Multiscale interaction with topography and extreme rainfall events in the northeast Indian region

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[1] Flash floods associated with extreme rain events are a major hydrological disaster in the northeast Indian (NEI) region because of the unique topographic features of the region as well as increased frequency of occurrence of such events. Knowledge of the spatiotemporal distribution of these events in the region and an understanding of the factors responsible for them, therefore, would be immensely useful for appropriate disaster preparedness. Using daily rainfall data from 15 stations over the region for 32 years (1975–2006), it is shown that the frequency of occurrence of these events is largest not during the premonsoon thunderstorm season but during the peak monsoon months (June–July–August). This fact together with the fact that most of these events occur during long rainy spells indicate that the extreme events in the NEI region largely occur in association with the monsoon synoptic events rather than isolated thunderstorms. We also find that the aggregate of extreme rain events over the region has a significant decreasing trend in contrast to a recent finding of an increasing trend of such events in central India (Goswami et al., 2006). This decreasing trend of extreme events is consistent with observed decreasing trend in convective available potential energy and increasing convective inhibition energy over the region for the mentioned period. Examination of the structure of convection associated with the extreme rain events in the region indicates that they occur through a multiscale interaction of circulation with the local topography. It is found that at all the stations, the events are associated with a mesoscale structure of convection that is embedded in a much larger scale convective organization. We identify that this large-scale organization is a manifestation of certain phases of the tropical convergence zone associated with the northward propagating active-break phases of the summer monsoon intraseasonal oscillation. Further, it is shown that the mesoscale circulation interacting with the local topography generates southward propagating gravity waves with diurnal period. The strong updrafts associated with the gravity waves within the mesoscale organization leads to very deep convective events and the extreme rainfall. The insights provided by our study would be useful when designing models to improve the prediction of extreme events.

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1. Introduction

[2] Monsoon rain has always been of a great significance in the northeast Indian (NEI) region (Figure 1) as the agriculture of the region is mostly dependent upon the natural water resources. The seasonal mean (June–September) rain over the region (approximately 151.3 cm) being much larger than the all India average (86.5 cm) [*Parthasarathy et al.*, 1995] coupled with the local topography makes the region flood prone. In addition to large-scale floods, flash floods associated with extreme rainfall events pose a major threat in the region damaging not only crops but also livestock and property. Therefore, knowledge of the space-time distribution of extreme rain events in the region could be useful for disaster preparedness. However, no good documentation of the space-time distribution of extreme rain events exists over the region because of lack of good high-resolution rainfall data. A high-resolution daily 1° × 1° gridded data set has been constructed by *Rajeevan et al.* [2006] for the period 1951–2004 based on 1803 stations distributed over the country. This data set was used by *Goswami et al.* [2006] to demonstrate that both the frequency of occurrence and intensity of extreme rain events over the central India (CI) show a significant increasing trend, while low and moderate events show a significant decreasing trend over the past 50 years. Unfortunately, the same analysis could not be blindly extended to the NEI region as the number of stations going in

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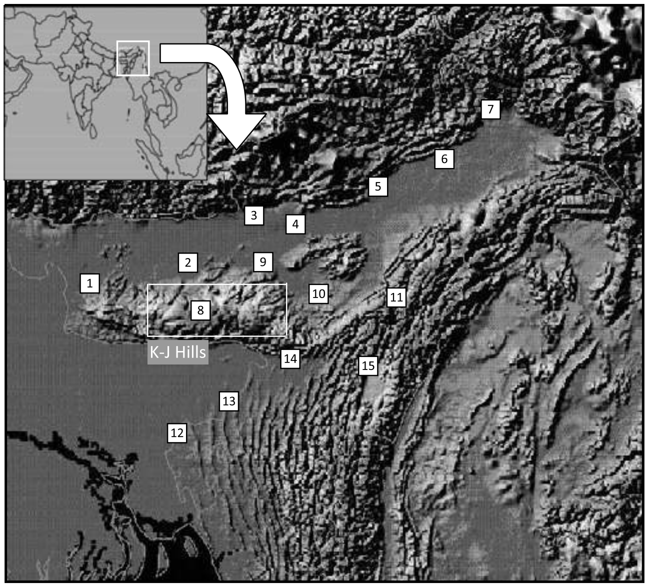

Figure 1. Topographic features of the northeast India (NEI) region and locations of the 15 stations. Inset indicates location of NEI region within the Indian subcontinent.

to each 1° × 1° boxes is rather small [see *Rajeevan et al.*, 2006]. Therefore, the first objective of this study is to examine the trend in frequency of occurrence and intensity of extreme rain events over the region by collecting data from as many stations as possible. As described in section 2, for this purpose, we collected relatively continuous data for a period of 32 years (1975–2006) from 15 stations in the region (see locations on Figure 1). The following questions will be addressed. Is the trend of extreme events over this region similar to that seen over CI? If not, why? Can we relate the observed trend to any large-scale driving forces?

[3] Very little has been done toward understanding causative factors leading to the extreme events over the Indian region. *Francis and Gadgil* [2006] studied intense rainfall events along the west coast of India and concluded that most of the extreme events are associated with large-scale organized convective activity and that the northward propagating tropical convergence zone (TCZ) provides the large-scale environment over which a large fraction of these events occur. *Goswami et al.* [2006] investigated the trend of extreme rainfall events over central India (CI) and suggested that the increasing trend of these events over the region may be related to increased moisture content of the atmosphere because of global warming. However, mechanisms responsible for individual events were not discussed in detail in this study. A better understanding of factors responsible for the extreme events over the NEI region is a necessary prerequisite for improved predictive capability for these events using appropriate mesoscale models. The second objective of this paper, therefore, was to derive some insight regarding factors responsible for the extreme rainfall events in the region. To do this, we must recognize that with the mighty Brahmaputra valley surrounded by relatively tall mountain ranges on three sides, the NEI occupies a special place in the geography of the Indian monsoon region (Figure 1). Interaction between large-scale circulation and the local topography plays a crucial role in determining the weather and climate over this region. On interannual time scales, it is known that the monsoon rainfall (June–September) over this region has a weak out-of-phase relationship with the monsoon rainfall over homogeneous region of the central and western India (EOF1, Figure 14.5 in the study by *Shukla* [1987]; Figure 2.14 in the study by *Mooley and Shukla* [1987]; Figure 10a in the study by *Guhathakurta and Rajeevan* [2008]). On intraseasonal time scales, the dominant pattern of convection or rainfall has a quadruple structure [*Annamalai and Slingo*, 2001; *Annamalai and Sperber*, 2005; *Krishnamurthy and Shukla*, 2000, 2007; *Goswami*, 2005a] with the NEI region sitting in the northeast quadrant of this quadruple pattern. As a result, even on intraseasonal scales, the rainfall over the NEI region tends to go out of phase with that over the central and western India. As the large-scale circulation associated with the dominant intraseasonal variability (ISV) tends to cluster synoptic activity [*Goswami et al.*, 2003], it is conceivable that the large-scale circulation associated with ISV could also modulate the synoptic and mesoscale activity over the NEI region. The synoptic and mesoscale activity in the regions, in turn, interacting with the local topography could modulate the extreme rain events. By using a suite of high-resolution satellite products, we show that most of these heavy rain events at almost all stations are associated with a mesoscale organization that is embedded in the large-scale organized convection associated with some specific phases of the monsoon ISV. Further, we find that depending on the location of the station, the mesoscale event interacting with the topography generates some south ward propagating gravity waves that help trigger the extreme events.

[4] The data used and the methodology employed are described in section 2, while some gross characteristics of the extreme rainfall events and their trends are discussed in section 3. The spatial structure of convection associated with the very heavy rain events over all the stations and the relationship with large scale organization of convection is brought out in section 4. Results are summarized and relevance of the findings is highlighted in section 5.

2. Data and Methodology

[5] We collected daily rainfall data from 15 stations (see Figure 1) from India Meteorology Department (IMD, National Data Centre (NDC), Pune) from 1950 onward. However, it was found that there were rather long gaps during the period prior to 1975. Therefore, we decided to concentrate on the period after 1975. Also, data for very recent years were missing from the data obtained from NDC, IMD. We augmented the recent data by copying directly from journal records available at Regional Meteorological Centre at Guwahati. In this manner, we have constructed a reasonable continuous daily accumulated precipitation data over the 15 stations for 32 years (1975–2006). The data were passed through some gross quality control checks. All negative values were first removed. All-time high one-day rain fall anywhere in the country was recorded to be 1563 mm at Cherapunji on 16 June 1995 [*Guhathakurta*, 2007]. The values larger than this value were identified in our records. It was found that all these values occurred because of human error of missing a decimal point and were corrected. Even though the mean rainfall during the premonsoon months of April and May are not

Table 1. Station Names (Short Form), Their Location, Total Seasonal Rainfall and 99th Percentile of Daily Rainfall Values

Station Name	Lat(N)-Lon(E)	Average Total Seasonal Rainfall (mm) (Decreasing Order)	99th Percentile Value (mm)
Passighat (PGT)	28.07/95.34	3944.94	190.00
Dibrugarh (DIB)	27.48/95.02	3110.44	166.67
N 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	2045.60	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)	25.66/94.12	1469.84	63.86
Imphal (IMP)	24.76/93.90	1204.13	63.39
Lumding (LMD)	25.75/93.17	1102.00	78.35

very large, severe thunderstorms known as norwesters (locally also known as Bardoiseela) devastate this region during these 2 months. Also, summer monsoon tends to extend until October with a significant amount of rainfall occurring during October. Therefore, we have considered the period of April to October to examine the extreme events over the region.

[6] We have also used the gridded daily rainfall in the study by *Rajeevan et al.* [2006] to define a monsoon intraseasonal oscillation (ISO) index over the central India in order to see the large-scale organization of convection with respect to the active-break spells over CI. India Meteorological Department has updated the data set described by *Rajeevan et al.* [2006] to cover the recent years up to 2007 and we use this updated data set. The CI region within 15°N–25°N and 72°E–86°E was assumed to experience homogeneous rain and a daily rainfall climatology was constructed for that region by area averaging the gridded rainfall. Then the 20–90 days filtered anomaly of the daily rainfall was normalized by its own standard deviation to identify the active and break phases of the monsoon in that region. A Lanczos filter [*Duchon*, 1979], known for its sharp response function has been used for the band-pass filter.

[7] A daily 1° × 1° outgoing longwave radiation (OLR) composite for the active and break phases were made taking the peak date of the respective phases as zero lag. Also a large-scale daily 1° × 1° OLR composite was made for events at each station to see the large-scale connection and the favored ISO phase, if there is any. A 3 hourly 1° × 1° OLR composite was made to see the mesoscale organization. For the OLR, SRB_REL2.5_LW_3HRLY-GEWEX Longwave 3-Hourly Data Set (Atmospheric Science Data Center, NASA Langley Research Center: http://eosweb.larc.nasa.gov/cgi-bin/searchTool.cgi?Dataset = SRB_REL2.5_LW_3HRLY) is used. Finally, ERA-40 [*Uppala et al.*, 2005] data were used to calculate the convective available potential energy (CAPE) and convective inhibition energy (CINE) for the NEI region for a possible explanation of the obtained results.

[8] How do we define extreme rainfall events? Objectively, we define extreme rainfall 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. However, even within these 15 stations, there is considerable variation in the climatological mean rainfall (Table 1) and hence rainfall representing the 99th percentile. With this definition, 491 events have been identified over the 15 stations during the period. Many of these events correspond to rainfall of 6–8 cm/d having relatively low hydrological disaster potential. From the point of hydrological disaster, it is only the really heavy rain events that count as extremes. Hence, we also define another metric of extreme events as those events with more than 150 mm rainfall per day. With this definition, total number of extreme events over the period reduces to 295. We examine the aggregate of extreme events every year as defined by both metric and their trends. It is found that the trend of aggregate of extreme events over the region is nearly identical for both the metrics. Hydrologically, it is the very heavy events (>150 mm/d) that are very important, we try to examine the origin of these heavy events. For this reason, we consider how the organization of convection on a regional as well as on a large scale is associated with these events.

3. Some Gross Statistics, Linkages With Monsoon, and Trend

3.1. Seasonality and Linkage With Monsoon

[9] Are the extreme events associated predominantly with isolated severe thunderstorms or are they predominantly associated with monsoon synoptic events? If dominated by thunderstorms, the frequency of occurrence of the extreme events should be highest during premonsoon April–May months as the NEI region is known to be dominated by severe thunderstorms during this period. The monthly distribution of extreme events (>150 mm/d) over the whole region derived from all available data (Figure 2) shows that the events do not have maximum during April–May but are mostly concentrated in the peak monsoon time, June–July–August. This indicates that even though a large fraction of monsoon rainfall may come from stratiform rain [*Schumacher and Houze*, 2003; *Houze et al.*, 2007]; the large-scale circulation associated with the Indian monsoon (most likely the synoptic circulation) manages to trigger

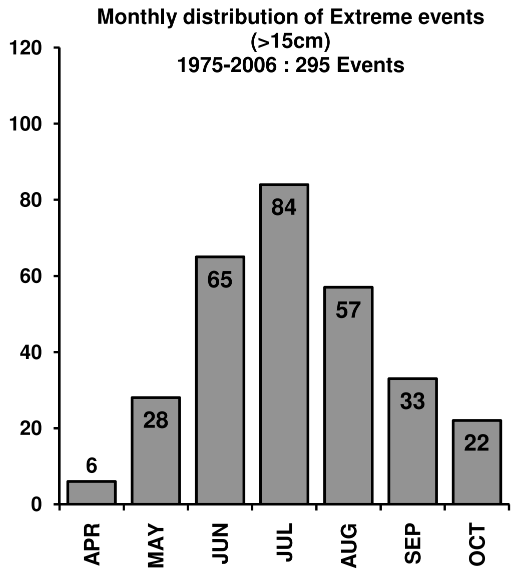

Figure 2. Total number of extreme events (daily precipitation >15 cm) counted over the region for the whole period for each month from April to October.

many extreme rain events in this region. This point is further supported by the fact that most of these extreme events are associated with a long spells of rain. A rainy spell is defined as days when there is continuous measurable rain at the station. During the summer monsoon, stations in the NEI region get spells of rain lasting even up to 65 days. Figure 3 shows clustering of the extreme events as a function of the length of the spells and phase of the spell. While a tiny fraction of the total extreme events (7) occurring in rain spells lasting for only a day may come from isolated thunderstorms, the majority of the extreme events (288) coming from rain spells lasting for more than 2 days must be associated with either mesoscale, synoptic, or large-scale events. The number of extreme events occurring during spells lasting between 2 and 4 days is 41, that occurring in spells lasting between 5 and 9 days is 106, between 10 and 14 days is 62, and more than 15 days is 79. It is also interesting to note that an appreciable number of extreme events do occur in association with the rain spells lasting as large as 30 days or more. These very long spells are generally of light rain sustained by steady large-scale forced ascent. Through interaction with the topography of the region the large-scale circulation still can trigger some extreme events.

[10] The fact that topography plays a subtle role in generating the extreme events could also be inferred by the fact that the frequency of occurrence of these events does not show any relation with the percentage of rainy days at the station. In Figure 4a, the number of events at each station exceeding three different thresholds is shown together with number of rainy days shown as fraction of available days. It is seen that Silchar with more than 66% of rainy days has far fewer extreme events compared to Dhubri (DHB) with 54% of rainy days. Also, there is no relationship between the altitude of the station and the frequency of occurrence (Figure 4b) of extreme events. Again, Shillong (SHL) with much higher altitude has much lower number of extreme events compared to PGT, Dibrugarh, and DHB. Thus, it is the strategic location of the station that is more important than the total number of rainy days or altitude. SHL is at the top of the K&J Hills, while PGT is located at the foothills of the Himalayan mountain range with a sharply rising mountains behind it. The steep topographic gradient appears

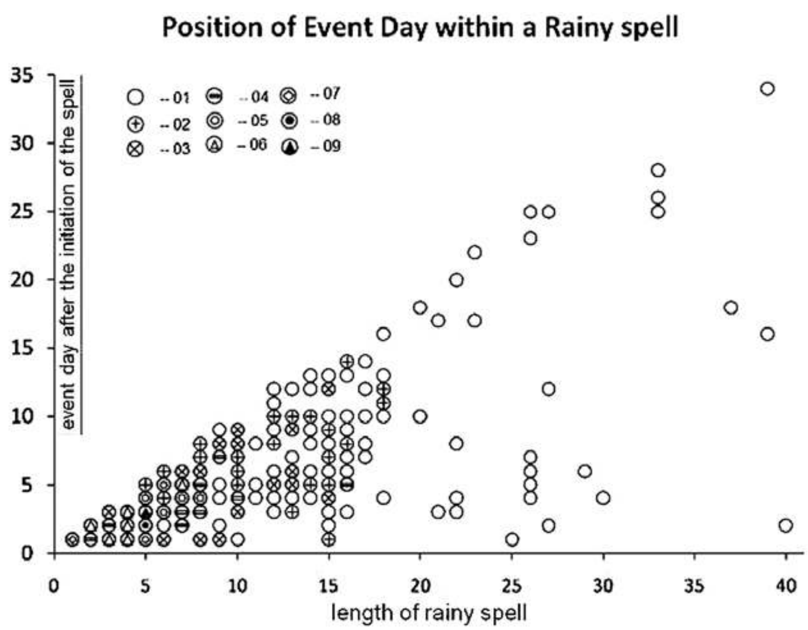

Figure 3. Occurrence of the extreme events with respect to phase of spells of different lengths. On the x axis, length of spells are shown, while y axis shows the days after the initiation of the spell. Thus, a circle represents when the extreme event takes place within the spell. For brevity, two events (65,51), (65,60) associated with very long spells are not shown in the figure.

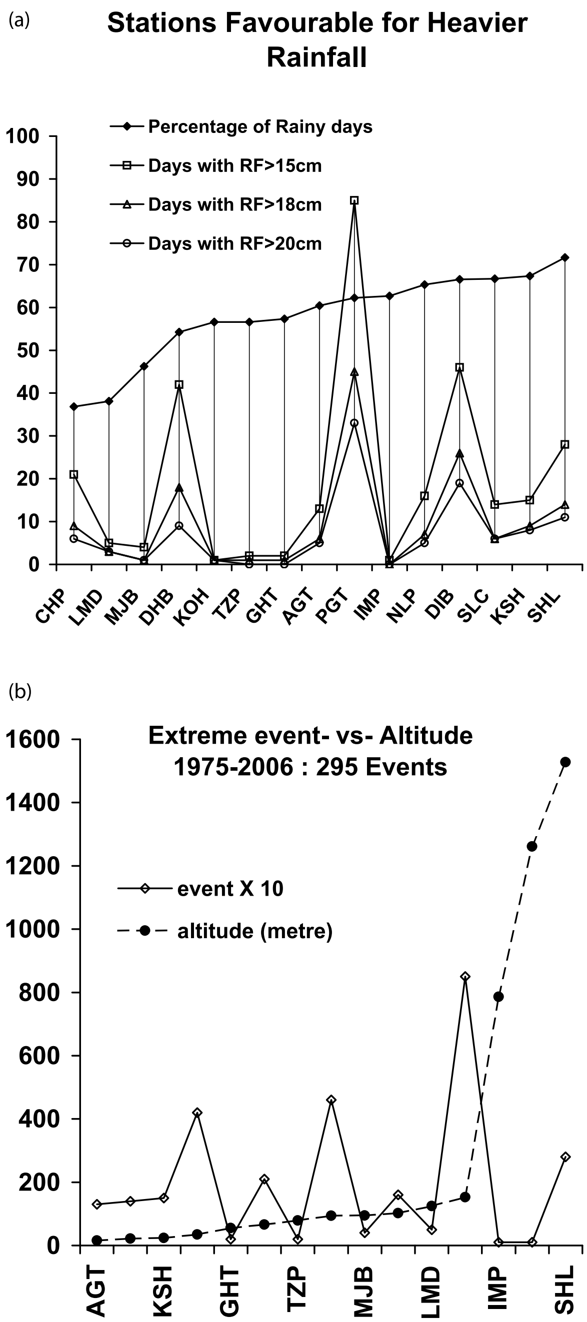

Figure 4. (a) Stations (x axis) favorable for extreme events. Number of extreme events as defined by daily rain >15 cm, >18 cm, and >20 cm over the whole period are shown by solid lines. The hashed line shows number of rainy days at each station as percentage of total number of days between April and October. (b) Number of extreme events (daily rain >15 cm) at all stations and their elevations.

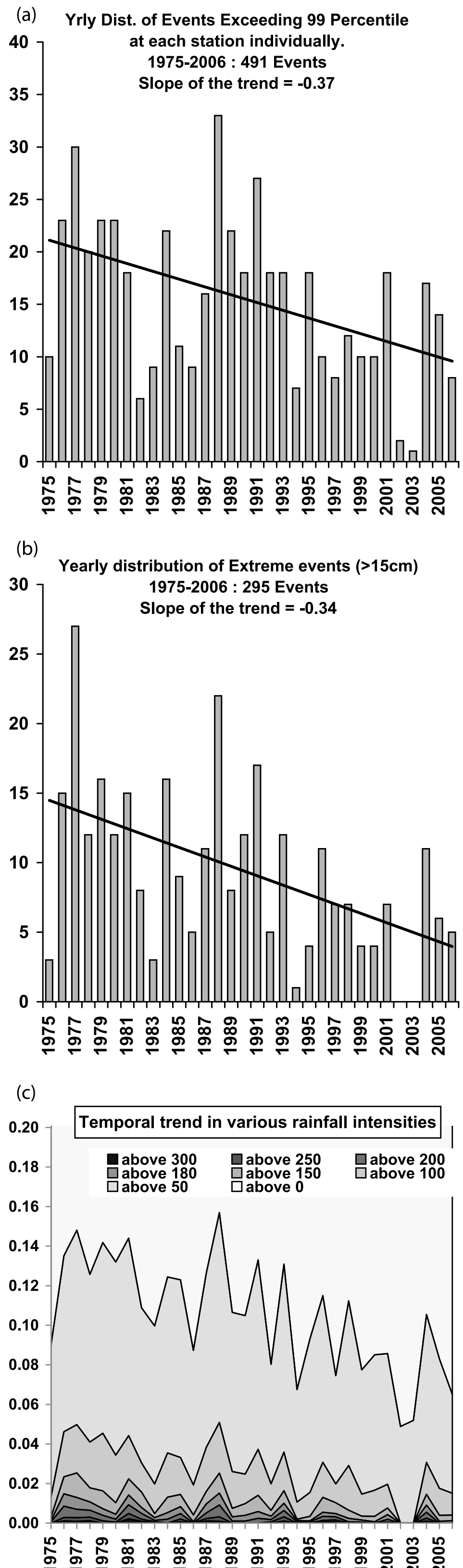

Figure 5. (a) Number of events in exceedance of 99th percentile and its linear trend. (b) Same as Figure 5a but for number of events exceeding daily rainfall of 15 cm and its linear trend. (c) Percentage of total rainfall explained by events exceeding different thresholds.

to be conducive for producing the strong updrafts necessary for producing the deep convective events.

3.2. Decreasing Trend of Aggregate of Events

[11] The temporal variation of the aggregate of extreme events over the region shows a decreasing trend over the period under consideration. This is seen in both metrics of

Table 2. Total Number of Extreme Events (Daily Precipitation > 15 cm) on each Station for the Whole Period (75–06), the Earlier Half (75–90), the Later Half (91–06) and for the Period 1985–2004 for Which OLR Analysis Has Been Done

	Total	1975–1990	1991–2006	1985–2004 (for OLR Analysis)
PGT	85	52	33	54
DIB	46	44	2	2
DHB	42	25	17	27
SHL	28	17	11	20
CHP	21	16	5	9
NLP	16	11	5	8
AGT	15	7	6	7
KSH	15	7	8	10
SLC	13	5	9	11
LUM	5	3	2	1
MJB	4	2	2	2
TZP	2	2	0	2
GHT	2	1	1	2
IMP	1	1	0	1
KOH	1	1	0	1

extreme events defined earlier in section 2. First, Figure 5a shows that the number of events exceeding the 99th percentile has a trend decreasing at the rate of 0.37 events/yr. The trend of extremes as defined by very heavy rainfall events with daily rainfall greater than 150 mm (Figure 5b) is found to be similar, decreasing at 0.34 events/yr. The least squares linear trends in both cases (Figures 5a and 5b) are found to statistically significant at 99% level using a Student *t* test. The decreasing character is spatially pervasive as it is seen in almost all stations. This is shown in Table 2 where the total number of extreme events is broken down into two periods. The decreasing trend of extreme events is rather interesting as it is in contrast to the increasing trend of heavy rainfall events in CI [*Goswami et al.*, 2006]. In order to see whether the intensity of the very heavy events is also changing, we plot a figure similar to Figure 4a in the study by *Goswami et al.* [2006]. In Figure 5c, we show the temporal variation percentage of seasonal total explained by events exceeding certain thresholds. It shows a significant negative trend and indicates that the intensity of the very heavy events is also decreasing.

[12] Over the CI region, the increasing trend of extreme events has been attributed to increasing instability of the atmosphere because of increasing moisture content in the atmosphere. Recently, *Mani et al.* [2009] has shown that the CAPE averaged over the season and over the region shows a significant increasing trend, while CINE shows a decreasing trend consistent with the above hypothesis. In contrast to CI, is the NEI region becoming increasingly more stable? To test this, we calculated the CAPE and CINE from ERA40 averaged during June–September and over the NEI region between 1975 and 2001 (restricted by availability of ERA40 data). It is very interesting to note that the CAPE has a decreasing trend, while the CINE has an increasing trend in this region (Figure 6). Both the least squares linear trends in this figure are found to be statistically significant at 97.5% level. Thus, over this region, not only is the atmosphere becoming more stable but also inhibition is increasing making it difficult to realize the available energy.

[13] The opposing trend of extreme rainfall events over CI and NEI and their linkage to opposing trends of indices of stability of the atmosphere over the two regions may be linked with an interdecadal mode of variability of the ocean-atmosphere system. The spatial pattern of El Niño-Southern Oscillation (ENSO) like interdecadal mode of variability of the Indian monsoon has been shown to be similar to that of interanual ENSO mode of monsoon variability [*Goswami*, 2005b] with spatial pattern having out of phase relation between CI and NEI. The large-scale changes of circulation and moisture transport cause the decrease in the stability of the atmosphere leading to decrease in frequency of occurrence and intensity of the extreme rainfall events over the NEI region.

4. Organization of Convection and Multiscale Interaction

[14] At any station, is there an underlying pattern of convection anomalies or organization of convection that is

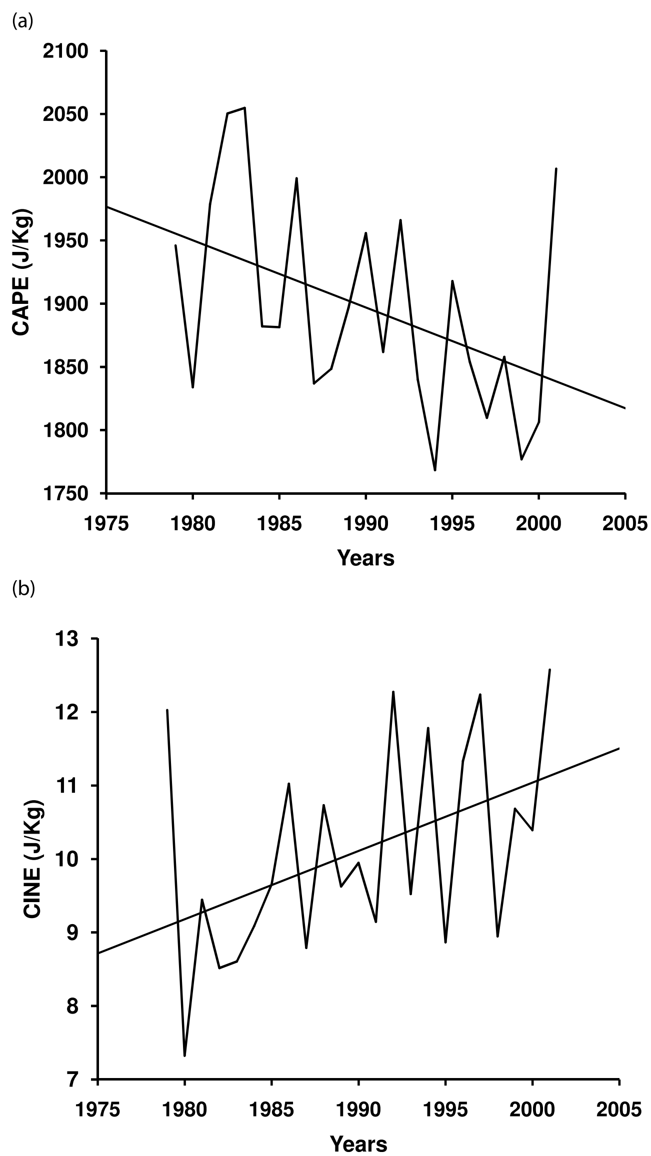

Figure 6. (a) June–September CAPE averaged over the NEI region between 1975 and 2001 and its linear trend calculated from ERA40 data. (b) Same as Figure 6a but for CINE.

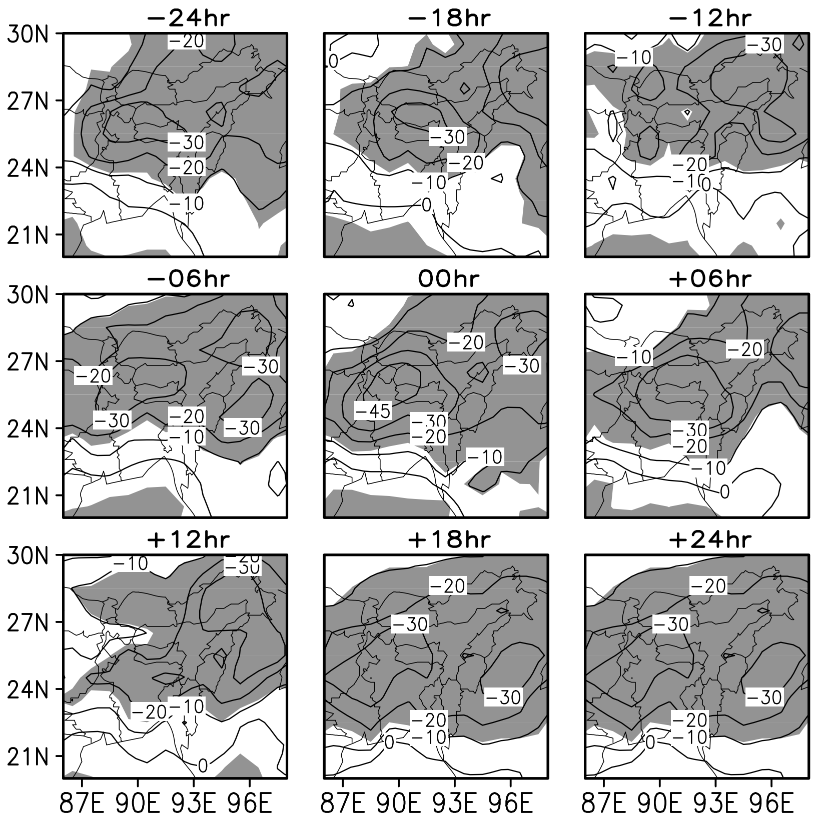

Figure 7. Lag composite of OLR anomalies (Wm^{-2}) with respect 0000 h of the day of the extreme events at Passighat from −24 h to +24 h over the NEI region. Composites are calculated every 3 h but shown here at 6 h intervals. Composite anomalies statistically significant at 95% level are shaded.

common to all events? If such a structure exists, what is its scale and how is it related to the larger-scale organization of convection? In order to answer these questions, we construct lag composites of OLR anomalies for each station at 3 hourly lags and leads with respect to 0000 h of the day on which the event takes place. Such lag composites going from −24 h to +24 h at 6 hourly intervals for the station PGT are shown in Figure 7 based on 54 events during the period between 1985 and 2004 over which the high-resolution OLR data are available. It is seen that a mesoscale organization of size of about 400 km (as seen from anomalies larger than −30 Wm^{-2}) persists over the station for almost 2 days. It is noted that the composite anomalies are statistically significant over a much larger area and the deep mesoscale convection is embedded in a larger-scale organization of convection with much larger zonal scale compared to the meridional scale. The long persistence of the mesoscale structure indicates that it is associated with and embedded in the large scale tropical convergence zone (TCZ).

[15] Is this organization of convection associated with extreme events special only at this station or generic to extreme events in most stations over the region? To investigate this question, lag composites were constructed at all stations with significant numbers (7 or more, see Table 2) of extreme events and composites for 0000 h are shown in Figure 8 for all the stations. It is clear that at all stations the extreme events tend to be associated with a mesoscale organization of deep convection embedded in some phase of the northward and eastward migrating TCZ. It is found (not shown) that the mesoscale organization persists for at least 2 days (similar to Figure 7) indicating that they are triggered by synoptic activity (low-pressure systems).

[16] How do the synoptic systems help generate these very small scale extreme rainfall events? In order to gain insight into this question, the lag composites were extended from −48 h to +48 h and the composite OLR anomaly averaged between plus-minus two longitudes about the exact location as a function of latitude and time are shown in Figure 9. Southward propagating events with approximate period of 24 h are seen in all stations except Shillong (SHL). They appear to be southward propagating gravity waves with phase speed between 9 and 10 ms^{-1}. Convective heating associated with the synoptic events interacting with mountains to the north seems to generate these gravity waves. Absence of the gravity waves over SHL is consistent with the fact that SHL sits on top of Khasi and Jayantiya hill at an altitude of 1528 m. Strong updrafts associated with the gravity wave with much smaller spatial scale seem to be responsible in generating very deep convection on a small scale leading to the extreme events [*Liu and Moncrieff*, 2004].

[17] The indication from the above analysis that the organization of convection during the extreme events is part of a much larger organization in the form of TCZ. This is further explored in Figure 10, where lag composite of daily OLR corresponding to days of all extreme events at eight

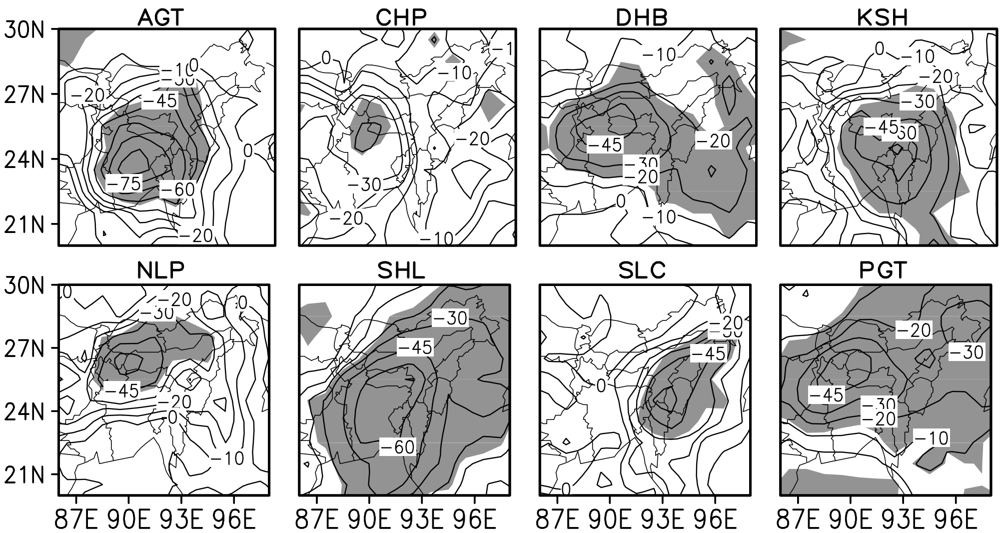

Figure 8. Same as Figure 7 but for composite of OLR anomalies (Wm^{-2}) at 0000 h (3 hourly data) at a number of stations. Shading represents anomalies significant at 95% significant level except at Chaparmukh (CHP) where it represents significant at 90% level.

stations are shown over a much larger domain. It is noted that the large-scale pattern associated with the extreme event over this station has a horseshoe shape and persists over several days. In order to see if similar patterns occur over other stations, 0 day composites of extreme events at eight stations are shown in Figure 11. It may be noted (Figure 11) that in the case of six out of eight stations, the extreme events occur associated with a very large scale organization of convection in the form of horseshoe pattern. In the other two stations, the patterns are different but still organized on the large TCZ scale. The TCZ fluctuates on ISO time scales and repeatedly propagates northward and eastward during the monsoon season [*Sikka and Gadgil*, 1980; *Krishnamurti*, 1985; *Goswami*, 2005a]. We believe that the organization of

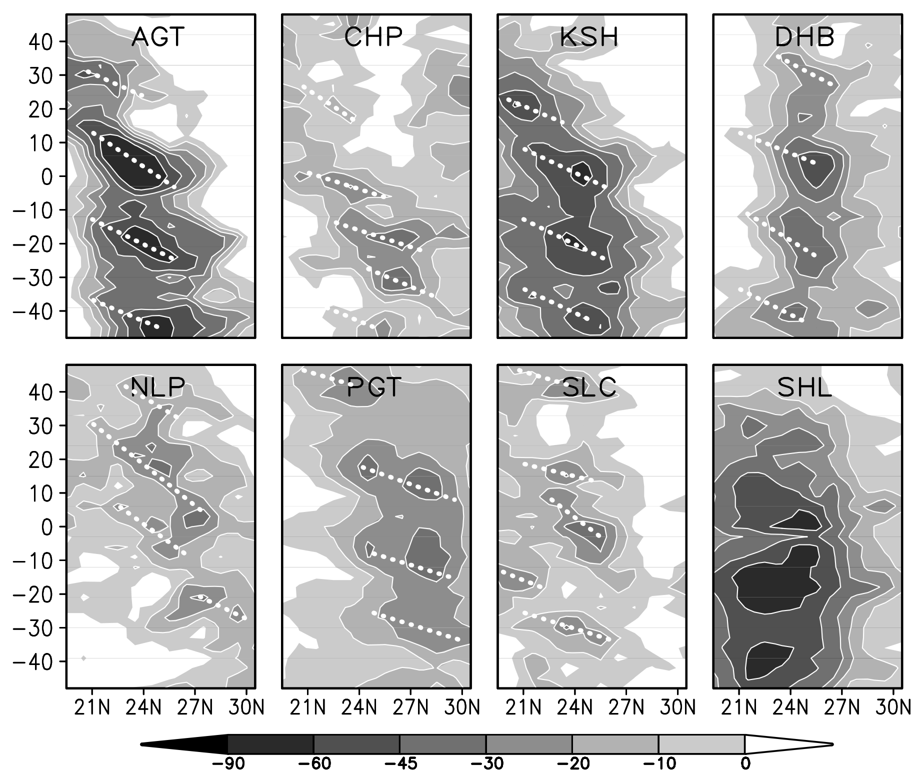

Figure 9. Lag-latitude plot of composite of OLR anomalies (Wm^{-2}) averaged between plus-minus 2 longitudes about the exact location for eight stations (stations having not less than 5 events in the period 1985–2004).

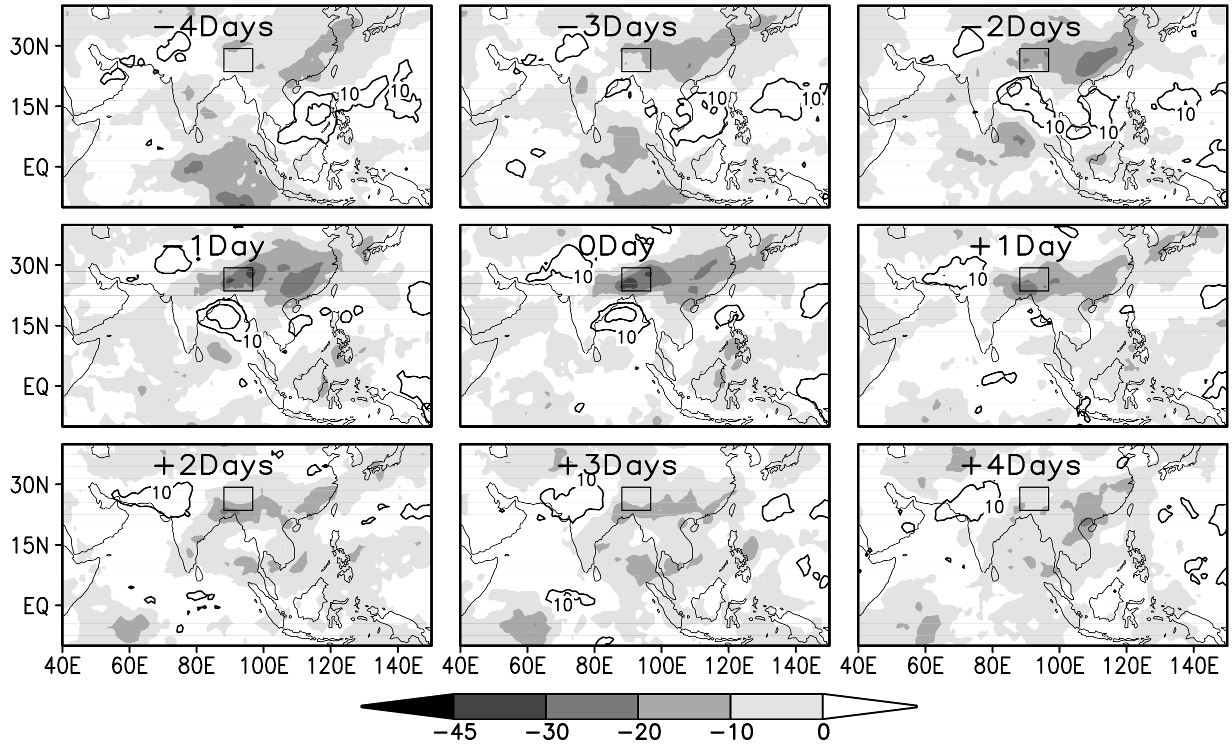

Figure 10. Composite of daily mean composite of OLR anomalies (Wm^{-2}) for the days on which the extreme events occurred over a much larger domain indicating the large scale organization. The location of NEI region is shown by a box in the figure.

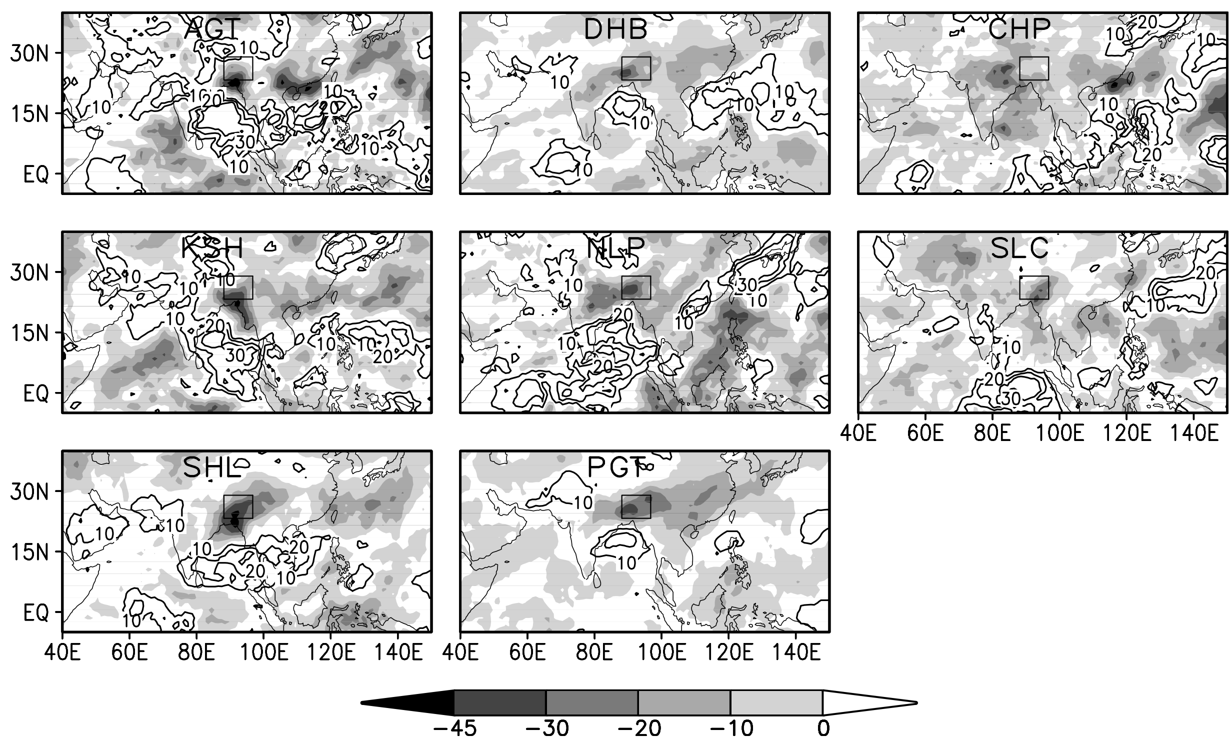

Figure 11. Same as Figure 10 but for composite of OLR anomalies (Wm^{-2}) at 0000 h (daily data) at a number of stations. All stations show similar large-scale organization except two (CHP and Silchar (SLC)). The location of NEI region is shown by a box in the figure.

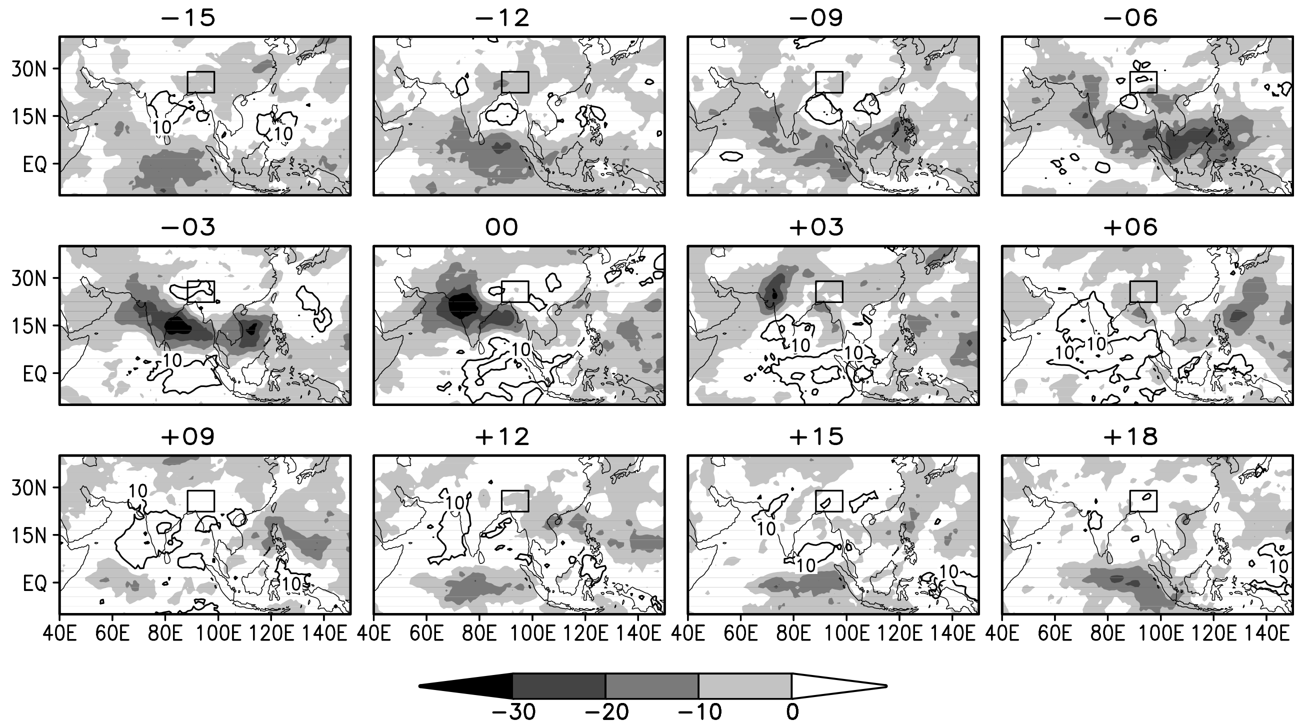

Figure 12. Composite evolution of daily mean OLR anomalies during nine phases of a typical summer monsoon intraseasonal oscillation (ISO). Composites are constructed with respect to an ISO index based on 20–90 days filtered daily rainfall anomalies averaged over central India (15°N–25°N and 72°E–86°E). Zero-day composite refers to peak active condition. The location of NEI region is shown by a box in the figure.

convection associated with certain phases of the monsoon ISO provides the large-scale environment for the extreme events to occur. In order to test this hypothesis, we construct large-scale structure of organized convection during different phases of the summer monsoon ISO. To do this, we define an ISO index as 20–90 day filtered rainfall anomaly averaged over Central India (72°E–86°E, 15°N–25°N) normalized by its own standard deviation. An index larger than 1.5 is considered as the peak active condition. Composites of OLR anomalies corresponding to peak active days and for days going backward up to 20 days and going forward up to 20 days are constructed. These represent the evolution of convection with different typical phases of the monsoon ISO. These composites every 3 days apart are shown in Figure 12. Comparison of Figures 11 and 12 indicate that the organization of convection during extreme events over the six stations is close to the ISO phase corresponding to peak active minus 12 days. On the other hand, that for the other two stations correspond to peak active minus 3 days (Chaparmukh) and peak active (Silchar), respectively. The complex interaction of large-scale circulation with topography that results in the extreme events is sensitive to location of the station. As a result, different phases of ISO seem to give rise to extreme events in different locations.

[18] The multiscale interaction involving the southward propagating gravity waves that leads to the extreme rain events in the NEI region has some similarity to similar organization observed over the Bay of Bengal in several recent studies [*Webster et al.*, 2002; *Zuidema*, 2003; *Liu et al.*, 2008]. It is rather interesting to note that *Liu et al.* [2008] also find similar southward propagating diurnal gravity waves in TRMM precipitation over the Bay of Bengal during summer monsoon season embedded in the northward propagating ISO with phase speed of about 8 m/s. While we have not provided conclusive evidence that the southward propagating diurnal oscillations are gravity waves, our hypothesis that they are gravity waves is based on work of *Grabowski and Moncrieff* [2001], who show that such convective organization could be explained in terms of convectively generated gravity waves.

5. Conclusions

[19] The NEI region is the breeding ground for a larger number of extreme rainfall events responsible of frequent hydrological disasters like flash floods in the region. Using daily rainfall data over 15 stations in the area over a period of 32 years, we have examined the spatiotemporal variation of occurrence of these events over the region and make an attempt to gain insight into the origin of these events with respect to their multiscale interaction with the local topography. The following major conclusions can be made.

[20] Although severe thunderstorms like norwesters frequent the region during the premonsoon months of April–May, the largest number of heavy rainfall events (>15 cm/d) over the region occur not during the premonsoon but during monsoon months of June–July–August. Also, 288 out of the 295 events occur in rain spells that last only for 2 days or longer. As rain spells of 2 days or longer duration comes

from mesoscale, synoptic, or intraseasonal oscillations, it indicates that large-scale monsoon circulation favors the genesis of intense rainfall events over the region. This conclusion is somewhat similar to the one arrived at by *Francis and Gadgil* [2006] for the extreme events in the western part of the country.

[21] No matter whether we define the extreme events as those in exceedance of 99th percentile or those with the daily rainfall larger than 15 cm/d, the frequency of occurrence of extreme events over the region shows a significant decreasing trend. This is interesting in the backdrop of the finding that similar extreme events over CI are increasing [*Goswami et al.*, 2006]. It is shown that the decreasing trend of extreme events over the region is consistent with a decreasing trend of CAPE and an increasing trend of CINE over the region.

[22] Because of the special topographic features, the monsoon circulation also drives long rainy spells over the NEI region. It is found that a large fraction of the extreme events occur during rainy spells exceeding 5 days. This again emphasizes the fact that very few of the extreme events in the NEI region occur because of isolated thunderstorms while most of them occur with monsoon systems.

[23] In an attempt to identify drivers for these extreme events, we find that almost all of them at all stations are associated with a mesoscale organization which is embedded in a large-scale organization. We also identify that these large-scale organizations are a manifestation of the TCZ associated with different phases of the monsoon active-break cycle. The mesoscale systems interact with the topography and generate southward propagating gravity waves with a period of about 24 h. The strong updrafts associated with the small-scale gravity waves produce the deep convection and the extreme events. Thus, a truly multiscale interaction with topography seems to be responsible for the extreme events over the NEI region.

[24] The last conclusion has implications for simulation and forecasting of these extreme rainfall events in the NEI region. Any model that attempts to simulate or predict these events must have the correct representation of summer monsoon intraseasonal oscillations. Since the monsoon ISOs have very large spatial scale, one needs a global model to simulate them reasonably well. In fact, even the state of art global models have certain serious biases in simulating the summer ISOs [*Waliser et al.*, 2003]. Some recent studies [*Masunaga et al.*, 2008; *Miura et al.*, 2007] indicate that one may need very high resolution cloud resolving global models to simulate the tropical ISOs correctly. Thus, in principle, a global very high resolution nonhydrostatic model may be required for predicting these events. If a regional model is used, proper care should be taken to include the correct ISO forcing in the boundary conditions.

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