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Heavy rainfall occurrences in northeast India

Rahul Mahanta,[a]* Debojit Sarma[a] and Amit Choudhury[b]
[a] *Department of Physics, Cotton College, Guwahati, India*
[b] *Department of Statistics, Gauhati University, Guwahati, India*

ABSTRACT: In operational meteorology, forecasting heavy rainfall (HRF) events has been a long-standing challenge in India. This is especially true in certain regions where the physical geography lends itself to the creation of such HRF events. Northeast India (NEI) is one such region within the Asian monsoon zone, which receive very HRF during the pre-monsoon and summer monsoon season and the summer–autumn transition month of October. These events cause flooding, damage crops and bring life to standstill. In the present work, the characteristics of HRF events in NEI are studied. The seasonal and spatial variations of HRF occurrences are analysed using 31 year (1971–2001) of daily rainfall data from 15 rainfall stations. Using the daily data obtained from the Indian Meteorological Department, the most favorable locations were found for the stations between 27.5 °N and 28.1 °N. The most favorable time of occurrence of these events are between 10 June and 5 August. July records the largest number of HRF events followed by June and August. The aggregate of extreme rain events over the region has a significant decreasing trend over the region. Before the monsoon sets in, there is considerable thunderstorm (TS) activity in this region in the month of April and May that are also the cause of HRF events. While many of these HRF events occur associated with the pre-monsoon Nor'westers (tornadoes), some severe TSs may occur during the monsoon season. So, we present a climatology of severe TS days. Also we present the annual and seasonal variation of convective available potential energy (CAPE) and convective inhibition energy (CINE) at Guwahati as the index of the thermal instability. Between 1973 and 2001, CAPE shows a decreasing trend whereas CINE shows an increasing trend which seems reasonable due to the HRF events' decreasing trend. Copyright © 2012 Royal Meteorological Society

KEY WORDS heavy rainfall events; thunderstorm; CAPE; CINE; northeast India

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1. Introduction

Heavy rainfall (HRF) events and their associated flooding have made tremendous impacts on human society in terms of property damage and loss of human life. While HRF is possible anywhere, some areas are more susceptible or vulnerable than other areas (Easterling *et al.*, 2000). Mountainous regions are prone to heavy rainfall development and flooding due to terrain or orographic effects. Airflow can impinge upon the mountain slopes, leading to upslope flow and sustained ascent and precipitation development over long periods of time. Surrounded by mountains in the north, east and south with smaller mountains within the region and with opening only in the west to receive moisture transported by westerlies (Figure 1), northeast India (NEI) is characterized by unique weather systems. The southwest monsoon is responsible for a large bulk of the annual rainfall of NEI. The seasonal mean (June–September) rainfall over the region (approximately 151.3 cm) being much larger than the all India average (86.5 cm; Parthasarathy *et al.*, 1995). The normal rainfall between April and October is approximately 227 cm with a standard deviation of 38 and forms around 80% of the annual rainfall.

It is also interesting to note that NEI is one of the regions in India with low variability of the seasonal rainfall, the variation being 10%. If we consider the individual months of the monsoon season, the variability is 19.3 in June, 18.4 in July, 18.2 in August and 24.4% in September (Parthasarathy and Dhar, 1974). Monsoon sets in over NEI in the last week of May or in the first week of June and withdraws in the second week of October. The rainfall during the month of July is highest for the season and it gradually decreases thereafter. Another interesting feature is that even before the monsoon sets in there is considerable thunderstorm (TS) activity in this region in the month of April and May and the rainfall caused by these TSs is comparable in magnitude to the rainfall in any of the monsoon months. Hence, for the purpose of HRF event selection and study, April and May are equally important.

The climate of this region is also different from the rest of India. For example, on a seasonal mean time scale, the summer monsoon rainfall during June–September (JJAS) over this region is negatively correlated with that over rest of India (Shukla, 1987; Goswami *et al.*, 1999). The annual cycle of rainfall is also significantly different from that over rest of the country (Figure 2(a)). On interannual time scale, it is known that the monsoon rainfall (June–September) over this region has a

* Correspondence to: R. Mahanta, Department of Physics, Cotton College, Guwahati, India. E-mail: rahulmahanta@gmail.com

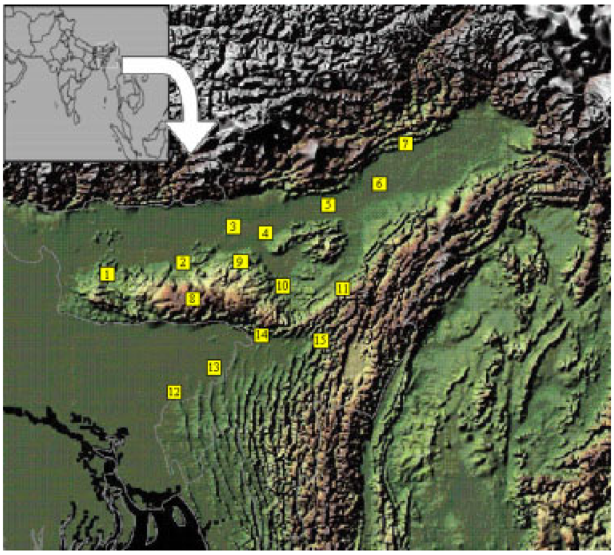

Figure 1. Topographic features of the northeast India (NEI) region and locations of the 15 stations. Inset indicates location of the NEI region within the Indian subcontinent. (1) Dhubri, (2) Guwahati, (3) Majbat, (4) Tezpur, (5) North Lakhimpur, (6) Dibrugarh, (7) Passighat, (8) Shillong, (9) Chaparmukh, (10) Lumding, (11) Kohima, (12) Agartala, (13) Kailashahar, (14) Silchar and (15) Imphal.

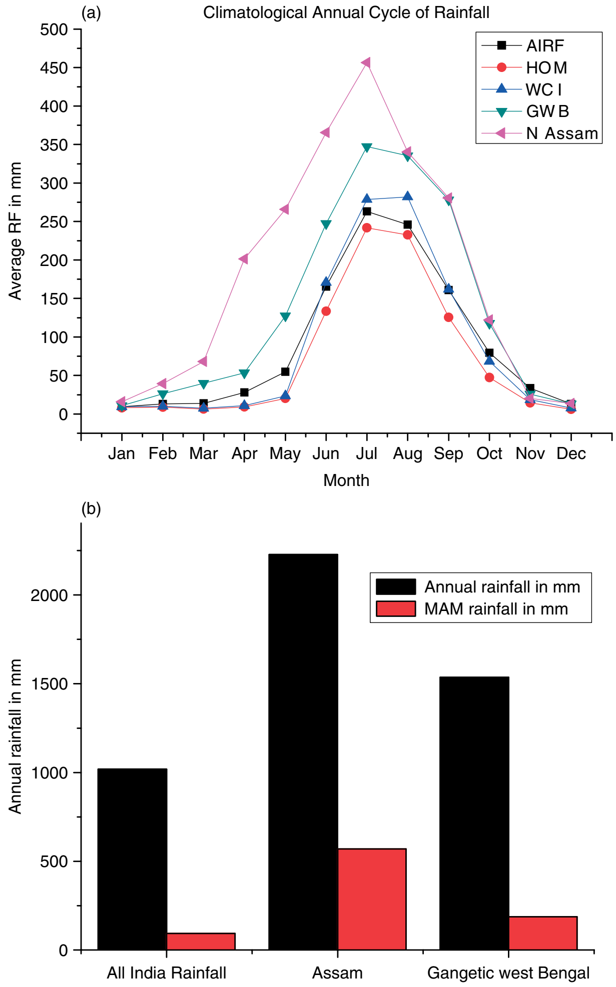

Figure 2. (a) Climatological annual cycle of rainfall in Assam compared to that in Gangetic West Bengal and for All India rainfall (AIR), homogeneous monsoon rainfall (HOM) and west central India (WCI) rainfall. (b) MAM rainfall as a percentage of annual rainfall for Assam, Gangetic West Bengal and AIR.

weak out of phase relationship with monsoon rainfall over homogeneous region of central and western India (Mooley and Shukla, 1987; Shukla, 1987; Guhathakurta and Rajeevan, 2008). On the intraseasonal time scale, the dominant pattern of convection or rainfall has a quadruple structure (Krishnamurthy and Shukla, 2000, 2007; Annamalai and Slingo, 2001; Annamalai and Sperber, 2005; Goswami 2005) with the NEI region sitting in the northeast quadrant of this quadruple pattern. As a result, even on intraseasonal scale, the rainfall over the NEI region tends to go out of phase with that over central and western India. An interesting aspect of the annual cycle of rainfall in the northeast region is that unlike the rest of India, the region receives a significant amount of rainfall during the pre-monsoon season of March–May (MAM) (Figure 2(b)). While rest of the country receives about 8% of the annual rainfall during MAM, NEI receives more than 25% of its annual rainfall during MAM. As the total annual rainfall in this region is quite high, the MAM rainfall represents a significant amount. Since hardly any synoptic events occur during this period, almost all the rainfall during MAM comes from TSs. Many of these TSs become severe TSs or Nor'westers and are associated with HRF events with rainfall exceeding 15 cm in 24 h. As the severe TSs usually last for only a few hours, often more than 15 cm rainfall actually occurs only over a couple of hours. With many tributaries of Brahmaputra embedded in the sloping terrain, such HRF events often lead to flash floods. While many of these HRF events occur associated with the pre-monsoon Nor'westers, some TSs occur during the monsoon season. In addition to the flash floods caused by these severe TSs, they also cause damage of life and property through lightning, hailstorms and by spawning tornadoes. It may be noted that even in the Gangetic West Bengal, where Nor'westers occur during MAM, the total rainfall during MAM is much smaller than that over North Assam (Figure 2(c)). Thus, it is possible that these TSs in NEI may be generated *in situ*. Statistics of occurrence of HRF events occurring in other parts of the world and the dynamics of intense convection associated with them have been studied extensively (Cotton and Anthes, 1989; Asnani, 1993). These intense convective events, while having some common characteristics across the world, are unique to individual regions as the local conditions such as topography and ground hydrology significantly influence the genesis and evolution of the systems. A systematic study of intense rainfall events along the western coast of India was carried out by Francis and Gadgil (2002). Using daily rainfall data obtained from the Indian Meteorological Department (IMD) they found the most favorable locations for intense rainfall events and the most favorable time of occurrence. Goswami and Ramesh (2008) have prepared a map of India for areas vulnerable to extreme rainfall. To our knowledge, no comprehensive study exists even on the characterization of extreme rain events in NEI. The purpose of this study is to examine the characteristics of some of the HRF events that occurred over this region during the 31 year period (1971–2001). Using daily data obtained from the IMD, the most favorable locations and time of occurrence of these events are identified. Attention has been given to the Brahmaputra catchment lying within Assam and its neighbourhood, since we are primarily interested in rainfall events that are likely to cause floods in the Brahmaputra valley. Also we present a climatology of severe TS days over NEI as these TSs are also the cause of HRF events and their nature is like that of tropical cyclones that last for about an hour and have horizontal scale of 50–100 km. NEI is one of the regions of very high thermal instability in South Asia (Yamane and Hayashi, 2006). We also examine the seasonal variation of convective available potential energy (CAPE) and convective inhibition energy (CINE) at Guwahati as the index of thermal instability. The qualitative evaluation of these climatological aspects will provide useful information for understanding the mechanism of the occurrence and development of HRF events, leading to forecasting and mitigating damage across NEI. The data used and the methodology employed are described in Section 2, Section 3 provides a description of rainfall features during pre-monsoon and monsoon season, while some gross characteristics of the HRF events and their trends are discussed in Section 4. Section 5 presents a climatology of severe TSs and thermal instability over the region. Results are summarized and the relevance of the findings is highlighted in Section 6.

2. Data and methodology

Following Soman and Krishna Kumar (1990), in what follows, we use the term ‘rainy day’ to indicate a day on which a measurable amount of rain (0.1 mm or more) has been recorded at any station. At rain gauge stations in India, the rainfall for a day is reckoned as the rain amount collected from 0300Z (0830 IST) of the previous day to 0300Z of that day. The rainfall is measured correct to 0.1 mm. We shall use the term ‘rain intensity’ to indicate the 24 h rainfall amount. For the present study we use daily rainfall data at several stations in NEI obtained from the IMD. Historical daily rainfall data are available from 1901 to 2007 for 48 weather stations within the states of NEI. The numbers of stations at which data are available vary from year to year. Between 1971 and 2007, we have data for maximum number of stations over NEI. Hence for formulating the criteria for the identification of HRF events and deriving the probability of occurrence we consider the period 1971–2001. The data for certain years in the early part of 1970s and for very recent years were missing from the data obtained from National Data Center, IMD, Pune. We augmented the recent data by copying that data directly from journal records available at Regional Meteorological Centre, India Meteorology Department, at Guwahati. In this manner, we have constructed reasonable continuous daily accumulated precipitation data over 15 stations for 31 years (1971–2001). Prior to creating the daily databases, individual station data time series were evaluated for potential irregularities through time; weather stations with 30% or more missing daily data were eliminated. The data was passed through some gross quality control checks such as removing all negative values and all exceptionally large values that may have occurred due to human error of missing a decimal point etc. In addition, stations with gaps of three or more years in between series were also discarded as were stations with clearly erroneous precipitation values. Then from the daily data we created the annualized data with the criteria that an individual year would be considered missing if more than 10% of the daily data were missing in a given year throughout the period 1971–2001. Even though the mean rainfall during the pre-monsoon months of April and May are not very large, severe TSs known as Nor’westers (locally also known as ‘Bardoiseela’) devastate this region during these 2 months. Also summer monsoon tends to extend till October over this region with significant amount of rainfall occurring during October (Parthasarthy *et al*., 1987). Therefore, we have considered the period of April to October to examine HRF events over the region. In the end we were left with 15 stations located throughout NEI with elevations averaging 345.25 m, ranging from 16–1500 m above mean sea level. Our network of stations averaged 225 cm of rainfall per season (April–October) with a spatial range from 105.3 to 404.56 cm per season. When averaged across the study area, the mean seasonal rainfall shows small variability from year to year with a range from 371.19 cm in 1984 to 175.79 cm in 1992.

2.1. Identification of intense rainfall events

We first consider how heavy the daily rainfall has to be for it to be considered as a HRF event over NEI. Objectively, we define HRF events as those exceeding the 99th percentile. Therefore, one metric is the aggregate of number of events exceeding the 99th percentile over all 15 stations every year. Table I shows that even within these 15 stations there is considerable variation in the climatological mean rainfall and hence rainfall representing the 99th percentile. Table II shows the percentage of days with rainfall above given threshold during April–October (AMJJASO) at one or more stations in NEI. Over the region, rainfall of 5 or 10 cm d^{-1} is not a rare event. For the present study we find that on about 96% of days rainfall exceeds 0.01 cm d^{-1}. It is seen from the table that rainfall above 5 cm d^{-1} at one or more stations in a season is expected to occur on about 50% of rainy days and above 10 cm d^{-1} on about 16% of rainy days. Thus, events of up to 10 cm d^{-1} occur frequently and hence people must have evolved effective methods of managing their impacts. Therefore, the threshold for defining a HRF event must be larger than 10 cm d^{-1}. Hence, we define another metric of extreme rainfall events as those events with more than 15 cm rainfall per day. Additionally, we

Table I. Station names (short form), their location, total seasonal rainfall and 99th percentile of daily values.

Station name	Latitude °N/ Longitude °E	Total seasonal rain (mm) (decreasing order)	99th percentile of daily rain (mm)
Passighat (PGT)	28.07/95.34	3944.94	190
Dibrugarh (DIB)	27.48/95.02	3110.44	166.67
North Lakhimpur (NLP)	27.29/94.10	2989.14	115.92
Silchar (SLC)	24.91/92.98	2802.14	114.75
Dhubri (DHB)	26.15/90.13	2542.34	169.65
Kailashahar (KSH)	24.31/92.01	2401.89	114.00
Chaparmukh (CHP)	26.20/92.52	2204.48	165.68
Shillong (SHL)	25.57/91.88	2045.06	129.01
Majbat (MJB)	26.75/92.35	1913.65	106.08
Agartala (AGT)	23.89/91.24	1882.65	108.77
Tezpur (TZP)	26.62/92.78	1644.04	80.00
Guwahati (GHT)	26.12/91.59	1568.14	88.94
Kohima (KOH)	–	1469.84	63.86
Imphal (IMP)	24.76/93.90	1204.13	63.39
Lumding (LMD)	25.75/93.17	1102.00	78.35

find that, on an average, events with intensity greater than 25 or 35 cm d^{-1} are expected to occur only 2 d and 1 d per season, respectively. In fact no station received rainfall above 25 cm d^{-1} in 8 out of 31 years and rainfall above 30 cm d^{-1} in 15 out of 31 years. Hence, if the threshold is chosen as 25 or 30 cm d^{-1}, there will not be sufficient number of cases available for studying the associated systems. Therefore, the threshold chosen for identifying intense rainfall events have to be between these limits. So we consider thresholds of 15 and 20 cm d^{-1} as HRF events.

2.2. TS and Nor'wester data

TSs, as defined in the synoptic code, are frequent lightning events accompanied by thunder with or without localized torrential rain. This category is extended for Nor'westers to include damaging wind gusts greater than 20 knots. Hail is included in this definition as this can also cause damage. We used TS data archived by the Regional Meteorological Centre, IMD, Guwahati, for the available meteorological observatories for the period 1991–2001, and constructed a climatology of severe TS activity over the region.

Table II. Percentage of days with rainfall above given threshold during April–October at one or more stations in northeast India.

Threshold cm d^{-1}	Percentage of days with rain above the threshold
>0.01	95.92
>5	49.11
>10	15.66
>15	6.00
>20	2.68
>25	1.01
>30	0.55
>35	0.28

2.3. CAPE data

The IMD upper air sounding data for the period 1973–2001 were used for the calculation of CAPE and convective inhibition energy (CINE) at Guwahati. The IMD data sets are archived for 0000 UTC and 1200 UTC everyday. The choice of the station was due to the availability of continuous upper air data, twice daily. (The other two stations in NEI with upper air sounding data do not have a continuous data set.) In this study, CAPE is calculated two times a day for Guwahati and the daily CAPE was made of the average of these two values. Also only non-zero CAPE values were selected because we considered only situations with convection. Monthly CAPE is the monthly average of daily CAPEs and annual cape is the seasonal (AMJJASO) average of daily CAPE. In calculating CAPE, we chose to use a parcel with thermodynamic properties averaged over the lowest 100 hPa as applied in many past studies (e.g. Brooks *et al*., 1994; Craven *et al*., 2002) and the integral was carried out from the Level of Free Convection (LFC) to 300 hPa.

3. Rainfall over NEI

NEI is one of the regions which receives very HRF during the pre-monsoon and summer monsoon season. Average monsoon rainfall (April–October) over parts of Meghalaya, Assam and Arunachal Pradesh exceed 250 cm. Figure 3(a) and (b) shows the variation of average daily rainfall over NEI during two summer seasons with good and bad seasonal rainfall. Rainfall over the region shows variability within the season, with long active spells of HRF and short weak spells with little or no rainfall. The duration of active/weak spells as well as the intensity varies from year to year. On many occasions, at some stations, rainfall exceeds 20–25 cm d^{-1} and occasionally 30 or even 40 cm d^{-1}. These HRF events cause extensive damage in the plains. In the present work, the characteristics of extreme rainfall events are

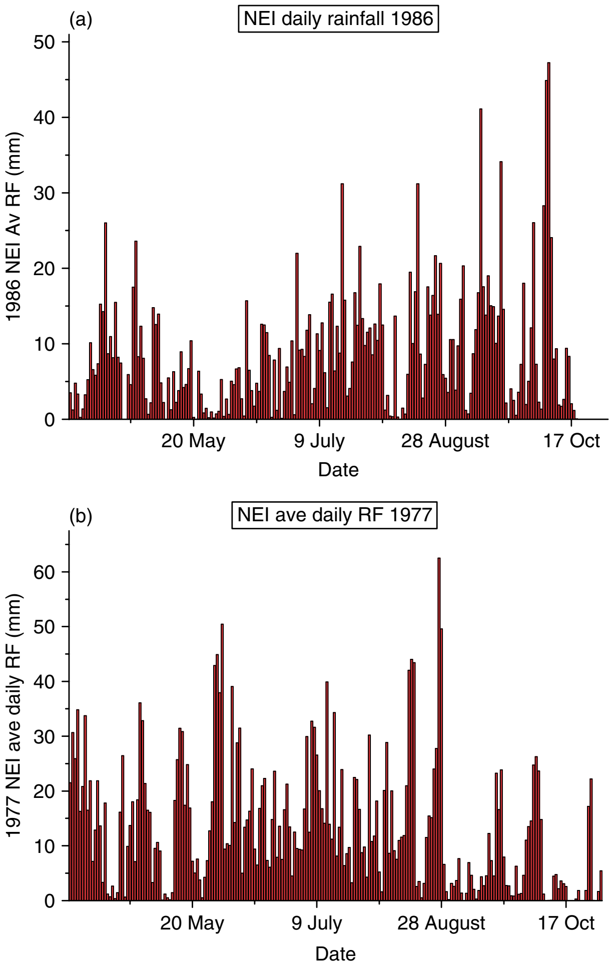

Figure 3. JJAS average daily rainfall over northeast India for (a) a year with good seasonal rainfall and (b) a year with poor seasonal rainfall.

studied. The rainfall over the region varies from station to station and at any station it varies on daily, seasonal and interannual scales. The variation of the rainfall in some stations for years with good rainfall and years with poor rainfall are shown in Figures 4(a)–(e) and 5(a)–(e). At stations like Lumding, rain occurs only for few days. However, occasionally these stations receive very HRF, exceeding even 40 cm in a day. At high altitude stations like Shillong, wet spells tend to be longer and often comprise days with heavy rain. Over the central parts of the region along the river Brahmaputra, even though some rainfall occurs on most days, the chance of HRF events is lower. Figure 5(a)–(e) shows the daily rainfall of the same stations as in Figure 3 for years with low rainfall. It is seen that in 1998, Lumding received very low rainfall and there was not even a single event above 10 cm d^{-1}. Even though the intensity of rainfall at Pasighat was less in 1992, there were well-marked wet spells separated by weak spells as in 1988. Similarly at Guwahati, active and weak spells of rainfall were seen in 1977, as in 1979, but rainfall above 10 cm d^{-1} was observed less frequently and above 15 cm d^{-1} did not occur at all. At Agartala, in 1982, the number of days with some rain above 5 cm d^{-1} was much smaller than in 1993 and there are rather long weak spells during the period. Pasighat records the largest number rainy days per season (Figure 6). Chaparmukh gets the least number of rainy days in a season but gets the highest average rainfall on a rainy day. The mean rainfall per season is the maximum for Pasighat being 405 cm. Imphal and Lumding get the minimum seasonal rainfall being 112 and 115 cm per season. However, the average number of rainy days in a season for Imphal is almost 120. The average rainfall on a rainy day is the maximum for Chaparmukh being almost 3 cm d^{-1} and Imphal receives the minimum average rainfall on a rainy day. For Shillong even though the average number rainy days in a season are large, its average rainfall on a rainy day is around 14 cm.

4. HRF events over NEI

- Over NEI the daily mean rainfall per season is about 1.1 cm with a standard deviation of 0.45 cm.
- For the region as a whole, July records the largest number of HRF events followed by June and August. April records the least number of HRF events. These events occur more frequently in October than in April and May (Figure 7). Also June and August gets almost 22 and 21% of the total HRF events in a season.
- The mean seasonal (AMJJASO) rainfall over the region is 227 cm with a range of 195 cm and a standard deviation 38 cm.
- For Tezpur and Guwahati, HRF events with rainfall above 20 cm d^{-1} do not contribute to the station rainfall, but 0.1% of HRF days with rainfall 15 cm d^{-1} contributes around 1% of seasonal rainfall.
- For Shillong on average 0.2% days with rainfall above 20 cm d^{-1} contributes around 3.5% of the seasonal rainfall (AMJJASO) and 0.4% of events with rainfall 15 cm d^{-1} contributes around 5% of seasonal rainfall.
- For Pasighat on average around 0.8% days with rainfall above 20 cm d^{-1} contributes around 8% of seasonal rainfall and 1% days with rainfall above 15 cm d^{-1} contributes around 7% seasonal rainfall.
- For Silchar, Kailasahar and Agartala days with rainfall above 20 cm d^{-1} comprising around 0.2% days contributed between 2 and 4% of the seasonal rainfall. Again for these three stations contribution from HRF days to seasonal total is about 2%.
- During the period 1971–2001, Pasighat records the highest number of HRF events per year followed by Dibrugarh and Rupsi, Kohima, Lumding and Tezpur get the least number of HRF events in a year.
- The frequency of HRF events vary from station to station. For example, for Pasighat, the maximum frequency is for the month of July (28 events), followed by the months of June (21) and August (20).
- For the study period there were no events in the month of April. Shillong also records the highest number of HRF events in the month of July followed by June. October also records around 20% of HRF events. The month of April is free of such events.

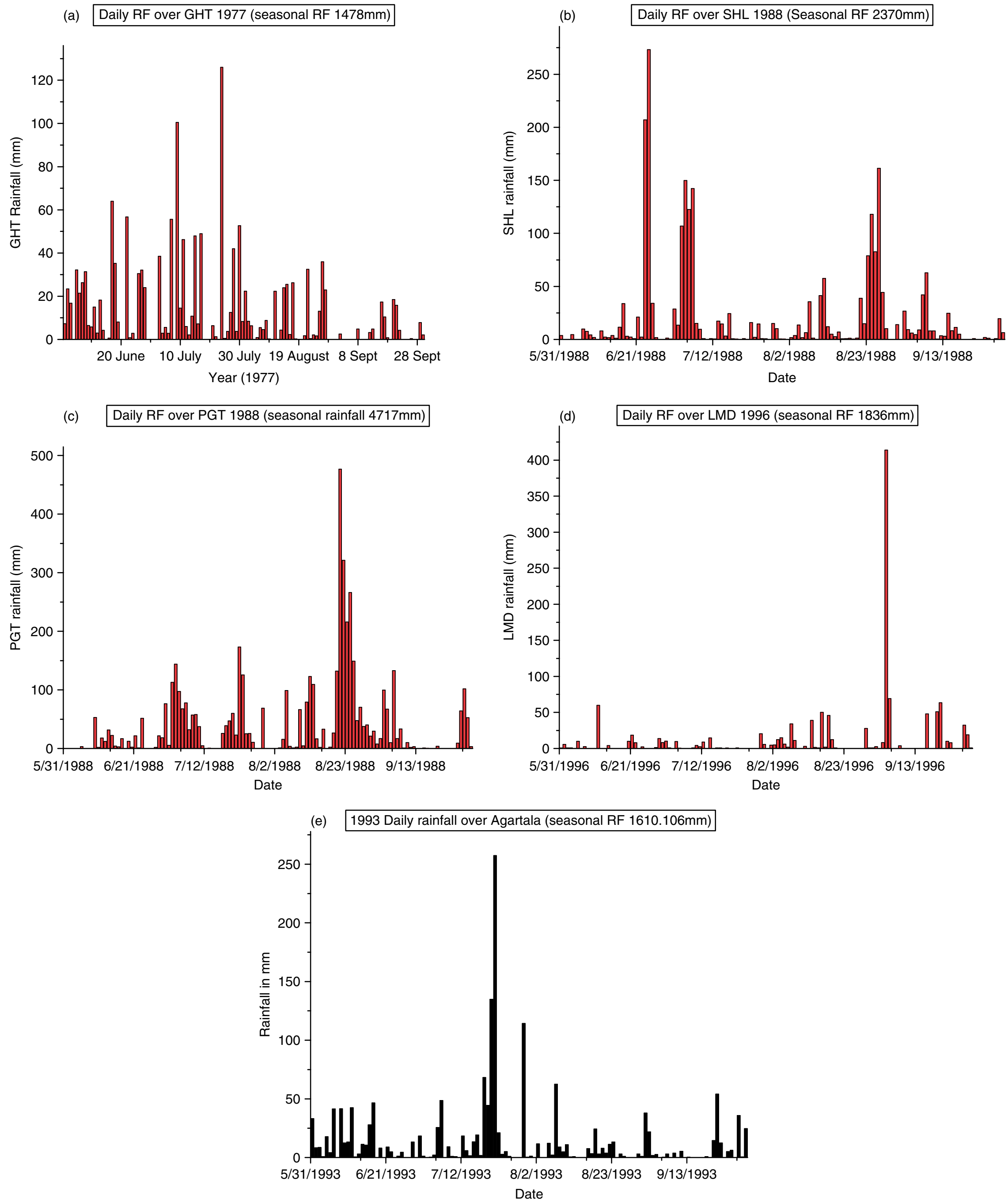

Figure 4. Daily rainfall at some stations in some years with high seasonal rainfall (a) Guwahati, (b) Shillong, (c) Pasighat, (d) Lumding and (e) Agartala.

The temporal variation of the aggregate of HRF events over the region shows a decreasing trend over the period under consideration as shown in Figure 8(a) and (b). The decreasing character is spatially pervasive as it is seen in almost all stations. The decreasing trend of extreme events is rather interesting as it is in contrast to the increasing trend of HRF events in Central India (CI) (Goswami *et al*., 2006).

4.1. When and where are HRF events likely to occur?

Next, we consider the temporal and spatial distribution of HRF events to get information about the most favourable time and location of these events. The probability of getting rainfall above thresholds of 15, 20, 25 and 30 cm d^{-1} at one or more stations over NEI in each week during the period April–October is shown in the Figure 9(a) and (b). The maximum probability of getting rainfall above 25 and 30 cm d^{-1} in any week is less than 5%. Events with rainfall above 15 or 20 cm d^{-1} in a week are not so rare. From the figure it can be seen that between the 10th and 17th week (10 June and 5 August), the chance of getting rainfall above these thresholds is high. Within this period, there are three peaks in the probability of occurrence for most of the threshold. One peak occurs in

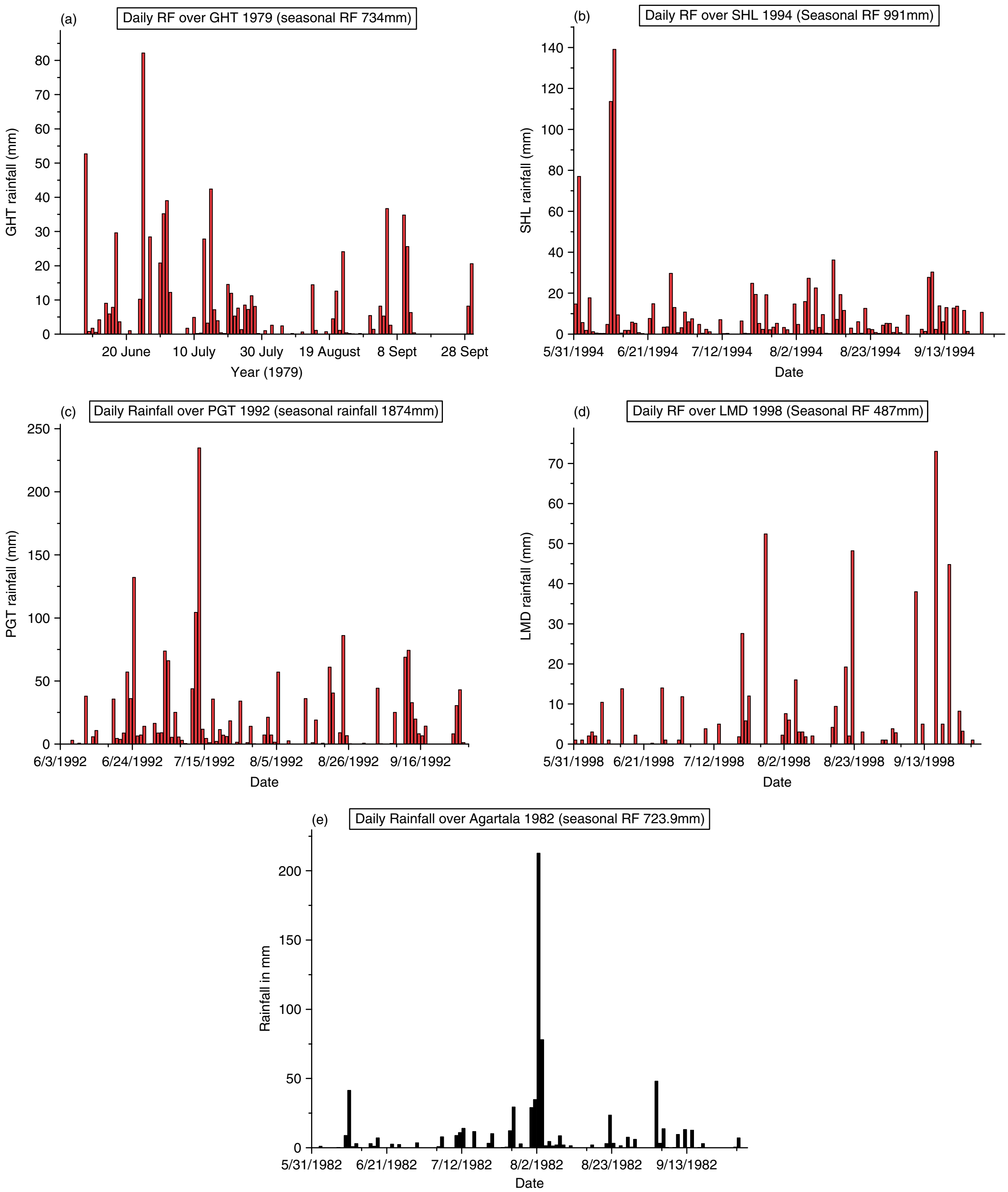

Figure 5. Daily rainfall at some stations in some years with poor rainfall at (a) Guwahati, (b) Shillong, (c)Pasighat, (d) Lumding and (e) Agartala.

the middle of June and the other two peaks at the last two weeks of August. The probabilities of all the thresholds show a dip in the second week of July. In September, the probability for each threshold is low and decreases progressively.

The probability of at least 1d or 2 d with rainfall above 20 cm d^{-1} in the given period starting on the specified date is shown in Table III. From the table

- In 23.3% of years (8 out of 31 years), at least one of the stations reported rainfall above 20 cm on at least 1 d in the period of 1 week starting on 1 June. Obviously the probability increases as the period increases, being 70% for the 6-week period starting on 1 June.
- The probability is maximum at about 87% for the 6 weeks starting on 8 June or 15 June and is high – about 73% for commencement in the previous or next week. The probability decreases towards the end of the season. Considering the probability of getting at least 2 d with rainfall above 20 cm d^{-1}, we find that there is about 58% chance in the 6-week period starting from 15 June and 22 June.

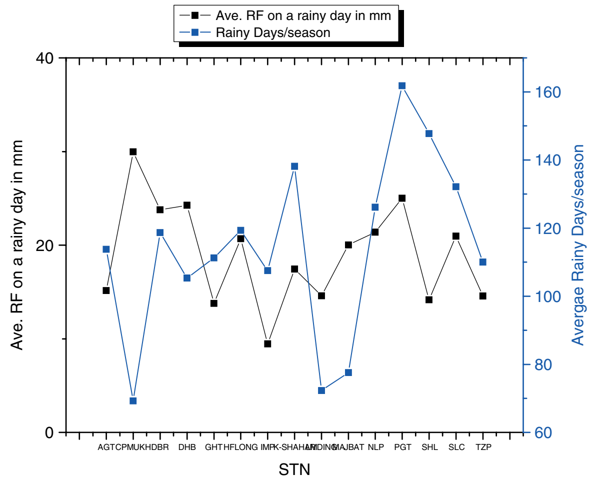

Figure 6. Station-wise distribution of average rainfall on a rainy day and average rainy days each season.

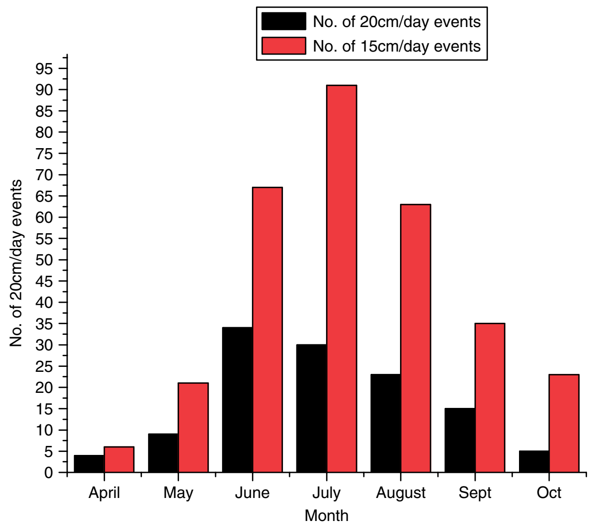

Figure 7. Total number of extreme events (daily precipitation >15 cm) counted over the region for the whole period for each month from April to October.

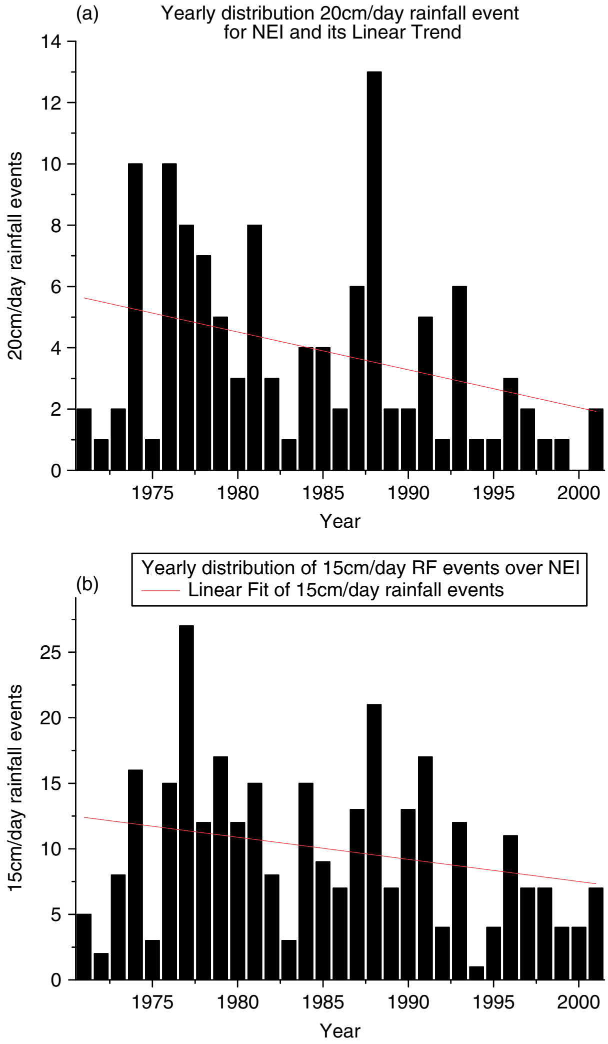

Figure 8. Number of events exceeding (a) daily rainfall of 15 cm d^{-1} and (b) daily rainfall of 20 cm d^{-1} and their linear trend for the period 1971–2001 in NEI.

The probability of occurrence of HRF events is not the same for all the stations over NEI. In fact, it varies a great deal, depending upon the geographical location of the station. The variation of the expected number of days with rainfall above 15 cm d^{-1} and 20 cm d^{-1} in a season at stations at different latitudes is shown in Figure 10(a) and (b). The maximum expected number of days is about 1.5 d in a season for a threshold of 15 cm d^{-1} and about 1 d in a season for a threshold of 20 cm d^{-1}. The maximum probability is found for the stations between 27.5 and 28.1 °N. These stations are at the foot hills of eastern Himalayan range. There is a secondary peak in the probability near Dhubri. The chance of getting HRF is very small at the stations along the Brahmaputra valley. The latitudinal variation of probability of rainfall above the 20 cm d^{-1} threshold is similar to that of 15 cm d^{-1} threshold.

4.2. Contribution of different rainfall classes to total rainfall

We consider next the contribution to total rainfall by rainfall of different intensities over NEI. Percentage of days with rainfall in specified limits and the contribution to total rainfall at each station by different rainfall classes are given in Tables IV and V. Eight out of 15 Stations received rainfall between 0.01 and 5 cm d^{-1} above 90% of rainy days, the highest being at Imphal and Kohima for about 97–98% of days, all stations received rainfall between 0.01 and 5 cm d^{-1} for more than 80% of rainy days.

At stations like Imphal and Kohima rainfall between 0.01 and 5 cm d^{-1}, occurring on 97–98% of days contributes more than 84% of the rainfall. The contribution of rainfall decreases rapidly with increase in the minimum limit of rainfall. For example Guwahati, where 24.37% of mean seasonal rainfall is contributed by events between 5 and 10 cm d^{-1}, but only 3.9% for rainfall between 10 and 15 cm d^{-1}. For stations like Chaparmukh, Pasighat,

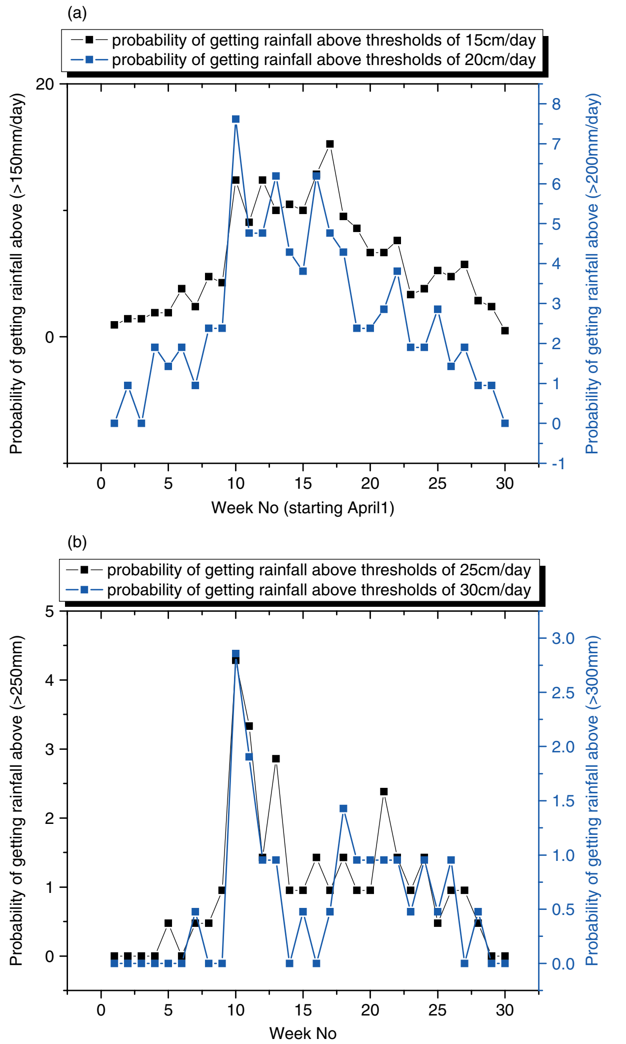

Figure 9. The probability of getting rainfall above thresholds of (a) 15 and 20 cm d^{-1}, (b) 25 and 30 cm d^{-1} at one or more stations in NEI in each week from 1 April to 31 October.

Mazbat and North Lakhimpur, 30–33% of total rainfall is from days with rainfall above 5 cm d^{-1}, which accounts for 10–14% of rainfall days. For Dibrugarh, Pasighat, Chaparmukh and Shillong, days with rainfall above 15 cm d^{-1} contribute between 5 and 8.5% of total rainfall. The percentage of days with rainfall above 15 cm d^{-1} is also the highest in these stations (0.4–1.2% of days). In Lumding on average 2.52% of the rainfall is contributed by rainfall events >40 cm d^{-1}, followed by Silchar, which receives about 1.5% of seasonal rainfall from events >40 cm d^{-1}. Kohima receives about 1.5% of the rainfall from events of (35–40) cm d^{-1}, which occurs on about 0.1% of days. Dibrugarh gets 1.71% of the rainfall from events (30–35) cm d^{-1} that occur on about 0.12% days.

5. Severe TSs and thermal instability over NEI

Mesoscale disturbances like severe TSs, including tornadoes, damaging hail and wind gusts, frequently occur in NEI (e.g. Peterson and Mehta, 1981, 1995; Goldar

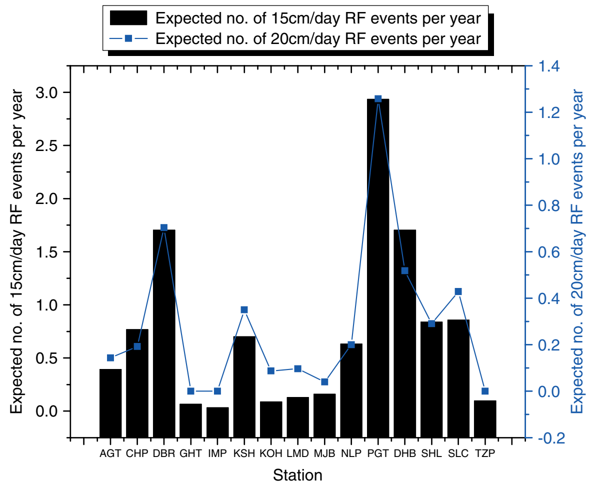

Figure 10. Variation of expected number of days with rainfall above 15 and 20 cm d^{-1} at various stations.

et al., 2001) and cause loss of life and property almost every year. These mesoscale disturbances are locally called Nor'westers in NEI, which is derived from TSs coming from the northwest direction. While many of these HRF events occur associated with the pre-monsoon Nor'westers, some severe TSs may occur during the monsoon season. The climatology of severe TSs has been studied by many researchers. Fujita (1973) studied the spatial distribution of tornadoes in the world and has shown that in South Asia, the place of tornado occurrence concentrates only over the northern and northeastern area of the Indian subcontinent. We studied the distribution of severe TSs over NEI. Figure (11) shows monthly frequency of Nor'westers in NEI from 1991 to 2006. About 70% of Nor'westers occur in the pre-monsoon season (from March to May) and the largest number occurs in April. And we compared the seasonal variations of CAPE with the seasonal variations of severe TSs in NEI. The temporal distribution of thermal instability is evaluated for Guwahati in order to provide a qualitative interpretation of the climatological features of HRF events from severe TSs in NEI. The seasonal distribution of CAPE and CINE are examined at Guwahati as a representative station in the region.

5.1. TS distribution

TSs occur over the region during the period from January to October. The monthly distribution of severe TSs days (Figure 12(a)), shows that the number of thunderstorms recorded in November and December is very small compared with the remaining months. The TS activity begins perceptibly in February, gradually attains a maximum in July, and subsides only slightly during the months of August–September to dwindle gradually by the end of October. The areas of highest TS activity are the valley stations. Tezpur has the highest TS activity exceeding 115 d in a year; the average over Guwahati is almost 100 d in a year, Mohanbari has an average of 80 d and Imphal 65 d. The lowest value of 50 d is found

Table III. Probability of getting rainfall above 20 cm d^{-1} – at least 1 or 2 d in the given period (JJAS).

Starting date	Probability (%) of heavy rainfall (HRF) events							
	1 d in the period				2 d in the period			
	1 week	2 weeks	4 weeks	6 weeks	1 week	2 weeks	4 weeks	6 weeks
1 June	23.3	33.3	56.6	70	9.68	19.35	41.94	41.56
8 June	16.7	40	53.3	86.6	9.68	22.58	32.26	48.39
15 June	30	50	66.6	86.6	9.68	25.81	35.48	58.06
22 June	30	40	50	73.3	9.68	19.35	41.94	58.06
29 June	23.3	36.6	66.6	73.3	6.45	9.68	41.94	51.61
6 July	16.7	56.6	73.3	83.3	0	9.68	29.03	41.94
13 July	40	50	66.6	73.3	9.68	22.58	38.71	25.81
20 July	20	36.6	56.6	73.3	12.9	19.35	32.26	35.48
27 July	20	33.3	43.3	63.3	6.45	12.9	22.58	29.03
3 August	20	33.3	50	53.3	6.45	12.9	19.35	25.81
10 August	20	20	46.6	63.3	0	3.23	16.13	22.58
17 August	3.3	26.6	40	63.3	3.23	9.68	12.9	25.81

Table IV. Percentage of days in different rainfall classes.

Station	% of days with rainfall in different classes(mm d^{-1})								
	>400	350–400	300–350	250–300	200–250	150–200	100–150	50–100	0–50
AGT	0	0	0.03	0.03	0.06	0.22	1.13	5.81	92.72
AIZWAL	0	0	0	0	0	0.05	0.58	5.21	94.16
CPMUKH	0	0	0	0.06	0.22	0.83	2.39	14	82.5
DBR	0	0	0.12	0.12	0.34	0.84	2.09	9.83	86.65
DHB	0	0	0	0.11	0.39	1.16	2.67	10.27	85.41
GHT	0	0	0	0	0	0.06	0.46	4.9	94.58
HFLONG	0	0	0	0	0.25	0.5	1.68	7.54	90.03
IMP	0	0	0	0	0	0.03	0.14	1.95	97.89
KOH	0	0	0.04	0	0.04	0	0.16	2.35	97.41
K-SAHAR	0	0.07	0	0.07	0.14	0.22	1.12	7.09	91.28
LMDING	0.09	0.04	0	0	0.04	0.04	0.27	4.19	95.31
MAJBAT	0	0	0	0	0.05	0.1	1.08	9.33	89.43
NLP	0.03	0	0	0.03	0.11	0.34	1.43	9.86	88.21
PGT	0.04	0.02	0.1	0.1	0.5	1	3.59	11.8	82.85
SHL	0	0	0.02	0.04	0.13	0.39	1.22	3.82	94.37
SLC	0.04	0	0.04	0	0.14	0.32	1.44	8.43	89.59
TZP	0	0	0	0	0	0.09	0.56	4.98	94.37

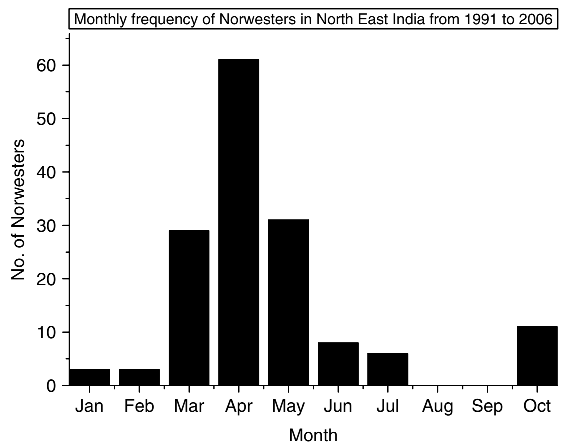

Figure 11. Monthly frequency of Nor'westers in northeast India from 1991 to 2006.

over North Lakhimpur. There seems to be a north–south and an east–west gradient of TS activity over the region. (For its detection we need a higher density of observation stations which will be worked out at a later period). Tezpur also records the highest number of TS events in a year, 318.6 events per year, and the lowest activity is over North Lakhimpur, about 81 events per year.

5.2. Contribution of TS days to total rainfall days

In NEI, each year on average about 40% of the total rainfall days are contributed by TS days. This contribution is maximum in the month of April (about 80%) and minimum in January (about 13%) as shown in Figure 12(b). On a seasonal scale, for the pre-monsoon season (MAM), on average TS days account for 66% the total rainfall

Table V. Contribution to total rainfall by different rainfall classes.

	% contribution to total rainfall by different classes (mm d^{-1})								
Station	0–50	50–100	100–150	150–200	200–250	250–300	300–350	350–400	>400
AGT	60.75	25.9	8.76	2.47	0.93	0.53	0.65	0	0
CPMUKH	50.37	32.66	10.08	4.75	1.59	0.55	0	0	0
DBR	48.14	28.6	10.9	5.98	3.2	1.46	1.71	0	0
DHB	45.65	28.42	13.09	8.25	3.48	1.11	0	0	0
GHT	71.03	24.37	3.88	0.72	0	0	0	0	0
IMP	84.98	13.02	1.55	0.45	0	0	0	0	0
KOH	84.93	11.92	1.42	0	0.7	0	1.03	0	0
K-SAHAR	58.76	27.2	7.56	2.02	2.02	0.93	0	1.53	0
LMDING	74.73	18.58	1.91	0.48	0.69	0	0	1.1	2.52
MAJBAT	60.77	31.59	6.29	0.82	0.53	0	0	0	0
NLP	56.71	30.69	7.87	2.72	1.08	0.32	0	0	0.61
PGT	35.94	32.4	17.35	6.72	4.44	1.1	1.06	0.29	0.71
SHL	63.55	18	10.32	4.68	2.09	0.84	0.51	0	0
SLC	58.64	27.11	8.14	2.4	1.59	0	0.59	0	1.53
TZP	71.9	22.45	4.63	1.01	0	0	0	0	0

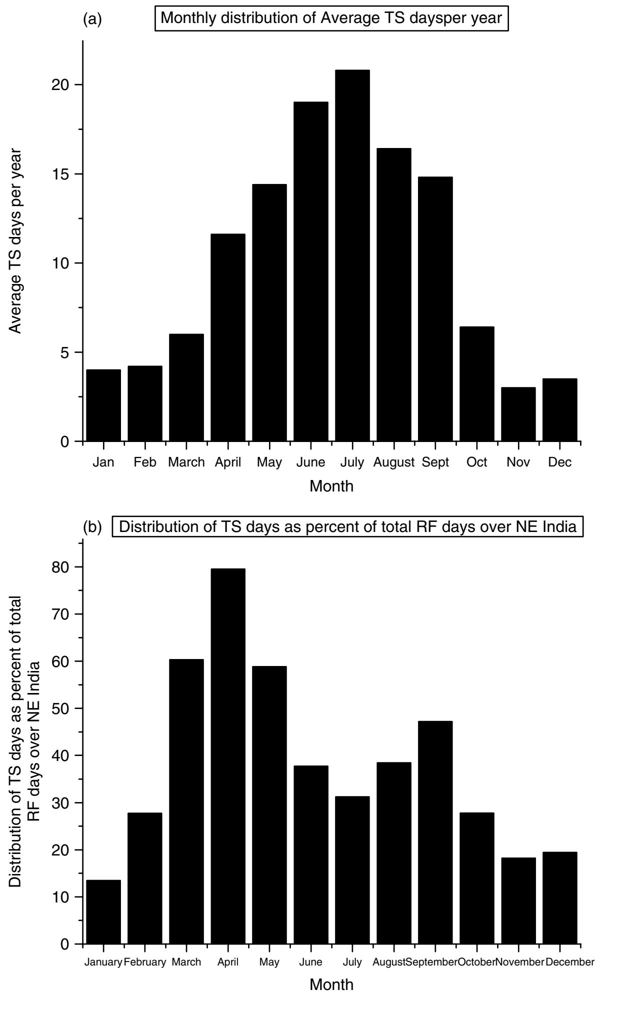

Figure 12. Average monthly occurrence of thunderstorm days in northeast India for the period 1991–2001. (a)Monthly distribution of average TS days per year and (b) distribution of TS days as percent of total RF days over NEI.

days, and for the summer monsoon season, (JJAS), 39% of the total rainfall days are TS days.

5.3. Nor'westers (tornadoes)

Nor'westers are severe TSs that normally dominate the weather in the eastern part of India between March and pre-onset of summer monsoon. Violent squalls, on the average one per week, with speeds exceeding 40–50 knots on many occasions occur in association with TSs, particularly during March, April and May. The directions of these squalls (Nor'westers), although predominantly north–northwesterly, vary from west northwesterly to northeasterly. Sometimes, squalls coming from southerly or southeasterly directions, attaining a maximum speed of 50 knots, have been observed. Severe squalls with TSs also occur in September and October, even when the monsoon is withdrawing. The month-wise frequency distribution of Nor'westers is shown in Figure 11.

5.4. Seasonal distribution

The dry season accounts for around 7%, and the post-monsoon season accounts for 6% of total annual TS days. The pre-monsoon months of March, April and May account for about 40% and monsoon season accounts for nearly 50% of annual total TS days.

Winter: TS activity is markedly low in the winter season. During this season, the TS activity is confined to the valley stations of Mohanbari, Tezpur and North Lakhimpur. In January TS activity is lowest with practically no TSs over Imphal, elsewhere the frequency is 1–2 d, except Mohanbari, where it is nearly 3 d. In February there is a general increase in the number TS days over all the stations. In northeast Assam, over Mohanbari and Tezpur, the monthly average exceeds 4 d. An average of 3 d is noted for the entire region.

Pre-monsoon: The hot weather period (pre-monsoon season) is known for the intense convective activity and near adiabatic lapse rates over a large portion of the country. Maximum TS activity is observed over Guwahati and Tezpur with about 66–70 d of thunder.

Monsoon: A noteworthy feature of the monsoon season (June–September) is the large scale TS activity over NEI. More than half of the days this season are days of TS. The highest frequency is reported from Tezpur. During monsoon season Imphal and North Lakhimpur get the least TS activity. The average TS days for June persist till the monsoon withdraws from the region.

Also the pattern is similar from May to September. Occurrence of TSs on a large number of days during the monsoon months is an interesting feature of the weather over the region. There may be a possibility that breaks in the monsoon and passage of an upper air trough stimulates considerable TS activity over NEI for many days, but will not be discussed in this paper. For the season AMJJASO, almost 50% of the total rainfall days comprise of TS days.

5.5. CAPE analysis

We compared the seasonal variations of CAPE with the seasonal variations of severe local storms in NEI. The grid point 91.6 °E, 26.1 °N was selected as a typical grid point in NEI and the seasonal and interannual variation of CAPE and CINE at this point was investigated. The selection of the station for CAPE calculations was guided by the availability of upper air radiosonde data. For the grid point, we have continuous data from 1973–2007. Figure 13 shows the monthly distribution of CAPE at 91.6 °E, 26.1 °N (based on the daily upper air soundings at two times a day (0000 UTC, 1200 UTC) from 1994 to 1998). Monthly CAPE is the monthly average of daily CAPEs. In calculating CAPE, we chose to use a parcel with thermodynamic properties averaged over the lowest 100 hPa as applied in many past studies (e.g. Craven *et al.*, 2002; Brooks *et al.*, 2003) and the integral was carried out from the Level of Free Convection (LFC) to 300 hPa. In this study, CAPE is calculated two times a day for Guwahati and non-zero CAPE values were selected because we considered only situations with convection. Mean monthly CAPE increases gradually from January and peaks in September and thereafter decreases sharply in the post-monsoon season. The CAPE data for the months of April and May show similar values. Monthly mean CAPE is not zero for any of the months. In a year, daily CAPE is increasing from late February and has two peaks, one before the monsoon onset in April–May, second peak appears after monsoon is fully established over the region and stays more or less constant for the monsoon season, third peak appears in August–September while decreasing gradually in the post-monsoon season (Figure 14(a)). In the dry season (from December to February) daily CAPE is very low (around 0 J kg^{-1}). Figure 14(b) shows that the CINE value decreases continuously from April till first week of July and thereafter it stays almost constant.

We also calculated the annual CAPE and CINE averaged during April–October for the station at Guwahati between 1973 and 2001. Interestingly, the CAPE calculated has a decreasing trend while the average CINE has a strong increasing trend in Guwahati (Figure 15(a) and (b)). However, the CAPE calculated for 0000 UTC sounding has a larger gradient of decrease than the 1200 UTC sounding. This indicates that over northeast

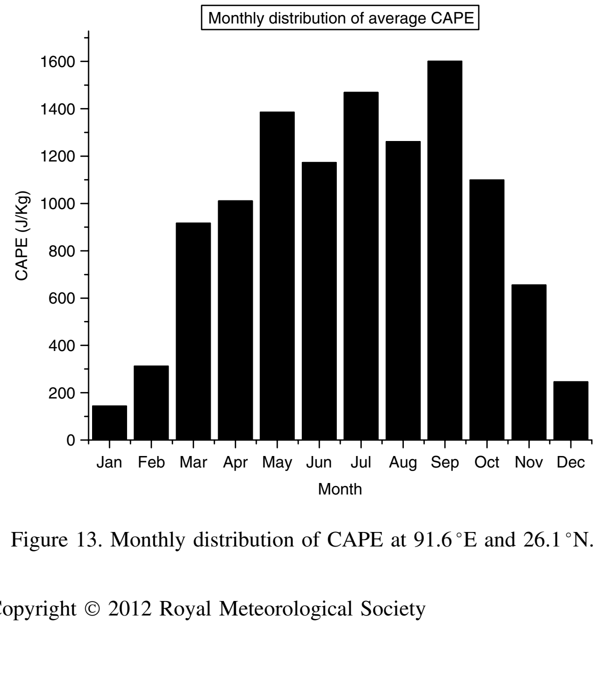

Figure 13. Monthly distribution of CAPE at 91.6 °E and 26.1 °N.

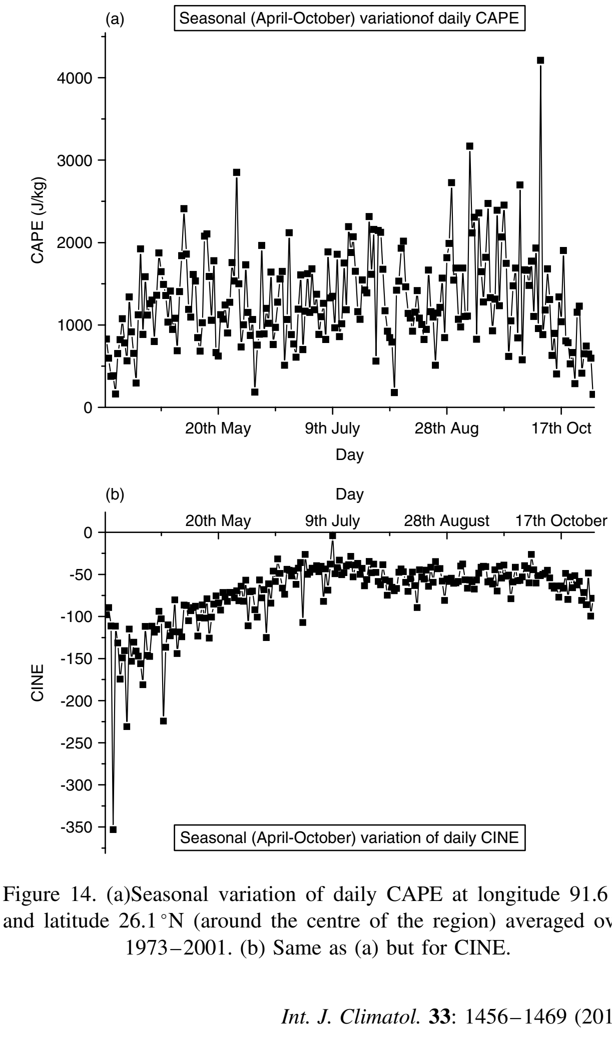

Figure 14. (a)Seasonal variation of daily CAPE at longitude 91.6 °E and latitude 26.1 °N (around the centre of the region) averaged over 1973–2001. (b) Same as (a) but for CINE.

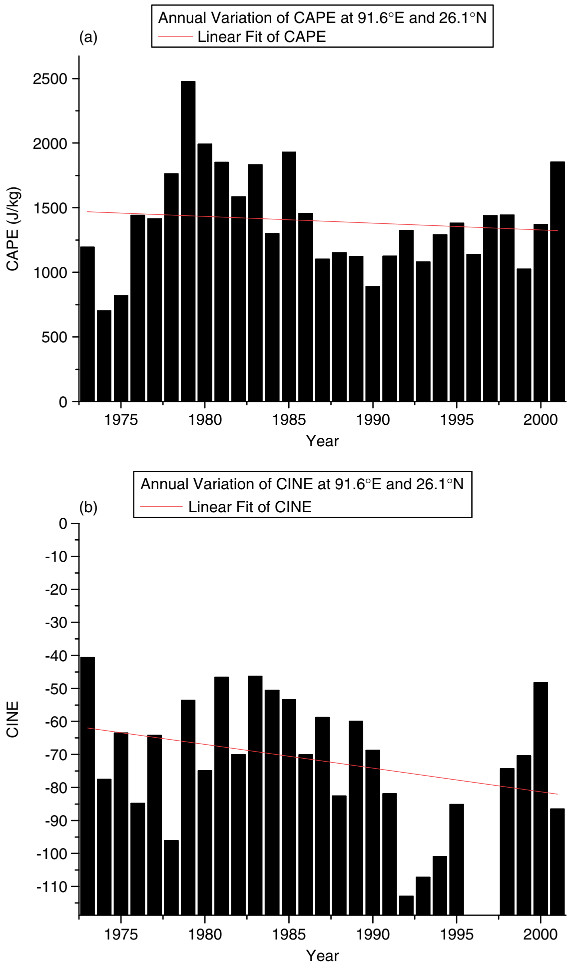

Figure 15. (a) April–October CAPE over Guwahati between 1973 and 2001 and its linear trend calculated from IMD upper air sounding data. (b) Same as (a) but for CINE.

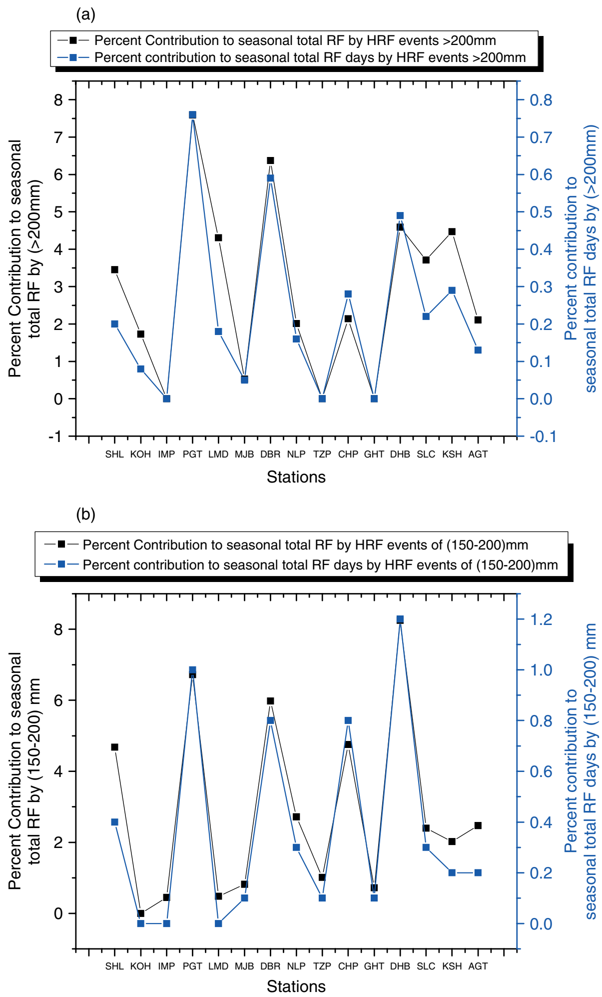

Figure 16. Percentage contribution to seasonal rainfall and rainfall days by HRF events of intensity: (a) >200 mm d^{-1} and (b) 150–200 mm d^{-1}.

India, not only the atmosphere is becoming more stable but also inhibition is increasing making it difficult to realize the available energy. Our results show that the thermal instability is quantitatively high for both pre-monsoon and monsoon season and is highest in the month of August in a year in NEI. This indicates that mesoscale disturbances frequently tend to occur in the NEI in the pre-monsoon season and monsoon season.

The cause that CAPE increases in pre-monsoon season in NEI and Bangladesh could be considered as follows: in the pre-monsoon season, the southwesterly wind becomes predominant in the lower troposphere over NEI and Bangladesh. However, the westerly cold flow (subtropical jet) is still prominent in the upper troposphere. So, the lapse rate of temperature between the lower and the upper troposphere is large. On the other hand, the heating of the Tibetan plateau causes relative higher temperature region in the upper troposphere in the monsoon season and the lapse rate of temperature is small. Moreover, the strong southwesterly inflow transports moisture in the lower troposphere from the pre-monsoon season to monsoon season (The Bay of Bengal is on the south west side of this region).

6. Conclusion

From mid-May to early October, with abundant moisture, potential instability, and the presence of mountainous terrain, HRF days are frequent and all the stations recorded HRF (>15 cm d^{-1}) during the period. During the monsoon season, especially in June–July, these events are more widespread than in other months, followed by August. It seems the orographic effects are important in determining the spatial distribution of HRF occurrences with a pronounced high altitude maximum, especially during the summer months under the southwesterly monsoon flow. After the summer–autumn transition, HRF days are almost non-existent under the northeasterly monsoon flow. The HRF events are infrequent during the winter months because of stable atmospheric stratification with low moisture content. Severe TS accompanied by HRF events start in mid-April and early May and become more frequent in late summer and early autumn. During the analysis period, HRF occurrences are widespread and dominated by HRF events of intensity 30 cm d^{-1} after the establishment summer monsoon. For the season AMJJASO, almost 50% of the total rainfall days comprise of

TS days in the NEI stations. For most of the days starting from March till October, the atmosphere over NEI has high value of CAPE, indicating that there are few (no) days during the pre-monsoon and monsoon season without thermal instability being present in the atmosphere. However, there is a decreasing trend of CAPE and an increasing trend of CINE between 1973 and 2001. The result qualitatively indicates that the environment of NEI during a year, especially in the pre-monsoon and monsoon seasons have a greater potential for HRF events accompanied by local severe TSs. However, the thermal instability is maximum in September and both HRF events and TS activity peaks in July. Thus, the fact that even with large CAPE values fewer TSs or HRF events have occurred shows that factors other than CAPE are also important in the genesis of such systems over the region. Apart from high CAPE, operation of certain trigger mechanism is necessary to release this energy, which in turn helps the development of cumulonimbi clouds. Possible trigger mechanism can be solar heating in the lower layers of the atmosphere, low level horizontal convergence, sufficient wind shear, etc.

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