyclones in the North Pacific between 140°–160° E increases during negative phases of SO. Figure 5 shows that the CC between SOI and tropical cyclone frequency over the Bay of Bengal during May is +0.3 and the corresponding CC for November is +0.2 implying that there is a reduction in the tropical cyclone frequency during negative phases of SO. The CC for May is significant at 99% level and that for November is significant at 95% level. CCs for Arabian Sea are not statistically significant showing that ENSO has only limited impact on the cyclone frequency over the Arabian Sea.

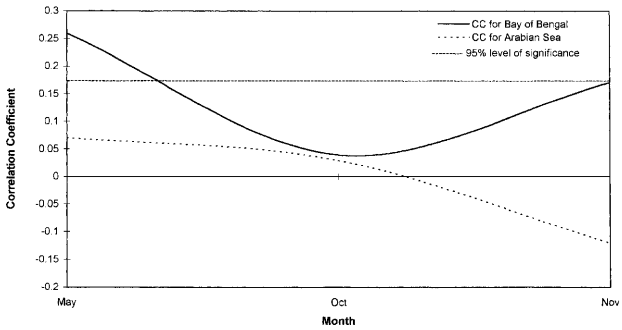


Fig. 5. Correlation between SOI and the frequencies of tropical cyclones

Four significant negative peaks in SOI in Fig. 6b correspond to the years 1896, 1953, 1972 and 1987 (all ENSO years). It is noteworthy that during none of these years any cyclone formed over the Bay of Bengal in the month of May.

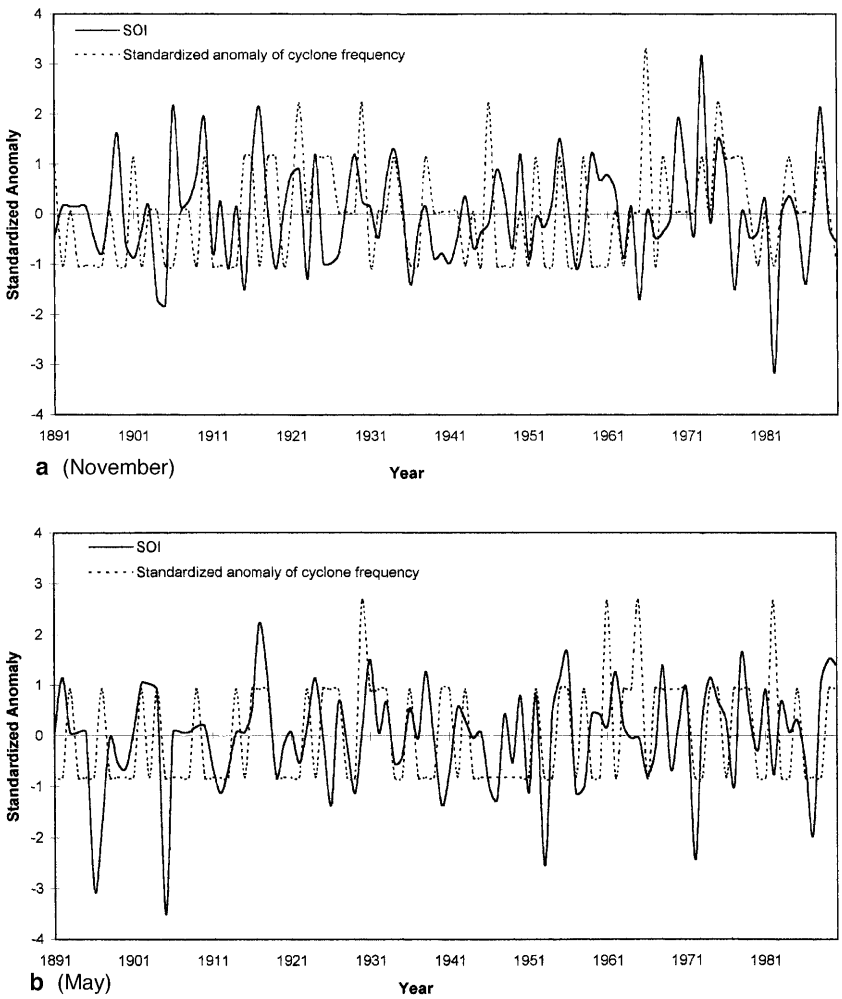


Fig. 6a,b. Standardized anomaly of tropical cyclone frequency in the Bay of Bengal and SOI for November and May (1891–1990)

Negative peaks in the standardized anomaly of cyclone frequency during all these years in Fig. 6a signify this aspect. When we consider the anomalies for November (Fig. 6a), we find that highest negative SOI occurred during 1982. No cyclone formed over the Bay of Bengal during that month. Thus an inverse relationship between SO and the tropical cyclone frequency over the Bay of Bengal is apparent from the examination of Fig. 6a,b.

5. Conclusions

Over the past decades the frequency of tropical cyclones in the North Indian Ocean has registered significant increasing trends during November and May which account for maximum number of intense cyclones. The increasing trend has been primarily due to the increased frequency over the Bay of Bengal. The frequency of severe cyclones has increased at a faster rate registering an increase of 20% per hundred years in the intensification rate of tropical depressions to severe cyclones in the month of November. The frequency of only severe cyclones has registered more than two-fold increase in the North Indian Ocean during intense cyclonic period of the year, i.e., May, October and November.

The tropical cyclone frequency in the North Indian Ocean is characterized by an ENSO scale (2–5 years) oscillations. The annual frequency also possesses a 29 years oscillation. The tropical cyclone frequency over the Bay of Bengal diminishes in May and November during the negative phases of Southern Oscillation.

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References

Blackman RB, Tukey JW (1958) The measurement of power spectra. New York: Dover Publications, 190 pp

Chan JC-L (1985) Tropical cyclone activity in the northwest Pacific in relation to the El Niño/Southern Oscillation phenomenon. Mon Wea Rev 113: 599–606

Dugam SS (1997) Global warming and its impact on tropical cyclone. Proc. IGB Symposium on ''Changes in Global Climate due to Natural and Human Activities''. Allied Publishers, New Delhi, India, 296 pp

Gray WM (1984) Atlantic seasonal hurricane frequency. Part I: El Niño and 30 mb quasi-biennial oscillation influences. Mon Wea Rev 112: 1649–1668

IMD Atlas (1979) Tracks of storms and Depressions in the Bay of Bengal and Arabian Sea. New Delhi: IMD

Jenkins GM (1961) General considerations in the analysis of spectra. Technometrics 3(2): 133–166

Mandal GS, Neumann CJ (1976) Climatology of North Indian Ocean tropical cyclones by 2 1/2 degree latitude-longitude square. Fellowship report of senior authors. New Delhi: India Meteorological Deptartment

Neumann CJ (1981) Trends in forecasting the tracks of Atlantic tropical cyclones. Bull Amer Meteor Soc 26: 1473–1485

Nicholls N (1984) Predictability of interannual variations of Australian seasonal tropical cyclone activity. Mon Wea Rev 113: 1144–1149

Panofski HA, Brier GW (1958) Some applications of statistics to meteorology. Pennsylvania: Pennsylvania State University, 224 pp

Riehl H (1979) Climate and weather in the tropics. London: Academic Press, 395 pp

Sadler JS (1984) The anomalous tropical cyclones in the Pacific during the 1982–1983 El Niño. Postprints of 15th Tropical Meteorology, Amer. Meteor. Soc., Boston, 51–55

Shapiro L (1982) Hurricane climate fluctuations, Part II: Relation to large scale circulation. Mon Wea Rev 110: 1014–1023

Sikka DR, Suryanarayana R (1968) Forecasting the movement of tropical cyclone/depression in the Indian region by computer oriented techniques using climatology and persistence. New Delhi, IMD 76: 268 pp

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