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SPATIAL VARIABILITY OF DAILY RAINFALL OVER ORISSA, INDIA, DURING THE SOUTHWEST SUMMER MONSOON SEASON

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ABSTRACT

Southwest summer monsoon rainfall over Orissa, a state of eastern India, shows characteristic spatial and temporal variability, due to the interaction of basic westerly flow with orography and the synoptic-scale monsoon disturbances developing over the northern Bay of Bengal and moving west-northwestwards along the monsoon trough. The aim of this study is to find out the main features of the spatial variability of daily monsoon rainfall over Orissa and associated synoptic systems. Empirical orthogonal function (EOF) analysis is a good tool to filter out the main components from any noise, and this was applied to daily monsoon rainfall (June–September) data of 31 uniformly distributed stations over a period of 20 years (1980–1999). The association of synoptic systems with significant EOFs has been confirmed by analysing daily synoptic systems over Orissa and its neighbourhood during the same period.

The first three EOFs in S-mode may be attributed to good monsoon rainfall in association with low-pressure systems/cyclonic circulation (LPSC), like lows, depressions, cyclonic storms and cyclonic circulation extending up to the mid-tropospheric level over the northwest (NW) Bay/NW and the adjoining northeast (NE) Bay, over Gangetic West Bengal (GWB) and over Orissa/NW and the adjoining west central (WC) Bay. The fourth and fifth EOFs may be attributed to a weak monsoon condition being associated only with a monsoon trough without any embedded system and LPSC over the NE and the adjoining NW Bay respectively. Based on rotation of significant EOFs in T-mode, which gives better regionalization, Orissa consists of five homogeneous regions of daily monsoon rainfall: (i) eastern Orissa, (ii) western Orissa, (iii) northwest Orissa, (iv) north Orissa and (v) northeast Orissa. Eastern Orissa gets higher rainfall than the other regions, due to LPSC over NW Bay/NW and the adjoining NE Bay, western Orissa rainfall is due to LPSC over Orissa/NW and the adjoining WC Bay; likewise, northwest Orissa rainfall is due to LPSC over GWB, north Orissa rainfall is due to LPSC over the NE and the adjoining NW Bay, and northeast Orissa rainfall is due only to a monsoon trough without any significant embedded system over Orissa and adjoining land/sea areas.

KEY WORDS: EOF analysis; daily monsoon rainfall; regionalization; Orissa (India)

1. INTRODUCTION

The southwest summer monsoon rainfall (June–September) over India is characterized by a semi-permanent monsoon trough that extends from west Pakistan to Burma across northwest India and the northern Bay of Bengal, by low-pressure systems and cyclonic circulations extending up to mid-tropospheric level (LPSC), which frequently develop over the northern Bay of Bengal and move in a west-northwesterly direction across Orissa or Gangetic West Bengal, and by a westerly trough that occasionally moves in an easterly direction across the central parts of India. However, there is variation in monsoon rainfall over India, both in space and time, due to interaction of the basic monsoon flow and synoptic-scale systems like LPSC. Also, there is interaction of convection with the Western Ghats, Eastern Ghats, other hill peaks and, above all, the Himalayas.

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Therefore, the monsoon rainfall over India is highly complex in nature. There have been many studies on spatial variability of rainfall over India, e.g. Rakhecha and Mandal (1981), Hastenrath and Rosen (1983), Rasmusson and Carpenter (1983), Prasad and Singh (1988), Kripalani *et al.* (1991) and Majumdar (1998).

Orissa State, a meteorological subdivision of India, lies on the east coast of India, adjacent to the northern Bay of Bengal. The monsoon rainfall over Orissa is more complex than that over all India and is significantly different from that of India due to the larger influence of LPSC developing over the northern Bay of Bengal and significant interaction between convection and basic flow due to the varied physiography of Orissa, which includes the Eastern Ghat hill ranges. Hence, to understand the daily rainfall variability and to predict the daily rainfall over Orissa, it is essential to find out the main features of daily rainfall over the region by filtering out any noise. As empirical orthogonal function (EOF) analysis is one of the best techniques for this purpose, this was applied to daily monsoon rainfall over Orissa.

In view of the significance of precipitation in a climatological/meteorological context, the majority of studies involving application of EOF/principal component analysis (PCA) have utilized rainfall data to study the spatio-temporal variability of the precipitation regime over various regions (e.g. Murata, 1990; Drosdowsky, 1993; Sumner *et al.*, 1993). The daily rainfall over a region was studied by Sumner *et al.* (1993) to find out the spatial organizations of daily rainfall over Mallorca, Spain, based on data for 4 years. A detailed discussion of the principal components and common factor methodologies can be found in Morrison (1976), Mathur (1976) or Harman (1976). When applied to atmospheric flow parameters, EOF analysis leads to the concept of map typing (Richman, 1981) and the specification of characteristic modes of variation in the data (Barnston and Livezey, 1987).

Studies on spatial variability of monsoon rainfall over India using EOF/PCA include those of Bedi and Bindra (1980) on seasonal (June–September) monsoon rainfall of 70 stations during 1911–70; of Hastenrath and Rosen (1983) on annual total rainfall of 31 meteorological subdivisions of contiguous India during 1900–72, as estimated by the India Meteorological Department (IMD); of Rasmusson and Carpenter (1983) on seasonal area-weighted monsoon rainfall of 31 meteorological subdivisions calculated from 31 representative stations during 1875–1979; of Shukla (1987) on seasonal monsoon rainfall of 31 meteorological subdivisions during 1901–70 of Prasad and Singh (1988) on area-weighted seasonal moonsoon rainfall of 31 subdivisions during 1901–80; and of Gregory (1989) on area-weighted seasonal rainfall of 29 meteorological subdivisions during 1871–1985 as calculated from rainfall over 306 stations representing 306 districts of contiguous India (Parthasarathy *et al.*, 1987). Applications of EOF/PCA in the medium-range scale have been made by Gadgil and Iyengar (1980), Kripalani *et al.* (1991) and Majumdar (1998). Kripalani *et al.* (1991) used pentad rainfall data during the monsoon season over 52 blocks of 2.5° × 2.5° latitude–longitude grids for the period 1901–80, whereas Gadgil and Iyengar (1980) used the 50 year mean pentad rainfall data (total 73) pertaining to 53 stations in peninsular India, based on data for 1901–50 as compiled by Ananthakrishnan and Pathan (1971). Majumdar (1998) used weekly rainfall departures from normal during the southwest monsoon period for all 35 meteorological subdivisions from 1977 to 1986, as calculated by the IMD. The first EOF of all the above-mentioned studies indicates that the rainfall pattern remains the same throughout India except for the northeast and the extreme southeast of India. This pattern may represent extreme seasonal rainfall leading to all-India flood/drought years. There is a strong spatial coupling between monsoon rainfall over northwest and central India, including Orissa, whereas these regions have little affinity with northeastern and southeastern India. Comparing other significant EOFs in the above studies, there is a characteristic pattern over a zonal band extending from Orissa and adjoining regions to northwest India, opposite to that over the rest of India. This zonal band is also the region of the monsoon trough and movement of low-pressure systems like depressions, etc., developing over the Bay of Bengal. Whereas Orissa and Gangetic West Bengal constitute a separate homogeneous region according to Prasad and Singh (1988), Orissa, Chhatishgarh and east Madhya Pradesh constitute a homogeneous region according to Gregory (1989).

All the above studies, though giving a broad pattern of monsoon rainfall over India and the role of the monsoon trough and monsoon depressions, could not determine objectively the spatial variability of rainfall with respect to the region of formation and movement of synoptic disturbances like LPSC over the Bay of Bengal. Unlike the above-mentioned studies, which used pentad, weekly, monthly and seasonal rainfall this study uses daily rainfall, which will help in objectively linking the spatial variability of monsoon rainfall over Orissa to the LPSC and monsoon trough. It will also help in classification of Orissa into different homogeneous regions. This study will be useful for further analysis and for designing statistical forecast models for short-range prediction of monsoon rainfall over Orissa.

2. DATA AND METHODOLOGY

Orissa State, a meteorological subdivision of India, lies on the east coast of India adjacent to the northern Bay of Bengal (Figure 1(a)). Figure 1(a) describes the surface isobaric pattern, the basic monsoon flow at 0.9 km above mean sea level (a.m.s.l.) over the Indian region, the location of the mean position of the monsoon trough and the regions of rainfall maxima and minima with respect to the monsoon trough during the representative month of July. The tracks of cyclonic disturbances developing over the Bay of Bengal during the representative monsoon month of July clearly demonstrate the west-northwesterly movement of these systems along the monsoon trough (IMD, 1979). Hence, the basic flow in the lower levels extending up to about 6 km a.m.s.l. is westerly over the region south of the monsoon trough. As westerly winds are relatively dry and continental over Orissa, because of the long path over the land mass from the west coast to Orissa, these are less rain-bearing. Hence, Orissa does not get any appreciable amount of rainfall in the absence of any synoptic-scale monsoon disturbances over the northern Bay. In the presence of disturbances like LPSC over the NW Bay, there is an interaction between the basic westerly flow, which is a relatively dry, continental wind, and the monsoon disturbance, leading to maximum convergence in the southwest sector of the system. As Orissa lies in the southwest sector of the system over the northwest Bay and neighbourhood, where the maximum number of these systems develops during the monsoon season, Orissa gets maximum rainfall. Many studies, like those of Rao and Rajamani (1970, 1975), Raghavan (1973), Rajamani and Rao (1981) and Pathan (1993), have confirmed that the southwest sector of the westwards-moving monsoon depression gets maximum rainfall due to maximum convergence.

In addition to the interaction between the basic westerly flow of the monsoon and monsoon disturbances like LPSC, there is also an orographic interaction due to Eastern Ghat, which extends from southwest to northeast in south Orissa. Also, there is an orographic interaction due to smaller hill peaks in different parts of Orissa. The different physiographical regions and districts of Orissa are shown in Figure 2(a). Physiographically, Orissa

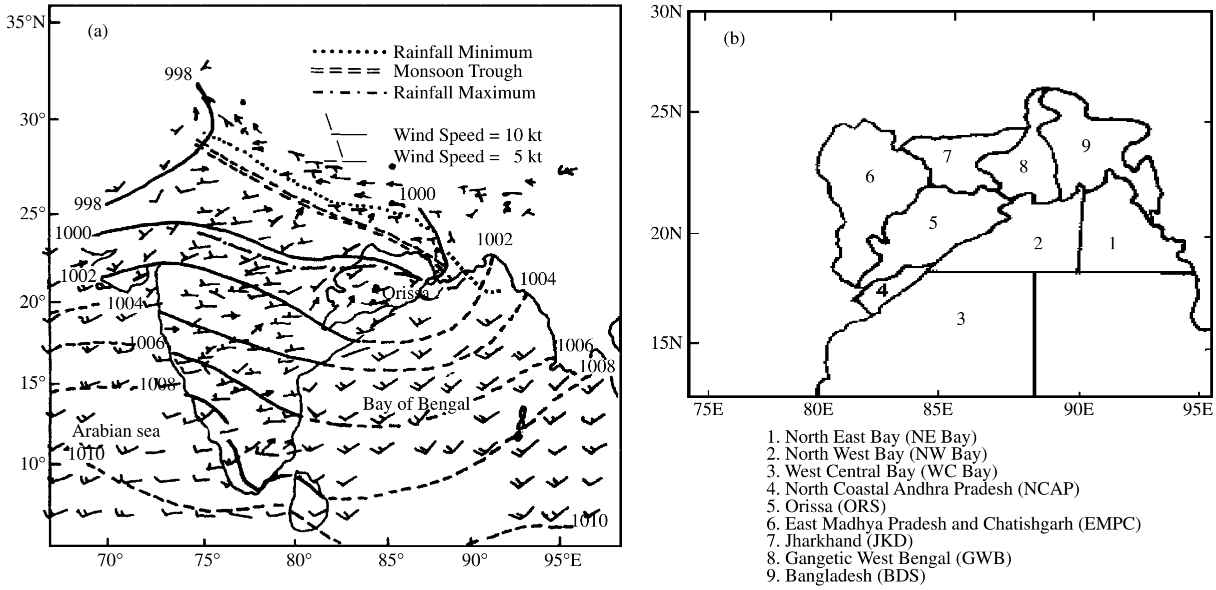

Figure 1. (a) Mean sea level pressure (hPa) pattern and mean wind (knots) at 0.9 km during representative month of July (source: India Meteorological Department) and (b) regions of low pressure systems/cyclonic circulation (LPSC) under consideration

consists of broadly four regions. (i) coastal plain; (ii) southwest hilly region of Eastern Ghat; (iii) northern upland; and (iv) central river basin. There are a number of hill peaks in the Eastern Ghat region and northern upland. Though the Eastern Ghat hill ranges extend from Tamilnadu State in the southwest to Orissa in the northeast, being parallel to the east coast of India they are more prominent in south Orissa. The eastern part of Koraput and the interior part of Ganjam districts lie on the eastern side of Eastern Ghat. The districts mentioned in Figure 2(a) are 13 undivided districts of Orissa. Though, recently, these districts have been subdivided to form a total of 30 districts, the present study has been based on these 13 districts; Balasore and Cuttack constitute north coastal Orissa, Puri and Ganjam constitute south coastal Orissa, Kalahandi, Bolangir, Koraput and Phulbani constitute south interior Orissa and the remaining districts constitute north interior Orissa.

Owing to all the above-mentioned factors, the daily monsoon rainfall over Orissa is highly complex in nature. The basic objective of this study is to find out the main features of the spatial variability of daily

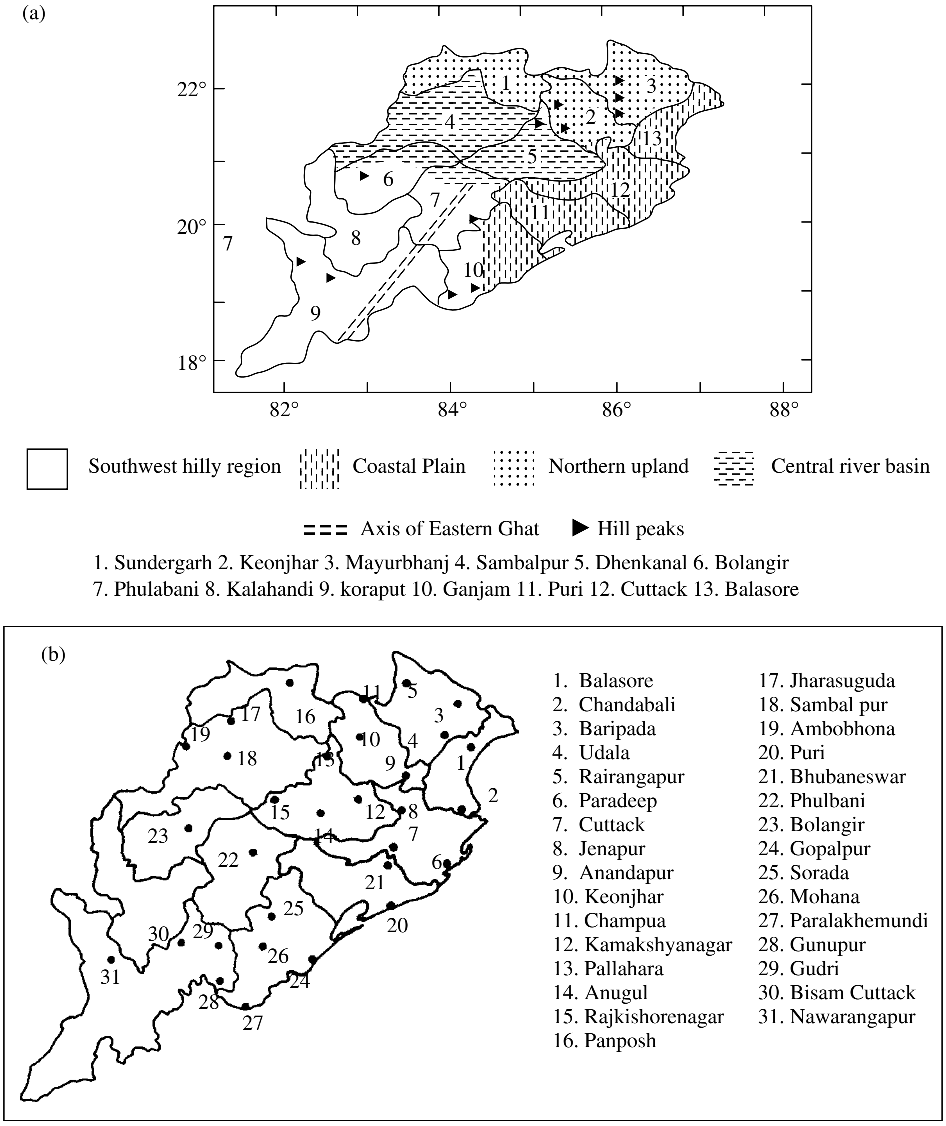

Figure 2. (a) Physiographical map of Orissa and (b) selected rain gauge stations of Orissa

monsoon rainfall over Orissa by filtering out the noise and to correlate these main features of rainfall variability with the broad-scale synoptic systems like LPSC. This study uses EOF analysis applied to the daily monsoon rainfall data from 31 stations in Orissa for a period of 20 years (1980–99). As the monsoon season (June–September) consists of 122 days, the data matrix used in the study is a matrix of 31 × 2440 stations by days form. Also, an attempt is made to find out different homogeneous regions of daily monsoon rainfall over Orissa by rotating the significant EOFs.

On a real-time basis, daily rainfall is recorded at about 60 stations in Orissa. However, a continuous record of daily rainfall during the monsoon season for the period of 20 years (1980–99) is only available for 31 stations. These 31 stations, which are almost uniformly distributed in Orissa, have been selected for this study (Figure 2(b)). The necessary quality control of the data has been carried out and the missing data, though very few in number for these 31 stations, have been filled in by considering the rainfall at surrounding stations. The correlation between the daily average rainfall over Orissa based on real-time data and the daily average rainfall over Orissa based on the data from 31 selected representative stations in Orissa is found to be 0.93, which is highly significant. Hence, the daily rainfall over Orissa can be well represented by these 31 stations.

2.1. *Modes of analysis*

For the present study, the parameter (rainfall) is fixed, and hence there are two possible modes of analysis: space (S) and time (T) modes (Richman, 1986). In S-mode analysis, the variables are the stations and the observations are the values of daily rainfall. The EOF loading matrix then contains the correlations of each variable or station with each component. These can be plotted on a map to depict the spatial pattern of each component. This matrix can also be multiplied by the original data matrix to form the component amplitudes or score matrix, which contains the time series of each component. This is usually standardized to have zero mean and unit variance. The procedure followed in this study is based on the algorithm proposed by Von Storch and Hannoschock (1984). According to this algorithm, each row is assumed to be a sample (here, a station) and each column a time variable (here, the daily rainfall) in the data matrix. The zero-averaged data set is calculated from the data matrix and then the singular value decomposition of the problem (i.e. the decomposition of the matrix into a sum of rank-one matrices formed as an outer product of the basis vectors for the rows and columns with a premise that the basis vectors are orthogonal with any specified metric) is determined from the zero-averaged data set. The large eigenvalue (EV) matrix is then rewritten to a vector and the appropriate normalization is also applied.

Richman (1981) has noted that the S-mode analysis, which groups stations with similar temporal variations, may not be the best method of map typing, and suggests the use of a T-mode analysis. In T-mode analysis, the data matrix is transposed so that each individual time is a variable and each rainfall station an observation. This analysis produces components with loadings on the individual days and amplitudes on the observations or spatial variables. A potential problem with this form of analysis is the manner in which the similarity between the spatial patterns is measured. The measure of similarity mostly used in EOF analysis is the covariance or correlation coefficient. In this study, the covariance matrix has been used for T-mode analysis.

2.2. *Rotation of EOFs*

It has been found that the EOFs form a predictable set of patterns, due largely to the orthogonality constraint. The first EOF maximizes the explained variance by having generally large loadings on all variables, and subsequent components are dipoles or more complex patterns. In addition to this domain dependence, Richman (1986) has shown that unrotated EOFs suffer from a number of further deficiencies. These can be remedied by rotating the EOFs. The most important difficulty involved in rotation of EOFs is that no generally applicable criterion exists to determine the number of EOFs to be rotated, and this number is significant, since the loadings on the rotated EOFs depend on the number of EOFs retained for rotation. Also, for unrotated components, the significant components represent the signal and the remaining higher order EOFs the noise. Thus, it is important to know the number of EOFs that are significantly different from the noise and that can be explained by physical processes. The other major difficulty is that the best method of rotation also depends to some extent on the particular data set being analysed.

There are different techniques to determine the significance of the EOFs. Most of these techniques can be viewed as dominant variance rules. Kaiser (1958) suggests the Kaiser–Guttman test, which is based on the assumption that eigenvectors that have eigenvalues less than unity for a correlation matrix explain less variance than uncorrelated white noise. The scree test (Cattel, 1966) looks for a cut-off in the difference between successive EVs or a break in slope in EV sequence, with the EVs representing noise decreasing in geometric progression. Craddock and Flood (1969) suggest that the break is more distinct in a plot of log(EV) against eigenvector number. Preisendorfer *et al.* (1981), Overland and Preisendorfer (1982) and Preinsendorfer (1988) have used Monte Carlo simulations with independent random sequences to determine confidence levels for the EVs. The procedure involves repeatedly generating sets of vectors of independent Gaussian random numbers with the same dimension and sample size as the data being analysed and then computing the EVs of their dispersion matrices. The Monte Carlo EV curves are plotted for 95% and 5% levels of confidence. The normalized EVs are calculated from the original data EVs and then plotted against eigenvector number. Significant data EVs are those that lie above the Monte Carlo curve corresponding to the 95% level of confidence. The above procedure is applicable to a data set of smaller dimension. When the dimension of the data set is relatively large (around 100 or above), the expense of finding the EVs for the Monte Carlo test according to the above rule can be excessive, and asymptotic theory of EVs of large symmetric random covariance matrices may be applied (Preisendorfer *et al.*, 1981). In this theory, there are so many EVs that we only work with fractional amounts of total EVs, e.g. the highest 95% of them. The detailed calculation and the average asymptotic EVs for selected choices of the fractional index are given by Preisendorfer *et al.* (1981). A potential problem with the above two rules is that data may not be approximately Gaussian, e.g. rainfall variable, which is the precondition for these rules. The resampling procedure will not simulate accurately the physical process that generated them and the results of the test may be misleading. Hence, Preisendorfer *et al.* (1981) have suggested, the above two tests should not necessarily eliminate any of the higher components, which may be found to be significant under other tests, especially if the EOF can represent the evolution of a geophysical process. As the present study deals with a large data set, the asymptotic theory has been applied. North *et al.* (1982) have used sampling theory to establish error limits for the EVs and have suggested that eigenvectors whose EVs overlap form degenerate multiplets and should not be split when truncating the eigenvector sequence. The rotation of EOFs (whether orthogonal or oblique) attempts to produce a simple structure. Richman (1986, 1987) also argues for the rotation of components and for the establishment of a simple structure in pair-wise plots between the main EOFs so that each EOF used should, as far as possible, have high associations with some original axes and low associations with others. In practice, if a simple structure exists in the data then it is seen in the EOFs with large loadings on a few variables and near zero loadings elsewhere. In the S-mode analysis, this results in a clustering or regionalization of the spatially distributed variables, which is useful for isolating specific areas for further detailed study. Rotation of T-mode components produces a clustering of the temporally distributed variables, i.e. a compositing of similar anomaly maps. Here, all the above techniques are applied to find out the significant EOFs in both S- and T-modes. The significant EOFs in both the modes are rotated by the varimax method. The results from both methods are examined in this study.

2.3. Significant EOFs and physical processes

To find out the physical processes that can be linked to the significant EOFs, the percentage contributions of different synoptic systems to the seasonal total monsoon rainfall over different stations in Orissa during 1980–99 are calculated. For this purpose, the frequencies of days with LPSC like lows, depressions, cyclonic storms and cyclonic circulation extending up to the mid-tropospheric level (cycir) over the different regions (Figure 1(b)) — NW Bay, NW and the adjoining NE Bay, NE and the adjoining NW Bay, NW and the adjoining WC Bay, WC and the adjoining NW Bay, WC Bay off north coastal Andhra Pradesh (NCAP), Bangladesh, Orissa and the adjoining meteorological subdivisions like GWB, east Madhya Pradesh, Chhatishgarh, NCAP and Jharkhand, etc. — are found out from different weather reports published by the

IMD. A day is considered as an LPSC day for a region if a low/depression/cyclonic storm/cycir is found in the synoptic chart according to the 0300 UTC observation. Also, the days with an all-India break(weak) monsoon (AIBM) condition and monsoon trough without any significant embedded systems like LPSC over the above-mentioned regions are found out from different weather reports published by the IMD. The past 24 h rainfall recorded at 0300 UTC on the day following the day of occurrence of each type of synoptic systems above is considered to find out the total rainfall due to the different synoptic systems during 1980–99. The percentage contribution to the seasonal monsoon rainfall over each station from a synoptic system is calculated from the ratio of total rainfall over that station due to all the days of occurrence of that synoptic system and the total rainfall over that station during the whole period (1980–99). The spatial patterns of percentage contributions over different stations in Orissa due to different synoptic systems/combination of systems are analysed to find out the pattern of percentage contribution most similar to the spatial pattern of each significant EOF. Also, the correlation between the loadings of each significant EOF (31 loadings of each EOF corresponding to 31 stations) and the percentage contributions to seasonal monsoon rainfall over the 31 corresponding stations due to the different synoptic systems are calculated. The synoptic systems/combination of synoptic systems for which percentage contributions to seasonal monsoon rainfall show the highest correlation with the loadings of a significant EOF may be attributed to that significant EOF.

3. RESULTS AND DISCUSSION

3.1. Mean daily rainfall distribution

The mean daily monsoon rainfall distribution in Orissa based on the data for 1980–99 is given in Figure 3(a). The mean daily rainfall varies from 6.0 mm at Gopal Pur (Ganjam district) to 11.5 mm at Pallahara (Dhenkanal district in the northern upland). In general, the mean daily rainfall is less (< 8.0 mm) on the eastern side of Eastern Ghat and the adjoining areas of south coastal Orissa. It is higher (≥ 10 mm) on the western side of Eastern Ghat, the western side of the central river basin and many parts of the northern upland except the Keonjhar district. This pattern of distribution may be due to the fact that Orissa generally gets rainfall in the monsoon season due to the LPSC developing over the northern Bay of Bengal with the monsoon trough from the system extending in a west-northwesterly direction. As the basic monsoon flow becomes westerly in this situation, the eastern and western sides of Eastern Ghat become lee and windward sides respectively with respect to the basic westerly flow. This results in higher rainfall over the western side and less rainfall over the eastern side of Eastern Ghat. The diminished rainfall activity over some parts of the Keonjhar district and the western part of Sambalpur may be attributed to similar reasons due to the hill peaks to the west of these regions.

The standard deviations in the daily monsoon rainfall over different stations in Orissa are given in Figure 3(b). The standard deviations are generally less (<16 mm) over the eastern side of Eastern Ghat in the southwest hilly region and the adjoining areas of south coastal Orissa. It is also less over the northern upland, being <16 mm over parts of the Keonjhar district. It is higher over the western side of the Eastern Ghat. There is a region of higher standard deviation extending from the central part of coastal Orissa in the southeast towards the Sambalpur district in the northwest. The higher variability in this region may be due to the fact that: (i) the rainfall over Orissa is generally associated with the LPSC developing over the northern Bay with the monsoon trough from the system extending in a west-northwesterly direction; and (ii) the frequency of these LPSCs is highly variable in time and space within the season and also from year to year. It is also found that, over the eastern side of Eastern Ghat, where the mean daily rainfall is small, the standard deviation is also small.

There are about 1000 days out of 2440 days for any individual station during which the rainfall is nil, though there are only 36 days when all the stations under consideration have received nil rainfall simultaneously. Hence, the mean and standard deviation in daily rainfall are also calculated for each station considering only those days with rainfall. It is found that the spatial patterns of mean and standard deviation are almost same as that shown in Figure 3(a) and (b) respectively.

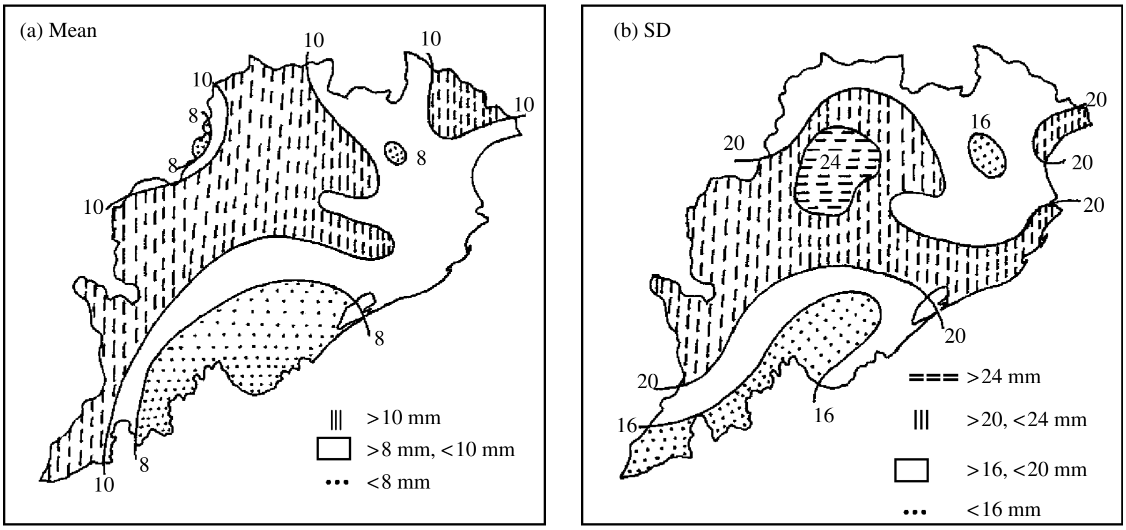

Figure 3. Daily monsoon rainfall (mm) over Orissa. (a) mean; (b)standard deviation (SD)

3.2. Interstation correlation in daily monsoon rainfall over Orissa

The correlation coefficient (CC) between daily rainfall recorded at different stations during 1980–99 (2440 days) is found to be positive for all the stations, except that the daily rainfall recorded over Paralakhemundi (GNJ district) has insignificant negative correlation with daily rainfall over Sambalpur, Jharsuguda (both in Sambalpur district), Pallahara (Dhenkanal district) and Panposh (Sundergarh district). It also indicates that the correlation between rainfall over stations on the eastern side of Eastern Ghat in the southwest hilly region and adjoining areas of south coastal Orissa and rainfall over stations on the western side of Eastern Ghat, adjoining the central river basin and the western part of northern upland is relatively lower. The interstation CC ≥ 0.3, ≥ 0.4 and ≥ 0.5 are illustrated in Figure 4(a)–(c). From Figure 4(a), it can be concluded that the daily rainfall distribution over most parts of Orissa during the monsoon season is homogeneous and maybe associated with broad-scale features of the monsoon circulation. The spatial coherence in the daily rainfall activity over different stations gradually decreases when considering the higher threshold values of CC like 0.4 and 0.5, leading to different sub-homogeneous regions. Considering CC > 0.4, there are two different homogeneous regions, viz. (i) north Orissa and (ii) the eastern side of Eastern Ghat. Considering CC > 0.5, the different homogeneous regions are (i) the eastern side of Eastern Ghat, (ii) the western side of Eastern Ghat, and (iii) north coastal Orissa and the adjoining area. However, the regions based on the threshold values of interstation CC are not well defined and distinct from each other.

3.3. Unrotated EOFs in S-mode analysis

The results of the EOF analysis indicate that 16 EOFs are required to explain 80% of the total variance of the rainfall (Table I). The scree test and the plot of log(EV) indicate a break in slope near EOF number 4 (Figure 5(a)–(b)). According to asymptotic theory (Preisendorfer *et al*., 1981), five EOFs are significant (Figure 5(c)). These first five EOFs explain about 54% of the total variance in daily monsoon rainfall over Orissa. Hence, an attempt has been made to interpret the first five EOFs individually to find out the large-scale features of the monsoon circulation associated with monsoon rainfall over Orissa. The plots of first five EOFs are given in Figure 6.

The loadings of EOF_1, which explain about 28.8% of total variance, are positive throughout the state (Figure 6(a)). Though the amplitude varies in space, the values of EOF_1 are uniform and consistent in nature. Also, there is a region of maxima extending from the Cuttack–Puri districts' coasts in the east-southeast towards Sambalpur district in the west-northwest. This pattern represents an active/vigorous monsoon

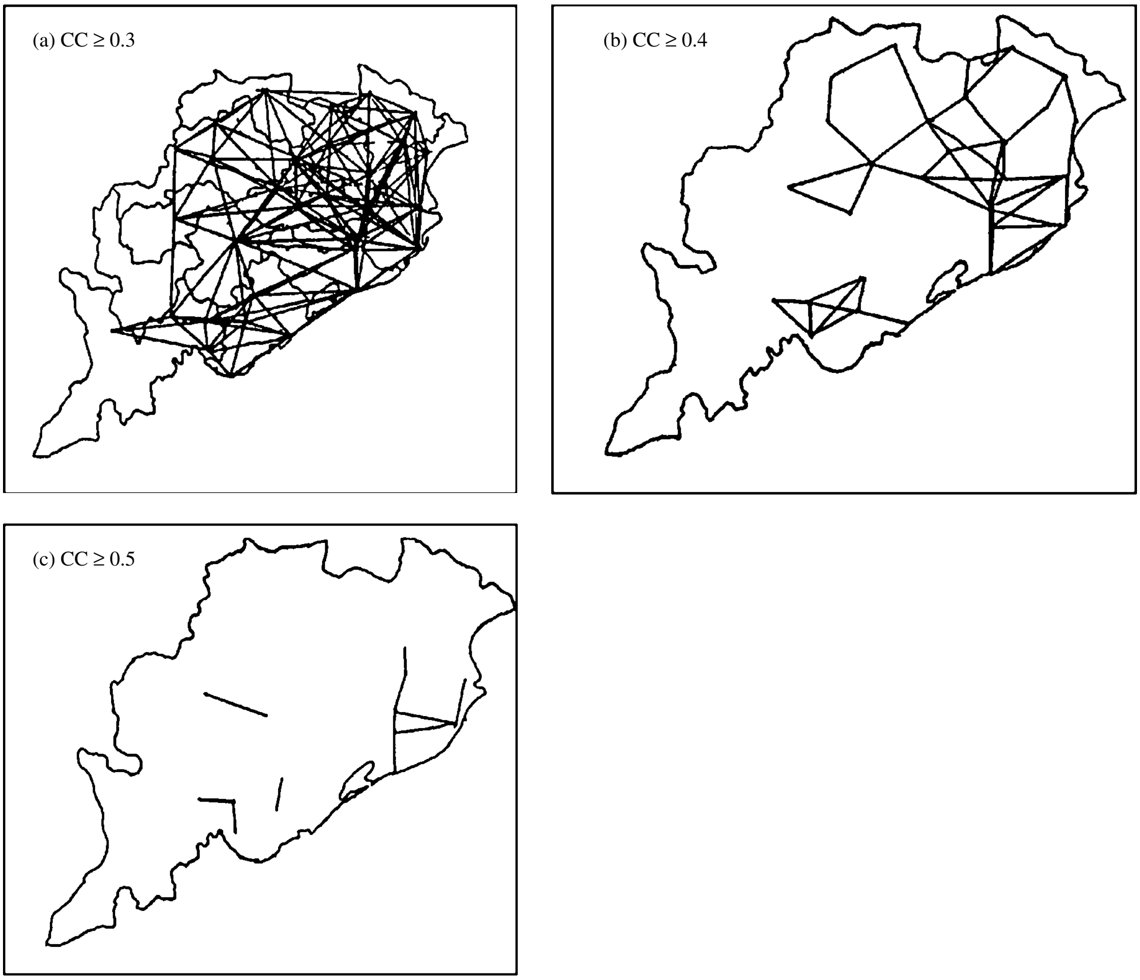

Figure 4. Interstation correlation coefficients (CC) of daily monsoon rainfall over Orissa. (a) CC > 0.3; (b) CC > 0.4; (c) CC > 0.5

condition over Orissa. The spatial distributions of percentage contribution of LPSC over different regions, attributed to different EOFs, are shown in Figure 7. It is found that the spatial pattern of the total percentage contribution from LPSC over NW Bay and NW and the adjoining NE Bay to monsoon rainfall over different stations (Figure 7(a)) and the spatial pattern of EOF$_1$ (Figure 6(a)) are similar. Also, the CC between the loadings of EOF$_1$ over different stations and the percentage contributions of LPSC over NW Bay and NW and the adjoining NE Bay to monsoon rainfall over corresponding stations under consideration is found to be 0.8, which is highly significant. The CCs > 0.35 and > 0.30 are significant at the 95% and 90% levels of confidence respectively. Hence, EOF$_1$ may be associated with the LPSC over the NW Bay/NW and the adjoining NE Bay with the monsoon trough from the system extending in a west-northwesterly direction across GWB or north Orissa. The above pattern is possible, as Orissa lies in the southwest sector (sector of maximum low-level convergence) of the LPSC over NW Bay or NW and the adjoining NE Bay. The contrasting feature on the eastern and western sides of the Eastern Ghat with loadings on the eastern side being less than 0.1, though positive (not shown in figure), is possible with this LPSC, as with these systems the western and eastern sides of Eastern Ghat behave as windward and lee sides respectively with basic monsoon flow as westerlies.

The loadings of EOF$_2$, which explain about 8.3% of the total variance, are negative or insignificantly positive over coastal Orissa and the adjoining areas. These are positive over interior Orissa (Figure 6(b)).

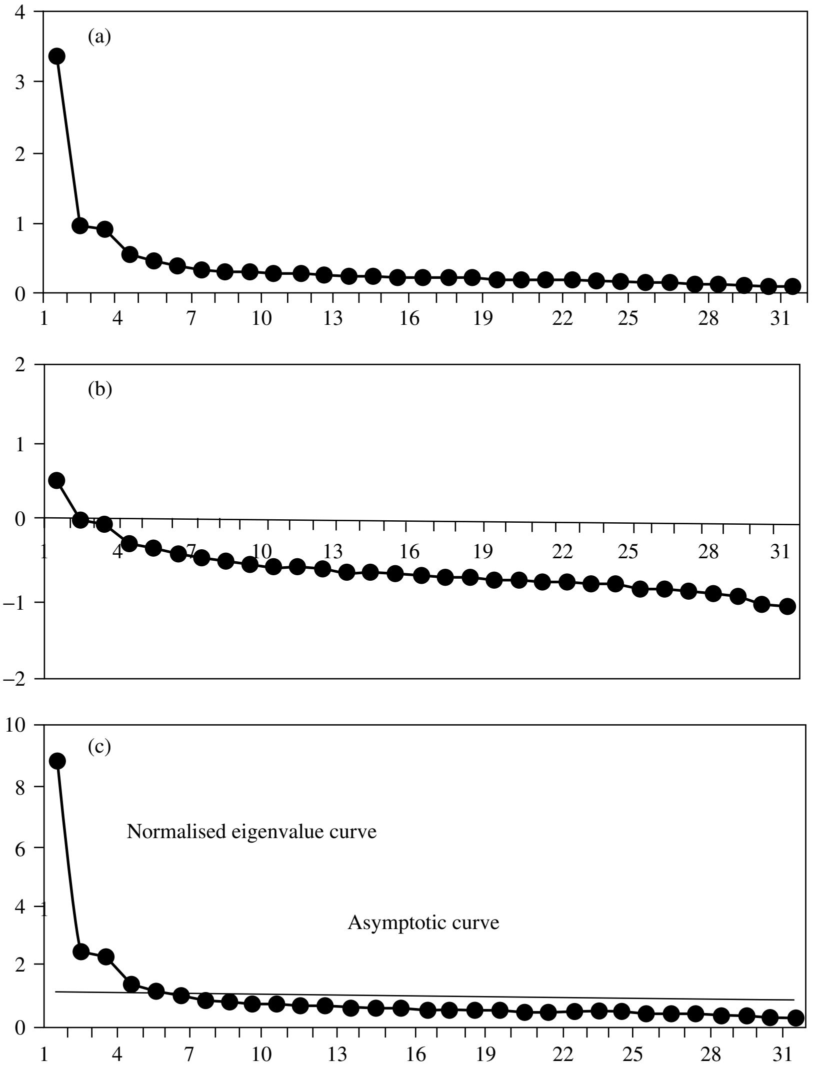

Figure 5. (a) EVs (b) log(EV) and (c) normalized EV curve versus asymptotic curve for average EVs of EOFs in S-mode

The positive loading is maximum over the Sambalpur district and the negative loading reaches a maximum just along the coast. This type of rainfall distribution is associated with below-normal activity over coastal Orissa and slowly increasing activity towards interior Orissa. It is found that both the spatial patterns of EOF_2 (Figure 6(b)) and the percentage contribution of rainfall over different stations due to the LPSC over GWB (Figure 7(b)) are similar. Also, the correlation between the loadings of EOF_2 and the percentage contributions of rainfall over the corresponding stations due to the LPSC over GWB is 0.86, which is highly significant. Hence, the EOF_2 may be associated with the LPSC over GWB and its neighbourhood.

The loadings of EOF_3, which explain about 7.9% of total variance, are positive over south Orissa, SBP district and some areas of PRI and DNK districts (Figure 6(c)). These are negative over the rest of Orissa. The positive loading is higher on the western side of Eastern Ghat and the negative loading reaches a maximum over the northernmost parts of Orissa, covering the Balasore and Mayurbhanj districts. This type of rainfall activity, like deficient rainfall over the northern part and excess rainfall over the southern part, may be attributed to the LPSC over Orissa/NW and the adjoining WC Bay with the monsoon trough extending from the system towards the west-northwest. The spatial distribution of percentage contributions to seasonal rainfall

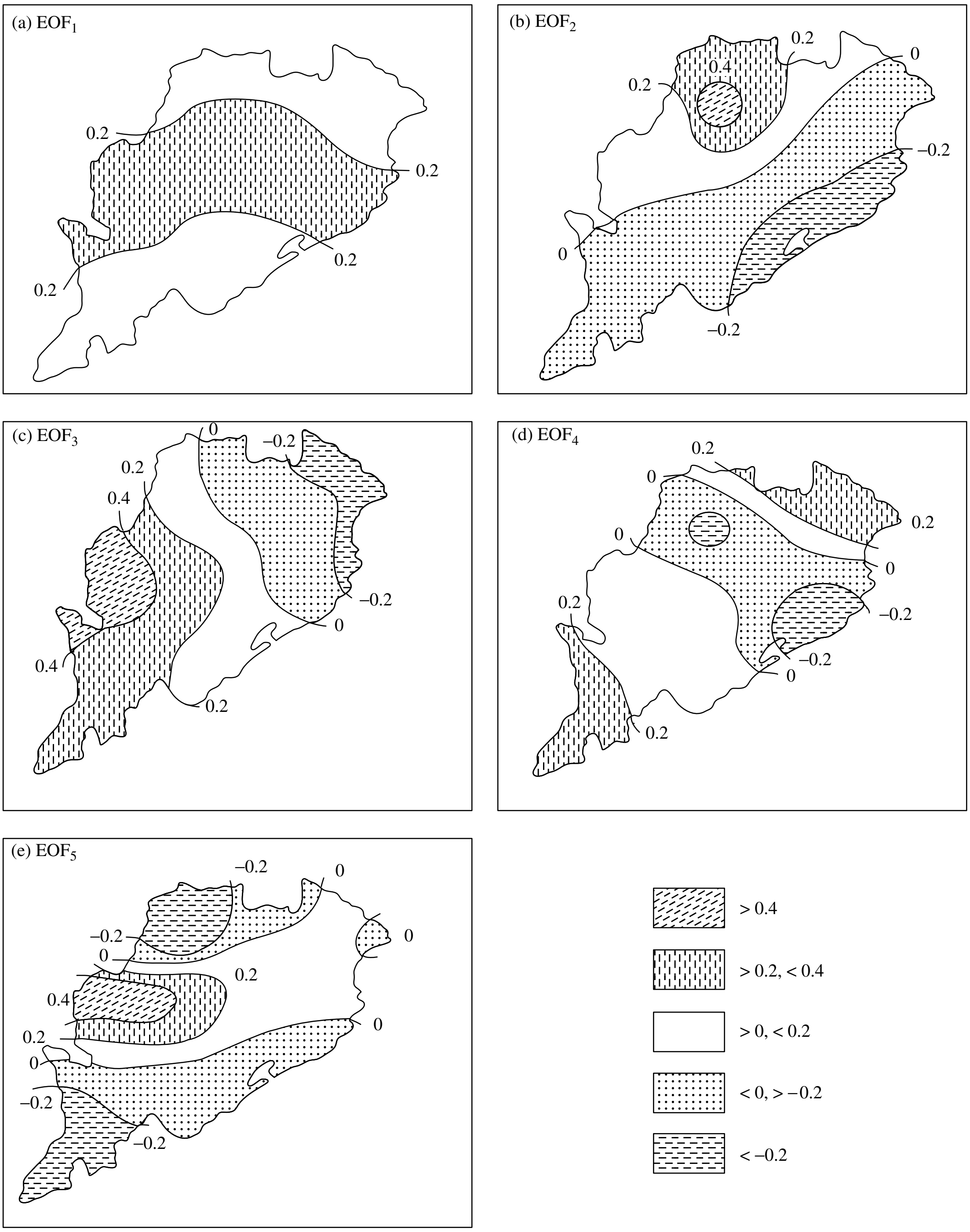

Figure 6. Unrotated EOFs of daily monsoon rainfall over Orissa in S-mode: (a) spatial pattern of EOF_1; (b) spatial pattern of EOF_2; (c) spatial pattern of EOF_3; (d) spatial pattern of EOF_4; (e) spatial pattern of EOF_5

over different stations in Orissa due to the LPSC over Orissa/NW and the adjoining WC Bay (Figure 7(c)) and the distribution of loadings of EOF_3 (Figure 6(c)) are similar. Also, the CC between them is 0.86, which is highly significant.

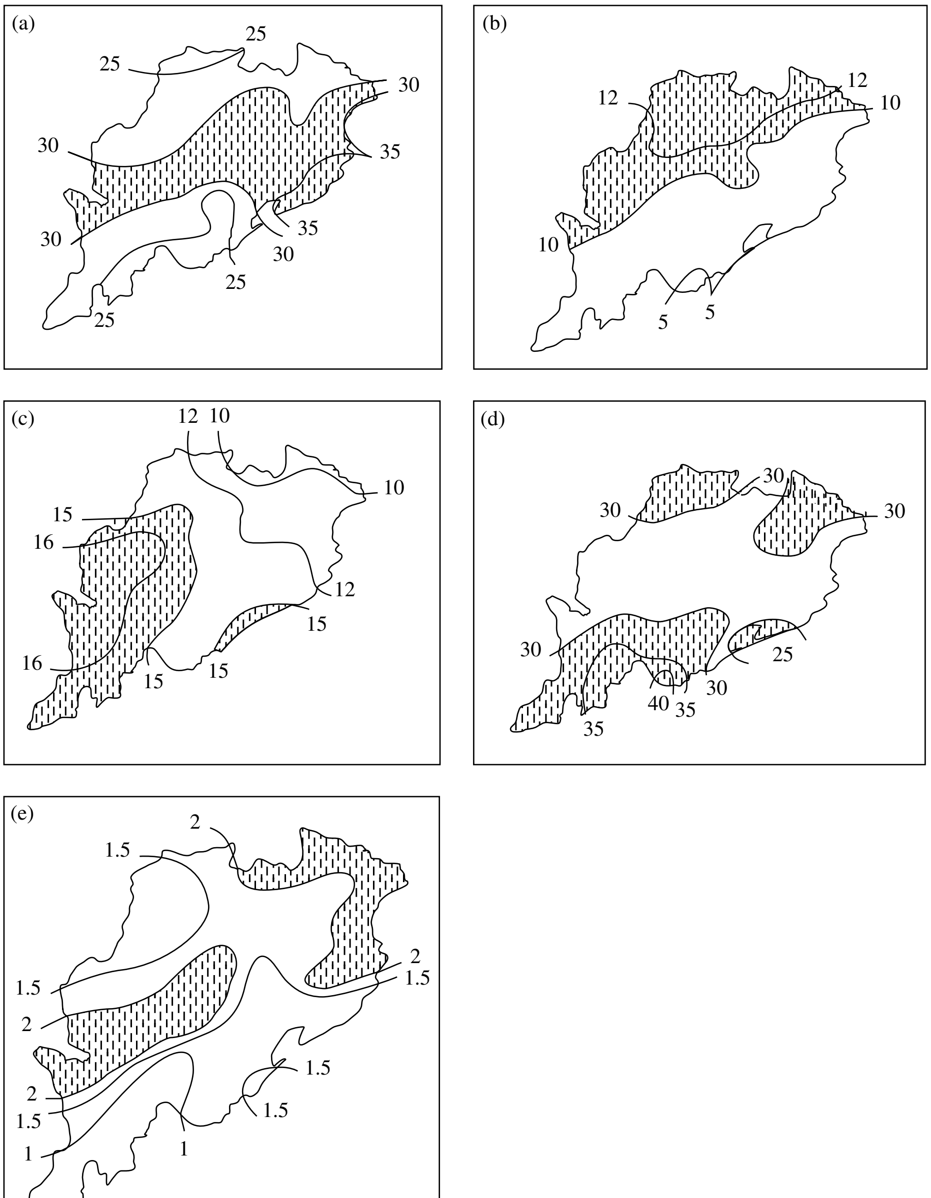

Figure 7. Percentage contribution to total monsoon rainfall by different systems attributed to EOFs in S-mode: (a) LPSC over NW Bay and NW and the adjoining NE Bay; (b) LPSC over GWB; (c) LPSC over Orissa and NW and the adjoining WC Bay; (d) only monsoon trough without any embedded system over Orissa and its adjoining land/sea areas; (e) LPSC over NE and adjoining NW Bay

The loadings of the EOF_4, which explain about 4.5% of the total variance, are negative over a region extending from the Cuttack–Puri districts' coasts and the adjoining area of Balasore in the southeast towards the Sambalpur district in the west-northwest across the Dhenkanal district (Figure 6(d)). These are positive over the rest of Orissa. The positive loadings gradually increase from both sides of the region of negative loadings. This type of rainfall distribution is attributed to a weak monsoon situation over Orissa when only the monsoon trough exists without any significant embedded systems over Orissa or its neighbouring land/sea areas. Sikka and Gadgil (1980) have also discussed the shifting of the maximum cloud zone during different

Table I. The variance explained by the first 16 EOFs in S-mode

EOF number	Variance (%)	Cumulative total variance (%)
1	28.8	28.8
2	8.3	37.1
3	7.9	45.0
4	4.6	49.6
5	4.0	53.6
6	3.5	57.1
7	3.0	60.1
8	2.8	62.9
9	2.5	65.4
10	2.4	67.8
11	2.3	70.1
12	2.2	72.3
13	2.0	74.3
14	1.9	76.2
15	1.9	78.1
16	1.9	80.0

phases of the monsoon. Comparing the spatial pattern of percentage contribution of only the monsoon trough without any significant embedded systems over Orissa and its adjoining land/sea areas to the seasonal rainfall (Figure 7(d)) with Figure 6(d), both the patterns are similar, thus supporting the above argument. Also, the CC between the loadings and the percentage contribution to seasonal rainfall over corresponding stations from the above-mentioned synoptic system is 0.36, which is significant.

The loadings of EOF_5, which explain about 4% of the total variance, are positive over the region, extending from the eastern side of Mayurbhanj district in the northeast towards Bolangir and Kalahandi districts in the southwest (Figure 6(e)). There is a negative loading in the rest of Orissa. This type of distribution represents weak monsoon activity over Orissa as a whole. It may be attributed to LPSC over NE and the adjoining NW Bay with the monsoon trough from the system extending northwestwards across Bangladesh. The LPSC over NE and the adjoining NW yields a systematic pattern of weak monsoon rainfall over Orissa as a whole, even though it yields good rainfall in some parts of Orissa. Comparing Figure 6(e) with Figure 7(e), the spatial distribution of percentage contributions of LPSC over NE and the adjoining NW Bay to seasonal rainfall over Orissa and the spatial pattern of EOF_5 are similar. Also, the correlation between loadings and percentage contributions over corresponding stations due to this system is 0.33, which is significant at the 90% level of confidence.

As there are a few studies devoted to EOF analysis with daily rainfall, the study by Kripalani *et al.* (1991) using pentad rainfall is compared with the present study. Another study by Majumdar (1998) on weekly rainfall departure from normal is based on a smaller period of data of 10 years and the study has a bias towards deficient rainfall. Comparing the results with those obtained by Kripalani *et al.* (1991), it is found that in both cases the first EOF is associated with a strong/active monsoon, indicating the predominant role of the LPSC over NW Bay/NW and the adjoining NE Bay with the monsoon trough from this system extending to northwest India for rainfall activity over India and Orissa; the variance explained by EOF_1 of the present study (28.8%) is higher than the variance explained by EOF_1 determined by Kripalani *et al.* (1991; 20.4%). This indicates a more significant role of the LPSC over NW Bay/NW and the adjoining NE Bay on Orissa rainfall than that on all-India rainfall.

3.4. Rotated EOFs in S-mode analysis

To ascertain the simple structure, pair-wise plots of loadings in both unrotated and rotated EOFs have been inspected. It is found that rotation clearly succeeds in yielding strong, simple structures. However, rotation of the first four EOFs yields the simplest structure. The intra-EOF correlations also indicate that the rotated EOFs for rotation of the first four EOFs are most uncorrelated to each other. However, the rotations are carried out for the first two, three, four and five EOFs to find out the significance. Considering the values of EOFs >0.2, the isopleths are drawn and based on these isopleths, daily rainfall affinity areas are determined for rotation of the first two, three, four and five EOFs. The results of regionalization are shown in Figure 8.

Though the rotation of the first two EOFs yields two distinct regions without any overlapping, the regionalization does not cover most parts of Orissa (Figure 8(a)). The rotation of the first three EOFs, though, yields three regions (Figure 8(b)): the region (iii) overlaps with the southern parts of the regions (i) and (ii). The regionalization based on rotation of the first four EOFs (Figure 8(c)) gives four distinct regions with minimum area of overlapping. The region of overlapping consists of some parts of Bolangir and Kalahandi districts. The rotation of the first five EOFs (Figure 8(d)) yields a more complicated structure, with more regions of overlapping. Hence, the rotation of four EOFs yields distinct regionalization with a minimum area of overlapping and

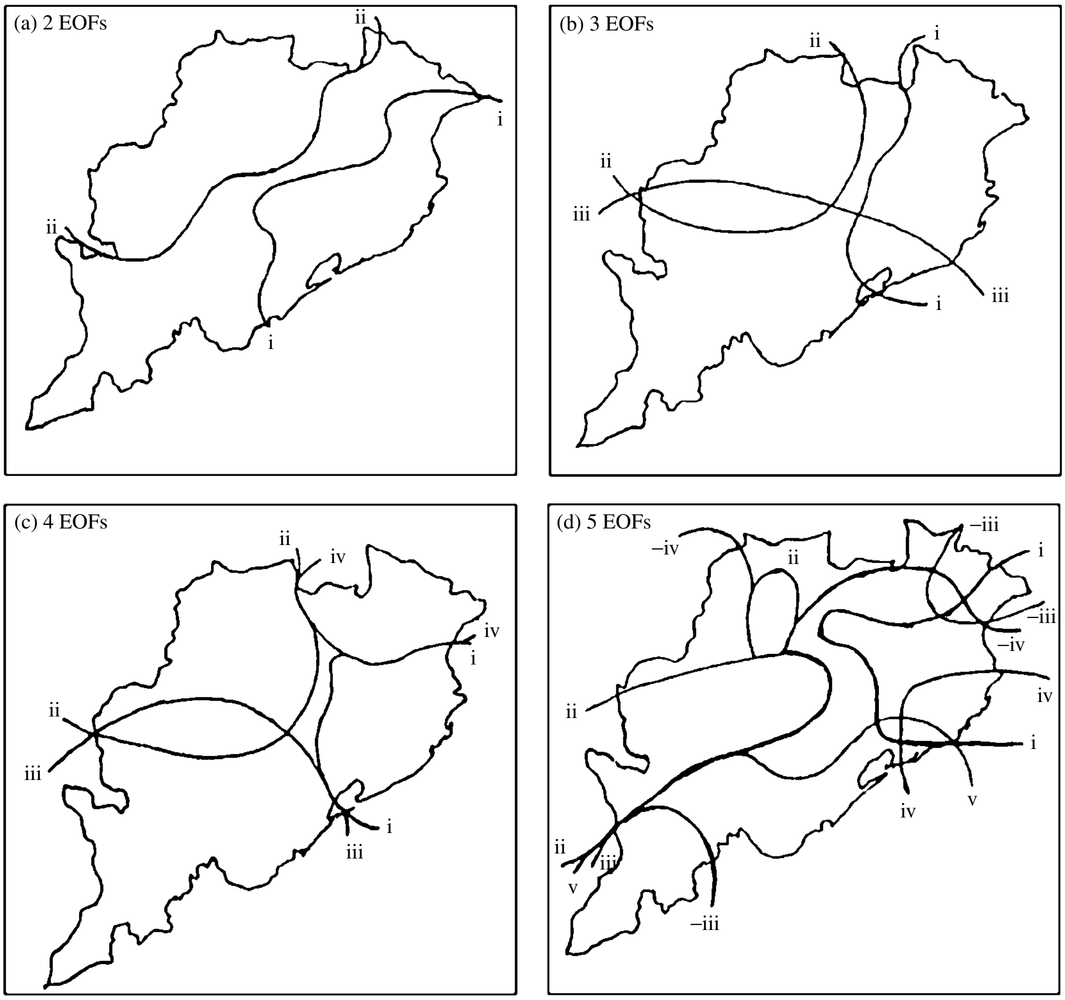

Figure 8. Regionalization defined by ≥ 0.2 loading isopleths in rotated S-mode EOFs; (a) rotation of first two EOFs; (b) rotation of first three EOFs; (c) rotation of first four EOFs; (d) rotation of first five EOFs

distinct geophysical processes associated with different regions. The limitation of this regionalization is that it could not distinguish the western and eastern sides of Eastern Ghat, which show different rainfall characteristics in association with synoptic disturbances, like the LPSC over Orissa and the adjoining land/sea regions.

Considering the mean loadings of the first four unrotated and rotated EOFs over four different regions obtained by the above process (Table II), it is found that region (i) is characterized by a significantly higher positive mean loading of rotated EOF_1. Hence, region (i) gets higher rainfall than the other regions due to the LPSC over NW Bay/NW and the adjoining NE Bay. Region (ii) is characterized by significantly higher positive mean loading of rotated EOF_2; hence, compared with the other regions, it gets more rainfall due to the LPSC over GWB. Region (iii) is characterized by a significantly higher positive mean loading of rotated EOF_3 and, hence, gets more rainfall than the other regions due to the LPSC over Orissa/NW and the adjoining WC Bay. Region (iv) is characterized by a significantly higher positive mean loading of rotated EOF_4 and, hence, gets more rainfall than the other regions due to the monsoon trough without any significant embedded systems over Orissa and the adjoining land/sea areas.

3.5. Unrotated EOFs in T-mode

The scree test and the plot of log(EV) indicate a break in slope near EOF number 5 (Figure 9). The first five EOFs explain about 75% of the total variance in daily rainfall (Table III). The spatial distributions of the first five unrotated EOFs in T-mode are depicted in Figure 10. It is found that the values of EOF_1 (Figure 10(a)), which explain about 32.9% of total variance, are positive for all stations in Orissa except the eastern side of Eastern Ghat. It is higher over the western side of Eastern Ghat, the adjoining areas of the central river basin and the western side of the northern upland. Like EOF_1 of the S-mode, it may be associated with the composite anomaly of rainfall distribution due to the LPSC over NW Bay and NW and the adjoining NE Bay with the monsoon trough extending from the system to a west-northwesterly direction across GWB/north Orissa. The values of EOF_2 (Figure 10(b)), which explain about 18.5% of the total variance, are positive over south Orissa except for some areas of the Puri district. It is also positive over the adjoining areas of the northern upland and the central river basin. The positive values are higher over the western side of Eastern Ghat and the adjoining areas of the central river basin. The negative values are higher over north coastal Orissa and adjoining areas of the Mayurbhanj district. This may be associated with the composite anomaly of rainfall due to the LPSC over Orissa/NW and the adjoining WC Bay with the monsoon trough extending west-northwestwards across the centre of the system like the EOF_3 in S-mode. The values of EOF_3 (Figure 10(c)), which explain about 14.2% of the total variance, are negative over the region extending from Cuttack–Puri districts' coasts in the east towards the Kalahandi district in the west. It is positive elsewhere, being at a maximum over the northernmost part of Orissa. This may be associated with the composite anomaly pattern of rainfall distribution over Orissa due to the LPSC over GWB with the monsoon trough extending west-northwestwards from the centre of the system. So, it corresponds to EOF_2 in S-mode. The values of EOF_4 (Figure 10(d)), which explain about 5.6% of the total variance, are positive over northeast Orissa and most parts of Eastern Ghat except the easternmost side. The positive values are higher over the extreme northeast of Orissa and some parts of the Sambalpur and Bolangir districts. The negative values are oriented over the regions (i) extending along coastal Orissa and (ii) extending from Cuttack–Puri

Table II. Mean values of the first four EOFs in S-mode[a]

	Unrotated				Rotated			
	EOF1	EOF2	EOF3	EOF4	EOF1	EOF2	EOF3	EOF4
Region (i)	**0.21**	−0.17	−0.1	**−0.2**	**0.34**	0.02	0.04	−0.01
Region (ii)	**0.21**	**0.21**	0.11	−0.03	−0.01	**0.32**	0.06	0.03
Region (iii)	0.12	−0.11	**0.21**	0.12	−0.03	0.03	**0.29**	−0.06
Region (iv)	0.16	0.03	**−0.2**	**0.26**	0.0	−0.01	0.09	**0.36**

[a] Mean values > |0.2| are in bold.

districts' coasts in the southeast towards the Sundergarh district in the northwest. Like EOF_4 in S-mode, this may be attributed to the monsoon trough without any embedded system over Orissa and its adjoining land/sea areas, but representing the composite anomaly pattern. The values of EOF_5 (Figure 10(e)), which explain about 3.7% of the total variance, are positive over a region in north Orissa covering parts of Dhenkanal, Keonjhar and Mayurbhanj districts. It is also positive over the western side of Eastern Ghat and the adjoining areas of Sambalpur district. The values are negative elsewhere. Like EOF_5 in S-mode, this pattern is attributed to the composite anomaly pattern of rainfall over Orissa due to the LPSC over NE and the adjoining NW Bay with the monsoon trough extending west-northwestwards across Bangladesh.

3.6. Rotated EOFs in T-mode

The pair-wise plots of loadings in both unrotated and rotated EOFs suggest that rotation of the first five EOFs yields the simplest structure. The intra-EOF correlations also indicate that the rotated EOFs for rotation of the first five EOFs are most uncorrelated to each other. However, the rotation is carried out for the first three, four, five and six EOFs. Considering the values of rotated EOFs equal to 0.2, the isopleths are drawn and based on these isopleths, daily rainfall affinity areas are determined for various rotations. The results of regionalization are shown in Figure 11.

The regionalization due to rotation of the first three EOFs in T-mode does not cover most parts of Orissa (Figure 11(a)). Also, some parts of the Sambalpur and Sundergarh districts are the overlapping region for (ii) and (iii). The rotation of the first four EOFs results in four regions (Figure 11(b)). However, regions (i) and (ii), (ii) and (iii), and (iii) and (iv) overlap with each other. The region of overlapping increases from that of rotation of the first three EOFs. Considering the rotation of the first five EOFs, a simpler structure is obtained with minimum area of overlapping (Figure 11(c)). Considering the rotation of the first six EOFs, it is found that the structure becomes more complicated, with a number of overlapping regions (Figure 11(d)). Hence, the rotation of the first five EOFs yields the simplest structure and the regionalization based on this rotation is more appreciable.

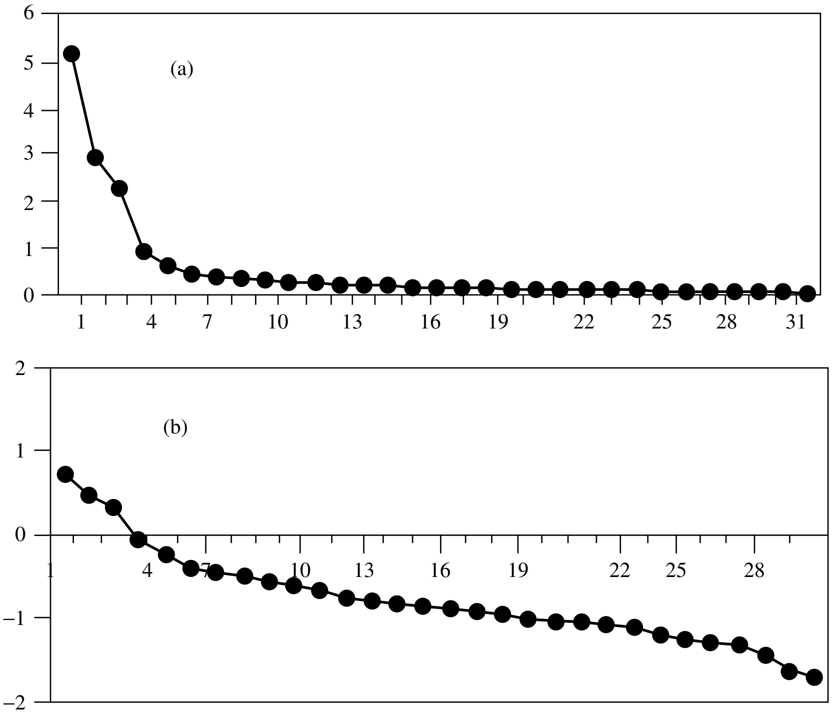

Figure 9. (a) EV and (b) log(EV) of EOFs in T-mode

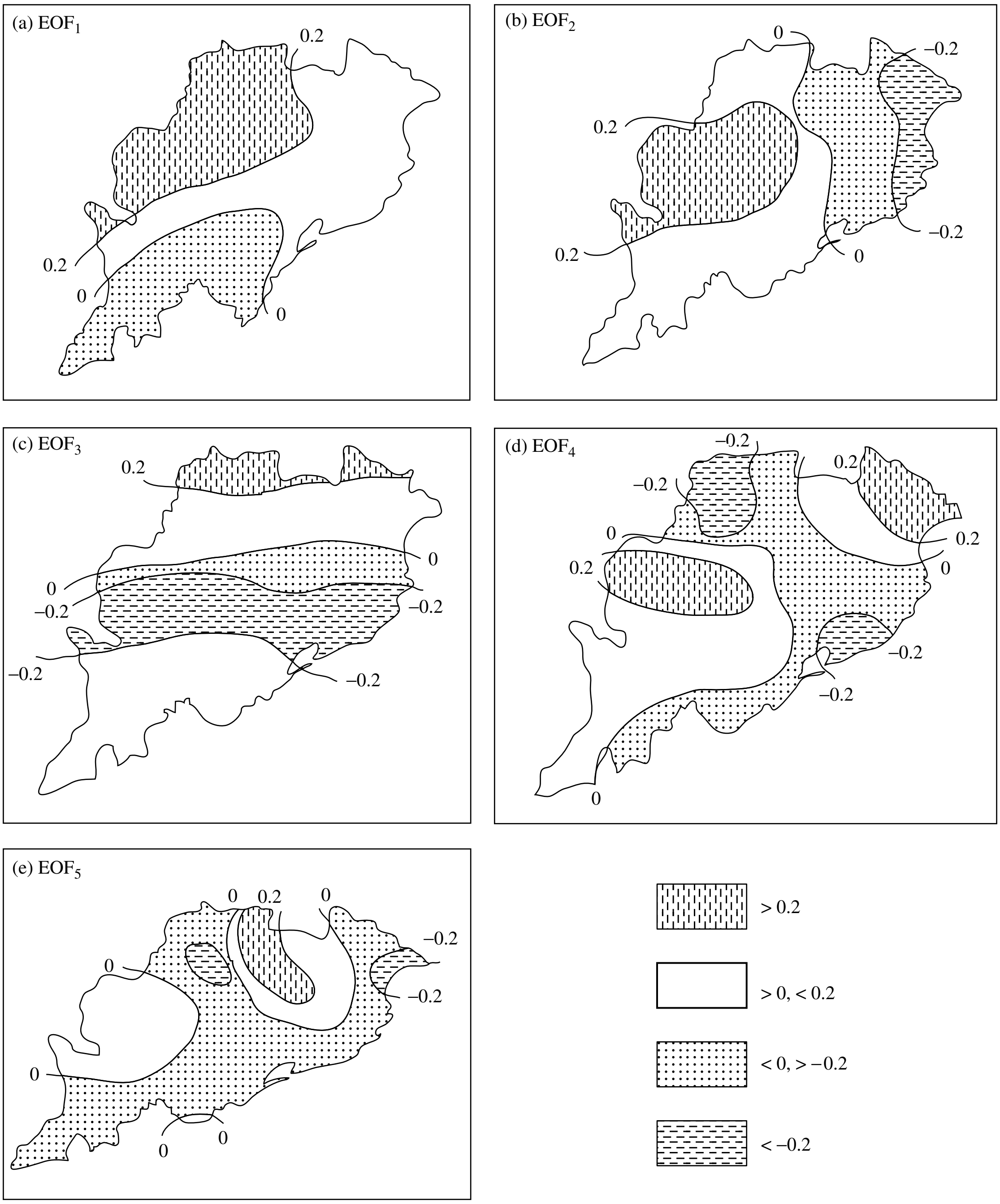

Figure 10. The spatial pattern of unrotated EOFs in T-mode: (a) EOF$_1$; (b) EOF$_2$; (c) EOF$_3$; (d) EOF$_4$; (e) EOF$_5$

The mean values of the first five unrotated and rotated EOFs over different regions obtained by the above process are given in Table IV. It is found that, like S-mode regionalization, each of the different regions obtained by rotation of the first five EOFs is dominated by a single major rotated EOF. Region (i) is characterized by a significantly higher positive mean value of rotated EOF$_1$ and, hence, gets more rainfall than other regions with the LPSC over NW Bay/NW and the adjoining NE Bay. Region (ii) is characterized by a significantly higher positive mean value of rotated EOF$_2$ and, hence, gets more rainfall than the other regions

Table III. Variance and cumulative variance explained by the first 16 EOFs in T-mode

EOF number	Variance (%)	Cumulative variance (%)
1	32.9	32.9
2	18.5	51.4
3	14.2	65.6
4	5.6	71.2
5	3.7	74.9
6	2.6	77.5
7	2.4	79.9
8	2.2	82.1
9	1.9	84.0
10	1.6	85.6
11	1.5	87.1
12	1.2	88.3
13	1.1	89.4
14	1.1	90.5
15	1.0	91.5
16	0.9	92.4

with the LPSC over Orissa/NW and the adjoining WC Bay. Region (iii) is characterized by a significantly higher positive mean value of rotated EOF$_3$ and, hence, gets significantly higher rainfall than the other regions with the LPSC over GWB. Region (iv) is characterized by a significantly higher positive mean value of rotated EOF$_5$ and, hence, gets significantly higher rainfall than the other regions with the LPSC over NE and the adjoining NW Bay. Region (v) is characterized by a significantly higher positive mean value of rotated EOF$_4$ and, hence, gets significantly higher rainfall than the other regions with only the monsoon trough without any embedded system over Orissa and its adjoining land/sea areas.

Comparing the regionalization due to rotation of significant EOFs in both S- and T-mode (Figure 8(c) and Figure 11(c)), it is found that the area of overlapping regions is less in the case of regionalization based on T-mode rotation. Whereas T-mode rotation successfully differentiates the rainfall pattern on the western and eastern sides of Eastern Ghat, the S-mode rotation fails to do so. Considering the mean rainfall distribution (Figure 3(a)), it is a fact that the rainfall distributions on the eastern and western sides of Eastern Ghat are different from each other. Though the region on the eastern side of Eastern Ghat is not a separate homogeneous region when considering the loadings >0.2, it behaves like a separate homogeneous region when considering the equal signs of loadings (either all positive or all negative) over different stations for all the significant EOFs. Prasad and Singh (1988) regionalized India by assuming that the region over which the

Table IV. Mean values of the first five EOFs in T-mode[a]

	Unrotated					Rotated				
	EOF1	EOF2	EOF3	EOF4	EOF5	EOF1	EOF2	EOF3	EOF4	EOF5
Region (i)	0.11	**−0.22**	**−0.21**	−0.07	−0.09	**0.34**	0.03	0.04	0.03	−0.01
Region (ii)	**0.25**	**0.28**	−0.23	**0.20**	0	−0.08	**0.52**	0.06	0.04	0.03
Region (iii)	**0.26**	0.19	0.12	**−0.25**	**−0.23**	−0.05	−0.02	**0.47**	−0.07	0.08
Region (iv)	**0.22**	−0.02	0.1	−0.05	0.19	−0.01	0.01	0.01	−0.06	**0.3**
Region (v)	0.12	**−0.23**	0.09	**0.26**	−0.19	0.09	0.02	0.01	**0.41**	0.05

[a] Mean values > |0.2| are in bold.

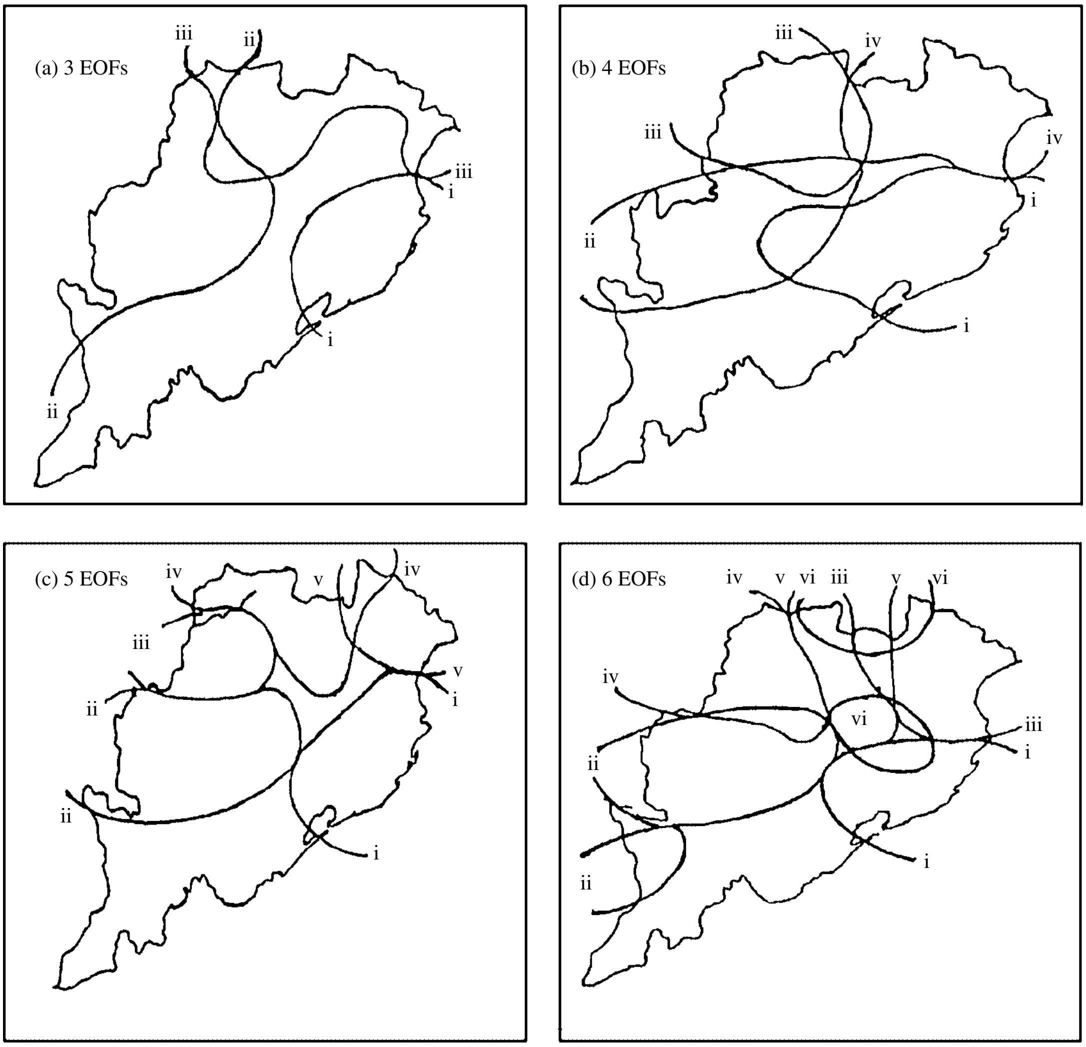

Figure 11. Regionalization defined by ≥ 0.2 amplitude isopleths in rotated T-mode EOFs: (a) rotation of first three EOFs; (b) rotation of first four EOFs; (c) rotation of first five EOFs; (d) rotation of first six EOFs

sign of the loadings remains unchanged in the case of all significant EOFs may be regarded as homogeneous. Considering all the above, the T-mode rotation of the first five EOFs yields better regionalisation of Orissa. The homogeneous regions, thus obtained, are shown in fig. 12.

4. CONCLUSIONS

The following broad conclusions are drawn from the results discussed above.

The mean rainfall distribution over Orissa is dominated by the LPSC developing over NW Bay/NW and the adjoining NE Bay with the monsoon trough extending west-northwestwards from the centre of the system across GWB/north Orissa.

The interstation CCs indicate homogeneous rainfall distribution over Orissa. Considering the higher threshold values of interstation CC, Orissa consists of different sub-homogeneous regions of daily rainfall. However, these regions are not clearly distinct from each other.

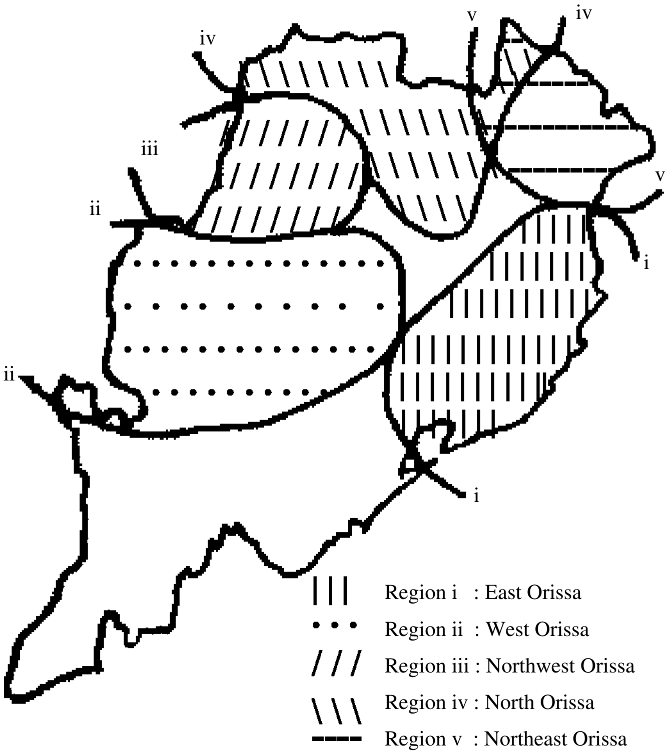

Figure 12. The homogeneous regions of daily monsoon rainfall over Orissa based on T-mode rotation of significant EOFs

In S-mode analysis, the first EOF may be attributed to the LPSC over NW Bay/NW and the adjoining NE Bay with the monsoon trough extending from the system in the west-northwesterly direction across GWB/north Orissa. The second EOF may be associated with the LPSC over GWB. The third EOF may be associated with the LPSC over Orissa/NW Bay and the adjoining WC Bay. The fourth EOF may be associated with a weak monsoon situation over Orissa, when only a monsoon trough exists without any significant system over Orissa and its neighbouring regions. The fifth EOF may be attributed to the LPSC over NE and the adjoining NW Bay with the monsoon trough from the centre of the system extending west-northwestwards across Bangladesh.

The unrotated EOFs in T-mode are attributed to almost the same type of synoptic pattern, but representing the composite anomaly pattern of the rainfall due to the systems. However, the EOFs in T-mode explain more variance than those in S-mode. The role of orography due to Eastern Ghat is highlighted in both the modes of analysis, being significantly so in T-mode.

The rotation of significant EOFs yields better regionalization in T-mode. According to rotation of significant EOFs in T-mode, Orissa consists of five homogeneous regions of daily monsoon rainfall: (i) eastern Orissa, (ii) western Orissa, (iii) northwest Orissa, (iv) north Orissa, and (v) northeast Orissa. Eastern Orissa gets higher rainfall than the other regions due to the LPSC over NW Bay/NW and the adjoining NE Bay; western Orissa rainfall is due to the LPSC over Orissa/NW and the adjoining WC Bay; northwest Orissa rainfall is due to the LPSC over GWB; north Orissa rainfall is due to the LPSC over NE and the adjoining NW Bay; and northeast Orissa rainfall is due only to a monsoon trough without any significant embedded system over Orissa and its adjoining land/sea areas.

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