

Spatial variability of daily rainfall over northeast India during summer monsoon season

M. MOHAPATRA, H. R. BISWAS* and G. K. SAWAISARJE**

India Meteorological Department, New Delhi, India

**Regional Meteorological Centre, Kolkata, India*

***India Meteorological Department, Pune, India*

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e mails : mohapatra_imd@yahoo.co.in; hrbimd@yahoo.co.in

सार — भारतीय क्षेत्र में पर्वतीय क्षेत्र से प्रारंभिक प्रवाह तथा क्षेत्र में बनने वाली सिनॉप्टिक पैमाना प्रणालियों की परस्पर क्रिया के कारण पूर्वोत्तर भारत में ग्रीष्मकालीन मानसून ऋतु में स्थानिक और कालिक परिवर्तनशीलता का पता चलता है। इस अध्ययन का उद्देश्य पूर्वोत्तर भारत और उससे संबद्ध सिनॉप्टिक प्रणालियों की दैनिक मानसून वर्षा की स्थानिक परिवर्तनशीलता की मुख्य विशेषताओं का पता लगाना है। ध्वनि के मुख्य घटकों को अलग करने का प्रमुख घटक विश्लेषण (पी. सी. ए.) एक अच्छा माध्यम है और इसका अनुप्रयोग 10 वर्षों (1991–2000) की अवधि के पूर्वोत्तर भारत के समान रूप से वितरित 50 केन्द्रों के दैनिक मानसून वर्षा (जून–सितम्बर) आँकड़ों पर किया गया है। सिनॉप्टिक प्रणालियों के साथ महत्वपूर्ण प्रमुख घटकों (पी.सी.) की संबद्धता की पुष्टि इसी अवधि के दौरान पूर्वोत्तर भारत और उसके निकटवर्ती क्षेत्र में दैनिक सिनॉप्टिक प्रणालियों द्वारा की गई है।

पूर्वोत्तर भारत में दैनिक मानसून वर्षा की लगभग 46 प्रतिशत कुल परिवर्तनशीलता बताने वाले 8 प्रमुख घटक महत्वपूर्ण हैं जो विभिन्न भौतिक प्रक्रियाओं की विशेषता बताते हैं। पूर्वोत्तर भारत में अच्छे मानसून की स्थिति से जुड़ा पहला प्रमुख घटक उप हिमालयी पश्चिम बंगाल (एस.एच.डब्ल्यू.बी.) में निम्न दाब क्षेत्र की विशेषता बताता है। इसी प्रकार दूसरा प्रमुख घटक पूर्वी मध्य प्रदेश और छत्तीसगढ़ (ई.एम.पी.सी.) में निम्न स्तरीय चक्रवातीय परिसंचरण (साइसिर) के कारण अच्छे मानसून की स्थिति की विशेषता बताता है, तीसरा प्रमुख घटक बिहार में अवदाब के कारण अच्छे मानसून की स्थिति की विशेषता बताता है, चौथा प्रमुख घटक अरुणाचल प्रदेश में निम्न स्तरीय चक्रवातीय परिसंचरण की विशेषता बताता है, पाँचवा घटक और छठवाँ प्रमुख घटक क्रमशः पश्चिमी मध्य खाड़ी में निम्न दाब के कारण मानसून की कमजोर स्थिति तथा तटीय आन्ध्र प्रदेश के उत्तर में मध्य क्षोभमंडलीय स्तर (एम.टी.एल.) तक फैले चक्रवातीय परिसंचरण की विशेषता बताता है, सातवाँ तथा आठवाँ प्रमुख घटक बंगलादेश और उत्तर पश्चिम खाड़ी में एम.टी.एल. तक फैले चक्रवातीय परिसंचरण वर्षा की गतिविधि की विशेषता बताता है।

एस. मोड में इन महत्वपूर्ण प्रमुख घटकों के घूर्णन के अनुसार पूर्वोत्तर भारत में आठ समवर्षा वाले क्षेत्र बनते हैं जिनमें प्रत्येक क्षेत्र एक महत्वपूर्ण प्रमुख घटक के साथ प्रबल रूप से संबद्ध रहता है।

ABSTRACT. The summer monsoon rainfall over northeast India shows characteristic spatial and temporal variability due to the interaction of basic monsoon flow with orography and the synoptic scale systems developing over Indian region. The aim of this study is to find out the main features of spatial variability of daily monsoon rainfall over northeast India and associated synoptic systems. The principal component analysis (PCA) is a good tool to filter out the main components from the noise and this is applied to daily monsoon rainfall (June-September) data of 50 almost uniformly distributed stations of northeast India over a period of 10 years (1991-2000). The association of synoptic systems with significant principal components (PC) has been confirmed by analyzing daily synoptic systems over northeast India and neighbourhood during the same period.

Eight PCs explaining about 46% of the total variance of daily monsoon rainfall over northeast India are significant and can be attributed to different physical processes. The first PC associated with good monsoon condition over northeast India may be attributed to low over Sub Himalayan West Bengal (SHWB). Similarly, the second PC may be attributed to good monsoon condition due to low level cyclonic circulation (cycir) over East Madhya Pradesh and Chattisgarh (EMPC), third PC to good monsoon condition due to depression over Bihar, fourth PC to good monsoon condition due to low level cycir over Arunachal Pradesh, fifth and sixth PCs to weak monsoon condition due to low over west central Bay and cycir extending upto mid tropospheric level (MTL) over North Coastal Andhra Pradesh respectively, seventh and eighth PCs to rainfall activity due to cycir extending upto MTL over Bangladesh and northwest Bay respectively.

According to rotation of these significant PCs in S-mode, northeast India consists of eight homogeneous regions with the rainfall over each region being dominantly associated with one significant PC.

Key words – Principal component analysis, Daily monsoon rainfall, Regionalisation, Northeast India.

1. Introduction

The summer monsoon rainfall over India is characterized by (i) semi-permanent monsoon trough normally extending from west Pakistan to north Bay of Bengal (ii) the low pressure systems (LPS) and cyclonic circulations (cycir) frequently developing over the north Bay of Bengal and moving in a west-northwesterly direction across Orissa or Gangetic west Bengal and (iii) westerly trough/cycir occasionally moving across the northern part of India (Rao, 1976). However there is variation in monsoon rainfall over India both in space and time, due to variation in the characteristics of monsoon circulation, monsoon trough and LPS/cycir. Also the monsoon circulation is considerably influenced by the Western Ghats, Eastern Ghat, northeastern hill ranges, other hill peaks and above all the Himalayas. There have been many studies on the spatial variability of rainfall over India *e.g.*, Rakhecha and Mandal (1981), Hastenrath and Rosen (1983), Rasmusson and Carpenter (1983), Prasad and Singh (1988), Gregory (1989), Kripalani *et al.* (1991) and Mujumdar (1998).

In general, the monsoon rainfall characteristics of northeast India are opposite to that of the central India (Prasad and Singh, 1988, Kripalani *et al.*, 1991, Mujumdar, 1998). This region gets good rainfall when the break monsoon conditions are realized (Ramamurty, 1969). During break monsoon condition the monsoon trough lies close to the foothills of the Himalayas. The systems like the trough and cycir in the lower level westerlies which occasionally prevail during break monsoon condition causes good rainfall over northeastern region (Rao; 1976). The rainfall occurs over the region when the trough approaches from the west. A higher frequency of LPS and cycir (LPSC) forming over the North Bay and moving westwards may not be favourable for rainfall over northeast India as it ensures existence of monsoon trough in normal position on more occasions which is not favourable for rainfall over this region.

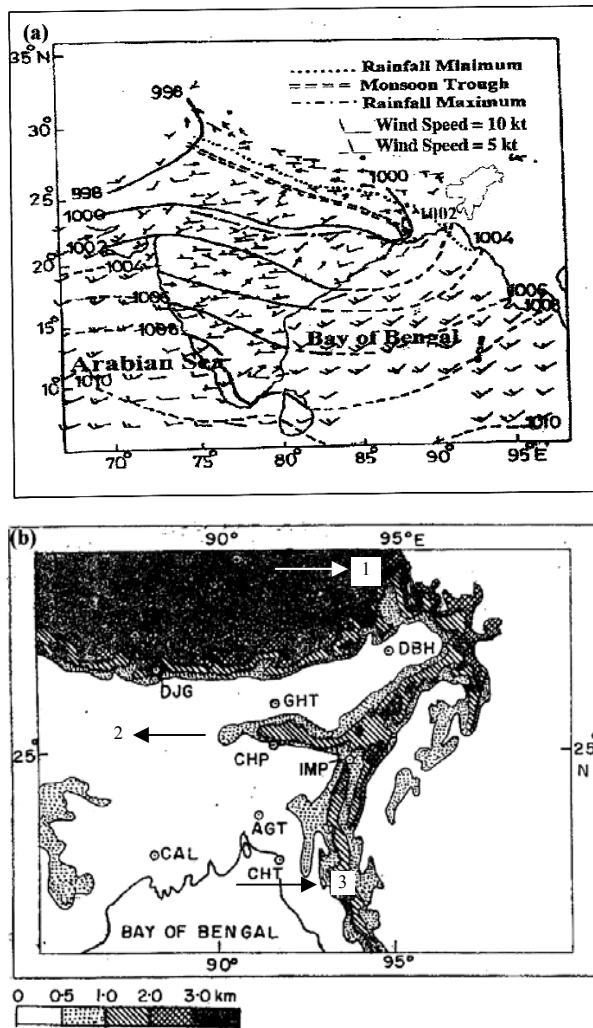
The northeast India is dominantly a hilly region due to its proximity to the eastern Himalayas and the presence of the north eastern hill ranges. The orographic dominance leads to enhanced convection making rainfall distribution more complex over the region.

Considering all the above, the spatial variability of rainfall over northeast India during monsoon season is

highly complex in nature. Further, the spatial variability of rainfall is significantly different from that of other regions of India due to the larger influence of the monsoon trough, westerly systems and significant interaction between convection and basic flow due to varied physiography of the region.

Homogeneity of rainfall is a relative term. A homogeneous rainfall region can be defined based on any one of the following parameters (i) daily rainfall (ii) daily normal rainfall (iii) monthly/seasonal rainfall and coefficient of variation of rainfall. India Meteorological Department (IMD) considers the northeast India to comprise of three meteorological sub-divisions of India, *viz.*, (i) Assam and Meghalaya (A&M), (ii) Arunachal Pradesh (ArP) and (iii) Nagaland, Mizoram, Manipur and Tripura (NMMT) for the issue of region specific daily weather report. IMD considers 3 meteorological subdivisions, *viz.*, A&M, ArP and NMMT for various purposes including description of rainfall. Normally IMD considers a meteorological subdivision as reasonably homogeneous for rainfall. However, considering the physiography of the region the above mentioned three subdivisions show large scale spatial variation of daily rainfall (Srinivasan *et al.*, 1972). These three subdivisions themselves include 7 administrative regions *viz.*, Assam, Meghalaya, ArP, Nagaland, Manipur, Mizoram and Tripura. Further each state is divided into districts. These administrative regions may not be homogeneous rainfall regions. In case of large state such as Assam and ArP, a group of districts could form a homogeneous region of rainfall. Considering all the above, the homogeneous region should be found out based on most logical statistical analysis.

Hence to understand the daily rainfall variability and to predict the daily rainfall over northeast India, it is essential to find out the main features of daily rainfall over this region by filtering out the noises. As principal component analysis (PCA) is an important technique for this purpose, the same has been applied to the daily monsoon rainfall over northeast India over a period of 10 years. A detailed discussion of the principal components (PC) and the methodology can be found in Morrison (1976) and Wilks (1995). When applied to the atmospheric parameters, the PCA leads to the concept of map typing (Richman, 1981) and the specification of the characteristic modes of the variation in the data (Barnston and Livezey, 1987). An attempt is also made to find out



1. Eastern Himalaya, 2. Garo khasi Jaintia hills, 3. Northeastern hill range

Figs. 1(a&b). (a) Mean sea level isobaric pattern (hPa) and mean winds (knots) in representative month of July plotted according to WMO code over Indian region and (b) Physiographical map of northeast India

the homogeneous regions of daily rainfall over northeast India by rotating the significant principal components and applying cluster analysis to the loadings of significant rotated principal components. The principal objective of this study is to find out the main features of spatial variability of daily monsoon rainfall over northeast India and the homogeneous regions of rainfall. This study can be utilized for understanding the physical processes and for further analysis. It can also be useful for short range prediction of rainfall over northeast India.

2. Data and Methodology

Fig. 1(a) presents the surface isobaric pattern, basic monsoon flow at 0.9 km above mean sea level (amsl) over

Indian region, the location of mean position of the monsoon trough and the region of rainfall maxima and minima with respect to the monsoon trough during representative monsoon month of July. In general, the northeast India gets good rainfall when the break monsoon conditions are realized with the monsoon trough lying close to the foothills of the Himalayas.

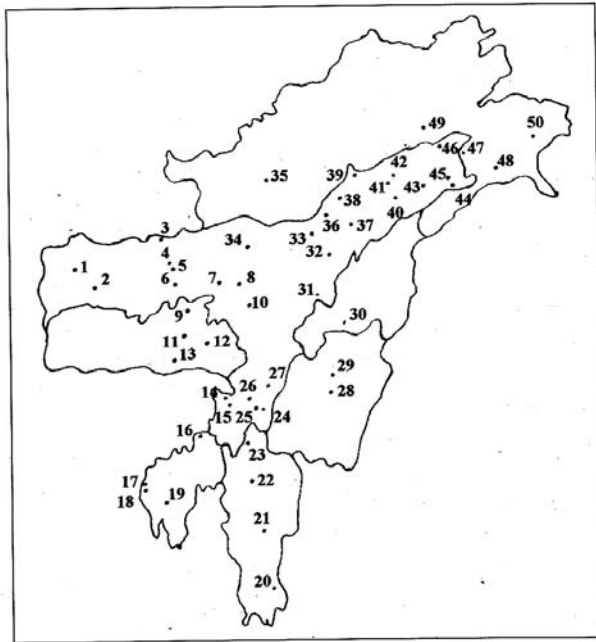
This region is dominantly a hilly region due to its proximity to the eastern Himalayas and the presence of the north eastern hill ranges extending from north to south. In addition, there are east-west oriented Garo Khasi Jaintia hills across Meghalaya and adjoining Assam [Fig. 1 (b)].

Considering all the above, the daily rainfall data for this study are collected from IMD. On real time basis, the daily rainfall is monitored by IMD under district wise rainfall monitoring scheme (DRMS) over 106 stations in northeast India. However, the continuous record of daily rainfall is not available for all these stations. Fifty stations which are almost uniformly distributed in northeast India except northern parts of ArP have been selected for the study [Fig. 2(a)]. The raingauge stations in ArP, which lies in the foothills of the Himalayas, are very meager. The necessary quality control of the data has been carried out and the missing data have been filled by considering the rainfall at surrounding stations.

The PCA has been applied to daily monsoon rainfall data from 50 stations of northeast India for a period of ten years (1991 to 2000). As the Monsoon season (June to September) consists of 122 days, the data matrix used in the study is a matrix of 50×1220 , stations by days form.

2.1. Modes of analysis

For the present study, the parameter (rainfall) is fixed and hence there are two possible modes of analysis, *viz.*; space (S) and time (T) modes (Richman, 1986). However in the present study the S-mode analysis has been considered. In S mode analysis, the variables are the stations and the observations are the values of daily rainfall. For the purpose of analysis, the 50×1220 actual data matrix in station/day form is reduced to 50×50 covariance matrix. The covariance matrix is then subjected to PCA. The PCA loading matrix then contains the correlation of each variable or station with each component. These can be plotted on a map to depict the spatial pattern of each component. The procedure followed in this study is based on algorithm proposed in Statistica Utility (1994) software. The large eigenvalue (EV) is rewritten to a vector and the appropriate normalization is applied (Richman, 1981).

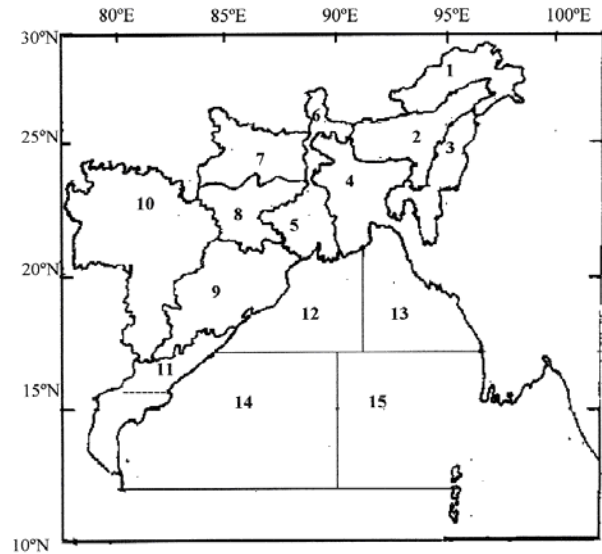


Sr. No.	Selected Raingauge stations	Sr. No.	Selected Raingauge stations	Sr. No.	Selected Raingauge stations	Sr. No.	Selected Raingauge stations	Sr. No.	Selected Raingauge stations
1	Kokrajhar	11	Shillong	21	Serchip	31	Bokajan	41	Khowang
2	Goalpara	12	Jowai	22	Aizwal	32	Golaghat	42	Dibrugarh
3	Mellabazar	13	Cherrapunji	23	Kolasib	33	Numaligarh	43	Naharkatia
4	Rongia	14	Karaminganj	24	Amaraghat	34	Tezpur	44	Margherita
5	Puthimari	15	Matijuri	25	Dholai	35	Seppa	45	Digboi
6	Guwahati	16	Kailasahar	26	Silchar	36	Badatighat	46	Namsai
7	Dharamtul	17	Agartala	27	Lakhipur	37	Neamatighat	47	Dhollabazar
8	Kampur	18	Arundhatinagar	28	Imphal	38	North Lakhimpur	48	Passighat
9	Nongpoh	19	Udaipur	29	Mantripukhri	39	Chouldhowghat	49	Mio
10	Kheronighat	20	Saiha	30	Kohima	40	Moranhat	50	Hawai

Fig. 2(a). Selected raingauge stations of northeast India

2.2. Rotations of PCs

It has been found that PCs form a predictable set of patterns, due largely to the orthogonality constraints. The first PC maximizes the explained variance by having generally large loadings on all variables and subsequent component are dipoles or more complex pattern. In addition to the domain dependence, Richman (1986) has shown that the unrotated PCs suffer from a number of other deficiencies. These can be remedied by rotating the PCs. The rotation of PCs yields simpler structure. The most important difficulty involved in the rotation of the PCs is that no generally applicable criterion exists to determine the number of PCs to be rotated. This number is significant, since the loadings on rotated PCs depend on the number of PCs retained for rotation. Also for unrotated components, the significant components represent the signal and the remaining higher order PCs the noise. Thus, it is important to know the number of PCs



1. Arunachal Pradesh (AP)
2. Assam & Meghalaya (A&M)
3. Nagaland, Manipur, Mizoram and Tripura (NMMT)
4. Bangladesh (BDS)
5. Gangetic West Bengal (GWB)
6. Sub Himalayan West Bengal (SHWB)
7. Bihar
8. Jharkhand (JKD)
9. Orissa
10. East Madhya Pradesh and Chhattisgarh (EMPC)
11. North Coastal Andhra Pradesh (NCAP)
12. North West (NW) Bay
13. North East (NE) Bay
14. West Central (WC) Bay
15. East Central (EC) Bay

Fig. 2(b) Regions of LPSC/LLC under consideration

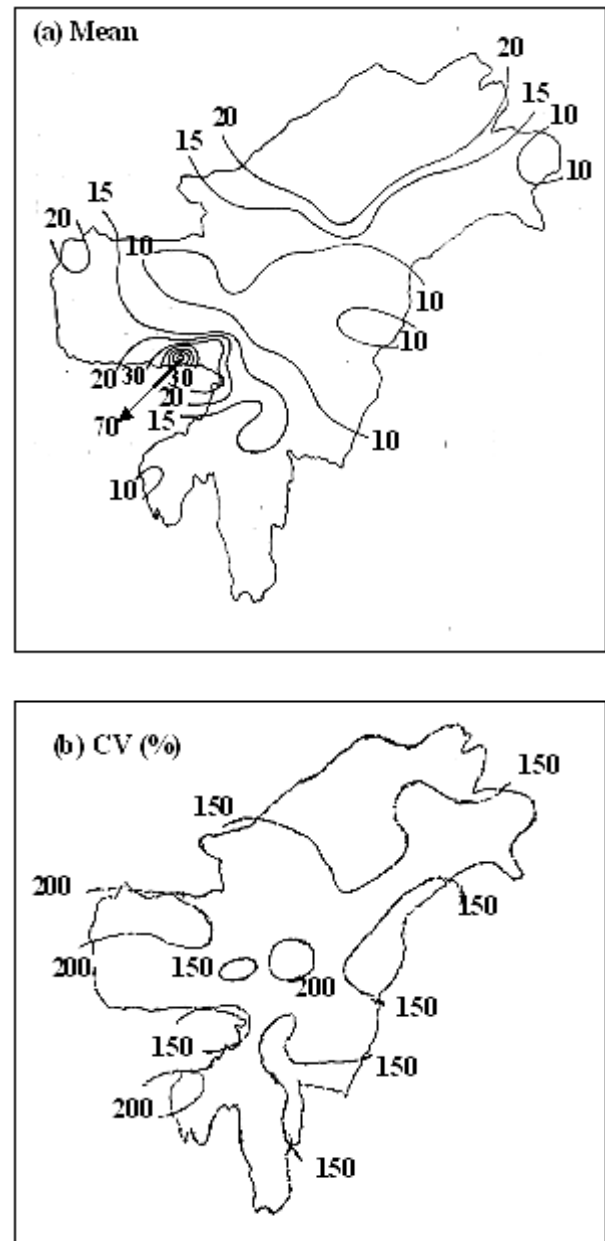
that are significantly different from the noise and that can be explained by physical processes. The other major difficulty is that the best method of rotation also depends to some extent on the particular data set being analysed. In the present study the varimax (normalized) method which aims at maximizing the variance explained by the PCs is used for rotation of significant PCs.

There are different techniques like Kaiser-Guttman test (Kaiser, 1958), Scree test (Cattel, 1966) and log eigenvalue (EV) test (Craddock and Flood, 1969) to determine the significant PCs. Most of these techniques can be viewed as dominant variance rules. The details of these tests are also available in Wilks (1995). Preisendorfer *et al.* (1981), Overland and Preisendorfer (1982) and Preisendorfer (1988) have used Monte Carlo simulations with random sequences to determine confidence levels for the EVs. However, 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 above rule can be excessive and asymptotic theory of EVs of large symmetric random matrices may be applied (Preisendorfer *et al.*, 1981). In this theory, there are so many EVs that we may 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 limitation 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 by other tests, especially if the PC can represent the evolution of the 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. All the relevant tests, as discussed above have been applied in the study to find out the number of significant PCs.

2.3. Significant PCs and physical processes

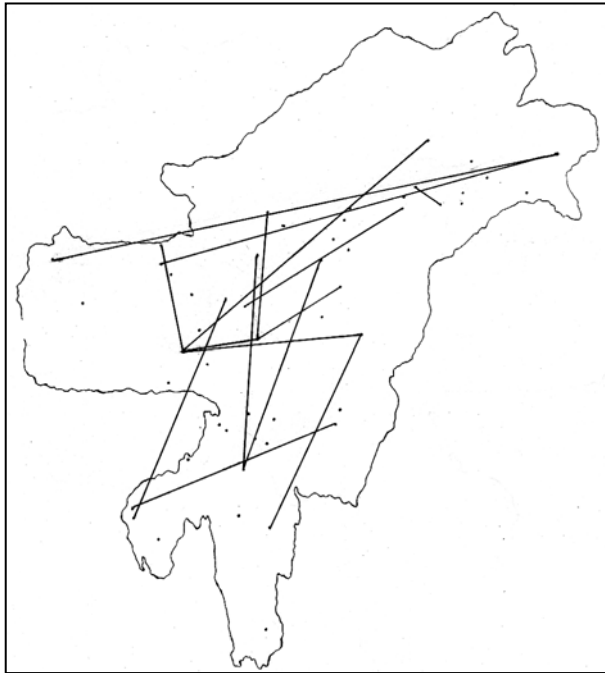
To find out the physical processes that can be linked to significant PCs, the mean daily rainfall over the selected stations in northeast India based on the data of 10 years (1991 to 2000) are calculated for different synoptic systems including LPSC and troughs prevailing over northeast India and neighbourhood. For this purpose, the daily rainfalls over different stations of northeast India due to synoptic system like LPSC over different meteorological sub-divisions of India [Fig. 2(b)] are found out. The data on synoptic systems are collected from different weather reports published by IMD. The mean daily rainfalls over different stations in region due to (i) LPSC over different locations (ii) all India break monsoon conditions (iii) low level north-south trough and (iv) different location of the monsoon trough, especially the monsoon trough passing through (a) northeast Assam and neighbourhood, (b) Mizoram and Manipur and (c) the secondary trough passing through northeast Assam when the primary monsoon trough lies over the normal position are calculated. The spatial patterns are compared with that of significant PCs to find out patterns most similar to the spatial pattern of the significant PCs. The correlation of the loadings of significant PCs (50 loadings of each PC corresponding to 50 rain gauge stations) and the mean daily rainfall over 50 stations due to different synoptic



Figs. 3(a&b). (a) Mean (in mm) and (b) Coefficient of variation (CV) (in %) of daily rainfall over northeast India during summer monsoon season

systems are calculated. The synoptic systems, for which the correlation coefficients (CC) are statistically significant at 95% level of confidence for a given PC, are attributed to that PC.

It may be mentioned that there may be more than one synoptic system influencing the rainfall. Also there may



— Indicates the correlation coefficient (≥ 0.5) between two stations

Fig. 4. Inter-station correlation coefficient (≥ 0.5) of daily rainfall over northeast India during the summer monsoon season

be other factors or combination of factors. Therefore, the system which lies nearby to the region and more dominantly influences the rainfall have been considered to prepare spatial pattern of mean daily rainfall due to different synoptic systems. This is the limitation of this study to be kept in mind.

3. Results and discussion

The mean daily rainfall over northeast India during summer monsoon season are presented and discussed in sec. 3.1. The interstation CC of actual daily rainfall over northeast India is calculated based on data of 1220 days during 10 years period of 1991-2000. The results are analysed and discussed in sec. 3.2. The number of significant PCs are found out and discussed in sec. 3.3. The spatial patterns of significant PCs in S mode analysis are presented and discussed in sec. 3.4. The regionalization of daily rainfall by rotation of significant PCs in S mode are analysed and discussed in sec. 3.5. The characteristics of different homogeneous regions are analysed and presented in sec. 3.6.

3.1. Mean daily rainfall

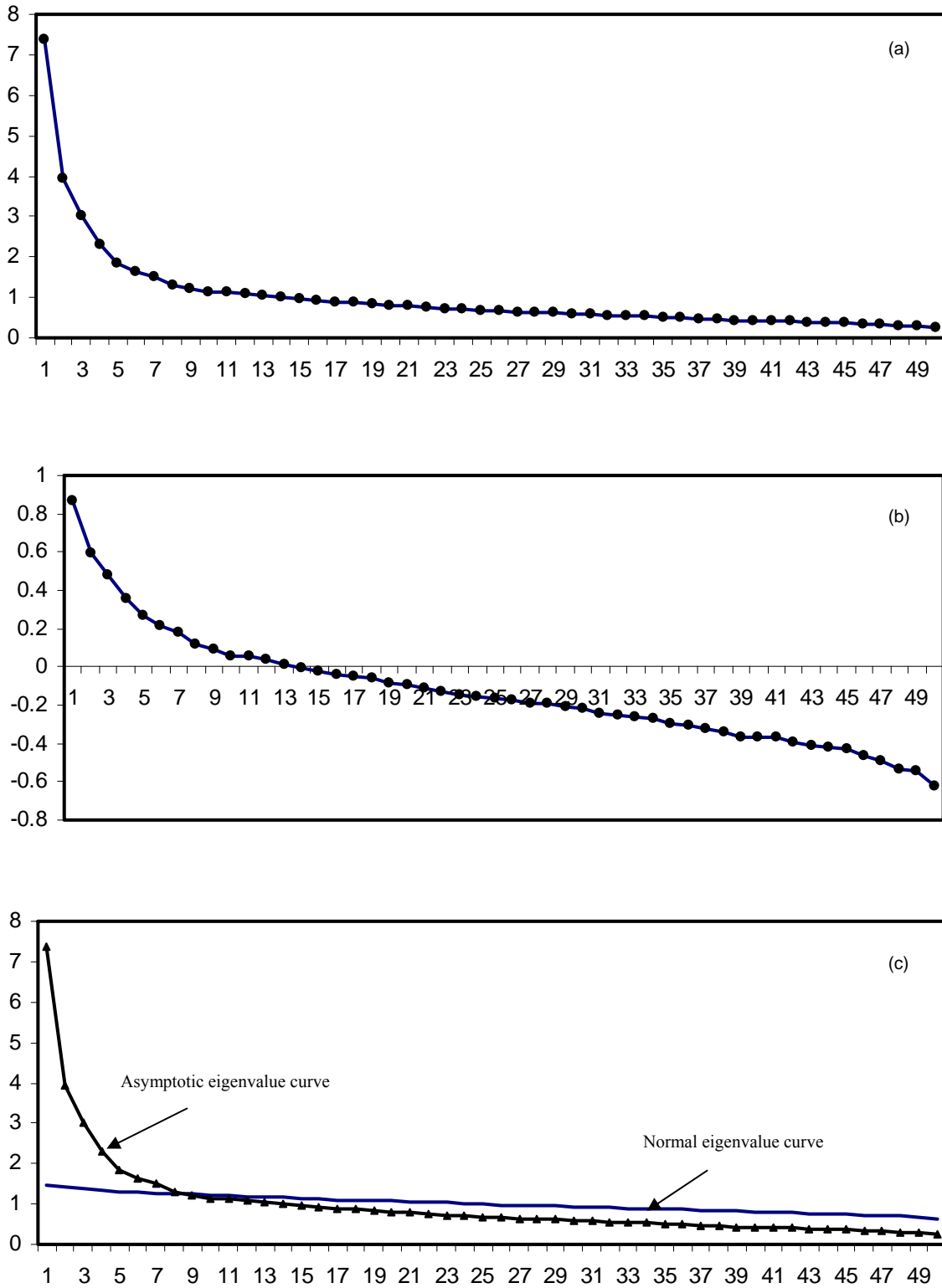
The mean daily monsoon rainfall distribution over northeast India based on the data of 1991 to 2000 is shown

TABLE 1

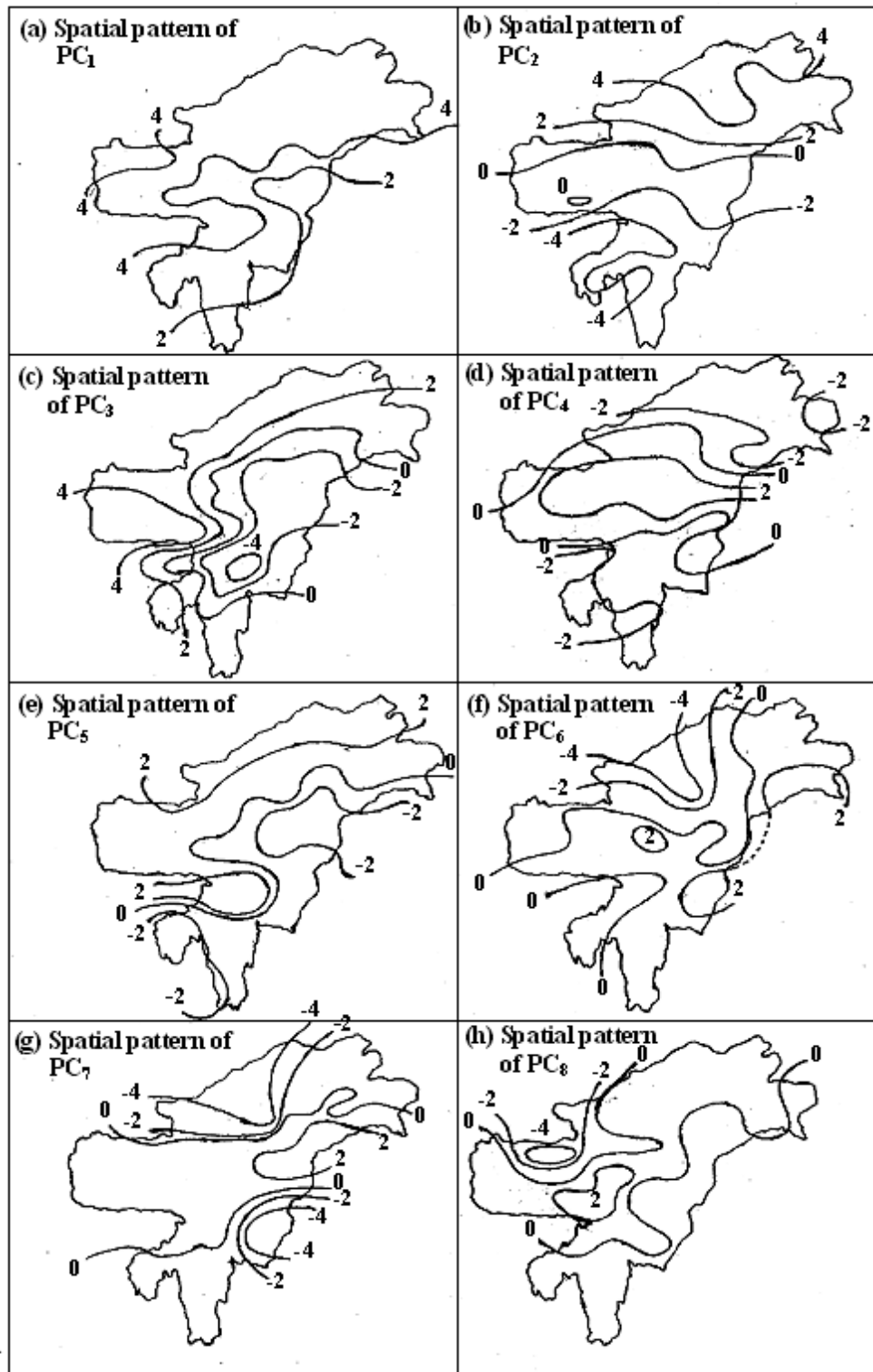
Variance explained by first 20 Principal Components (PC) of daily summer monsoon rainfall over northeast India

PC	Variance (%) explained	Cumulative variance (%)
1.	14.71	14.71
2.	7.88	22.59
3.	6.02	28.61
4.	4.58	33.19
5.	3.67	36.86
6.	3.29	40.15
7.	2.99	43.15
8.	2.63	45.78
9.	2.49	48.25
10.	2.26	50.50
11.	2.26	52.75
12.	2.19	54.95
13.	2.07	57.02
14.	1.99	59.01
15.	1.89	60.90
16.	1.81	62.70
17.	1.77	64.48
18.	1.73	66.21
19.	1.66	67.86
20.	1.61	69.47

in the Fig. 3 (a). The mean daily rainfall shows large spatial variation due to the varied physiography over the region. However, the pattern is similar to the climatological pattern (Srinivasan *et al.*, 1972). The rainfall is higher over southern slope of Garo Khasi Jaintia hills. It is mainly due to the interaction of orography with basic monsoon flow over this region. With the shifting of the monsoon trough to the foothills of the Himalayas, pressure gradient which is generally weak over the region due to normal position of monsoon trough [Fig. 1(a)] increases leading to steep velocity gradient with increase in southerly on the southern slope of the Garo Khasi Jaintia hills. In addition, if the LPSC lies over the northeastern region or adjoining Bangladesh, the pressure gradient further increases and the southerly component of the wind over southern slope of Garo Khasi Jaintia hills also further increases leading to higher rainfall. The rainfall is relatively less over the central belt to the north of Garo Khasi Jaintia hills as it lies on the lee side of this hill ranges with basic flow as southerly. The rainfall is also higher over most parts of ArP as it lies on the eastern Himalayas and there is orographic enhancement of rainfall.



Figs. 5(a-c). (a) Eigen values (EV), (b) Logarithmic Eigen values (LEV) and (c) Asymptotic eigen values of principal components of daily rainfall over northeastern India



Figs. 6(a-h). Spatial patterns of unrotated loadings ($\times 10$) of significant principal components (PC) (a) Spatial pattern of PC₁, (b) Spatial pattern of PC₂, (c) Spatial pattern of PC₃, (d) Spatial pattern of PC₄, (e) Spatial pattern of PC₅, (f) Spatial pattern of PC₆, (g) Spatial pattern of PC₇ and (h) Spatial pattern of PC₈

The coefficient of variation (CV) of daily rainfall over different stations is shown in Fig. 3(b). The CV is very large over the region. The CV also shows large spatial variation.

3.2. Inter-station correlation in daily rainfall over northeast India

The inter-station correlation coefficient (CC) ≥ 0.5 of actual daily rainfall over northeast India during summer monsoon season based on data of 1991-2000 are shown in Fig. 4. It is found that more than 50% of stations in the region do not have CC ≥ 0.5 among themselves. It indicates that the rainfall over the region is largely heterogeneous. It may be due to the fact that the rainfall over the region is influenced by different synoptic and mesoscale systems of both tropical and extra tropical origin in addition to varied physiography of the region. Considering the large heterogeneity, it is essential to find out different homogeneous regions of northeast India and the associated physical processes.

3.3. Number of significant PCs

The results of PCA indicate that about 15 PCs are required to explain 60% of the total variance of the daily rainfall (Table 1). The Scree test and the plot of log EV indicate a break in slope near PC number 8 (Fig. 5). According to asymptotic theory (Preisendorfer *et al.*, 1981), 8 PCs are statistically significant (Fig. 5). These 8 PCs explain about 46% of the total variance of daily monsoon rainfall over the region (Table 1). There are a few studies on PCA of daily rainfall over Indian region. Mohapatra *et al.* (2003) have carried out Empirical Orthogonal Function (EOF) analysis of daily rainfall over Orissa during monsoon season based on data of 20 years (1980-1999). Comparing with their results, the variance explained by the PCs in the present study is less. It indicates that the daily monsoon rainfall over northeast India is more complex than that over the States like Orissa, in Central India.

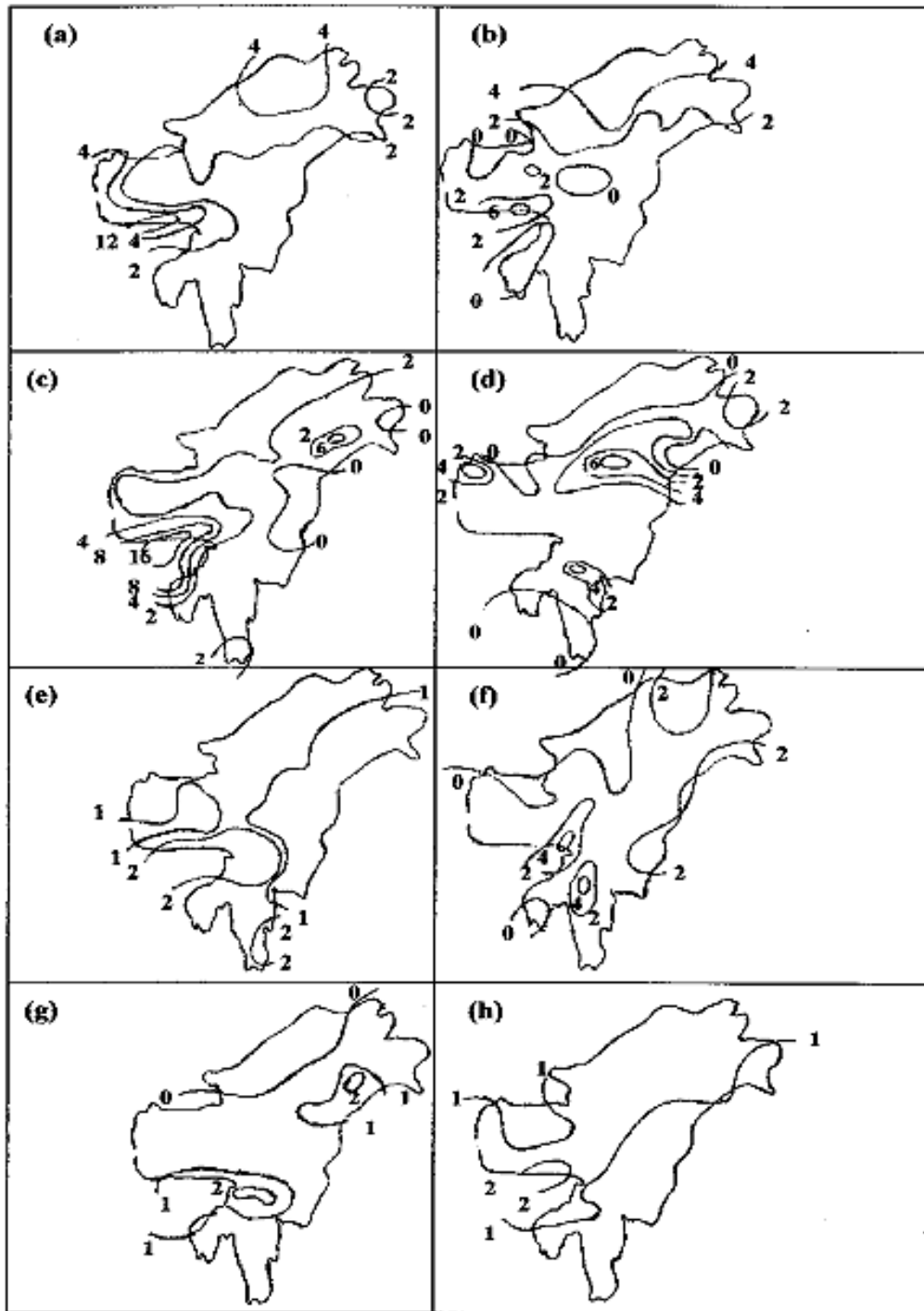
3.4. Spatial pattern of significant PCs in S mode

The plots of loadings of first 8 unrotated PCs are shown in Fig. 6. The loadings of PC₁, which explain about 15% of total variance (Table 1), are positive throughout the region. Though amplitude varies in space, the loadings of PC₁ are uniform and consistent in nature. There is a region of maxima extending from southwest to northeast across Meghalaya, Assam and Arunachal Pradesh. This pattern represents an active/vigorous monsoon over the

region. The spatial pattern of mean daily rainfall due to the synoptic systems most significantly associated with significant PCs are shown in Fig. 7. Comparing Fig. 6(a) and Fig. 7(a), the spatial pattern of loadings of PC₁ and the spatial pattern of mean daily rainfall due to the low over Sub-Himalayan West Bengal (SHWB) are similar to large extent. Also the CC between the loadings of PC₁ corresponding to 50 stations under consideration and the mean daily rainfall over the 50 corresponding stations is maximum for low over SHWB (CC = 0.55). Hence, the PC₁ may be partially attributed to the rainfall distribution due to low over the SHWB with the associated monsoon trough lying over northeast India at mean sea level. The mean daily rainfall distributions over northeast India due to different synoptic systems as considered in this study have been found out and analysed by Mohapatra *et al.* (2008). Their study indicates that active monsoon condition prevails over all three sub-divisions with low over SHWB. While the loadings vary from 0.2 to 0.4, the rainfall varies from 2 cm to 12 cm (over Cherapunjee area). Hence, the pattern of PC, could not explain the mesoscale occurrence of heavy rainfall. The pattern of PC₁ is most anti-analogous to mean daily rainfall pattern due to cycir extending upto MTL over North Coastal Andhra Pradesh (NCAP) with CC equal to -0.4. Hence the cycir over NCAP may be associated with deficient rainfall over northeast India.

The loadings of PC₂ are positive over northern parts and negative over southern part. Considering the CC between loadings of PC₂ and the mean daily rainfall due to different synoptic systems, the CC is maximum for low level cycir over EMPC (CC = 0.48). The spatial pattern of PC₂ and spatial pattern of mean daily rainfall due to cycir in lower levels over EMPC are also similar to large extent [Fig. 6(b) & Fig. 7(b)]. The pattern of PC₂ is most anti-analogous to daily rainfall pattern due to cyclonic storm over the west central (WC) Bay with CC equal to -0.57.

The pattern due to depression over Bihar is most significantly correlated (CC = 0.60) with the pattern due to PC₃. The depression over Bihar generally moves east/northeast wards under the influence of upper tropospheric trough in westerlies. The monsoon trough from the centre of the system extends eastwards across Assam. Hence the northwestern side of the region lies in the left forward sector and gets more rainfall. As the basic flow over the region becomes westerly in association with the depression over Bihar, the eastern side becomes lee side to get relatively less rainfall. The spatial pattern of PC₃ is anti-analogous to the mean daily rainfall pattern due to cycir extending upto MTL over Bangladesh (BDS) with CC equal to -0.41. Hence the cycir over BDS causes more rainfall over eastern side and less rainfall on the western side of the region.



Figs. 7(a-h). Spatial patterns of mean daily rainfall (SPMR) due to different systems attributed to eight significant principal components (PC) of daily summer monsoon rainfall over northeastern India. (a) SPMR due to low over SHWB attributed to PC₁, (b) SPMR due to cycir in lower levels over east MP and Chattisgarh attributed to PC₂, (c) SPMR due to depression over Bihar attributed to PC₃, (d) SPMR due to cycir in lower levels over Arunachal Pradesh attributed to PC₄, (e) SPMR due to low over WC Bay attributed to PC₅, (f) SPMR due to cycir extending upto MTL over north coastal Andhra Pradesh attributed to PC₆, (g) SPMR due to cycir extending upto MTL over Bangladesh attributed to PC₇, (h) SPMR due to cycir extending upto MTL over NW Bay attributed to PC₈.

TABLE 2

Average rotated loadings of significant principal components over different homogeneous regions of northeast India

Region	PC ₁	PC ₂	PC ₃	PC ₄	PC ₅	PC ₆	PC ₇	PC ₈
R _I	0.58	0.04	0.12	0.04	0.00	0.09	0.03	0.03
R _{II}	0.27	0.04	-0.03	0.37	0.03	0.47	0.03	0.05
R _{III}	0.03	0.10	0.18	0.38	0.00	-0.02	0.11	0.10
R _{IV}	0.04	0.05	0.19	0.09	0.08	0.04	0.08	0.68
R _V	0.15	0.02	0.48	0.01	0.11	0.20	-0.03	0.21
R _{VI}	0.06	0.70	0.04	0.06	0.11	0.04	0.06	0.04
R _{VII}	0.04	0.12	0.01	0.06	0.04	0.08	0.66	0.01
R _{VIII}	0.00	0.15	0.04	0.04	0.53	-0.02	0.09	0.04

Bold Figures indicate average loadings ≥ 0.4

The loadings of PC₄ are positive over central part extending from west to east covering Garo Khasi Jaintia hills. The pattern of PC₄ is similar to large extent to the pattern of mean daily rainfall due to low level cycir over Arunachal Pradesh (CC = 0.24). Generally, the low level cycir over Arunachal Pradesh develops as a system in extratropical westerlies and causes good rainfall over some parts of the region during break monsoon condition. The pattern of PC₄ is anti-analogous to the pattern of mean daily rainfall due to depression over Orissa with CC equal to -0.54. Hence, the central part covering Garo Khasi Jaintia hills of the region gets relatively less rainfall due to depression over Orissa.

The loadings of PC₅ are positive over western and northern sides and negative over eastern and southern sides. The spatial pattern of daily rainfall due to low over WC Bay is most similar to the pattern of PC₅. The pattern of PC₅ is anti-analogous to the pattern of daily rainfall due to depression over east central (EC) Bay with CC equal to -0.41.

The loadings of PC₆ are positive over the eastern part of region covering Nagaland and Manipur. The loadings significantly decrease to the northwest. The pattern of PC₆ is similar to rainfall pattern due to cycir extending to MTL over NCAP. The pattern of PC₆ is anti-analogous to the daily rainfall pattern due to low level cycir over Arunachal Pradesh with CC equal to -0.41. Hence, Nagaland and Manipur gets more rainfall due to cycir over NCAP and less rainfall due to low level cycir over Arunachal Pradesh.

The loadings of PC₇ are positive over the central zone extending from west to east. However, the values are

higher over the eastern parts of the central zone. The spatial pattern of daily rainfall due to cycir over BDS extending upto MTL is similar to the pattern of PC₇. The pattern of PC₇ is anti-analogous to the daily rainfall pattern due to low level cycir over Jharkhand (JKD) with CC equal to -0.39.

The pattern of loadings of PC₈ is similar to the pattern of mean daily rainfall due to cycir extending upto MTL over northwest (NW) Bay (CC = 0.34). The rainfall over the northwestern part is worst affected due to cycir over NW Bay. However, the higher loadings over the region extending from southwest to northeast over Meghalaya, eastern Assam and east Arunachal Pradesh indicates that this region may get relatively higher rainfall due to cycir over NW Bay. The above region get relatively less rainfall due to low over northeast (NE) Bay as the pattern of PC₈ is most anti-analogous to the daily rainfall pattern due to low over NE Bay with CC equal to -0.27.

3.5. Homogeneous regions

To ascertain the simple structure, pairwise plotting of the loadings of any two unrotated PCs are inspected. The plotting of pairs of loadings of different PCs like PC₁ & PC₂, PC₁ & PC₃, PC₂ & PC₃ etc. indicate that the unrotated PCs do not yield simple structure (not shown). Hence the unrotated PCs are not ideally Orthogonal to each other and can not be used to find out the homogeneous regions. The calculations of CC between loadings of any two unrotated PCs also indicate that unrotated PCs are not completely independent of each other (not shown). However, rotation of first eight PCs which are statistically significant yields more simple structure. The intra-PC correlations also indicate that the first eight rotated PCs are more

TABLE 3

Daily mean rainfall and coefficient of intraseasonal and interstataion variation of rainfall over different homogeneous region of northeast India

Parameter	Regions								Whole region
	I	II	III	IV	V	VI	VII	VIII	
Daily mean (mm)	13.8	14.9	9.0	9.3	26.1	16.6	7.8	12.4	14.4
Coefficient of intraseasonal variation (%)	100	101	89	159	126	111	112	99	67
Interstataion coefficient of variation (%)	31	36	24	4	84	15	38	22	69

uncorrelated with each other. Hence cluster analysis by Ward's K-mean method (Ward, 1963) with K equal to 8 is applied to rotated loadings of 8 significant PCs. The results of the regionalization are shown in Fig. 8. Considering the mean loadings of first eight rotated PCs (Table 2), it is found that region R_I, R_{II}, R_{III}, R_{IV}, R_V, R_{VI}, R_{VII}, R_{VIII} are characterized by significantly higher mean positive rotated loadings (≥ 0.4) of PC₁, PC₆, PC₄, PC₈, PC₃, PC₂, PC₇ and PC₅ respectively. The dominance of single PC for each region demonstrates the distinct characteristics of each homogeneous region. Hence, comparing with the synoptic systems associated with significant PCs, each region gets higher/less rainfall compared to the other regions due to specific synoptic systems.

3.6. Regional characteristics

The regional characteristics of rainfall have been analysed by considering the mean daily rainfall and its spatio-temporal variation.

3.6.1. Mean rainfall

The mean daily rainfall over different homogeneous regions (Fig. 8) are calculated and shown in Table 3. It indicates that the region (V) gets maximum rainfall followed by region (VI) and region (II). Most parts of region (V) covers Meghalaya and western parts of west Assam and extreme west ArP which is close to the Foothills of the Himalayas. The rainfall is minimum over region (VII) followed by region (III) and (IV). It may be due to the fact that the region (VII) lies on the eastern side of the north eastern hill ranges which covers Manipur and parts of Nagaland. During the break monsoon condition and northward shifting of monsoon trough, the basic flow over the region becomes westerly to southwesterly and region (VII) lies on the lee side of the northeastern hill

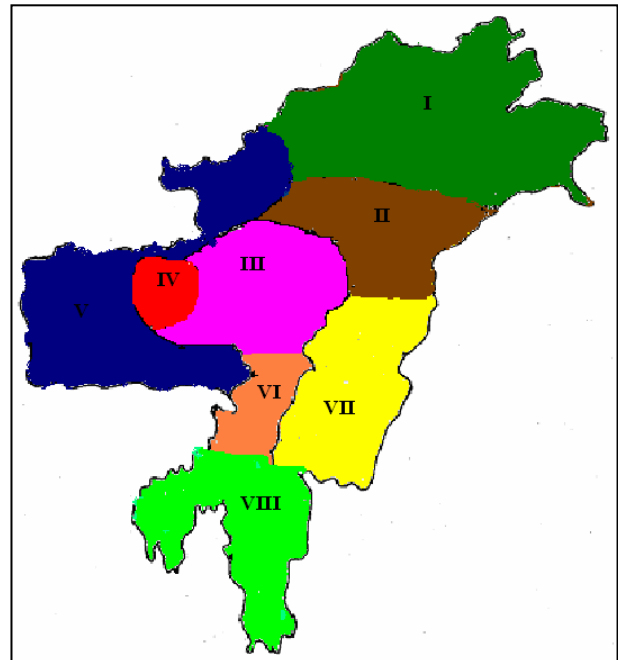


Fig. 8. Homogeneous regions of northeast India

range and hence gets relatively less rainfall. The regions (III) and (IV) lie on the lee side of Garo Khasi Jaintia hills with southerly component of wind over the region.

The mean monthly and seasonal monsoon rainfalls over different homogeneous regions are shown in Table 4. The rainfall over regions (IV), (V) and (VI) covering west central parts of the northeast India are maximum during June and gradually decrease towards September. The rainfall over region (I) and (II) covering northern part and region (VIII) covering extreme southern part increases

TABLE 4

Mean and Coefficient of variation (CV) of rainfall over different homogeneous regions of northeast India during different summer monsoon months and the season as a whole

Parameter	Period	Regions								Whole Region
		I	II	III	IV	V	VI	VII	VIII	
Mean (mm)	June	448.3	500.9	283.2	363.1	1069.2	566.7	212.3	389.2	500.6
	July	519.4	517.1	285.0	311.3	932.1	541.1	258.4	440.1	501.2
	August	398.8	446.9	297.3	286.1	739.7	518.8	286.9	374.4	433.1
	September	318.2	348.1	226.8	178.4	445.6	395.0	197.1	308.5	317.0
	Season	1684.7	1813.1	1092.4	1138.8	3186.6	2021.5	954.7	1512.2	1751.9
CV (%)	June	32	25	30	34	24	28	37	30	20
	July	21	15	16	29	30	26	21	40	19
	August	29	28	18	30	38	20	26	23	19
	September	32	33	25	46	43	26	36	33	25
	Season	18	13	13	23	20	7	14	20	12

from June to July and then gradually decreases towards September. The rainfall over region (III) and (VII) in the east-central part of the region increases from June to August and then it decreases towards September.

3.6.2. Intraseasonal and interannual variation of rainfall

The interstation CV of rainfall for each homogeneous region and northeast India as a whole has been calculated from the daily normal of various stations within that region. The results are presented in Table 3. It indicates that the interstation CV is significantly less for different homogeneous regions than that for whole northeastern region except region (V) which is the region of maximum rainfall. It may be due to the fact that region (V) covers the southern slope of Garo-Khasi-Jaintia hills and there is a varied physiography over this region leading to variation in the impact of orography on the rainfall distribution over the region. In addition, the synoptic system influencing rainfall over this region like northward shifting of monsoon trough and northward location of the systems shows large scale spatio-temporal variation causing spatial variation of rainfall over this region.

Considering the intraseasonal variation of rainfall over different homogeneous regions (Table 3), the rainfall is more variable over region (IV) followed by region (V). The variation is minimum over region (III). As expected the intraseasonal variation of each homogeneous region is higher than that of northeastern region as a whole (Table 3).

The coefficient of interannual variation indicates that (Table 4) the interannual variations of rainfall over different regions during the season as a whole are comparatively less as the CV varies from 7% over region (VI) to 23% over region (IV). The interannual variation gradually increases from June to September over region (V). It decreases from June to July and then increases towards September over regions (I), (II), (III), (IV), (VII). It decreases from June to August and then increases in September over region (VI).

4. Conclusions

The following broad conclusions can be drawn from the results as discussed above.

(i) Eight PCs explaining about 46% of the total variance of daily monsoon rainfall over northeast India are significant.

(ii) In S-mode, the first PC associated with good monsoon condition over northeast India may be attributed to low over SHWB. Similarly, the PC₂ may be attributed to good monsoon condition due to low level cycir over EMPC, PC₃ to good monsoon condition due to depression over Bihar, PC₄ to good monsoon condition due to low level cycir over Arunachal Pradesh, PC₅ and PC₆ to weak monsoon condition due to low over WC Bay, and cycir extending upto MTL over NCAP respectively and PC₇ and PC₈ to rainfall activity due to cycir extending upto MTL over BDS and NW Bay respectively.

(iii) According to the rotation of significant PCs in S-mode, northeast India consists of eight homogeneous regions of daily monsoon rainfall as shown in Fig. 8 with distinct characteristics.

(iv) The study endorses the climatological facts that the rainfall is maximum over region (V) covering southern slope of Garo-Khasi-Jaintia hills and western parts of west Assam and extreme west ArP which is close to the Foothills of the Himalayas and minimum over region (VII) lying to the east of northeast hill range. The rainfall over west-central part is maximum during June and gradually decreases towards September. The rainfall over the northern part of northeast India increases from June to July and then decreases towards September. The rainfall over east-central part increases from June to August and then decreases towards September.

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