

Daily summer monsoon rainfall over northeast India due to synoptic scale systems

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सार – उत्तर पूर्वी भारत में ग्रीष्मकालीन मानसून वर्षा अधिकांशतः उस क्षेत्र और निकटवर्ती क्षेत्रों में सिनॉप्टिक प्रणालियों तथा सिनॉप्टिक और उप-सिनॉप्टिक माप प्रणालियों सहित पर्वतीय क्षेत्रों में परस्पर क्रियाओं के कारण होने वाले संवहन पर आधारित होती है। हालांकि, इसमें निम्न दाब प्रणालियों (एल. पी. एस.) और विभिन्न क्षेत्रों में निम्न/मध्य क्षोभमंडलीय स्तरों तक विस्तारित चक्रवाती परिचालनों (साइसिर) जैसी विभिन्न सिनॉप्टिक प्रणालियों के कारण उत्तर पूर्वी भारत में माध्य दैनिक वर्षा वितरण का विप्लेषण करने का प्रयास किया गया है। उत्तर पूर्वी भारत के विभिन्न स्थानों पर मानसून द्रोणी के कारण होने वाली माध्य दैनिक वर्षा का भी विप्लेषण किया गया है। उपर्युक्त उद्देश्य के लिए 10 वर्षों की अवधि के (1991–2000) ग्रीष्मकालीन मानसून ऋतु (जून–सितम्बर) के दौरान उत्तर पूर्वी भारत में 50 एक समान वितरित केंद्रों के वर्षा के आंकड़ों पर विचार किया गया है। इस अध्ययन का मुख्य उद्देश्य उत्तर पूर्वी भारत में मानसून वर्षा की स्थानिक भिन्नताओं में विभिन्न सिनॉप्टिक प्रणालियों के योगदान का पता लगाना है।

विकसित सिनॉप्टिक अनुरूपी मानचित्र सिनॉप्टिक प्रणालियों के स्थान, तीव्रता और आगे बढ़ने की जानकारी सहित 24 घंटों की वर्षा का पूर्वानुमान लगाने के लिए पूर्वानुमानकर्ताओं के लिए उपयोगी हो सकते हैं। बृहत आंकड़ा सेट पर आधारित, मानसून द्रोणी और एल. पी. एस. के कारण वर्षा के संबंध में पूर्ववर्ती खोजों (श्रीनिवासन इत्यादि 1972) से प्राप्त परिणामों से पुष्टि होती है। निम्न स्तर के चक्रवाती परिचालन (एल. एल. सी.) भी उत्तर पूर्वी भारत में वर्षा की विविधता पर महत्वपूर्ण भूमिका निभाते हैं जैसा कि उस क्षेत्र में एल. पी. एस. की घटनाओं के दिनों की अपेक्षा एल. एल. सी. दिनों की संख्या उल्लेखनीय रूप से अधिक होती है। इस अध्ययन में विभिन्न सिनॉप्टिक प्रणालियों के कारण अधिक/कम वर्षा और सक्रिय/कमजोर मानसून की स्थितियों के क्षेत्रों का पता लगाया गया है।

ABSTRACT. The summer monsoon rainfall over northeast India mostly depends on the synoptic systems over the region and neighbourhood and the convection due to the interaction of orography with the synoptic and sub-synoptic scale systems. Hence, an attempt is made to analyse the mean daily rainfall distribution over northeast India due to different synoptic systems like Low Pressure Systems (LPS) and cyclonic circulations (cycir) extending upto lower/middle tropospheric levels over different regions. The mean daily rainfall due to monsoon trough over various locations in northeast India is also analysed. For the above purpose, the rainfall data over 50 uniformly distributed stations in northeast India during summer monsoon season (June-September) for a period of 10 years (1991-2000) are considered. The principal objective of the study is to find out the contribution of the different synoptic systems to the spatial variability of monsoon rainfall over northeast India.

The developed synoptic analog maps may be useful to the forecasters for 24 hours rainfall forecast with the knowledge of location, intensity and movement of the synoptic systems. Based on larger data set, the results confirm the earlier findings (Srinivasan *et al.*, 1972) with respect to rainfall due to monsoon trough and LPS. The Low Level Cycir (LLC) also plays significant role on the rainfall variability over northeast India, as the number of LLC days is significantly higher over the region, contrary to the days of occurrence of LPS. The study finds out the regions of excess/deficient rainfall and active/weak monsoon conditions due to different synoptic systems.

Key words – Northeast India, Monsoon, Variability.

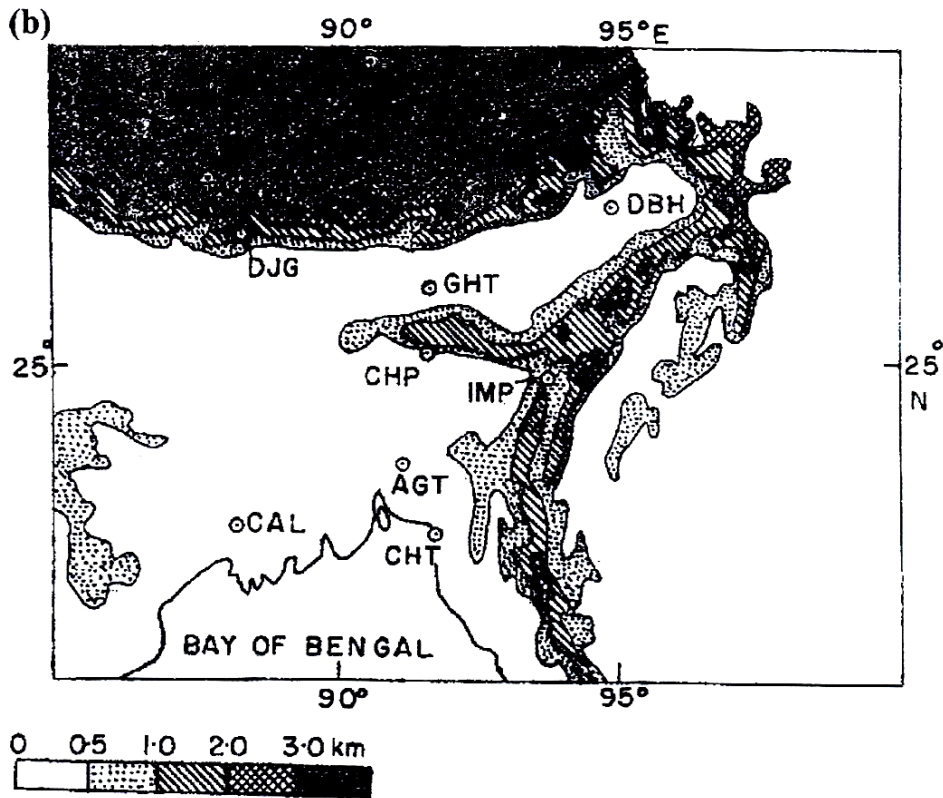
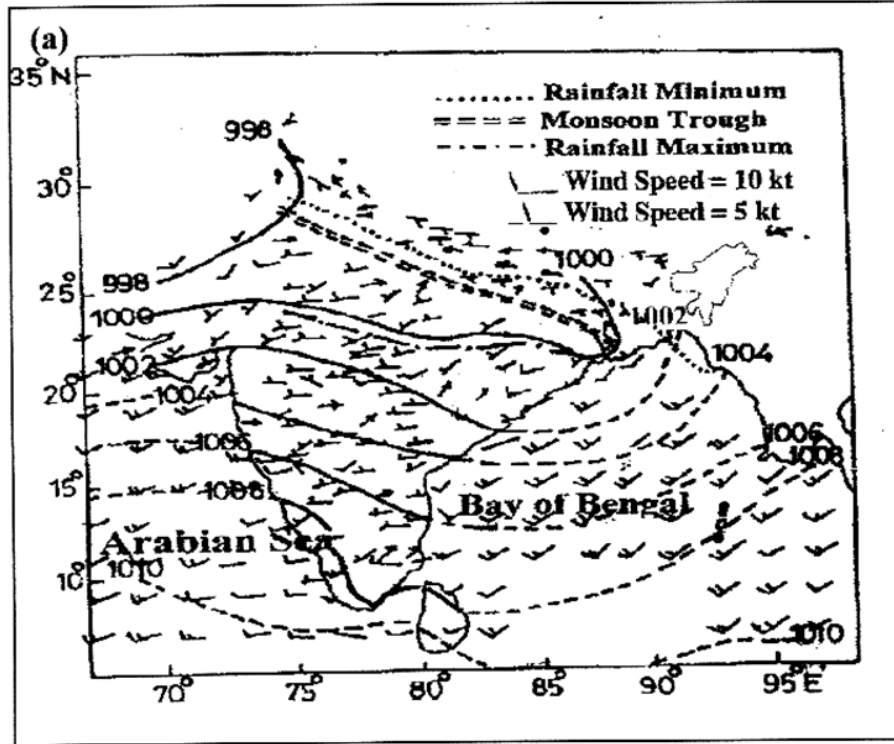
1. Introduction

The southwest monsoon rainfall over India is dominated by the semi permanent monsoon trough which normally extends from Pakistan to North Bay of Bengal and the low pressure systems (LPS) including low, depression and cyclonic storm. From Fig. 1(a), the maximum rainfall occurs to the south of the monsoon trough. The minimum rainfall zone lies to the north of the monsoon trough. Hence, during the normal location of the monsoon trough, the rainfall over northeast India which comprises meteorological sub-divisions of Assam & Meghalaya (A & M), Arunachal Pradesh (AP) and Nagaland, Manipur, Mizoram & Tripura (NMMT) is significantly less. During all India break monsoon condition (weak monsoon condition) the monsoon trough shifts to the foothills of the Himalayas. Accordingly, the maximum rainfall zone shifts to the northeast India. Prasad and Singh (1988), Hastenrath and Rosan (1983) and Gregory (1989) have shown that there is a strong coupling between rainfall in northwestern and central India, while these regions have little affinity with the rainfall over northeast India. During break monsoon condition, there is deficient rainfall in a large zonally oriented band across central India and significant positive departure over northeast India. The pattern is just opposite in the absence of break monsoon condition. According to Rao (1976), the monsoon activity is significantly controlled by the monsoon trough. While studying index of activity of the monsoon trough, Mooley and Shukla (1989a) have observed that on a majority of days (about 56%) during the monsoon season, the seasonal monsoon trough is the only synoptic scale system contributing to rainfall over Indian region.

Mooley and Shukla (1989b) have found that LPS adds largely to the activity of the monsoon trough. These disturbances mostly develop over northern parts of Bay of Bengal. (North of 15° N) during summer monsoon season (Jadhav, 2002; Mooley and Shukla, 1989b) and move westwards. However, some of them may move north/northeastwards towards northeast India under the influence of the upper tropospheric trough in westerlies (India Meteorological Department, 1979). In addition, some of the LPS develop over east Uttar Pradesh (UP) and adjoining Madhya Pradesh (MP) and move east/northeastwards under the influence of the upper tropospheric westerly flow (Rao, 1976). The detailed definition of LPS, as per the criteria of India Meteorological Department (IMD) has been discussed by Mooley and Shukla (1989b). Kumar and Dash (1999) have shown that number of days of LPS and cyclonic circulation (cycir) extending upto mid-tropospheric level is more significantly related than the only LPS days with the Indian summer monsoon rainfall (ISMR).

According to Prasad and Singh (1988), northeast India along with Sub Himalayan West Bengal (SHWB) & Sikkim constitutes one homogeneous region. According to Gregory (1989), northeast India constitutes single homogeneous region. The southwest monsoon season (June-September) contributes about 66% of the annual rainfall over northeast India (Srinivasan *et al.*, 1972). The rainfall over northeast India is influenced by the monsoon trough and tropical disturbances and the extra tropical systems in westerlies (Srinivasan *et al.*, 1972). According to Jadhav (2002), the rainfall over the sub-divisions in northeast India has significantly negative correlation with LPS over the grids of (75° - 80° E, 20° - 25° N), (80° - 85° E, 20° - 25° N), (85° - 90° E, 20° - 25° N), (75° - 80° E, 25° - 30° N) during July and August. Comparing the good and bad all India monsoon year (15 years each), Mooley and Shukla (1989b) have found that the LPS days over northeast India and neighboring Bangladesh, Bhutan and Nepal is less in all India good monsoon years than in all India bad monsoon years. Kripalani and Singh (1986) have shown that the depression over the Bay of Bengal can influence the rainfall over northeast India.

The spatial variability of rainfall over northeast India is also significantly dependent on the physiography of the region. The region is marked by eastern Himalayas in the north, Garo Khasi-Jaintia hills in the centre extending from west to east, northeast hill range extending from south to north over the eastern parts of the region [Fig. 1(b)]. Another important aspect of the physiography is the Brahmaputra Valley extending from east AP in the east to west Assam in the west. Smith (1979) has shown that a small scale circulation can interact with the orography to cause enhancement of rainfall. Banerjee (1929) has shown the enhancement of precipitation due to lifting of air as a result of perturbation caused in it by the orography leading to cooling, condensation and precipitation of moisture. However, the nature of the interaction is closely linked with the dynamics of the airflow. Hence, the intensity of rainfall due to orographic interaction depends on the location, intensity and movement of the synoptic systems like LPS and cycir (LPSC) extending upto mid-tropospheric level, low level cycir (LLC) and the monsoon trough. From Figs. 1(a&b), the windward slope of the Garo Khasi Jaintia hills lie almost in the direct path of the monsoon winds, thus getting copious rainfall and heavy clouding. The prevailing winds during southwest monsoon season are from southerly direction over southern parts of the region. The normal rainfall is found to increase from south to north as we proceed along a profile from the plains of Tripura to the Garo-Khasi and Jaintia hills. The orographical influence on the airflow over Brahmaputra valley has been discussed by Mukherjee *et al.* (1965). According to Sinha Ray *et al.* (1982), heavy rainfall in the



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

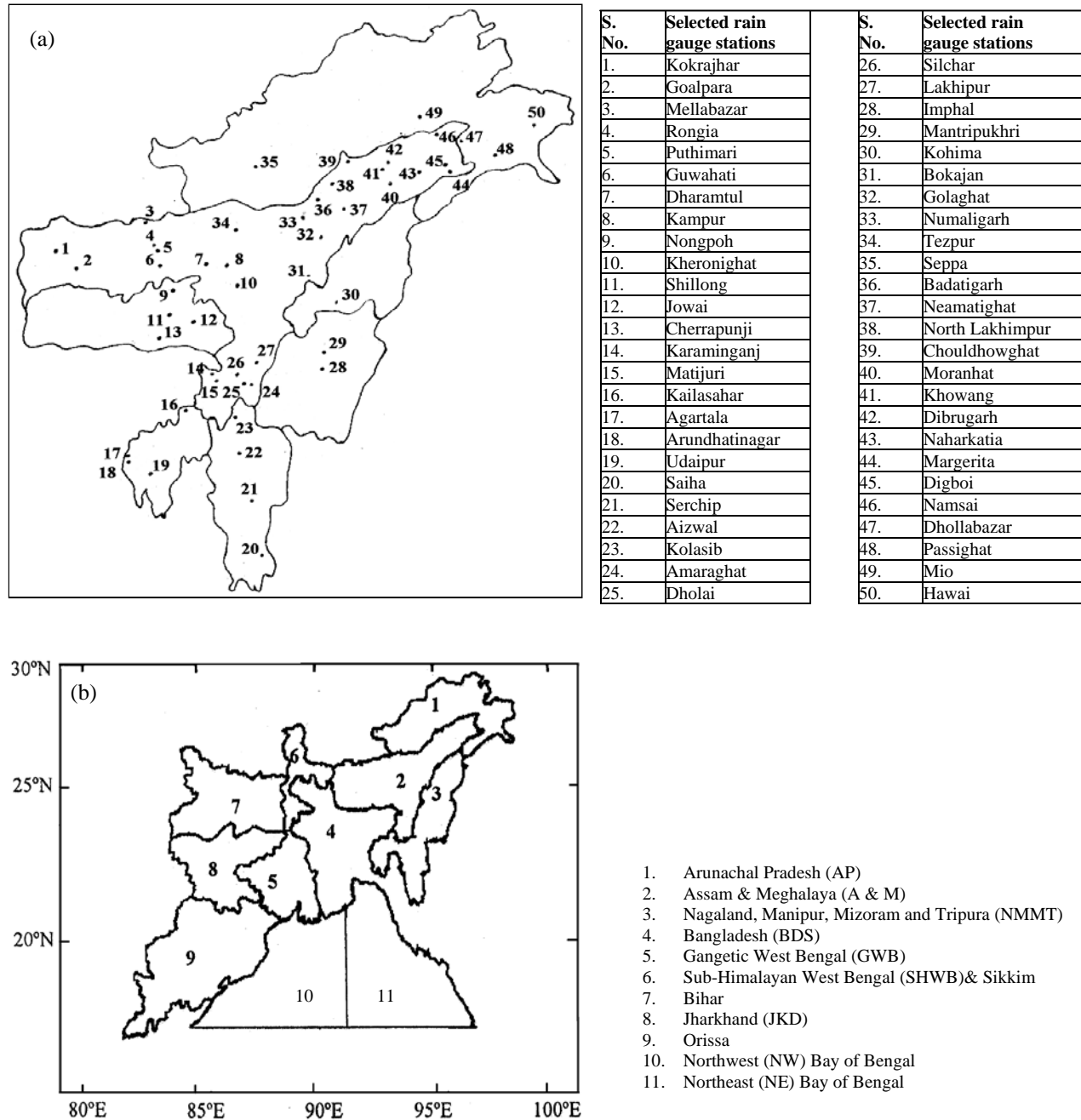


Fig. 2(a&b). (a) Selected rain gauge stations of northeast India and (b) Regions of occurrence of LPSC/LLC under consideration

windward side seems to be mainly due to synoptic, sub-synoptic and convective scale system. Heavy rainfall on the lee side seems to be mainly due to synoptic and convective scale systems.

Considering all the above, the daily rainfall variability over northeast India is highly complex in

nature and is different from that of all India and other meteorological sub-divisions of India. However, studies are limited on the spatial variation of rainfall over northeast India due to synoptic scale systems over the region and adjoining land and Bay of Bengal regions. Hence, an attempt is made to analyze main features of the spatial variability of daily rainfall over northeast India due

TABLE 1

Mean number of days of different synoptic weather systems influencing summer monsoon rainfall over northeast India during summer monsoon season

Region of occurrence of system	Synoptic systems				
	D	L	LPS	Cycir-MTL	LLC
NE Bay	#	0.3	0.3	#	0.1
NW Bay	1.2	11.2	12.6	1.9	0.8
Orissa	1.1	6.5	7.6	1.9	0.6
GWB	0.2	8.9	9.1	1.7	2.1
JKD	0.2	5.7	5.9	0.6	1.0
Bihar	0.1	5.6	5.7	0.4	2.0
SHWB	#	0.9	0.9	0.4	2.5
A & M	0.1	4.0	4.1	0.2	4.9
Arunachal Pradesh (AP)	#	0.5	0.5	#	0.1
NMMT	0.1	0.4	0.5	#	0.4
BDS	0.1	0.9	1.0	0.6	2.3
Total	3.1	44.9	48.2	7.7	16.8

The highest three values for each category of synoptic system are highlighted.

D : Depression, L: Low, LPS = Low + depression + cyclonic storm.
: Data insufficient

Cycir-MTL: Cycir extending upto mid-tropospheric levels,
LLC : Cycir extending upto lower tropospheric levels.

to synoptic scale systems. The principal objective of the study is to understand the physical processes contributing to the spatial variability of daily rainfall over the region. The study may be helpful to the weather forecaster to predict the rainfall over the region based on the location, intensity and movement of the synoptic system.

2. Data and methodology

The objective linking of the rainfall and the synoptic system can immensely help to a forecaster. The simplest way in which rainfall distribution around a synoptic system can be objectively linked with the synoptic system includes the process of compositing. The similar synoptic systems needed for compositing can be identified either by comparing the entire distribution of some meteorological fields over the region of interest or by comparing location and other features like movement of some prominent circulation system like LPSC. In the present study, the synoptic analogs of different synoptic systems over different regions influencing rainfall over northeast India are prepared and analyzed. While studying mean daily rainfall due to individual synoptic systems, it is noted that on many occasions, more than one system at the same time or overlapping systems contribute to the

TABLE 2

Average number of days per monsoon season associated with different locations of monsoon trough

S. No.	System	Average number of days
1	Monsoon trough close to the foothills of the Himalayas (AIBM Conditions)	4.9
2	Monsoon trough passing through northeast Assam and Neighbourhood	5.7
3	Monsoon trough passing through Manipur/Mizoram/Tripura	1.0
4	Secondary trough passing through northeast Assam and neighbourhood while primary monsoon trough extends to north Bay of Bengal	2.5

daily rainfall. In these cases, the systems closer to the northeast India have been considered to develop the analogs.

On real time basis, daily rainfall is received from about 100 stations in the region. However, continuous record of daily rainfall during monsoon season for the period of 10 years (1991-2000) is not available for all these stations. So, 50 stations, almost uniformly distributed in the region have been selected in this study [Fig. 2(a)]. The necessary quality control has been carried out and the missing data for these 50 stations have been filled up considering the rainfall at surrounding stations.

The data on day of occurrence and intensity etc. of the synoptic systems like LPSC including low, depression, cyclonic storm, cycir extending upto 5.8 km above mean sea level (amsl), LLC extending upto 3.1 km amsl or less and the position of the monsoon trough are collected from daily weather reports published by Regional Meteorological Centre, Guwahati. The depression and deep depression are considered together without any differentiation. A day is considered as an LPSC/LLC day over a region, if the system is located at 0300 UTC observation. The regions of occurrence of LPSC and LLC under consideration in this study are shown in Fig. 2(b). These regions are northwest (NW) Bay of Bengal, northeast (NE) Bay of Bengal, Orissa, Gangetic West Bengal (GWB), Jharkhand (JKD), Bihar, Sub-Himalayan West Bengal (SHWB) & Sikkim, Andhra Pradesh (A.P.), Assam & Meghalaya (A&M), Nagaland, Manipur, Mizoram & Tripura (NMMT) and Bangladesh (BDS). The contributions from the systems over the above regions are considered, as the contributions from the systems over other regions are very less. The monsoon trough at mean sea level in four categories, *viz.*, (i) the trough lying along/close to the foothills of the Himalayas, (ii) the monsoon trough extending through northeast Assam and

neighbourhood (iii) the monsoon trough extending through Manipur/Mizoram/Tripura and (iv) secondary trough passing through northeast Assam and neighbourhood, while the primary monsoon trough lies in its normal position extending to north Bay of Bengal is considered. The all India break monsoon (AIBM)/weak monsoon conditions which prevail when the monsoon trough lies close to or along the foothills of the Himalayas (Ramamurty, 1969) is one of the major causes for the variability of the monsoon rainfall over this region (Srinivasan *et al.*, 1972). Hence, the rainfall distribution during all the above four conditions of monsoon trough are also analyzed.

The average number of days associated with different synoptic systems in the monsoon season (June to September) are found out and analyzed. The mean daily rainfall distributions over the region due to low, depression, cyclonic storm, cycir extending upto 5.8 km amsl, LLC extending upto 3.1 km amsl or less and different locations of the monsoon trough at sea level as mentioned above are found and analyzed. Also the mean rainfall over different meteorological sub-divisions, *viz.*, (i) AP (ii) A&M (iii) NMMT as a whole due to above mentioned systems are found out and analyzed. To analyse the results, the rainfall over a sub-division has been considered as excess/deficient, if the actual rainfall is higher/less than the normal rainfall of the sub-division by (20-50)%. It has been considered as active and vigorous monsoon conditions for a sub-division, if the actual rainfall is higher than the normal by (51-300)% and more than 300% respectively. It is called as weak monsoon condition for a sub-division, if the actual rainfall is less than the normal rainfall by 51% or more. The above criteria of active, vigorous and weak monsoon conditions are used in IMD to describe the daily monsoon activity over meteorological sub-divisions. To substantiate the results of the study, the typical case studies are presented and analysed.

3. Results and discussion

The average pattern of occurrence of synoptic systems under consideration is analyzed and discussed in sec.3.1. The average daily rainfall distribution over northeast India is presented and discussed in sec.3.2. The mean daily rainfall pattern due to storms/depressions and lows are presented and analysed in sec.3.3 and sec.3.4 respectively. The mean daily rainfall due to cycir extending upto mid-tropospheric levels and LLC are analysed and discussed in sec.3.5 and sec 3.6 respectively. The mean daily rainfall due to different locations of monsoon trough at sea level are analyzed and presented in sec. 3.7. To substantiate the results of the study, the typical case studies are presented and discussed in sec.3.8.

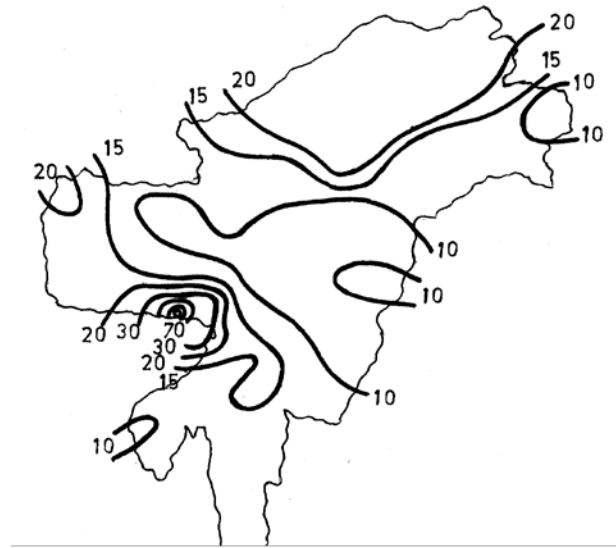


Fig. 3. Mean daily rainfall (mm) distribution over northeast India during summer monsoon season

3.1. Average pattern of occurrence and movement of synoptic systems

The average number of days associated with different synoptic systems during summer monsoon season based on the data of 1991-2000 is given in Table 1. As most of the depressions develop over NW Bay and move westwards along the monsoon trough across Orissa (Mohapatra and Mohanty, 2005), the number of depression days is maximum over NW Bay followed by Orissa. During this period, there has been recurvature/movement of depressions towards north/northeast, though the number of such cases is very less. The depression has not moved to AP during the period under study. As the lows mostly form over NW Bay and move across Orissa and GWB (Mohapatra and Mohanty, 2005), the number of low days is maximum over NW Bay followed by GWB and Orissa. Considering the cycir extending upto mid-tropospheric level (MTL), the number of days of cycir (Table 1) is also higher over NW Bay, Orissa and GWB. Contrary to the number of days of the major synoptic scale systems as discussed above, the number of LLC days (Table 1) is maximum over A&M followed by SHWB and BDS. According to Srinivasan *et al.* (1972), the LLC plays significant role on the rainfall variability over the northeast region due to the interaction of orography and basic monsoon flow over the region. The average numbers of days with different locations of the monsoon trough under consideration is shown in Table 2. The monsoon trough lies over the northeast India or close to the foothills of the Himalayas for about 14 days during the monsoon season.

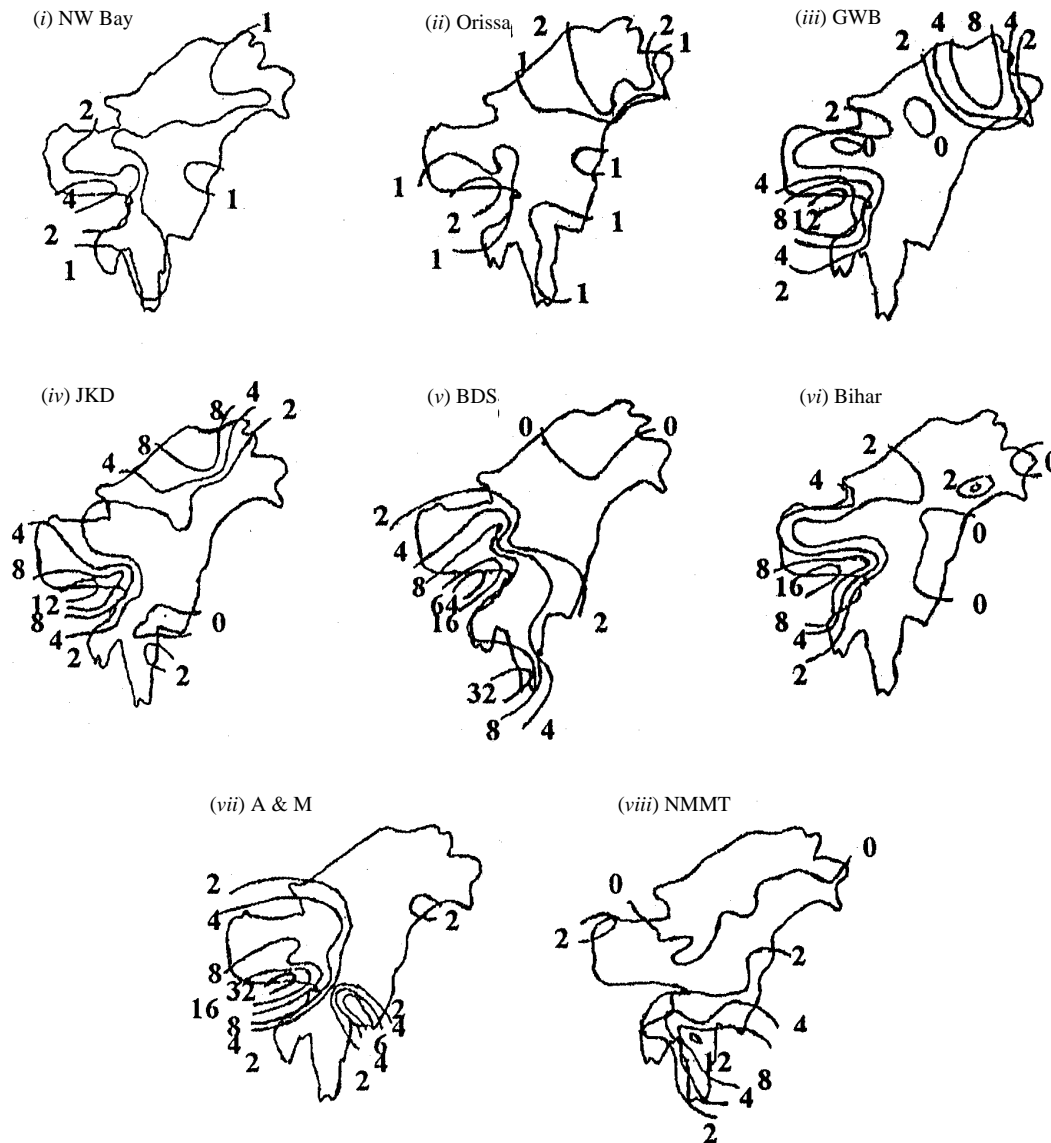


Fig. 4. Spatial distribution of mean daily rainfall (cm) over northeast India due to depression over (i) NW Bay, (ii) Orissa, (iii) GWB, (iv) JKD, (v) BDS, (vi) Bihar, (vii) A & M and (viii) NMMT

3.2. Average daily rainfall

The mean daily rainfall distribution over the northeast India based on the data of 10 years (1991-2000) is shown in Fig. 3. The spatial pattern of daily rainfall over northeast India is almost similar to the climatological pattern (IMD, 1971 and Srinivasan *et al.*, 1972). However considering Fig. 1(b) and Fig. 3, the effect of orography over distribution of rainfall is very pronounced in northeast India. Srinivasan *et al.* (1972) have also found out this fact. The major feature to be noted in the rainfall distribution is a pronounced east west orientated rainfall

maxima along the southern side of Garo hills and Khasi-Jaintia hills. The Khasi-Jaintia hills are well known for their very heavy rains. This area is one of the wettest place in the world. The exceptionally high rainfall over Khasi hills may be due to the fact that the prevailing low level moist winds from the Bay of Bengal strike (almost at right angle) at the Khasi hills which rise very steeply (reaching a height about 1.5 km within a distance of about 10 km). The strength of the southerly component of the wind at lower levels striking the hills and the moisture content may be good indication of intensity of rainfall over southern slopes of Garo Khasi and Jaintia hills. There is

TABLE 3

Mean daily rainfall (mm) over meteorological sub-divisions of northeast India during summer monsoon season due to depressions over different geographical locations

Location of depression	Meteorological sub-divisions		
	Arunachal Pradesh	Assam & Meghalaya	NMMT
NW Bay	13.6 (-6)	12.2 (-21)	12.0 (7)
Orissa	17.7 (23)	10.9 (-29)	10.1 ((-9)
GWB	58.7 (307)	20.2 (31)	20.1 (80)
JKD	29.1 (102)	22.5 (46)	10.4 (-7)
Bihar	13.2 (-8)	22.9 (49)	15.1 (34)
A & M	11.0 (-23)	48.5 (215)	14.2 (27)
NMMT	3.3 (-77)	7.7 (-50)	44.8 (300)
BDS	6.1 (-58)	51.9 (237)	79.9 (613)

Percentage departure from normal rainfall is shown in parenthesis. Active/vigorous and weak monsoon conditions are highlighted.

an east west oriented minima in rainfall just to the north of the maxima as it lies on the lee side with southerly basic monsoon flow over the region.

3.3. Mean rainfall due to cyclonic storms and depressions

The number of cyclonic storm days is very less during the period under study. There has been two cyclonic storm days over NW Bay due to two cyclonic storms (one each in June and September). In both the cases, the cyclonic storms have moved northeastwards and crossed BDS coast during next 24 hours. Hence, in both the occasions, the cyclonic storm over NW Bay has caused active monsoon condition over AP, A & M and NMMT.

The spatial patterns of daily rainfall over northeast India due to depressions over different locations under consideration are shown in Fig. 4. The western part of Meghalaya and neighbourhood (southern slope of Garo Khasi and Jaintia hills) gets relatively more rainfall due to depressions over all the regions under consideration except NMMT. The rainfall over this region is maximum due to depressions over BDS as it lies in the left forward sector of the mainly northward/northeastward moving depressions over BDS. The rainfall over this region is also higher due to depression over A & M and Bihar. Due to proximity of the trough line normally passing through GWB, the pressure gradient is generally weak over northeast India. However, when a depression or a cyclonic storm develops over the trough, there is a steep gradient, in the field of the disturbance leading to stronger monsoon flow over the region. With the depressions over

TABLE 4

Mean daily rainfall (mm) over meteorological sub-divisions of northeast India during summer monsoon season due to lows over different geographical locations

Location of low	Meteorological sub-divisions		
	Arunachal Pradesh	Assam & Meghalaya	NMMT
NE Bay	2.3 (-84)	9.3 (-40)	7.1 (-36)
NW Bay	6.4 (-56)	11.4 (-26)	10.4 (-7)
Orissa	13.0 (-10)	13.6 (-12)	10.3 (-8)
GWB	11.2 (-22)	14.1 (-8)	10.2 (-9)
JKD	10.8 (-25)	13.8 (-11)	9.3 (-17)
Bihar	15.4 (7)	17.9 (16)	9.6 (-15)
SHWB	27.6 (92)	22.7 (47)	8.1 (-28)
Arunachal Pradesh	23.6 (64)	14.8 (-4)	6.1 (-45)
A & M	15.4 (7)	18.2 (18)	14.2 (27)
NMMT	2.9 (-80)	8.5 (-45)	17.3 (55)
BDS	9.5 (-34)	15.2 (-1)	12.2 (9)

Percentage departure from normal rainfall is shown in parenthesis. Active and weak monsoon conditions are highlighted.

BDS, A&M and Bihar, the southerly flow becomes stronger leading to increase in orographic enhancement of rainfall, especially over the southern slope of Garo Khasi and Jaintia hills. With the depressions over NMMT, the wind pattern changes over the southern slope of Garo Khasi and Jaintia hills, being mainly westerly/northwesterly. It leads to reduced rainfall activity over the western part of Meghalaya (southern slope of Garo Khasi and Jaintia hills). The parts of NMMT get maximum rainfall due to depressions over NMMT followed by A & M. The rainfall over northern part of northeast India covering AP and adjoining areas is worst affected due to depressions over NMMT as the associated monsoon trough passes through BDS and NMMT and the significantly less rainfall occurs to the north of the monsoon trough. Considering the meteorological sub-divisions (Table 3), AP experiences active monsoon condition due to depressions over GWB and JKD and weak monsoon condition due to depressions over BDS and NMMT. A & M experiences active monsoon condition due to depressions over BDS and A & M. The rainfall is also excess over A & M due to depressions over GWB, JKD and Bihar. It experiences deficient rainfall due to depressions over NW Bay, Orissa and NMMT. Comparing different locations of depression, the NMMT gets active monsoon conditions due to depressions over NMMT, BDS and GWB. The rainfall is also excess over NMMT due to depressions over Bihar and A & M. Srinivasan *et al.* (1972) have shown that the monsoon

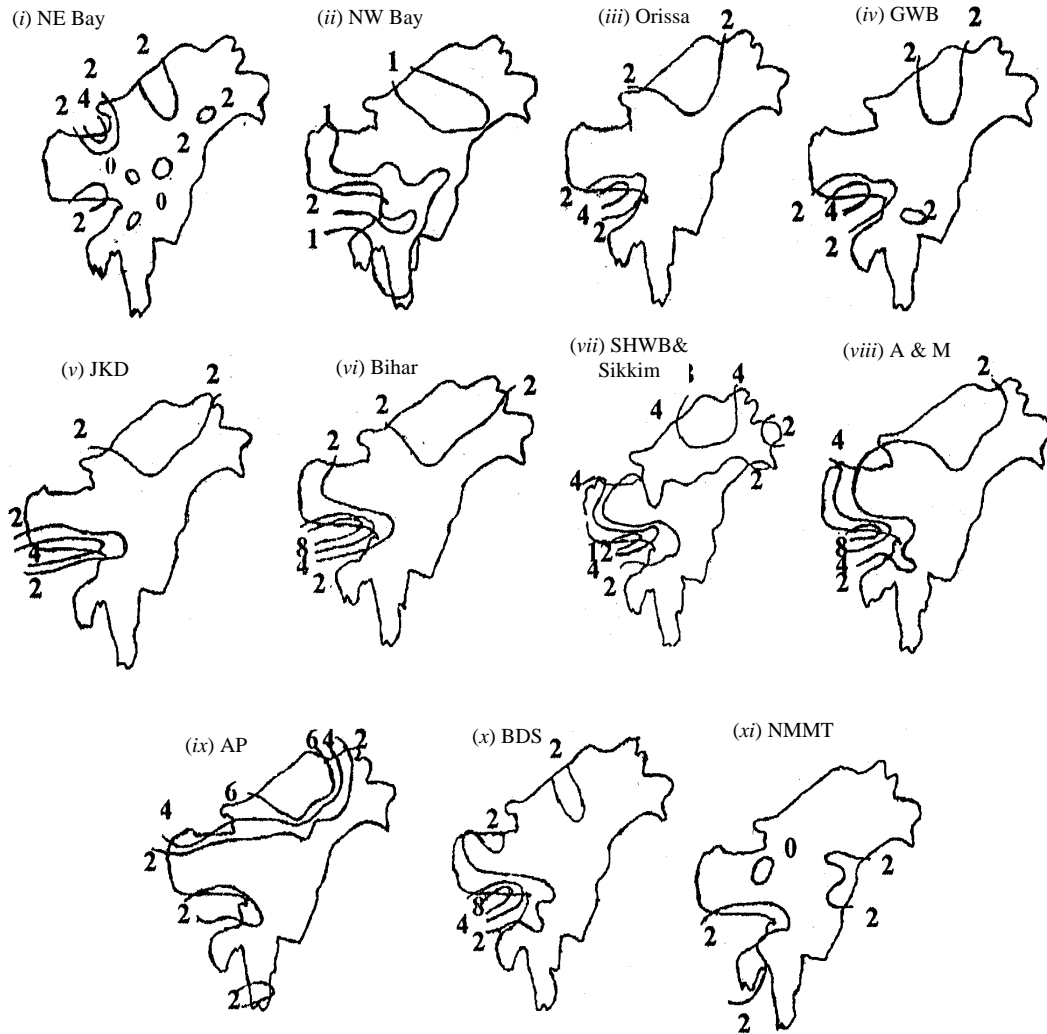


Fig. 5. Spatial distribution of mean daily rainfall (cm) over northeast India due to low over (i) NE Bay, (ii) NW Bay, (iii) Orissa, (iv) GWB, (v) JKD, (vi) Bihar, (vii) SHWB & Sikkim (viii) A & M, (ix) AP, (x) BDS and (xi) NMMT

remains weak over northeast India due to northwestward movement of depressions over NW Bay and GWB. According to them, the monsoon also remains weak over A&M and AP due to westward moving depressions over JKD. With the northward/north-northeastward movement of the depressions over GWB, rainfall becomes fairly widespread in the south and scattered in the northern part of the northeast India. On scrutiny, it is found that the depressions over GWB have moved northwestwards across JKD during the period under study.

3.4. Mean daily rainfall due to monsoon lows

The spatial patterns of mean daily rainfall over northeast India and the mean daily rainfall over different

meteorological sub-divisions under consideration due to monsoon lows are shown in Fig. 5 and Table 4 respectively. The western part of Meghalaya (southern slope of Garo Khasi and Jaintia hills) gets more rainfall than the northern slope due to lows over all the locations under consideration (Fig. 5). However, the lows over Bihar, SHWB & Sikkim, BDS and A & M are more favourable for rainfall over the western part of Meghalaya. It may be due to the orographic enhancement of rainfall by the interaction of basic monsoon flow with the mainly eastward moving lows and orography due to Garo Khasi and Jayantia hills as discussed in the previous section. A and M as a whole gets maximum rainfall due to lows over SHWB & Sikkim (Table 4). The rainfall over A & M becomes deficient due to lows over NMMT, NE Bay and

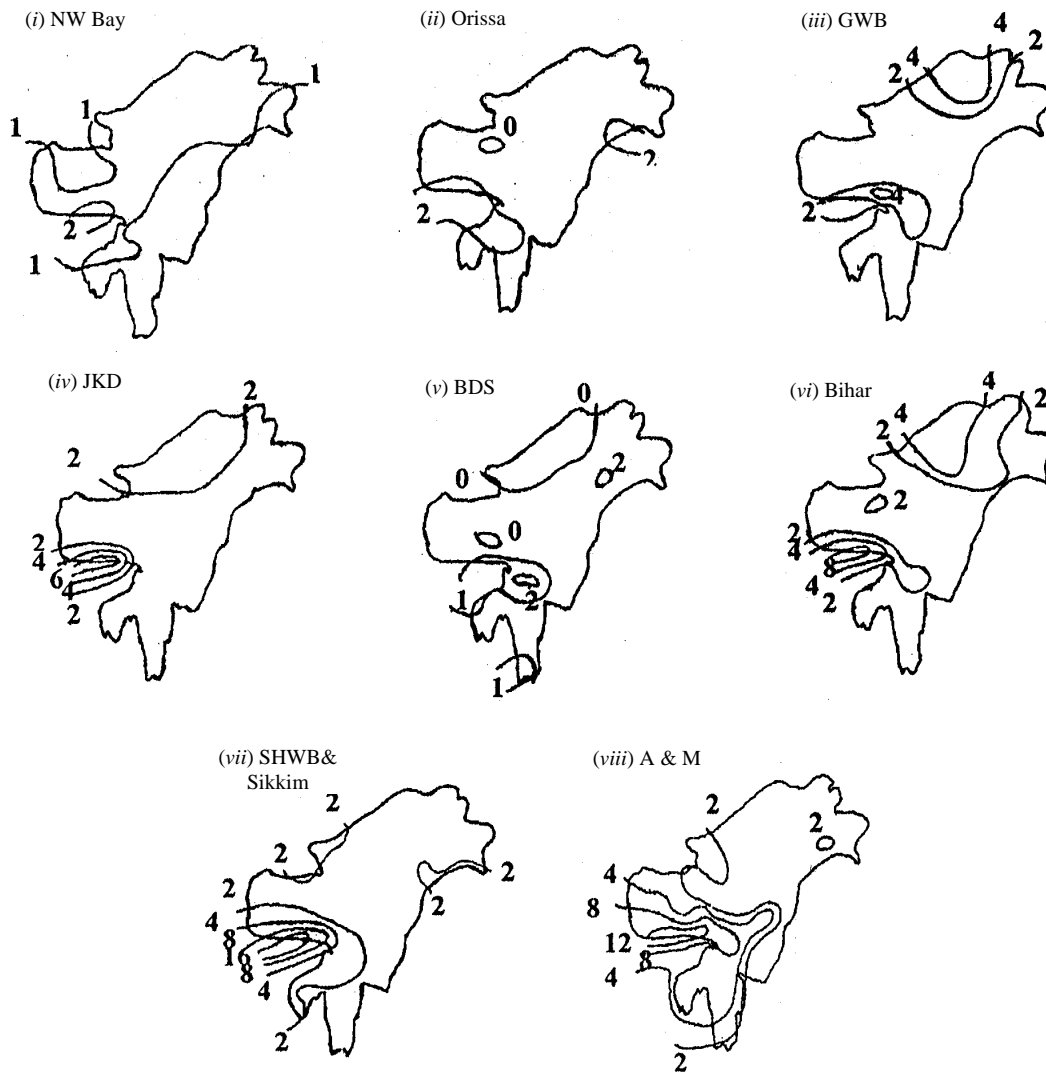


Fig. 6. Spatial distribution of mean daily rainfall (cm) over northeast India due to cyclonic circulation extending upto mid-tropospheric levels over (i) NW Bay, (ii) Orissa, (iii) GWB, (iv) JKD, (v) BDS, (vi) Bihar, (vii) SHWB & Sikkim and (viii) A & M

NW Bay. With the lows over NW Bay and NE Bay, the monsoon trough lies mostly in the normal/near normal position. There is absence/weaker southerly flow over the region (Fig. 1). It leads to less rainfall over northeast India. With the low over NMMT, the rainfall is also significantly less (Fig. 5 and Table 4) as most parts of A & M lie in the rear sector of this mainly eastward moving system.

As the lows over Bihar, SHWB & Sikkim, A & M and AP move eastwards under the influence of mid-latitude upper tropospheric westerly trough, most parts of AP lie in the left forward sector and hence get more

rainfall with these lows (Fig. 5 and Table 4). Also there is orographic enhancement of rainfall due to these systems, as AP lies on the eastern part of the Himalayas [Fig. 1(b)]. Its rainfall, like that over A & M is most adversely affected leading to weak monsoon condition with lows over NW Bay, NE Bay and NMMT.

The lows over NMMT generally move towards Myanmar under the influence of the extra tropical upper tropospheric westerly trough. Hence, major parts of NMMT lies in the left forward sector (sector of maximum lower level convergence and vertical motion) which gets maximum rainfall (Rajamani and Rao, 1981). Also the

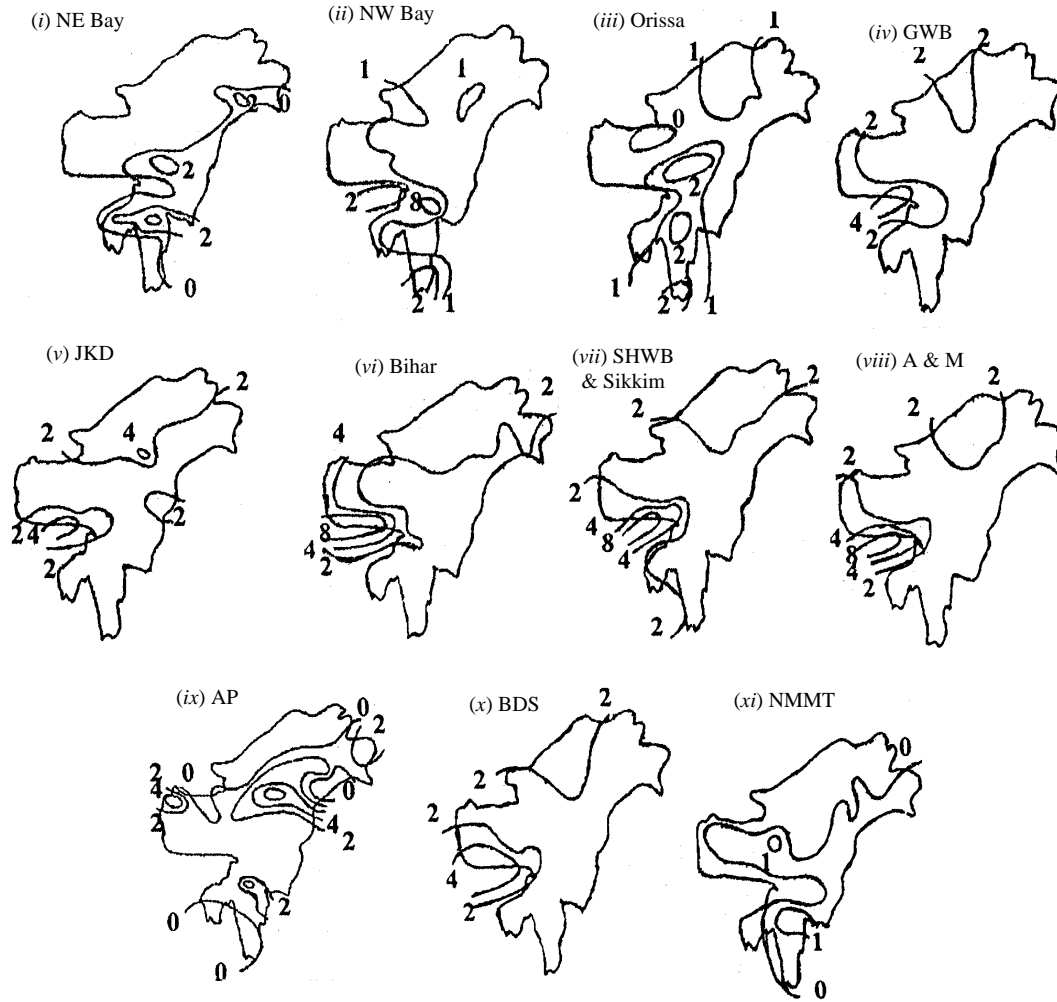


Fig. 7. Spatial distribution of mean daily rainfall (cm) over northeast India due to low level cyclonic circulation (LLC) over (i) NE Bay, (ii) NW Bay, (iii) Orissa, (iv) GWB, (v) JKD, (vi) Bihar, (vii) SHWB & Sikkim (viii) A & M, (ix) AP, (x) BDS and (xi) NMMT

orographic interaction due to the northeast hill range with the lows over NMMT helps in increasing the rainfall over major part of NMMT (Fig. 5). NMMT as a whole experiences active monsoon condition due to lows over NMMT (Table 4). The rainfall over NMMT becomes excess due to lows over A & M and deficient due to lows over AP, SHWB & Sikkim and NE Bay.

3.5. Mean daily rainfall due to cycir extending upto MTL

Considering the spatial patterns of daily rainfall due to cycirs extending upto MTL over different regions (Fig. 6), the southern slope of Garo Khasi and Jaintia hills gets relatively more rainfall than the northern slope due to cycirs over all the regions under consideration. However, the rainfall over the southern slope is higher due to cycirs

over SHWB, A&M and Bihar like that due to lows/depressions over these regions. The northern part, especially AP and neighbourhood gets more rainfall due to cycirs over Bihar, SHWB, JKD and GWB. Its rainfall is adversely affected due to cycirs over NW Bay, Orissa and BDS. Considering the rainfall over the individual meteorological sub-divisions (Table 5), AP experiences weak monsoon conditions due to cycirs over BDS and its rainfall becomes deficient due to cycirs over NW Bay and Orissa. Both A&M and NMMT get active monsoon conditions due to cycirs over A&M. While the rainfall over A&M becomes excess due to cycirs over Bihar and SHWB & Sikkim, that over NMMT becomes excess due to cycirs over SHWB. The rainfall becomes deficient over A&M due to cycirs over NW Bay, Orissa and BDS and over NMMT due to cycirs over NW Bay, GWB, JKD and BDS.

TABLE 5

Mean daily rainfall (mm) over meteorological sub-divisions of northeast India during summer monsoon season due to cycir extending upto mid-tropospheric level over different geographical locations

Location of the system	Meteorological sub-divisions		
	Arunachal Pradesh	Assam & Meghalaya	NMMT
NW Bay	10.2 (-29)	11.8 (-24)	8.3 (-26)
Orissa	11.1 (-23)	10.8 (-30)	13.3 (19)
GWB	19.0 (32)	13.3 (-14)	8.9 (-20)
JKD	18.0 (25)	12.5 (-19)	7.0 (-38)
Bihar	15.7 (9)	19.2 (25)	11.1 (-1)
SHWB	17.1 (19)	21.7 (41)	16.3 (45)
A & M	13.2 (-8)	31.2 (103)	44.0 (292)
BDS	1.3 (-91)	8.8 (-43)	6.7 (-40)

Percentage departure from normal rainfall is shown in parenthesis. Active and weak monsoon conditions are highlighted.

3.6. Mean daily rainfall due to low level cycir (LLC)

The southern slope of Garo, Khasi and Jaintia hills gets relatively more rainfall than the northern slope due to the LLCs over all the regions under consideration except NE Bay and NMMT (Fig. 7). With the LLCs over the Bay region, the trough shifts southwards and hence the rainfall over northeast region especially AP and A&M decreases (Fig. 7 and Table 6). When the LLC lies over NMMT, most parts of AP and A & M lie in the rear sector as most of these LLCs move eastwards towards Myanmar. As a result, they get relatively less rainfall (Fig. 7 and Table 6). AP experiences active monsoon condition with LLCs over Bihar and excess rainfall due to LLCs over SHWB & Sikkim (Table 6). It experiences weak monsoon condition with LLCs over NE Bay, NW Bay and NMMT and deficient rainfall due to LLCs over Orissa, GWB and AP. A & M experiences excess rainfall due to LLCs over Bihar. It experiences weak monsoon condition due to LLCs over NE Bay and deficient rainfall due to LLCs over NW Bay and Orissa. The weak monsoon condition prevails over NMMT due to LLCs over NMMT. The weak monsoon condition over NMMT due to LLCs over NMMT and deficient rainfall over AP due to LLCs over AP may be due to fact that these LLCs move mostly towards the east under the influence of extra tropical westerly trough in upper levels and cause less rainfall over NMMT and AP respectively.

TABLE 6

Mean daily rainfall (mm) over meteorological sub-divisions of northeast India during summer monsoon season due to cycir extending upto lower tropospheric levels (LLC) over different geographical locations

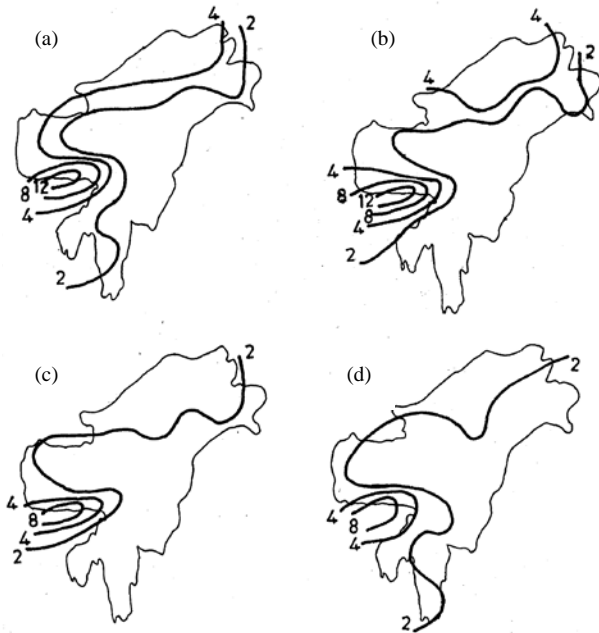
Location of the system	Meteorological sub-divisions		
	Arunachal Pradesh	Assam & Meghalaya	NMMT
NE Bay	1.0 (-93)	1.8 (-88)	9.9 (-12)
NW Bay	2.8 (-80)	11.1 (-28)	11.3 (1)
Orissa	7.9 (-45)	8.0 (-48)	10.1 (-10)
GWB	9.2 (-36)	15.9 (3)	10.2 (-9)
JKD	13.9 (-4)	14.6 (-5)	10.8 (-4)
Bihar	22.8 (58)	20.4 (33)	8.1 (-28)
SHWB	18.3 (27)	17.3 (12)	13.2 (18)
Arunachal Pradesh	7.2 (-50)	16.4 (6)	9.1 (-19)
A & M	13.5 (-6)	13.6 (-11)	10.5 (-6)
NMMT	1.8 (-87)	1.5 (-90)	2.3 (-80)
BDS	13.0 (-10)	15.9 (3)	9.4 (-16)

Percentage departure from normal rainfall is shown in parenthesis. Active and weak monsoon conditions are highlighted.

3.7. Mean daily rainfall due to monsoon trough

When monsoon trough lies close to the foothills of the Himalayas (AIBM condition) active monsoon condition prevails over all the three meteorological sub-divisions (Table 7). The rainfall is maximum over southern slope of Garo Khasi Jaintia hills and it generally decreases from north to south over remaining parts of the region [Fig. 8(a)]. When the monsoon trough lies close to the foothills of the Himalayas, there is an organised and increased north-south pressure gradient over the whole northeast India (Srinivasan *et al.*, 1972). In such conditions, a north-south oriented trough in westerlies appears over the region at lower and middle tropospheric levels (Chakraborty and Basu, 1957 and Srinivasan *et al.*, 1972). The trough sometimes develops as far west as west Madhya Pradesh and travels eastward upto Assam and adjoining states. It yields good rainfall over northeast India, when it approaches from the west. Moderate to strong southwesterlies prevail over the region, which helps in the increase in southerly component of wind and hence increase in the rainfall, especially over the southern slope of Garo Khasi Jaintia hills.

When the eastern end of the monsoon trough passes through northeast Assam and neighbourhood, the rainfall also increases over the region [Fig. 8(b)]. The spatial pattern is almost same as that due to AIBM condition [Fig. 8(a)]. However, the amount of rainfall is relatively less. The active monsoon condition prevails only over AP and excess rainfall occurs over A&M (Table 7). When



Figs. 8(a-d). Spatial distribution of mean daily rainfall (cm) over northeast India due to (a) monsoon trough lying close to the foothills of the Himalayas, (b) monsoon trough running through northeast Assam and neighbourhood, (c) secondary trough running through northeast Assam and neighbourhood and (d) monsoon trough passing through Manipur/ Mizoram/ Tripura

there is a secondary trough extending towards northeast Assam and neighbourhood in addition to the primary monsoon trough along normal position (extending to north Bay of Bengal), the rainfall is excess only over AP (Table 7). The spatial pattern of rainfall in association with secondary trough [Fig. 8(c)] is almost same as that with AIBM conditions (Fig. 8(a)) However, the rainfall amount is less than that due to AIBM conditions and the monsoon trough extending through NE Assam and neighbourhood. When the eastern end of the monsoon trough runs over northeast India but slightly to the south, *e.g.*, when it passes through Manipur/Mizoram/Tripura, the active monsoon condition prevails over NMMT only (Table 7). Considering the spatial pattern [Fig. 8(d)] of rainfall due to this trough, the southern slope of Garo Khasi Jaintia hills covering western Meghalaya and neighbourhood also gets maximum rainfall in this condition. Though, the spatial pattern is almost same as that in AIBM condition, the amount of rainfall is relatively less over western and northern parts of the region.

3.8. Case studies

Two case studies presenting the movement of a cyclonic storm from the Bay of Bengal towards northeastern states and movement of a low pressure

TABLE 7

Mean daily rainfall (mm) over meteorological sub-divisions of northeast India during summer monsoon season due to different locations of monsoon trough

Location of monsoon trough	Arunachal Pradesh	Assam & Meghalaya	NMMT
Monsoon trough close to the foothills of the Himalayas (AIBM conditions)	23.5 (63)	26.4 (72)	19.5 (74)
Monsoon trough passing through northeast Assam and neighbourhood	22.8 (59)	22.2 (44)	12.4 (10)
Monsoon trough passing through Manipur/Mizoram/Tripura	13.5 (-6)	16.7 (8)	17.7 (58)
Secondary trough passing through northeast Assam and neighbourhood	19.8 (38)	16.8 (9)	10.0 (-11)

Percentage departure from normal rainfall is shown in parenthesis. Active monsoon conditions are highlighted

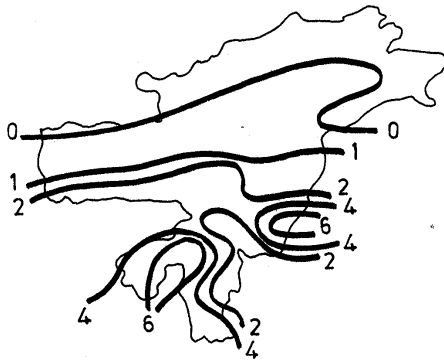
area from GWB to Bihar across JKD and subsequent formation of an LLC over Assam and neighbourhood are presented in sec. 3.8.1 and 3.8.2 respectively to substantiate the results of the study.

3.8.1. Cyclonic storm moving from the Bay of Bengal towards northeast India

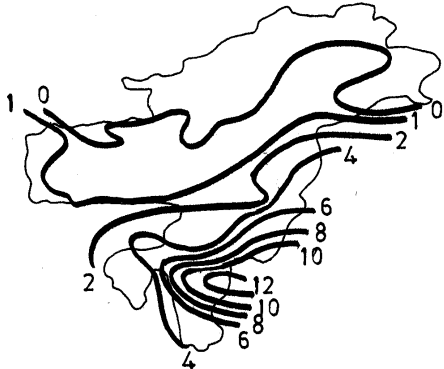
During the withdrawal phase of the monsoon over India, a low pressure area formed over West Central (WC) Bay of Bengal off Andhra Pradesh coast at 0300 UTC of 21 September 1997. It intensified into a depression and lay centred at 0300 UTC of 23rd near 15.5° N and 82.5° E over WC Bay. It intensified into a deep depression and lay centred at 0300 UTC of 24th near 16.5° N and 82.5° E over WC Bay. Under the influence of the upper tropospheric westerly trough lying to the left of the system roughly along 81° E upto 21° N at 300 hPa, the deep depression moved north-northeastwards. It intensified into a cyclonic storm at 0900 UTC of 24th and lay centred at 0300 UTC of 25th near 17.3° N and 83.7° E over WC Bay. It lay centred at 0300 UTC of 26th near 20.5° N and 87.5° E over NW Bay with a trough extending towards A&M from the system centre. Continuing the northeastward movement, the cyclonic storm crossed BDS coast in the early morning of 27th, weakened into a deep depression and lay centred at 0300 UTC of 27th near 24.0° N and 92.0° E, close to Agartala in Tripura. It rapidly weakened and was seen as an upper air cycir extending upto 2.1 km amsl over NMMT and adjoining Myanmar at 0300 UTC of 28th. It moved away eastwards on 29th.

Under the influence of the above system, the rainfall over the northeastern states peaked up from 26th onwards and continued till 28th. The past 24 hrs rainfall over

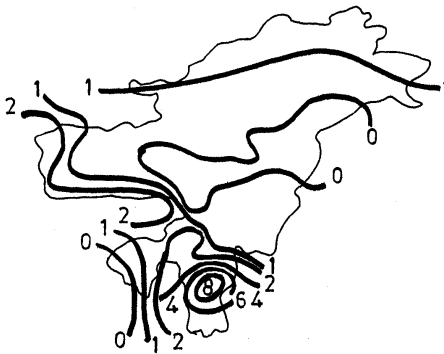
(a) Rainfall due to cyclonic storm over NW Bay (27 Sep 1997)



(b) Rainfall due to deep depression over Tripura (28 Sep 1997)



(c) Rainfall due to LLC over NMMT (29 Sep 1997)



Figs. 9(a-c). Past 24 hours rainfall distribution over northeast India recorded at 0300 UTC on (a) 27 Sep 1997 due to cyclonic storm over NW Bay, (b) 28 Sep 1997 due to deep depression over Tripura, centred near Agartala and (c) 29 Sep 1997 due to low level cyclonic circulation (LLC) over NMMT

northeastern states recorded at 0300 UTC of 27th, 28th and 29th September 1997 are shown in Figs. 9(a-c). Comparing the mean and the actual rainfall patterns due to different locations of cyclonic storms, the spatial pattern of rainfall distribution remains same, even though there is difference in intensity of rainfall due to unique characteristics of the individual systems.

3.8.2. Low pressure area moving from GWB to Bihar

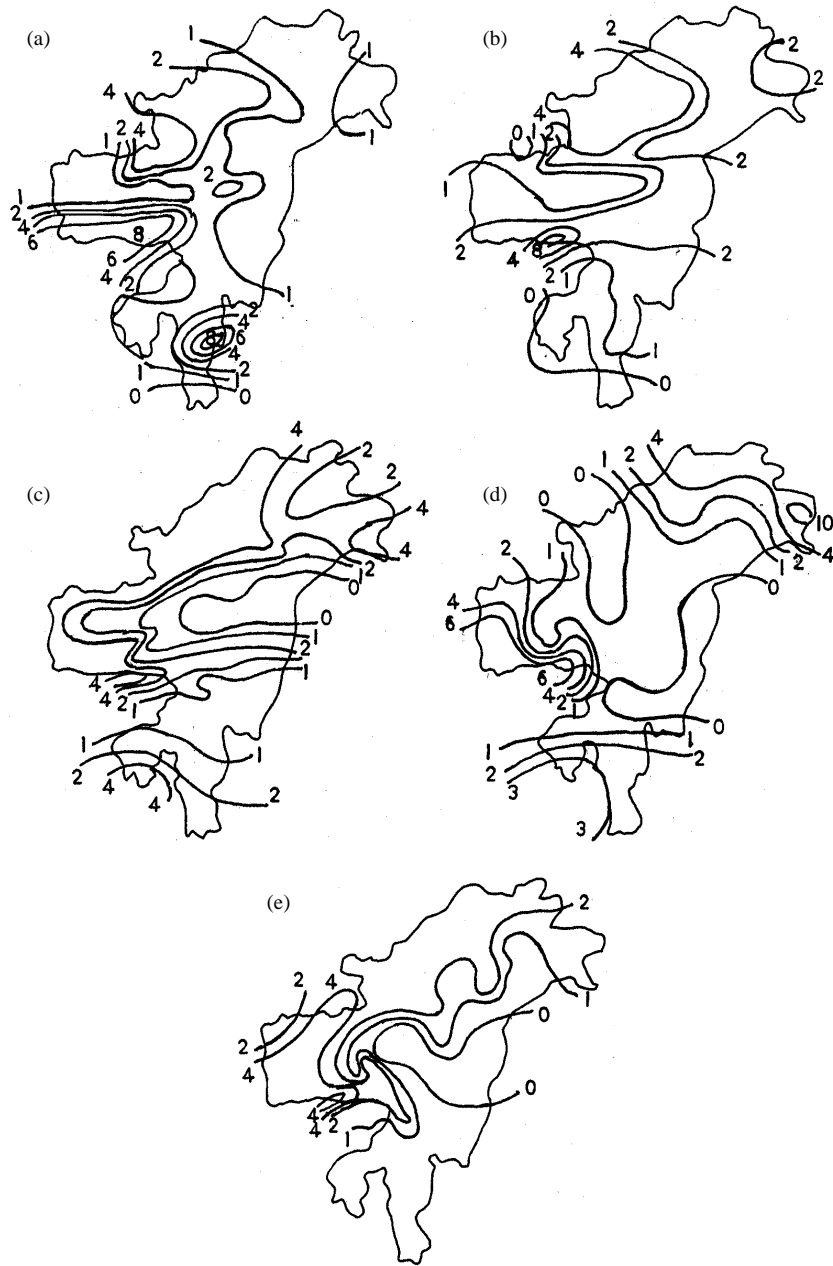
A low pressure area lay over NW Bay of Bengal with associated cycir extending upto mid-tropospheric level and tilting southwestwards with height at 0300 UTC of 2nd July 1998. Moving northwestwards along the monsoon trough, it lay over GWB and adjoining north Orissa and JKD on 3rd with associated cycir extending upto mid-tropospheric level and tilting southwestwards with height. The monsoon trough continued to remain in near normal position passing through the centre of the system and NW Bay. The low lay over JKD and neighbourhood with associated cycir extending upto mid-tropospheric level on 4th. The monsoon trough remained in near normal position passing through the centre of the system and NW Bay. The low lay over Bihar and adjoining JKD with associated cycir extending upto mid-tropospheric level on 5th. The monsoon trough shifted slightly northward of its previous day's location, passing through the centre of the system, GWB and north Bay. The low became less marked on 6th. However, the associated cycir extended upto 1.5 km above mean sea level over east Uttar Pradesh. The monsoon trough still extended to north Bay of Bengal lying a little to the north of its normal position. An LLC extending upto 2.1 km above mean sea level lay over A&M on 7th. The monsoon trough on that day extended to north Bay of Bengal lying a little to the north of its normal position.

The rainfall distributions over the northeastern states due to different locations of the low and LLC are shown in Figs. 10(a-c). Like the previous case study presented in sec. 3.8.1, the spatial pattern of rainfall distribution remains same as the mean pattern for different locations of the synoptic systems, even though there is difference in intensity of rainfall due to unique characteristics of the systems.

4. Conclusions

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

(i) The mean rainfall distribution over northeast India is dominantly pronounced by the interaction of orography of the region with the basic monsoon flow and synoptic scale systems. There is large scale variation in the occurrence and intensity of rainfall over the region depending on the location, intensity and movement of the synoptic systems. Based on larger data set, the results confirm the earlier findings (Srinivasan *et al.*, 1972) with respect to rainfall due to monsoon trough and other synoptic systems like lows and depressions. In addition, the study finds out the regions of excess/deficient rainfall and active/weak monsoon conditions due to different



Figs. 10(a-e). 24 hours rainfall distribution over northeast India recorded at 0300 UTC on (a) 03 July 1998 due to low over NW Bay, (b) 04 July 1998 due to low over GWB, (c) 05 July 1998 due to low over JKD, (d) 06 July 1998 due to low over Bihar and adjoining Jharkhand and (e) 08 July 1998 due to LLC over Assam and neighbourhood

synoptic systems. The developed synoptic analog maps may be useful to the forecasters for 24 hours rainfall forecast with the knowledge of location, intensity and movement of the synoptic systems.

(ii) Contrary to the days of occurrence of large scale systems like LPSC, the number of LLC days is maximum over A&M followed by SHWB. These LLCs play

significant role on the rainfall variability over northeast India. While the LLC over Bihar can cause active monsoon condition over AP and excess rainfall over A&M, that over SHWB & Sikkim can cause excess rainfall over AP. The LLC over Bihar can cause deficient rainfall over NMMT. While the LLC over NMMT can cause weak monsoon condition over all the sub-divisions, that over NE Bay, NW Bay and Orissa can cause weak

monsoon condition / deficient rainfall over A & M and AP and that over GWB can cause deficient rainfall over AP.

(iii) The monsoon trough at sea level lying close to the foothills of the Himalayas causes active monsoon condition over all the sub-divisions in northeast India. While the eastern end of monsoon trough passing through northeast Assam and neighbourhood causes active monsoon condition over AP and excess rainfall over A&M, the monsoon trough passing through Manipur/Mizoram/Tripura causes active monsoon condition over NMMT. The secondary monsoon trough extending through northeast Assam and neighbourhood, while the primary trough extends to the north Bay of Bengal causes excess rainfall only over AP.

(iv) The southern slope of Garo, Khasi and Jaintia hills gets relatively higher rainfall than other regions of northeast India due to all types of synoptic systems over the regions under consideration except NE Bay and NMMT. Comparing different locations of the depression, it gets maximum rainfall due to depression over BDS followed by A&M. Similarly, it gets higher rainfall due to lows/cyclones extending upto MTL over SHWB and Sikkim and A&M. It also gets relatively more rainfall than other regions due to different locations of the monsoon trough under consideration.

(v) The region to the east of northeast hill range covering major part of Nagaland and Manipur gets relatively higher rainfall than other regions due to LPSC over NMMT and LLC over AP.

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