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Centre for Energy Studies, Indian Institute of Technology, Delhi, Hauz Khas, New Delhi, India

Empirical Orthogonal Function (EOF) analysis of monsoon rainfall and satellite-observed outgoing long-wave radiation for Indian monsoon: a comparative study

C. V. Singh

With 5 Figures

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Summary

The present study involves the use of Empirical Orthogonal Function (EOF) analysis/Principal Component Analysis (PCA) to compare the dominant rainfall patterns from normal rainfall records over India, coupled with the major modes of the Outgoing Long-wave Radiation (OLR) data for the period (1979–1988) during the monsoon period (June–September). To understand the intraseasonal and interannual variability of the monsoon rainfall, daily and seasonal anomalies have been obtained by using the (EOF) analysis. Importantly, pattern characteristics of seasonal monsoon rainfall covering 68 stations in India are highlighted.

The purpose is to ascertain the nature of rainfall distribution over the Indian continent. Based on this, the percentage of variance for both the rainfall and OLR data is examined. OLR has a higher spatial coherence than rainfall. The first principal component of rainfall data shows high positive values, which are concentrated over northeast as well as southeast, whereas for the OLR, the area of large positive values is concentrated over northwest and lower value over south India apart from the Indian ocean. The first five principal components explain 92.20% of the total variance for the rainfall and 99.50% of the total variance for the outgoing long-wave radiation. The relationship between monsoon rainfall and Southern Oscillations has also been examined and for the Southern Oscillations, it is 0.69 for the monsoon season. The El-Niño events mostly occurred during Southern Oscillations, i.e., Walker circulation. It has been found that the average number of low pressure system/low-pressure system days play an important role during active (flood) or inactive (drought) monsoon year, but low-pressure system days play more important role in comparison to low-pressure systems and their ratio are (16:51) and (13:25), respectively. Significantly, the analysis identifies the spatial and temporal pattern characteristics of possible physical significance.

1. Introduction

Indian summer monsoon variability needs further introspection. The southwest monsoon accounting for more than 75% of the annual rainfall impacts the economy. However, the monsoon rainfall shows considerable interannual variability. This makes it a complex phenomenon with dependence on the regional circulation as well as global circulation. Periodic variation of south-west monsoon and seasonal rainfall forecasting are of key concern to meteorologists (Normand, 1953; Jagannathan, 1960; Rao, 1965; Rao, 1976; Singh, 1994). Rainfall anomalies are not uniform over the country despite regular variations in monsoon. According to an analysis by Subbramayya (1968), there is a negative correlation in rainfall between the northeastern and west central part of India, but this analysis does not indicate the variance explained by different rainfall patterns.

Stidd (1967) used EOF to represent the seasonal rainfall variations of rainfall over Nevada and found that the first three terms in order of importance account for 93% of the variance in the original 12×60 matrix data and these have features in common with the three natural cycles of precipitation. Singh (1999) has also shown the percentage of variance explained in different categories of monsoon rainfall (normal, flood and drought years) and concluded that the pattern has the physical significance.

Terray (1995) has used two low frequency models of monsoon variability during the period 1900–1970 and on this basis, he concluded that (1) in the summer monsoon, sea-level pressure can be interpreted as on expansion/contraction of the monsoon activity, since the mode is strongly coupled with rainfall variation over peninsular India (2) strong influence on the Indian summer monsoon, rainfall fluctuations are found particularly on the Ghats and in the Indo-Gangetic plains.

Kripalani et al (1997) have studied the association between the mid-latitude circulation and rainfall over the India region on an intra-seasonal time scale for the period (1974–1984) of the northern hemisphere 500 hpa geopotential height and rainfall data for Indian summer monsoon (June–September) on the basis of correlation analysis. They have concluded that some element of low-frequency variability influence the mid-latitude circulation and Indian rainfall. The inter-annual and the decadal variability are examined by using the Northern Hemisphere zonal index data for the period 1900–1923. It has been concluded that decadal-scale variability of the Indian Summer Monsoon Rainfall (ISMR) and the circulation features are connected. Sikka (1980) attributed the epochal behaviour of the ISMR to the frequencies of the occurrence of El-Niño events. A recent study by Kripalani et al (1997) have shown that these epochs are not forced by the frequencies of El-Niño or La-Niña events. Kane (1998) has found that mostly the El-Niño years were associated with drought years during the rainy season (June–September), but it is not true in all cases for, e.g., in the case of recent El-Niño (1997).

Krishnamurti et al (1977) Investigated a teleconnection between western pacific disturbances and Bay of Bengal disturbance on the basis of 44 years of surface pressure data. They concluded the existence of westward-propagating, surface pressure perturbation along about 20° N with phase and group velocities of about 6° and 2° latitude per day, respectively. Additionally, these perturbations are responsible for initiating monsoon disturbances near the northern Bay of Bengal.

Murakami (1980a) used the outgoing long-wave radiation data derived from the NOAA polar orbiting satellite to find some characteristic features at long period (20–30 days) oscillation of the Asian summer monsoon. The data has been further studied to investigate the regional nature of long and short period oscillations over the South China Sea, Indonesia Sea and Bay of Bengal during the winter (Murakami, 1980b; 1980c).

Prasad and Verma (1985) have analysed the dominant eigen-vector pattern of the outgoing long-wave radiation using eigen-vector analysis. Their study shows annual cycle with pronounced variations in the outgoing long-wave radiation over the tropical belt between 10° N to 20° N. They have also concluded that interannual variation of the outgoing long-wave radiation for the summer monsoon period shows a close association with the large-scale monsoon rainfall over India. The outgoing long-wave radiation data has been used in monitoring and understanding the tropical circulation changes and in modeling, for, e.g., Chelliah and Arkin (1992), Kousky and Kayano (1994), and Moron (1995). In the literature, the details of the principal components analysis technique are given by Grimmer (1963), Kutzbach (1967), Kidson (1975), Hastenrath (1978). In the present study, the Empirical Orthogonal Function (EOF) or Principal Component Analysis is used to compare the dominant rainfall patterns from normal rainfall records over India and the major modes of the outgoing long-wave radiation data for the period (1979–1988) during the monsoon period (June–September). The analysis identifies the spatial and temporal pattern characteristics of possible physical significance. The El-Niño/Southern Oscillation (ENSO) and its relationship with Indian monsoon have also been examined.

2. Data sets used

Daily precipitation data (in mm) of the monsoon season (June to September) for the period 1979

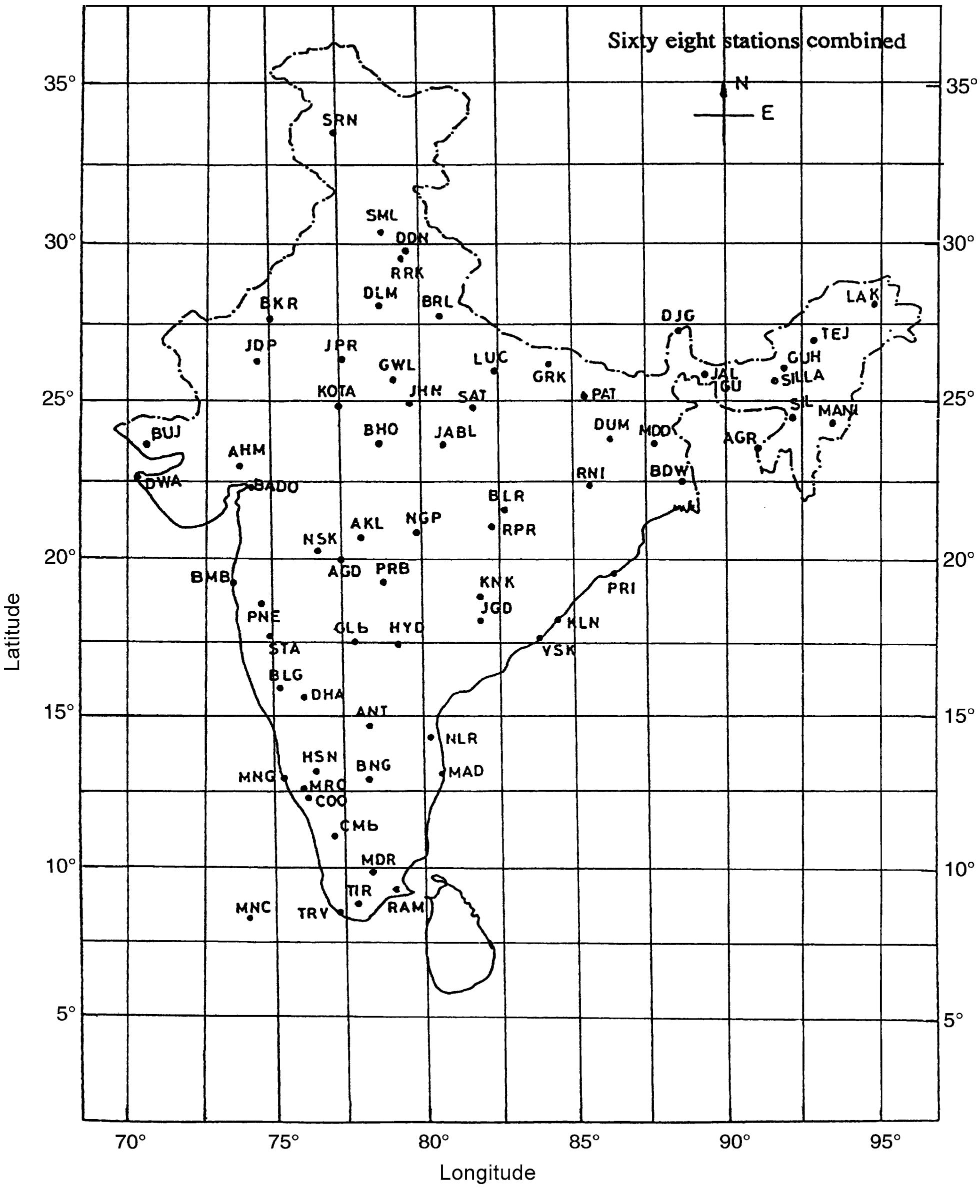


Fig. 1. Location of 68 stations with distribution of grid-points at 2.5° longitude–latitude intervals

to 1988 for sixty-eight stations have been considered in this study. Stations without any missing data have been used for present analysis. The data have been taken from the India Meteorological Department (I.M.D.) Pune, India, while for the outgoing long-wave radiation, the data sets of daily average values of outgoing long-wave radiation (OLR) have been used over the Indian region (5° N to 35° N) and (70° E to 95° E) at 2.5° longitude/latitude intervals for ten years period (1979 to 1988, June to September) without any gap.

Figure 1 shows the locations of 68 stations with grid points of interval of 2.5° longitude/latitude (stations locations with name) for which the present analysis has been carried out. The data has been taken from Dr. Brant Liebmann of the Climate Diagnostics Centre, Boulder, Colorado. This OLR data set is the average of two instantaneous measurements corresponding to the passage of the polar orbiting satellite. The usual time for these measurements is approximately 2:30 a.m. and 14:30 hours.

3. Data analysis and computing procedure

Monsoon rainfall over India during the months of June to September (122 days) exhibits interesting oscillations over the country. In the present analysis, the rainfall over the country has been expressed as a linear combination of orthogonal functions. This technique was suggested by Lorenz (1956) and later used by Kutzbach (1967), and Weare (1977) to evaluate the principal component of sea-level pressure over the Northern Hemisphere and sea-surface temperature over the Atlantic Ocean. Also, the daily OLR data sets (1979–1988) for the monsoon period (June to September) have been used at 2.5° longitude/latitude intervals with 68 stations in India. The location of 68 stations has been chosen on the basis that they have represented the true network of rainfall distributions over India. Interestingly, the set of 68 stations selected for the rainfall exhibited equally promising results alongwith a higher correlation with all India seasonal rainfall (Singh, 1994).

Let P be a $(n \times m)$ matrix of monsoon rainfall over m stations and a series of n years. Here, $n = 10$ years and $m = 68$ stations.

The element (P_{rs}) of P represents departure of rainfall from their mean value for the s-th station and r-th year.

Let P represents the time and space variability of rainfall. It can be defined that

$$P = QF, \tag{1}$$

where the matrix Q represents the time variation and F represents the space variation of monsoon rainfall. The element of the P matrix is given by

$$P_{rs}(x, y, t) = \sum_{k=1}^{m} q_{rk}(t) \times f_{ks}(x, y), \tag{2}$$

where the element $q_{rk}\,(t)$ represents the time and $f_{ks}\,(x, y)$ represents the space respectively. The matrix F is an orthonormal matrix, hence the transpose and product of this matrix should be represented as a unique identity matrix. It is defined that

$$F F' = I, \tag{3}$$

where F' is the transpose of F and I is the identity matrix. It is further stated that F and Q matrix derive from the matrix P after defining the matrix S, where

$$P' P = S.$$

This matrix S is a square matrix and P' is the transpose of the matrix P, hence from the above equation, it is concluded that

$$F' S F = Q Q' = D, \tag{4}$$

where D is a diagonal matrix. The columns of F are the eigenvectors of S, while the element of D is the eigenvalue of S. Every element of D is a measure of the percentage variance explained by the corresponding eigenvector. F and D were calculated from S by Jacobi's method (Greenstadt, 1960). This is an iterative process, which utilizes successive rotations of each element of s.

4. Results and discussion

During the examination of El-Niño/Southern Oscillations (ENSO) and its relationship with Indian monsoon, it was found that during ENSO years (1983; 1987); the monsoon rainfall over most part of the region was below normal, particularly in the west area (Krishnamurti et al, 1989). It is known that within many places, the proportion of rain comprises about 40–50% during 1–5 days and sometimes, over 100% of the total mean seasonal rainfall. Such an occurrence of rainfall extremes produces largest flooding during monsoon season. It is also possible that ENSO conditions may also affect the rainfall pattern.

EOF analysis of the rainfall and OLR data for 68 stations has been carried out and the results are presented in subsequent table and figures. Table 1 shows the percentage of variance explained by various principal components for rainfall and OLR data in a decreasing order. As can be seen, principal components up to 5 levels explain the variance of 92.20% for rainfall and the

Table 1. Percentage of variance explained in decreased order

Principal component	Variance (%)	
	Rainfall	OLR
First principal component	55.50	58.00
Second principal component	15.80	18.00
Third principal component	10.40	12.00
Fourth principal component	7.50	8.00
Fifth principal component	3.00	3.50

accompanying variance of 99.50% for OLR data. This table also shows that OLR has higher spatial coherence than rainfall. It is clear from Table 1 that each principle component has a pivotal role in accounting for the corresponding values of rainfall variance.

Figure 2a, b shows the first principal component explaining the percentage of total variance.

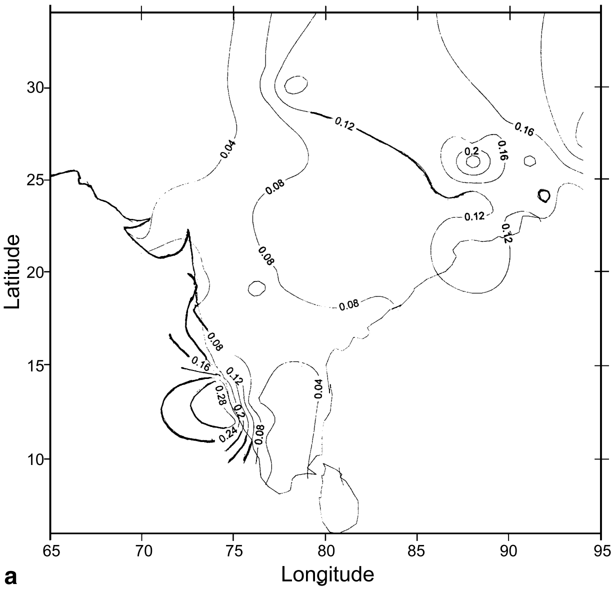


Fig. 2a. First component for rainfall pattern (variance explained 55.50%)

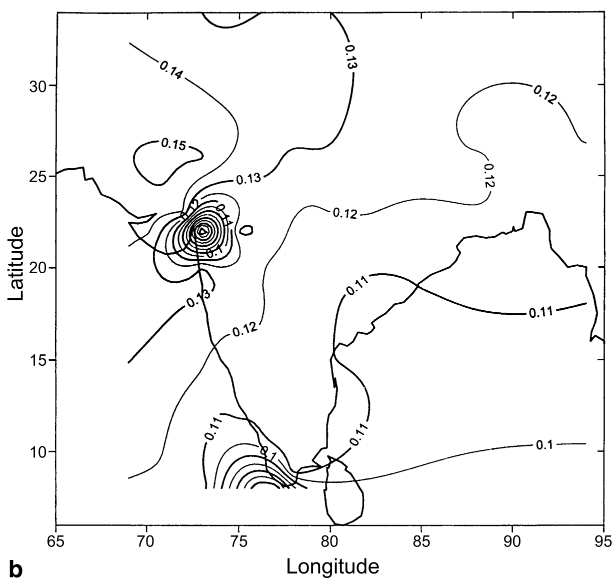


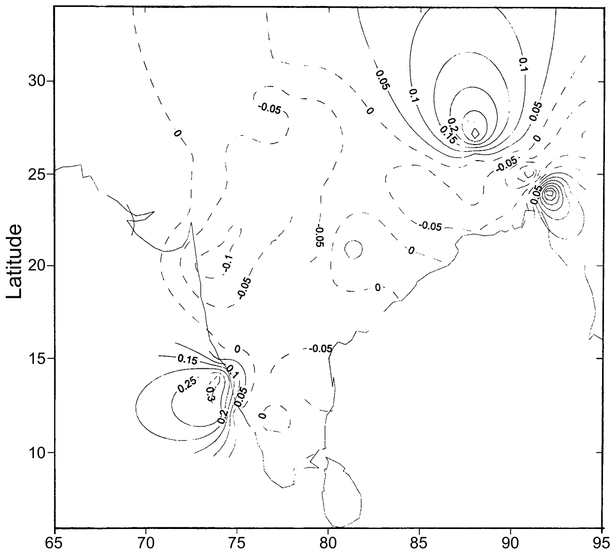
Fig. 2b. First component for OLR pattern (variance explained 58.00%)

It has been observed that for rainfall and OLR data, the first principal component explains 55.50% and 58.00% of total variance respectively and exhibits factor of one positive value throughout the sub-continent. Further, it has also been noticed from rainfall pattern (Fig. 2a) that the large positive values are concentrated over northeast as well as southwest coast of India. Such a pattern has been explained by Shukla (1987) due to Southern Oscillation while Bedi and Bindra (1980) attributed it to monsoon depression in the head Bay of Bengal, and mid-tropospheric low over westcoast of India.

The impact in rainfall over Northeast and Northwest India reveals an interesting phenomenon. Due to depression in the Bay of Bengal or southward movement of monsoon trough, the rainfall amount increases over Northeast India. High values of first principal components around the westcoast and over Northeast India could possibly be explained by the role played by topography in bringing rainfall to these areas, when the monsoon current passes over them.

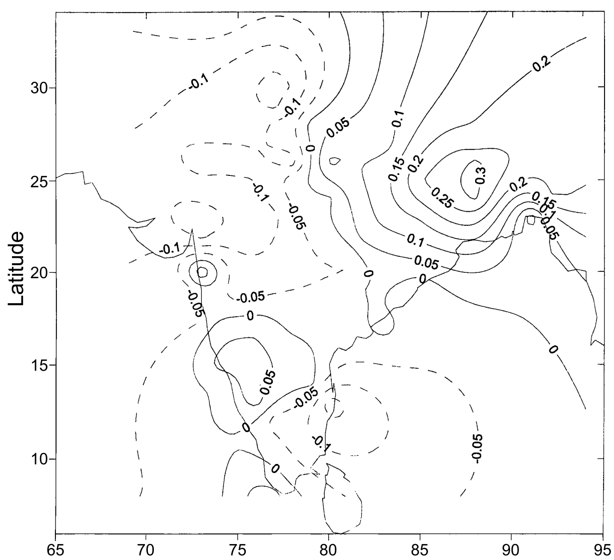
However, the OLR pattern (Fig. 2b) shows that the area of large positive values are concentrated over Northwest India and lower values over South India and elsewhere: Indian Ocean. The Northwest India is covered with seasonal heat-low and South Indian Ocean with seasonal high-pressure area. The intense heat low, with little or no clouds would contribute to higher values of OLR. Correspondingly, Indian Ocean High that is associated with clouds, will contribute to lesser OLR magnitude. It appears that major reason for the monsoon variability is the intensity and the fluctuations in the two major semi-permanent seasonal systems.

Figure 3a shows second principal component of rainfall pattern explaining 15.80% of the variance besides exhibiting factor of one positive value throughout northeast side and also in Konkan and Karnataka Coast, whereas most part of the country shows the lower rainfall pattern. This could be possible due to movement of monsoon lows/depressions in quick succession in the North Bay of Bengal, which also favours the development of a mid troposhperic low over west India. Figure 3b shows the second principal components of OLR pattern explaining 18.00% of the total variance exhibiting factor of a large variation along 25° N over the north India region



a

Fig. 3a. Second component for rainfall (variance explained 15.80%)



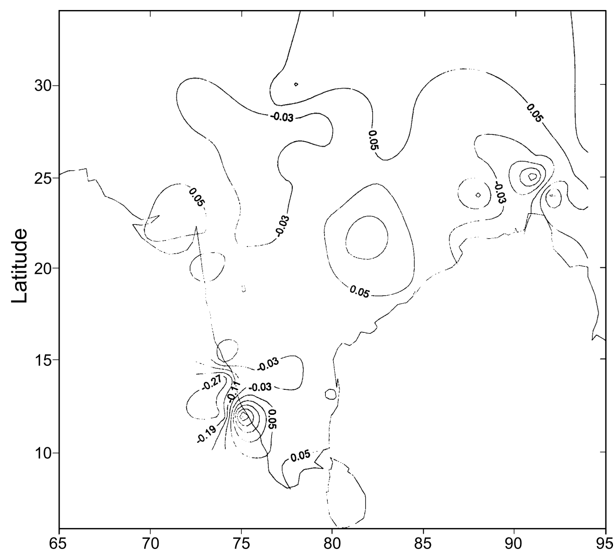
b

Fig. 3b. Second component for OLR pattern (variance explained 18.00%)

with positive values over Bengal and adjoining region and negative value over Northwest India.

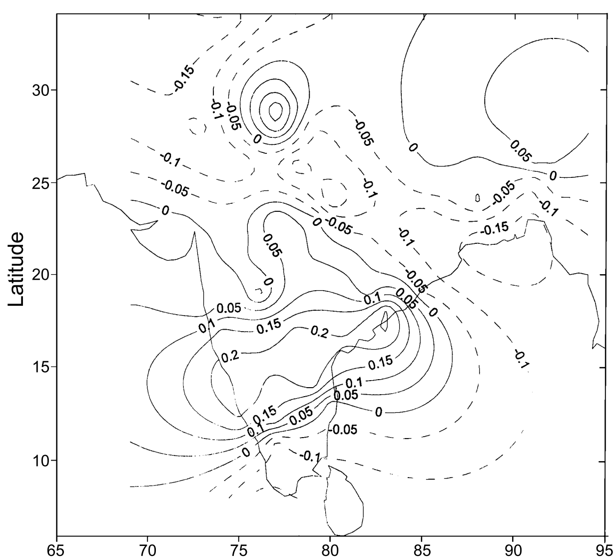
The second region of variation, though weaker as compared to the northern is located along 12° N and is reverse in direction, i.e., higher values over westcoast and lower values over eastcoast. The probable reason could be the synoptic systems such as monsoon depression/lows over the north bay and trough/vortices off westcoast in the Arabian sea.

Figure 4a, b depicts the third principal component explaining about 10.40% of the total variance for rainfall pattern and the third principal components explaining 12.00% of the total variance for OLR pattern. It has been noticed that certain positive and negative value are concentrated within certain zone (Fig. 4a). It could be



a

Fig. 4a. Third component for rainfall pattern (variance explained 10.40%)



b

Fig. 4b. Third component for OLR pattern (variance explained 12.00%)

possible that the monsoon trough is in opposition to the Himalayan foothills and the trough lays oscillating north–south. The same may be developing along it, while from OLR pattern (Fig. 4b) negative values along the region of monsoon trough line and positive value east–west are oriented 12–13° N. One possible reason could be variation from active to break monsoon and back.

Figure 5a, b shows the fourth principal component for rainfall and OLR pattern explaining 7.50% of the variance for rainfall, while the fourth principal components explaining 8.00% of the variance for OLR pattern. It has been found from Fig. 5a that positive values are concentrated only in north-east side, while as major part of the country shows negative value. This could be possible due to movement of monsoon trough to the north, thus giving a break in the monsoon rainfall. The deeper depression in the northwest direction form in the head Bay of Bengal looks to be a reason for the observed pattern, while from Fig. 5b, large positive values occur over Madhya Pradesh, Orissa, Karnatka and Tamilnadu. This is in direct comparison to the negative values demonstrated in case of Maharashtra, Gujarat, and Rajasthan. Such type of variations are possible at the time of withdrawal of monsoon, such as September month.

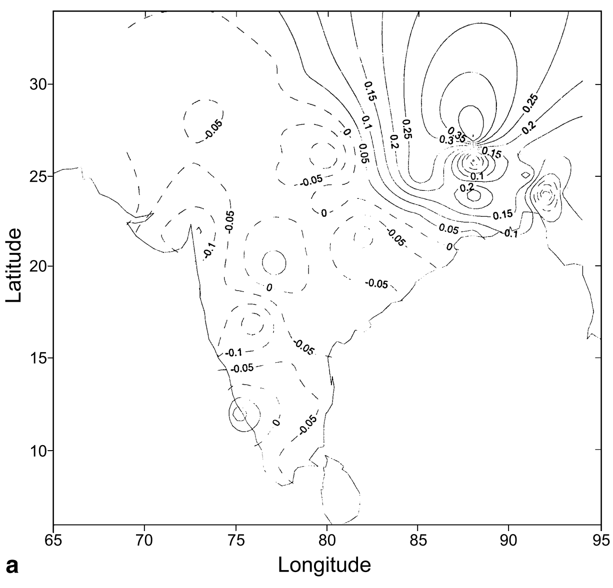


Fig. 5a. Fourth component for rainfall pattern (variance explained 7.50%)

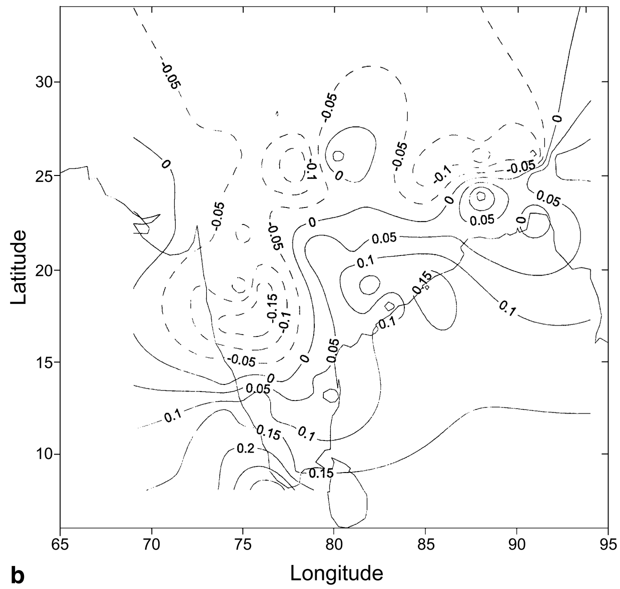


Fig. 5b. Fourth component for OLR pattern (variance explained 8.00%)

5. Conclusions

(1) It has been found that the lower-pressure system days play more important role in comparison to a low-pressure system.
(2) The EOF analysis of monsoon rainfall and outgoing long-wave radiation suggest that OLR has higher spatial coherence than rainfall.
(3) The rainfall and OLR patterns obtained from EOF analysis show that for rainfall, higher positive value are concentrated over north-east as well as south-east, while as for the outgoing long-wave radiation, the area of large positive value is concentrated over northwest and lower values over South India and adjoining Indian ocean.
(4) For rainfall, the positive values are concentrated throughout north-east side and also in Konkan and Karnataka coast, while as, for the outgoing long-wave radiation, the large variation exhibits along 25° N over the North India region with positive value over Bengal and adjoining region and negative value over Northwest India.

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Author's address: C. V. Singh, Centre for Energy Studies, Indian Institute of Technology, Delhi, Hauz Khas, New Delhi-110 016, India (E-mail: cvsingh@cas.iitd.ernet.in)