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ORIGINAL PAPER

Inter-annual variability of summer monsoon rainfall over Orissa (India) in relation to cyclonic disturbances

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Abstract The summer monsoon rainfall over Orissa, a state on the eastern coast of India, is more significantly related than Indian summer monsoon rainfall (ISMR) to the cyclonic disturbances developing over the Bay of Bengal. Orissa experiences floods and droughts very often due to variation in the characteristics of these disturbances. Hence, an attempt was made to find out the inter-annual variability in the rainfall over Orissa and the frequencies of different categories of cyclonic disturbances affecting Orissa during monsoon season (June–September). For this purpose, different statistical characteristics, such as mean, coefficient of variation, trends and periodicities in the rainfall and the frequencies of different categories of cyclonic disturbances affecting Orissa, were analysed from 100 years (1901–2000) of data. The basic objective of the study was to find out the contribution of inter-annual variability in the frequency of cyclonic disturbances to the inter-annual variability of monsoon rainfall over Orissa.

The relationship between summer monsoon rainfall over Orissa and the frequency of cyclonic disturbances affecting Orissa shows temporal variation. The correlation between them has significantly decreased since the 1950s. The variation in their relationship is mainly due to the variation in the frequency of cyclonic disturbances affecting Orissa. The variability of both rainfall and total cyclonic disturbances has been above normal since the 1960s, leading to more floods and droughts over Orissa during recent years. The inter-annual variability of seasonal rainfall over Orissa and the frequency of cyclonic disturbances affecting Orissa during monsoon season show a quasi-biennial oscillation period of 2–2.8 years. There is least impact of El Nino southern oscillation (ENSO) on inter-annual variability of both the seasonal rainfall over Orissa and the frequencies of monsoon depressions/total cyclonic disturbances affecting Orissa.

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1 Introduction

The air–sea interaction plays a significant role in the structure and dynamics of summer monsoon circulation over the Indian region. The most important by-product of this tightly coupled air–sea interaction during summer monsoon season is the cyclonic disturbance. Over the sea, wind strength is used as a criterion for classification of different intensities of cyclonic disturbances. As per criteria of the India Meteorological Department (IMD), a cyclonic disturbance is a depression if the wind speed is 17–27 knots (kt), a deep depression if the wind speed is 28–33 kt, a cyclonic storm if the wind speed is 34–47 kt, a severe cyclonic storm if the wind speed is 48–63 kt, a very severe cyclonic storm if the wind speed is 64–119 kt and a super cyclonic storm if the wind speed is more than or equal to 120 kt. However, over the land and adjoining sea area, the number of isobars at 2 hPa intervals around the central area of the disturbance is used as a criterion for classification of the intensity of cyclonic disturbance. The disturbance is identified as a depression if there are two closed isobars, a deep depression if there are three closed isobars, a cyclonic storm if there are 4–7 closed isobars, a severe cyclonic storm if there are 8–10 closed isobars, a very severe cyclonic storm if there are 11–39 closed isobars and a super cyclonic storm if there are 40 or more closed isobars.

Studies including that of Joseph (1976), Mooley and Parthasarathy (1984), Verma et al. (1985), Sontakke et al. (1993) and Parthasarathy et al. (1994) indicate a highly variable trendless behaviour of Indian summer monsoon rainfall (ISMR) with an epochal nature. Joseph (1976), using ISMR data of 1891–1974, has shown the existence of a low-frequency mode (LFM) in ISMR and described a 60 years period wave in terms of epochal behaviour. Kripalani and Kulkarni (1997) have analysed 125 years of ISMR (1871–1996), using Cramer's *t*-statistic, for 11 years' running mean and have shown that ISMR entered an above-normal epoch in 1990. They have concluded that LFM is important in modulating the performance of ISMR in inter-annual scale. In contrast to the insignificant trend in ISMR, there was a significant decreasing trend of 6.5 per 100 years in the annual frequency of monsoon depressions over the north Indian Ocean during the last century (Xavier and Joseph 1999; Singh 2001). According to Singh (2001), the frequency of monsoon cyclones has diminished considerably (1.9 per 100 years), with the falling trend being more pronounced during recent decades. Bhaskar Rao et al. (2001) have found that the monsoon depressions have three consistent trends, viz. a decreasing trend up to 1910 followed by an increasing trend up to 1950 and then a decreasing trend till the present time.

Considering the periodicity, Xavier and Joseph (1999) found higher amplitudes in harmonic analysis of ISMR during 1981–1990, with the periods of 60 years, about 2–2.7 years and 3.5 years. Pant et al. (1988) demonstrated that the LFM is not only limited to seasonal monsoon rainfall but is also found in various monsoon-related parameters, including cyclonic storms and depressions over the Bay of Bengal during the summer monsoon season. According to Bhaskar Rao et al. (2001), the periodicities of 2.2–2.8 years, 3.5–6.5 years and 10–15 years are consistently observed in the frequency of both depressions and cyclones over the north Indian Ocean in monsoon season. The periodicity of 2.2–2.8 years is attributed to the observed quasi-biennial oscillation (QBO), as reported by Elsner et al. (1999). The fluctuations of 3.5–6.5 years are attributed as consequences of the El Nino southern oscillation (ENSO), as reported by Trenberth (1976) and Elsner et al. (1999), and the signal with 10–15 years period is attributed to decadal oscillation, which may be in association with 11-year sun spot cycle activity (Elsner et al. 1999). According to Dhar et al. (1980), the change in monsoon depression frequency has no discernible impact on ISMR.

Orissa state, a meteorological sub-division of India, lies on the east coast of India, adjacent to north Bay of Bengal. Figure 1 describes the surface isobaric pattern, basic monsoon flow at 0.9 km above sea level (a.s.l.) over the Indian region, location of the mean position of the monsoon trough and the regions of rainfall maxima and minima with respect to the monsoon trough in the representative monsoon month of July (Pathan 1993). The regions of rainfall minimum and maximum with respect to the monsoon trough lie to the north and south of the monsoon trough, respectively. The region of rainfall maximum passes through Orissa. A number of cyclonic disturbances develop over northwest Bay of Bengal during the monsoon months and move normally westwards (IMD 1979 & 1996). In the presence of cyclonic disturbance over northwest Bay and the monsoon trough from the system extending westwards, Orissa lies in the southwest sector of the system and receives maximum rainfall. Rajamani and Rao (1981) have confirmed that the southwest sector of the westward moving monsoon depression receives maximum rainfall due to maximum low-level convergence. Owing to the above fact, the cyclonic disturbances developing over northwest Bay of Bengal and adjoining sea areas play a more significant role in the monsoon rainfall over Orissa. The understanding of the patterns of the frequency of cyclonic disturbances over the Bay of Bengal and its association with summer monsoon rainfall over Orissa assumes special importance. The principal objective of this study was to find the contribution of different categories of cyclonic disturbances to the inter-annual variability of seasonal monsoon rainfall over Orissa.

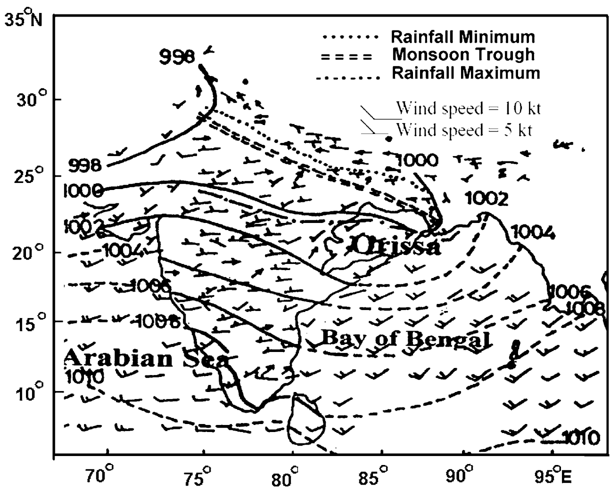


Fig. 1 Mean sea level isobaric pattern (hPa) and mean wind speed (knots) at 0.9 km above mean sea level over the Indian region

This study will help in further analysis and development of models for prediction of the frequency of cyclonic disturbances and monsoon rainfall over Orissa.

2 Data and methodology

The seasonal (June–September) monsoon rainfall data were obtained from Parthasarathy et al. (1995) over Orissa during 1901–2000. As the cyclonic disturbances developing over northwest Bay and its adjoining areas of northeast Bay and west central Bay contribute mostly to the summer monsoon rainfall over Orissa, the cyclonic disturbances, which cross the east coast between Visakhapatnam (17°43′ N and 83°14′ E) and Kolkata (22°39′ N and 88°27′ E), were considered for this study. The data on the frequencies of cyclonic disturbances for the period of 1901–1990 were collected from the *Tracks of storms & depressions in the Bay of Bengal and Arabian Sea*, published by IMD (1979 & 1996). The data on the frequencies of cyclonic disturbances during 1991–2000 were collected from weather reports published by IMD (1992–2001). Various categories of cyclonic disturbance (i.e., depression/deep depression, cyclonic storm and severe cyclonic storm/very severe cyclonic storm) were analysed to delineate their contribution to the inter-annual variability of monsoon rainfall over Orissa. There has been no super cyclonic storm affecting Orissa during monsoon season over the period under study.

The mean and coefficient of variation (CV) of the monsoon rainfall over Orissa and the frequencies of various categories of cyclonic disturbances during 1901–2000 were calculated and analysed. The 30-year moving averages and moving CVs were calculated to find the stability in the mean and variability. The linear trend coefficients in the seasonal monsoon rainfall over Orissa and the frequencies of different categories of cyclonic disturbances for the whole period were calculated to find the long-term trends. In order to verify the stability of these trends, we computed the linear trend coefficients for each 30-year period, moving forward by 1 year each time. A spectral analysis was performed in accordance with Blackman and Tukey (1958), with a maximum lag of 50 years, to delineate significant periods of oscillation in rainfall over Orissa. We analysed the relationship between the frequencies of cyclonic disturbances and monsoon rainfall over Orissa by calculating the correlation coefficients (CC), comparison of the averages, CVs, trends and periodicities in monsoon rainfall and the frequencies of different categories of cyclonic disturbances. We calculated the correlation coefficients between monsoon rainfall over Orissa and the frequencies of different categories of cyclonic disturbances for each 30-year period, sliding forward by 1 year each time (moving CC), to verify the stability of the relationship. We fitted the polynomials to the actual rainfall and frequency of different categories of cyclonic disturbances, their 30-year moving averages, moving CVs, moving trends and moving CCs to find out their future trends of variation.

3 Results and discussion

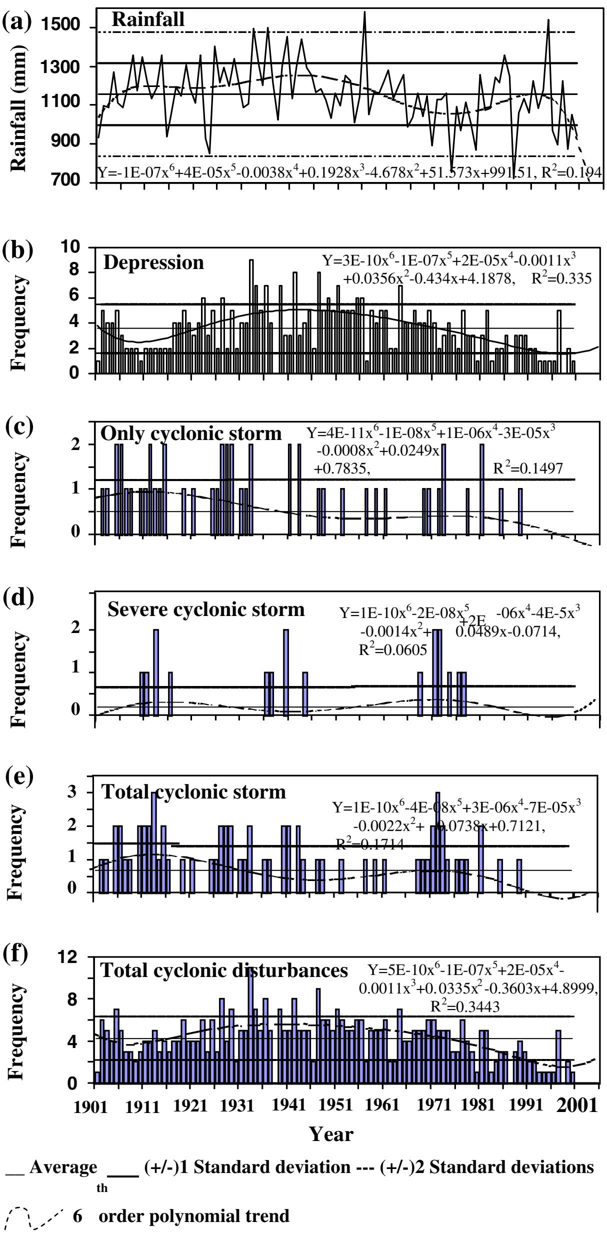
The mean and CV of rainfall and the frequency of cyclonic disturbances are analysed and discussed in the following section. The trends in rainfall and the frequency of cyclonic disturbances, the periodicities in rainfall and the frequency of cyclonic disturbances, and the correlation of rainfall with the frequency of cyclonic disturbances are presented and discussed in the sections thereafter.

3.1 Mean and CV of monsoon rainfall and frequency of cyclonic disturbances

The seasonal monsoon rainfall over Orissa during 1901–2000 is shown in Fig. 2a. The mean rainfall over Orissa during monsoon season (June–September) is approximately 116 cm, with a CV of about 14%. According to Parthasarathy et al. (1995), the average rainfall over India during monsoon season was approximately 88 cm, with a CV of about 10% based on data from 1871–1990. The rainfall and its variability are higher over Orissa than over all India, as rainfall over Orissa more significantly depends on the synoptic disturbances developing over north Bay of Bengal. Figure 2a indicates that the rainfall is changing from an excess rainfall phase during the beginning of the last century to a deficient rainfall phase towards the end of this century. It also indicates that the rainfall has been more variable, leading to more frequent floods and droughts over Orissa in recent years. The monsoon rainfall over Orissa does not show 30-year epochs, unlike ISMR, as found by Parthasarathy et al. (1994). Comparison with the study by Parthasarathy et al. (1995) indicates that flood years and drought years are not always common for all India and Orissa. The mean seasonal monsoon rainfall and the frequency of cyclonic disturbances affecting Orissa are shown in Table 1. Comparison with the mean frequency of cyclonic disturbances over the Bay of Bengal (IMD, 1996) indicates that approximately 66% and 72% of the total cyclonic disturbances and depressions, respectively, developing over the Bay of Bengal affect Orissa during monsoon season. The frequencies of the depressions/total cyclonic disturbances (Fig. 2) affecting Orissa were more frequently below normal during 1980–2000. According to the 30-year moving average in rainfall and frequency of cyclonic disturbances (Fig. 3), there is a similarity in the 30-year moving average curves of seasonal frequency of depression/cyclonic disturbances and the seasonal rainfall over Orissa during 1901–1955. It is observed that from 1955 the rainfall was not significantly dependent on the frequency of cyclonic disturbances until recent years. The 6th-order polynomial could be best fitted to the variation of rainfall and the frequency of cyclonic disturbances. According to these polynomials (Fig. 2), the rainfall over Orissa is likely to fall, even though the frequency of depressions/total cyclonic disturbances is likely to rise in future. The 6th-order polynomials could be well fitted to the 30-year moving average curves also (Fig. 3). There is a difference in the moving trends of monsoon depressions/total cyclonic disturbances and that in seasonal monsoon rainfall over Orissa in recent years.

The CV in the frequency of cyclonic disturbances affecting Orissa (Table 1) indicates that the disturbances with higher mean frequencies are associated with less CV. In general, the CVs are high in the frequencies of different categories of cyclonic disturbances, indicating larger inter-annual variation. There is a rising tendency in the 30-year moving CV of rainfall from around 1945, as seen in Fig. 4a. Also, there is a rising tendency of CV in depressions and total cyclonic disturbances from around the same period (Fig. 4b–f). The CVs in both rainfall and total cyclonic disturbances have been above normal since around the 1960s, leading to more frequent flood and drought years. The 6th-order polynomial could be well fitted to the curves of moving CVs, as the squared correlation coefficient (R^2) values are >80% in all the cases. According to these fitted polynomials, the higher than normal variability of rainfall and the frequencies of different categories of cyclonic disturbances may continue for some more years, leading to more frequent floods and droughts over Orissa.

Fig. 2 (**a**) The monsoon rainfall over Orissa; (**b**) frequency of monsoon depressions; (**c**) frequency of only cyclonic storms; (**d**) frequency of severe cyclonic storms; (**e**) frequency of total cyclonic storms and (**f**) the frequency of total cyclonic disturbances affecting Orissa during the monsoon season over the period 1901–2000



3.2 Trends in rainfall and frequencies of cyclonic disturbances

The annual monsoon rainfall over Orissa shows insignificant decreasing trend during the period of 1901–2000 (Table 1). The seasonal frequencies of all categories of cyclonic disturbances (Table 2) except the frequency of severe cyclonic storm show significant decreasing trend. The insignificant decreasing trend in monsoon rainfall

Table 1 Mean, coefficient of variation (CV) and linear trend coefficients (per 100 years) of monsoon rainfall over Orissa and the frequency of different categories of cyclonic disturbances affecting Orissa during 1901–2000

Parameters	Rainfall	Cyclonic disturbances				
		Only depressions	Only cyclonic storms	Severe cyclonic storms	Total cyclonic storms	Total cyclonic disturbances
Mean	1158 mm	3.6	0.5	0.18	0.68	4.3
CV (%)	13.7	54	141	266	120	49
Trend coefficients	–13.3 mm	**–1.29**	**–0.88**	–0.08	**–0.96**	**–2.25**

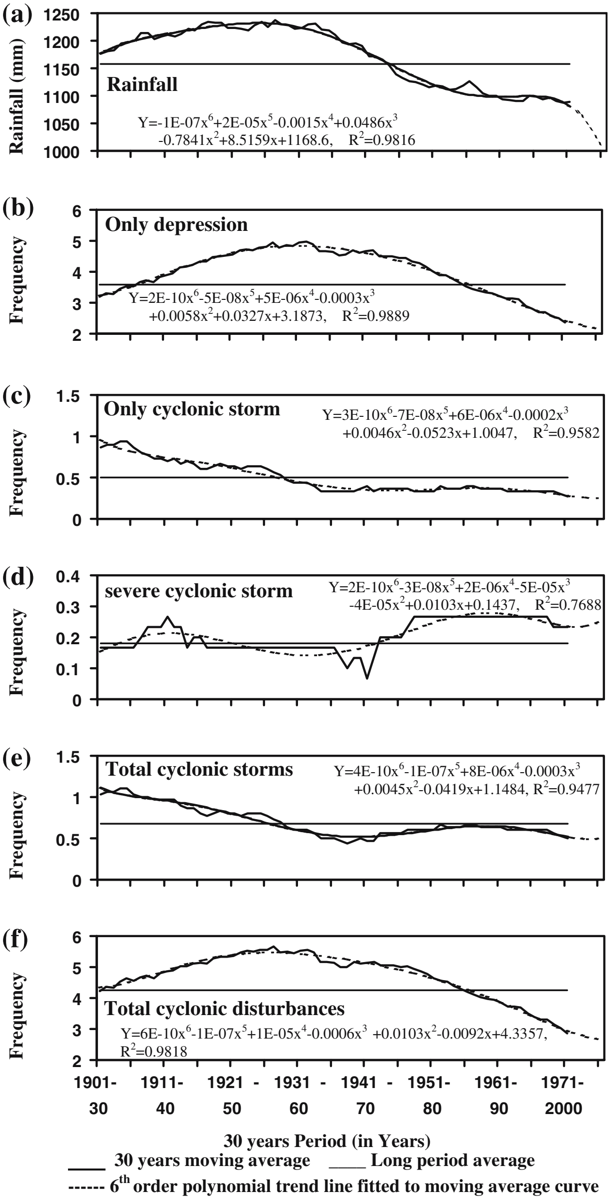
The trend coefficients significant at 95% level of confidence are shown in *bold type*

over Orissa, in spite of the significant decreasing trend in the frequency of cyclonic disturbances, may be due to the fact that the loss in rainfall due to decrease in frequencies of cyclonic disturbances has been compensated by the increase in frequency of low-intensity monsoon systems such as monsoon lows and upper air cyclonic circulations. From Fig. 5a, the 30-year linear trend has been significantly positive and negative for any 30-year period during 1914–1945 and 1939–1984, respectively. The trend coefficients of seasonal frequencies of both monsoon depressions (Fig. 5b) and total cyclonic disturbances (Fig. 5f) have entered into a decreasing phase for any 30-year period from 1907. The seasonal frequency of only depression shows a continuous negative trend for every 30-year period during 1931–2000. This continuous negative trend is significant from 1944. The frequency of total cyclonic disturbances shows a continuous decreasing trend from 1927, with the trend being significant for any 30-year period during 1955–2000. Hence, the frequency of monsoon depressions and total cyclonic disturbances affecting the Orissa coast has decreased more rapidly during recent years. Rajeevan et al. (2000) have also found a rapid decrease in frequency of monsoon depressions and total cyclonic disturbances over the Bay of Bengal during 1951–1998, at the rate of approximately one per decade each. In Fig. 5a, f, the trend curves are almost similar during 1901–1945. The trend in rainfall is significantly different from the trend in the frequency of cyclonic disturbances affecting Orissa in recent years. The 6th-order polynomial could be well fitted to the variation in trend values. According to the fitted polynomials, an insignificantly negative trend is likely to continue for some more years in the frequency of depressions/total cyclonic disturbances. It is likely to change from an insignificantly positive to an insignificantly negative trend in the monsoon rainfall over Orissa during the same period.

3.3 Periodicities in monsoon rainfall and the frequency of cyclonic disturbances

The periodicity of 2–2.8 years is significantly observed in the rainfall over Orissa and also in frequencies of all categories of cyclonic disturbances (Fig. 6). It may be attributed to the QBO. Earlier studies (e.g. Mukherjee 1985; Bhalme et al. 1987) have also reported significant direct relationship between ISMR and stratospheric QBO mode of zonal westerly wind. The periodicity corresponding to the ENSO cycle is not significantly observed in the rainfall over Orissa and seasonal frequencies of monsoon depressions and total cyclonic disturbances. The periodicity of 4.1 years,

Fig. 3 The 30-year moving averages of (**a**) monsoon rainfall over Orissa, (**b**) frequency of monsoon depressions, (**c**) frequency of only cyclonic storms, (**d**) frequency of severe cyclonic storms, (**e**) frequency of total cyclonic storms and (**f**) frequency of total cyclonic disturbances affecting Orissa during monsoon season over the period of 1901–2000



which may be attributed to the ENSO cycle, is significantly present only in the frequency of total cyclonic storms. The frequency of severe cyclonic storms (Fig. 6b) shows a significant periodicity of 33 years. Xavier and Joseph (1999) have also reported a 36-year cycle in the frequency of cyclonic storms over the north Indian Ocean. The 100 years cycle, which may correspond to 80–90 year sun spot cycle, is significantly observed in the seasonal frequency of depressions and total cyclonic disturbances. The numbers of sun spots show the existence of modes with periods of

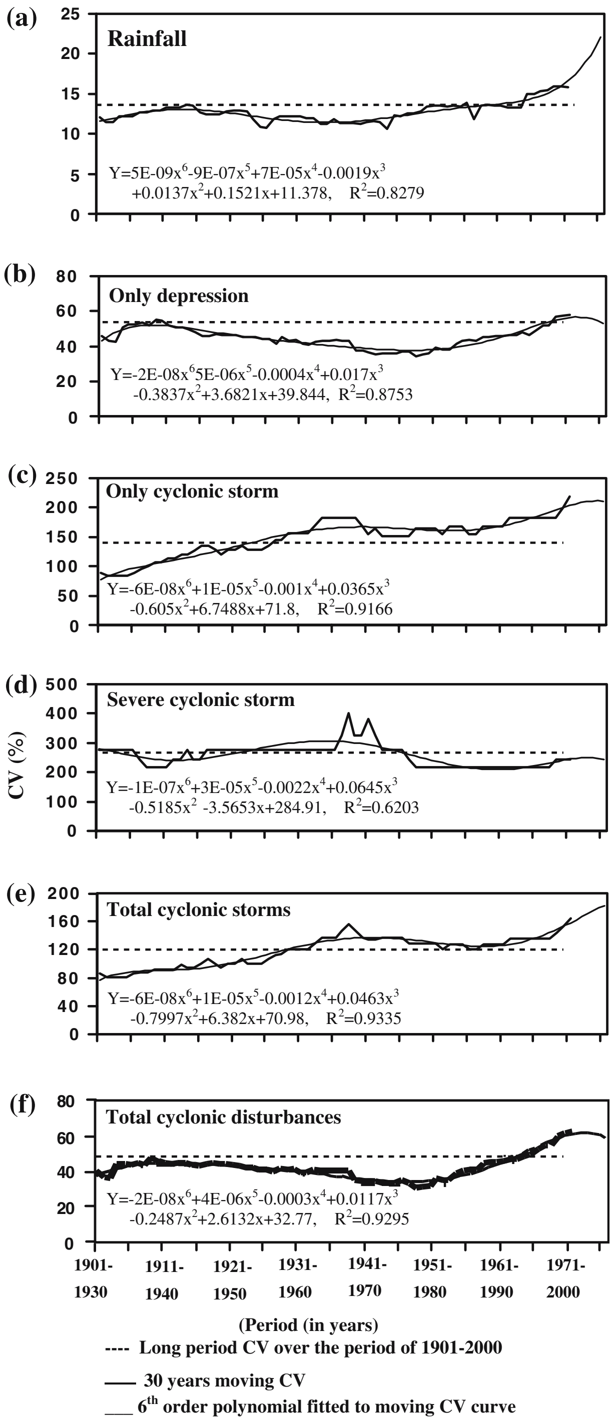


Fig. 4 The 30-year moving coefficients of variation (CV) of (**a**) monsoon rainfall over Orissa, (**b**) frequency of monsoon depressions, (**c**) frequency of only cyclonic storms, (**d**) frequency of severe cyclonic storms, (**e**) frequency of total cyclonic storms and (**f**) frequency of total cyclonic disturbances affecting Orissa during monsoon season over the period of 1901–2000

Table 2 Correlation coefficients (CC) of monsoon rainfall over Orissa with the frequency of different categories of cyclonic disturbances affecting Orissa during monsoon season over the period of 1901–2000

Cyclonic disturbances	CC of rainfall with frequency of cyclonic disturbances
Only depressions	**0.29**
Only cyclonic storms	0.15
Severe cyclonic storms	0.06
Total cyclonic storms	0.16
Total cyclonic disturbances	**0.34**

The CCs significant at 95% level of confidence are shown in *bold type*

5.5 years, 10–12 years, 22–23 years, 40–50 years and 80–90 years (Herman and Goldberg 1985). Jagannathan and Bhalme (1973) have found that mean rainfall is greater during the sun spot maximum over north India and central parts of the peninsula. Over remaining parts of the country, the rainfall during sun spot minima is greater. However, the rainfall over Orissa does not show any significant cycle corresponding to any of the above-mentioned significant sunspot cycles.

3.4 Correlation between monsoon rainfall over Orissa and frequency of cyclonic disturbances

The correlation between summer monsoon rainfall and the summer monsoon frequency of different categories of cyclonic disturbances are given in Table 2. It is observed that the seasonal rainfall over Orissa is directly and significantly correlated with frequency of total cyclonic disturbances and the frequency of monsoon depressions affecting Orissa. The 30-year moving CC between the frequencies of different categories of cyclonic disturbances and rainfall over Orissa during monsoon season revealed that the CC changed with time (Fig. 7), reaching a minimum during 1966–1995 after reaching a maximum during 1916–1945. Comparison of Figs. 6 and 7 suggests that the variation in CC is similar to the variation in the trend of frequency of total cyclonic disturbances affecting Orissa but different from the trend of the rainfall over Orissa. Hence, the variation in CC may be largely attributed to the variation in the frequency of total cyclonic disturbances affecting Orissa. Mooley and Shukla (1989) have found that the 30-year moving CC between frequency of low-pressure systems (LPS)/LPS days over the Indian region, which includes the Bay of Bengal and the Arabian Sea, and ISMR during 1888–1983 has also changed with time and that the CC has become significant after 1930. Hence, the reduction of rainfall due to the decrease in frequency of cyclonic disturbances has been compensated by increase in frequency of low-intensity systems such as monsoon lows in recent years. A 6th-order polynomial trend line could be well fitted to the variation in CC between seasonal rainfall and the seasonal frequencies of different categories of cyclonic disturbances, as the R^2 values are good, as seen in Fig. 7. This shows that the CCs in the cases of both monsoon depressions and total cyclonic disturbances affecting Orissa are likely to continue with the rising trends in future.

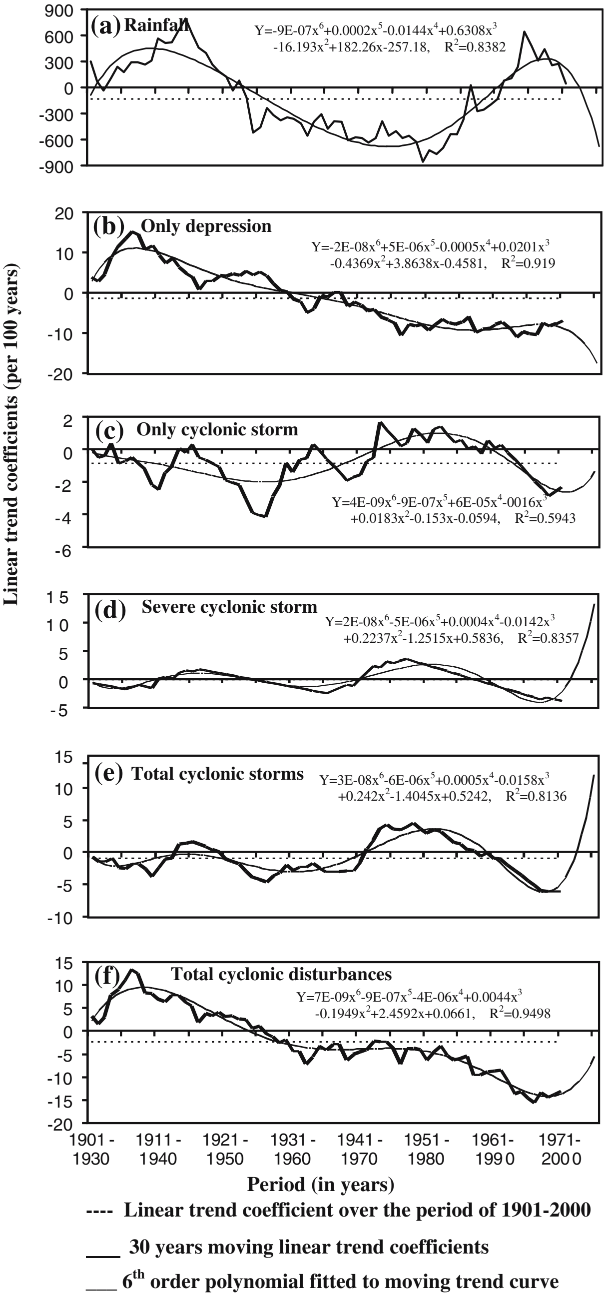


Fig. 5 The 30-year moving linear trends of (**a**) monsoon rainfall over Orissa, (**b**) frequency of monsoon depressions, (**c**) frequency of only cyclonic storms, (**d**) frequency of severe cyclonic storms, (**e**) frequency of total cyclonic storms and (**f**) frequency of total cyclonic disturbances affecting Orissa during monsoon season over the period of 1901–2000

4 Conclusions

The following broad conclusions are drawn from the above results and discussion.

The relationship between summer monsoon rainfall over Orissa and the frequency of cyclonic disturbances affecting Orissa shows temporal variation. The

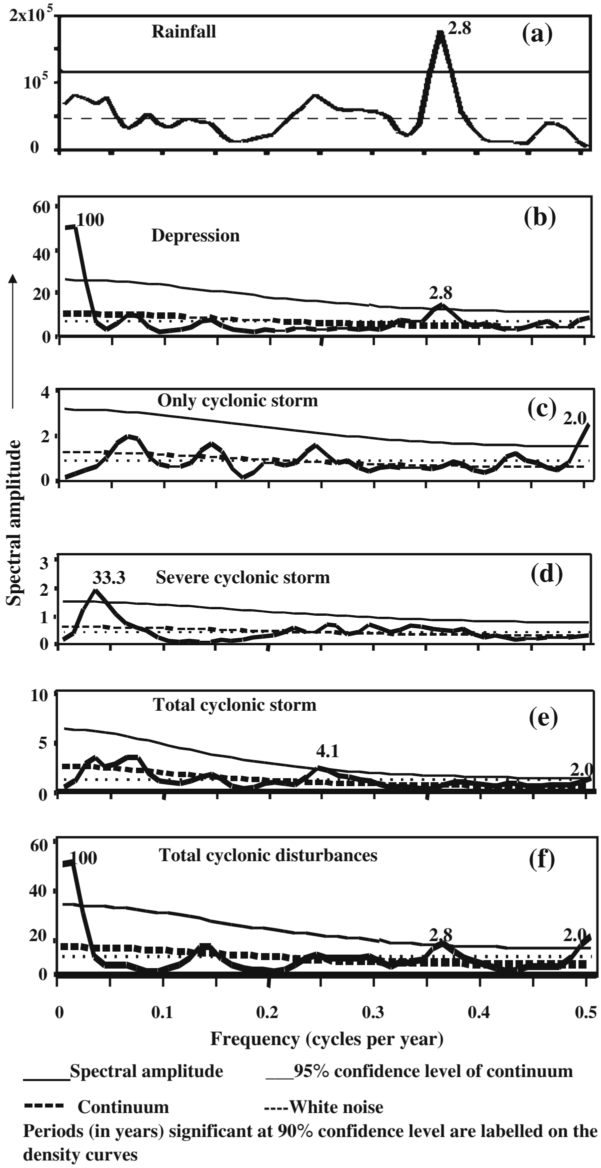
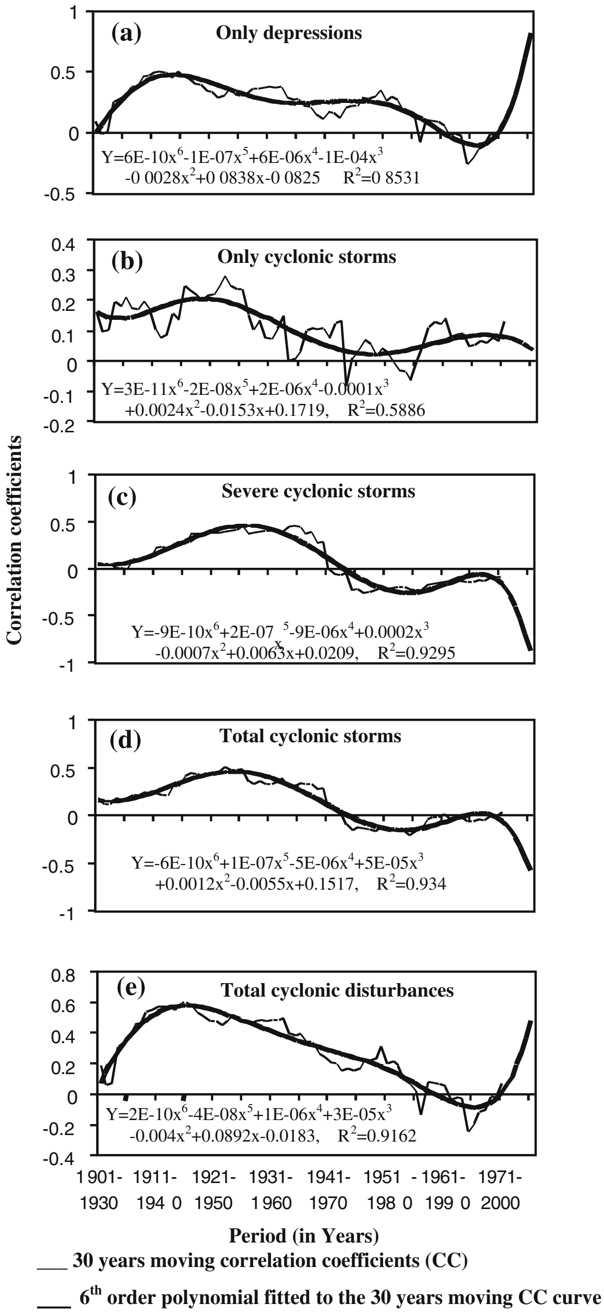


Fig. 6 The spectral amplitudes of (**a**) monsoon rainfall over Orissa, (**b**) frequency of monsoon depressions, (**c**) frequency of only cyclonic storms, (**d**) frequency of severe cyclonic storms, (**e**) frequency of total cyclonic storms and (**f**) frequency of total cyclonic disturbances affecting Orissa during monsoon season over the period of 1901–2000 with a maximum lag of 50 years

correlation between them significantly decreased from 1950 onwards. The trend in rainfall is not supported by the trend in the frequency of cyclonic disturbances in recent years. The variation in their relationship is due mainly to the variation in the frequency of cyclonic disturbances affecting Orissa. The correlation between them is likely to increase and be significantly positive after some years, due to likely increasing trend in the frequency of cyclonic disturbances.

According to the 30-year moving CV, the rainfall over Orissa and the frequency of cyclonic disturbances have shown increasing trends in their inter-annual variability since around 1945 and the variability has been above normal since 1960. This

Fig. 7 The 30-year moving correlation coefficients (CC) of monsoon rainfall over Orissa with the frequency of (**a**) monsoon depressions, (**b**) only cyclonic storms, (**c**) severe cyclonic storms, (**d**) total cyclonic storms and (**e**) total cyclonic disturbances affecting Orissa during monsoon season over the period of 1901–2000



above-normal variability of rainfall and total cyclonic disturbances may continue for some more years, causing more frequent floods and droughts over Orissa.

The oscillation of approximately 2–2.8 years corresponding to the QBO cycle is significantly observed in the summer monsoon rainfall over Orissa and in the frequencies of all categories of cyclonic disturbances except severe cyclonic storms affecting Orissa. There is least impact of ENSO on inter-annual variability of both the seasonal rainfall over Orissa and in the frequencies of monsoon depressions/total cyclonic disturbances affecting Orissa.

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