Dominant Synoptic Disturbance in the Extreme Rainfall at Cherrapunji, Northeast India, Based on 104 Years of Rainfall Data (1902–2005)

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ABSTRACT

The characteristics of active rainfall spells (ARSs) at Cherrapunji, northeast India, where extreme high rainfall is experienced, and their relationships with large-scale dynamics were studied using daily rainfall data from 1902 to 2005 and Japanese 55-Year Reanalysis from 1958 to 2005. Extreme high daily rainfalls occur in association with ARSs. The extremely large amounts of rainfall in the monsoon season are determined by the cumulative rainfall during ARSs. ARSs start when anomalous anticyclonic circulation (AAC) at 850 hPa propagates westward from the South China Sea and western North Pacific, and covers the northern Bay of Bengal. The AAC propagates farther westward and suppresses convection over central India during ARSs at Cherrapunji, and continues for 3 to 14 days. Consequently, a northward shift of the monsoon trough during the “break” in the Indian core region occurs. The westerly wind, which prevails in the northern portion of the AAC, transports moisture toward northeast India and enhances moisture convergence over northeast India with southerly moisture transport from the Bay of Bengal, and greatly intensifies the orographic rainfall. In the upper troposphere, the Tibetan high tends to extend southward with the onset of ARSs. A linear relationship can be seen between the length and total rainfall of an ARS. Longer ARSs tend to result in greater total rainfall. AACs with a greater zonal scale tend to produce longer and more intense ARSs. This study provides evidence for the effect of western North Pacific AACs on the Indian summer monsoon.

1. Introduction

The Indian summer monsoon has remarkable intraseasonal variation. Rainfall periods with above and below normal rainfall amounts have been called “active” and “break” spells, respectively. A detailed review of studies of active and break spells was conducted by Rajeevan et al. (2010). Traditionally, the active and break spells of the Indian summer monsoon have been based on the convective activity over northwest and central India [referred to as the “Indian core region” following Rajeevan et al. (2010)]. Negative (positive) rainfall anomalies over northeast India corresponded to active (break) spells over northwest and central India.

The synoptic condition during break spells has been described as a northward shift of the trough of low pressure toward the foothills of the Himalayas. Ohsawa et al. (2000) studied the intraseasonal rainfall variation during the 1995 summer monsoon season, and found that rainfall in Bangladesh increased when the monsoon trough was located at the foot of the Himalayas. Shrestha et al. (2012) analyzed rainfall over the central Himalayan region using 11 years’ worth of data from the Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar, and showed that rainfall was heavy over the southernmost hills of the Himalayas [called the Siwalik Range or sub-Himalayas; approximately 500–700 m above mean sea level (MSL)] when the monsoon trough was lying in the foothills of the Himalayas. Goswami et al. (2010) analyzed the extreme rainfall over
northeast India, and showed that these extreme events occurred in association with monsoon synoptic events rather than isolated thunderstorms. In general, studies that have focused on intraseasonal variation over northeast India have been limited.

Hartmann and Michelsen (1989) performed spectral analysis of rain gauge data for 70 years from 3700 stations in India, and noted that several stations along the southern flank of the Himalayas had spectral peaks of nearly 15 days. The 40–50-day spectral peak was not significant along the southern flank of the Himalayas, whereas it was dominant at most stations elsewhere in India. Ohsawa et al. (2000) detected a periodicity of around 20 days in an analysis of the 1995 summer monsoon season. Fujinami et al. (2011) analyzed rain gauge data for 20 years in Bangladesh, and showed that a 7–25-day spectral peak was dominant, while a 30–60-day spectral peak was not prominent. Fujinami et al. (2014) further investigated the spatiotemporal structure of a 7–25-day mode over the Meghalaya–Bangladesh–western Myanmar region.

A 10–20-day mode has been detected in various elements of the Indian summer monsoon system (e.g., Krishnamurti and Bhalme 1976). Past studies suggest that the 10–20-day mode in the Asian summer monsoon region originates over the equatorial west Pacific (Annamalai and Slingo 2001), propagates westward (Krishnamurti and Ardanuy 1980) with a double-cell structure (Chen and Chen 1993), and is a manifestation of the moist equatorial Rossby waves modified by the climatological mean flow (Kikuchi and Wang 2009). Fujinami et al. (2014) revealed that a westward-propagating anticyclonic anomaly related to the equatorial Rossby wave from the western North Pacific promotes rainfall over the Meghalaya–Bangladesh–western Myanmar region.

This study analyzes active rainfall spells (ARSs) in the monsoon season at Cherrapunji, which is a town located in northeast India. Cherrapunji is a unique station because it holds the world record for the highest rainfall in a calendar month and for longer time scales than a calendar month (Jennings 1950; Kiguchi and Oki 2010), as well as the highest daily rainfall records in India (Guhathakurta 2007). Rainfall at Cherrapunji has clear ARSs, and daily rainfalls with more than several hundred millimeters are common during ARSs (Fig. 3). The large daily rainfall at Cherrapunji during the ARSs is suitable to detect the synoptic-scale events with high sensitivity because it can minimize other noises caused by few local cumulonimbus clouds.

Cherrapunji is located on the southern slope of the Meghalaya Plateau (Fig. 1a) with a maximum elevation of around 2000 m above sea level. The plateau is divided from the Himalayan ranges by the Brahmaputra Valley. As the plateau is the first elevated terrain that warm, moist air from the Bay of Bengal encounters, maximum precipitation tends to occur (Houze 2012). It is connected to the Indo-Burma Range in the east. The southern margin of the Meghalaya Plateau is steep and rugged due to the tectonic motion along the Dauki fault at the southern boundary of the plateau. There are several deep valleys that open toward the south with steep cliffs on both sides (Fig. 1b): the town of Cherrapunji is situated near one such valley. Orographic amplification is the major plausible cause for the extreme precipitation at this location (e.g., Romatschke et al. 2010), although other factors, such as a local front between the southwest monsoon flow and east–northeast mountain winds in the Brahmaputra Valley, may also have an influence (Yoshino 1975).

Northeast India receives the heaviest rainfall in India. As the region includes hilly areas and adjoins the great Himalayas, orographic effects are important in rainfall in northeast India (Goswami et al. 2010). Our study reveals the relationship between the local orographic rainfall and large-scale circulation patterns at intraseasonal time scales. Understanding the rainfall patterns over northeast India might be crucial in understanding the hydrological processes over the Ganges–Brahmaputra–Meghna River basin (Hofer and Messerli 2006). For example, heavy rainfall during ARSs at Cherrapunji directly runs off toward Bangladesh and triggers flash floods. Also, the high monsoon rainfall years at Cherrapunji tended to correspond with severe flood years in Bangladesh (Murata et al. 2007).

Causes of the negative correlation between rainfall anomalies in the Indian core region and northeast India in the active–break cycle have not been discussed. The ARSs at Cherrapunji can be representative in northeast India because the extreme rainfall amount provides noiseless signal for favorable synoptic-scale events. The objective of this study is to answer the following questions by understanding the characteristics of the Cherrapunji ARSs (CARSs), and discuss the relationship with active–break cycle in the Indian core region:

1) What is the relationship between CARSs and largescale dynamics?
2) What is the contribution of CARSs to the extreme rainfall?

Section 2 describes the datasets used in this study. The definition and characteristics of CARSs are described in section 3. Section 4 gives the spatiotemporal structure of CARSs. The synoptic condition during CARSs, the relationship with the Indian core region, and the contribution to the extreme rainfall are discussed.
in section 5. Finally, the results are summarized in section 6.

2. Data

Data on the daily rainfall observed at Cherrapunji observatory of the India Meteorological Department (IMD) were obtained from the following different sources: the Research Data Archive at the National Center for Atmospheric Research (Computational and Information Systems Laboratory; ds.480.0) for data from 1902–70, and the Guwahati regional office of the IMD for daily rainfall data from 1970 to 2003. Daily rainfall data for 2003–05 were obtained directly from the Cherrapunji Observatory of the IMD. Five years of daily rainfall data at Cherrapunji are missing completely (1965, 1982–84 and 1987), and 7 years (1946, 1960, 1961, 1963, 1964, 1972, and 1986) have more than 10% missing data for June–September. To study the relationship between rainfall at Cherrapunji and that at other regions, the IMD rainfall dataset (Pai et al. 2014) on a 0.25° latitude–longitude grid was used for the period 15 October 2017 M U R A T A E T A L . 8239
1902–2005, and the APHRODITE V1101 rainfall dataset (Yatagai et al. 2009, 2012) on a 0.25° latitude–longitude grid was used for the period 1958–2005. The streamfunction, horizontal wind components and vertically integrated water vapor flux components of the Japanese 55-Year Reanalysis (JRA-55) (Ebita et al. 2011; Kobayashi et al. 2015) on a 1.25° latitude–longitude grid were used to analyze the features of circulation patterns and moisture transport during CARSs. Daily interpolated outgoing longwave radiation (OLR) data on a 2.5° latitude–longitude grid were used to show large-scale convective activity, including ocean areas from 1979 to 2005 (Liebmann and Smith 1996). In the composite analysis, the statistical significance of the differences from climatological values at each grid point was estimated using the Student’s $t$ test.

3. Features of ARSs at Cherrapunji

In this section CARSs are defined and described. Figure 2 shows the 92-summer ensemble spectrum of the Cherrapunji daily rainfall. The years for which more than 10% of the June–September daily data are missing were excluded; in total, 92 years were used, the first three harmonics of the annual cycle were removed, and the fast Fourier transform technique was used to calculate the spectra. A 5-point running mean in the frequency domain was applied to the raw spectra to reduce estimate errors. Pronounced peaks appear around a 10–30-day period and a peak of about 11 days exceeds the 95% confidence level. The spectrum is similar to that of all Bangladesh daily rainfall (Fujinami et al. 2011) and represents the dominance of the 10–20-day mode. Fujinami et al. (2011, 2014) examined the characteristics of the 10–20-day mode over the Meghalaya–Bangladesh–western Myanmar region. This study focused on the timing of onset, length, and total rainfall amount of CARSs because they are the important hydrological characteristics of this region.

Figure 3 shows examples of the daily rainfall from 21 May to 10 October in the years 1915 and 1974. The annual rainfall in 1915 was almost mean value and included four active spells. The annual rainfall in 1974 was the highest between 1902 and 2005. The solid curve illustrates the daily climatological rainfall: it shows the average daily rainfall in each year, and smoothing by the 15-day running mean twice. The daily climatological rainfall reaches a maximum in late June, which was more than 1 month earlier than the rainfall over the Indian core region (Rajeevan et al. 2010; Pai et al. 2016).

Heavy rainfall days (HRDs) are days with more than 1.5 times the daily climatological rainfall between June and September. CARSs are defined as consecutive HRDs on which the total rainfall exceeds 500 mm. For HRD periods that include 1 June or 30 September, the number of consecutive HRDs extended into May or October. There were only three (two) cases of 1-day (2-day) intervals between the two adjacent CARSs. Definitions of active–break spells can vary (Rajeevan et al. 2010). Fujinami et al. (2014) defined active and break monsoon spells according to filtered data. In this study unfiltered data are used to define ARSs, with no assumption regarding frequency. The shaded periods in Fig. 3 represent ARSs in this study. There were nine CARSs in 1974, which was the maximum number recorded during the analysis period. The CARSs repeated periodically at intervals of 10–20 days, which is consistent with the result of Fig. 2.

Table 1 shows the relationship between the total rainfall on consecutive HRDs and the duration of consecutive HRDs. The numbers in the column in Table 1 indicate the periods of consecutive HRDs between 1902 and 2005. The number of periods decreases as the total rainfall increases. Regarding the length of a period, there was a greater percentage of consecutive 3-day HRDs. A linear relationship is observed between the number of consecutive HRDs and the total rainfall. Greater rainfall is observed in the periods with more consecutive HRDs. There are some extreme cases when the total rainfall was between 3500 and 5000 mm during 7- or 9-day consecutive HRDs. In this study, CARSs are defined as events with more than 500 mm total rainfall, and the minimum length of a CARS is 3 days.

Variation between intra- and interannual scales has been considered. For example, Gadgil and Joseph (2003) showed that the interannual variation in all-India
summer monsoon rainfall is related to the number of days of rain breaks and active spells. Fujinami et al. (2011) showed that more frequent and strong submonthly-scale oscillations, and a greater number of rainy days, were related to the wet monsoon years in Bangladesh. Figure 4 shows that the cumulative rainfall of CARSs is proportional to total monsoon rainfall amount from June to September. The cumulative rainfall during the period without CARSs ranges from 2000 to 6000 mm and has a negative tendency with monsoon total rainfall because the number of days without CARSs decreases when CARSs increases.

Figure 5 shows the relationship between the cumulative number of CARSs and the cumulative rainfall amounts during CARSs over one year. As in the analysis of Fig. 2, data for 92 years were used. The bottom and top of the box are the first and third quartiles, respectively. The thick band inside the box is the median. The ends of the whiskers show the minimum and maximum. The number of CARSs ranges from one to nine per year. The years with four to nine CARSs over one year compose approximately half of the total sample years. In the range of one to four spells per year, there is a tendency for total rainfall to increase with the number of CARSs. However,

| TABLE 1. Relationship between the total rainfall of consecutive heavy rainfall days (HRDs; horizontal line) and the length of consecutive HRDs (vertical line). Asterisks denote cells with more than 10 periods. |
|---|---|---|---|---|---|---|---|---|
| 14-day | 1 | | | | | | | |
| 13-day | 0 | | | | | | | |
| 12-day | 3 | 1 | 2 | | | | | |
| 11-day | 0 | | | | | | | |
| 10-day | 5 | 1 | 3 | 1 | | | | |
| 9-day | 15 | 5 | 3 | 1 | 5 | 1 | | |
| 8-day | 13 | 1 | 3 | 5 | 3 | 1 | | |
| 7-day | 28 | 1 | 3 | *13 | 4 | 3 | 2 | 1 | 1 |
| 6-day | 57 | 1 | *10 | *30 | *14 | 2 | | | |
| 5-day | 90 | 2 | *46 | *28 | *11 | 3 | | | |
| 4-day | 103 | *15 | *70 | *18 | | | | | |
| 3-day | 167 | *103 | *64 | | | | | | |
| 2-day | 82 | *82 | | | | | | | |
| 1-day | 68 | *68 | | | | | | | |
| Total | 632 | 272 | 194 | 98 | 38 | 15 | 11 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
there is no clear trend toward an increase in rainfall when there are more than four CARSs per year. It is not always the case that years with a greater number of CARSs are wet monsoon years. It implies that CARSs with greater total rainfalls contribute to wet monsoon years in addition to a number of CARSs.

Figure 6 shows a composite of the anomalous rainfall from daily climatological rainfall over India during CARSs. This map was produced by using the IMD grid rainfall data for the period 1902 to 2005. Positive and negative values show regions of excess and less rainfall during CARSs, respectively. The hatched regions are significant at the 95% confidence level. While excess rainfall is observed over northeast India during CARSs, less rainfall is observed over central India and the Western Ghats. Usually, the active and break spells of the Indian monsoon are defined based on the rainfall over central India. Thus, it is important to note that northeast India generally has the opposite tendency to that of central India: the spatial distribution is very similar to that of the break monsoon composition of the Indian core region (e.g., Pai et al. 2016).

4. Relationship with large-scale circulation field

Figure 7 is the same as Fig. 6, but the APHRODITE dataset is used to provide an extended view over the Asian monsoon region. Although the analysis period (1958–2005) is shorter than that in Fig. 6, the distribution of high and low rainfall areas over India is similar. The region with significantly lower rainfall during CARSs extends longitudinally over Pakistan, central India, the Indochina Peninsula, and the northern Philippines. The region with significantly excessive rainfall during CARSs lies south and north of the relatively low rainfall area. The area of relatively low rainfall is consistent with the location of the monsoon trough or continental tropical convergence zone in past studies (Gadgil 2003). Usually, typhoons and other cyclonic disturbances, such as depressions or lows, move westward along the monsoon trough zone and produce rainfall over the monsoon trough area.

To explain the anomalous rainfall distribution during CARSs (Fig. 7), data from composite anomalous streamfunction and composite anomalous wind (Figs. 8a,b) and...
composite vertically integrated anomalous moisture flux and its divergence (Fig. 8d) were produced by using JRA-55 reanalysis data. The analysis period was 1958–2005. The composite of anomalous OLR is also shown (Fig. 8c) for comparison with the convective activity, including ocean areas. The analysis period is 1979–2005, due to the limited satellite data. Anomalous anticyclonic circulation (AAC) appears over central India and the northern Bay of Bengal, at both 200- and 850-hPa levels. Anomalous cyclonic circulations appear over the western equatorial Indian Ocean and the Tibetan Plateau at the 200-hPa level. The positive OLR anomaly (Fig. 8c) and anomalous moisture divergence (Fig. 8d) show intense convective suppression over the western Indian subcontinent. In the lower troposphere (Fig. 8b), the AAC is extended farther east over the South China Sea; this location is consistent with the area of relatively low rainfall in Fig. 7 and the positive OLR anomaly over the South China Sea and the Philippines in Fig. 8c. The convergence of the anomalous moisture flux over northeast India (Fig. 8d) corresponds well with active convection over northeast India during CARSs (Figs. 6 and 7), although negative OLR (Fig. 8c) does not represent well the convective activity over northeast India. The anomalous negative streamfunction is located over the central equatorial Indian Ocean at the 850-hPa level, and represents a double-cell structure.

To further investigate how synoptic conditions produce moisture convergence over northeast India, a composite of vertically integrated moisture flux and divergence during CARSs (Fig. 9b) is compared with a composite of climatological means throughout June to September (Fig. 9a). CARSs occupy only 8.5% of total analysis period, and the composite that excludes CARSs is almost same as the climatological mean. There is a large difference in the moisture flux field over 20°–30°N, while there is almost no difference south of 20°N, except that the moisture flux is somewhat smaller during CARSs. Climatologically, cyclonic circulation due to a monsoon trough appears over central India, and moisture transport is limited over this area (Fig. 9a). In contrast, a strong westerly moisture transport appears over central India, which intensifies moisture convergence over northeast India during CARSs (Fig. 9b). The location of moisture convergence over the foot of the central Himalayas is shifted slightly northward and intensifies during CARSs.

Figure 10 is the same as Fig. 8, but shows the composites of the CARS onset days. In the lower troposphere (Fig. 10b), AAC is distributed over the northern Bay of Bengal, the Indochina Peninsula, the South China Sea, and the western North Pacific along 10°–20°N. Compared with Fig. 8b, the AAC does not cover the Indian subcontinent. The location of the AAC is almost consistent with the convective suppression represented by positive OLR anomalies (Fig. 10c) and the divergence of the anomalous moisture flux (Fig. 10d). The anomalous negative streamfunction is located to the south of the AAC over the eastern Indian Ocean, and shows the double cell structure. Another anomalous negative streamfunction is located around Japan. In the upper troposphere (Fig. 10a), the AAC is located just over northeast India where convection is active (Fig. 10c). There are two other anomalous negative streamfunctions situated in the northeast and south of the AAC. The negative OLR anomaly (Fig. 10c) and the convergence of the anomalous moisture flux (Fig. 10d) are distributed not only in northeast India but also extend to southern China along the 20°–30°N zone; this location is consistent with the northern edge of the AAC at the 850-hPa level (Fig. 10b).

Table 1 shows that greater total rainfall tends to be observed during longer CARSs. The data were then divided by the length of CARSs, and compared with those in Fig. 11. The composite numbers of periods were 21, 40, and 9 for 3-, 5-, and 7-day CARSs, respectively. Figure 11 shows the composite of anomalous streamfunction and anomalous wind data at 850 hPa for 3- (Figs. 11a,d,g), 5- (Figs. 11b,e,h), and 7-day CARSs (Figs. 11c,f,i), respectively. The time evolution is also shown from day –2 to day +2. On day –2 (Figs. 11a–c), an AAC forms over the South China Sea. This AAC propagates westward, and the onset of CARSs (Figs. 11d–f) occurs when the AAC covers the northern Bay of Bengal. The AAC moves farther westward on day +2 (Figs. 11g–i). The westward propagation speed is...
in the range of 5–10 m s\(^{-1}\). On day \(-2\), the AAC extends more zonally toward the western North Pacific in 7-day periods than in 3-day periods. Furthermore, the AACs are more intense in 7-day periods than in 3-day periods. On day \(+2\), the westerly anomalies still remain over the western North Pacific along 20\(^\circ\)N in the 5- and 7-day periods. In the 7-day periods, the center of the AAC is still located in the western North Pacific.

The time evolution of the vertical structure was analyzed. The composites of the anomalous streamfunction and anomalous wind at 500 hPa were almost the same as in Fig. 11 (figures not shown). Figure 12 shows the composite of the anomalous streamfunction and anomalous wind at 200 hPa in 5-day periods on day \(-2\) (Fig. 12a), the onset of CARSs (Fig. 12c), and day \(+2\) (Fig. 12e). They are compared with anomalous OLR on day \(-2\) (Fig. 12b), the onset of CARSs (Fig. 12d), and day \(+2\) (Fig. 12f) to examine the effect of diabatic heating on the circulation field in the upper troposphere.

A significant AAC over the Tibetan Plateau tends to move southward with the onset of CARSs, and lies over the convectively active area. The comparison between the onset day of the CARSs and day \(+2\) shows a westward propagation. The composite of 3- and 7-day CARSs showed similar AAC movement toward the south, but they did not reach significance (figures not shown), possibly due to the relatively weak signal for 3-day CARSs and insufficient number of samples for 7-day CARSs.

5. Discussion

a. Synoptic conditions during CARSs

The composite of the CARS onset days implies that the CARSs begin when the AAC in the lower troposphere is over the Bay of Bengal (Fig. 10b). This AAC signal formed in the South China Sea and the western...
North Pacific propagates westward along 10°–20°N (Fig. 11). An anomalous negative streamfunction is situated to the south of the AAC, and makes a double-cell structure (Fig. 10b). During the CARSs, the AAC propagates farther westward over central India (Fig. 8b), and causes convective suppression (Fig. 8c). The AAC over central India has a barotropic structure (Fig. 8a). These features are consistent with the results of Fujinami.
et al. (2014) and other studies in the 10–20-day mode analysis. The AAC signal in the upper troposphere moved southward from the Tibetan Plateau and covered over central and northeast India (Fig. 12).

During CARSs, suppressed convective anomalies are distributed over a zonally elongated band from southern Pakistan, via central India, the northern Bay of Bengal, the Indochina Peninsula, and the Philippines, to the western North Pacific (Figs. 7 and 10c). A similar elongated band, but with opposite sign, was shown by Moon et al. (2013) during the active phase of the Indian summer monsoon, and by Takahashi et al. (2015) during above-normal precipitation over the Indochina Peninsula. The zonally elongated band is formed due to the westward propagation of AAC.

Wang and Xie (1997) simulated the similar elongated precipitation band over northwest India toward the equatorial central Pacific. They used the extension of the model developed by Wang and Li (1994). It is an equatorial beta-plane channel model with a model atmosphere consisting of a two-layer free troposphere and a well-mixed boundary layer, and includes surface evaporation in the moisture budget. The instability generated by convection–frictional convergence produced a low-frequency multiscale convective complex in which the condensation heating coupled moist Kelvin wave and moist Rossby wave with the gravest meridional structure \( n = 1 \) mode. Wang and Xie (1997) introduced the climatological July mean flow at 200- and 850-hPa levels and July mean surface specific humidity over Asian monsoon region as the model’s basic state.

The path, propagating speed, and horizontal scale of the observed westward propagating AACs in this study (Fig. 11) are similar to that of the simulated northern cell of the \( n = 1 \) equatorial Rossby waves in Wang and Xie
The structure of the simulated Rossby wave was highly asymmetric about the equator, featuring the intensified northern cell propagated from the South China Sea to the Arabian Sea and the much weaker southern cell that was located much closer to the equator over the Indian Ocean sector. This happens because the vertical easterly shear and high specific humidity are confined to the Northern Hemisphere. Xie and Wang (1996) showed that an easterly shear can effectively destabilize Rossby waves and the convective heating can further amplify waves with the most unstable wavelength (about 4000 km) for reasonably realistic parameters.

While the composite during CARSs shows the barotropic structure over central India (Figs. 8a,b), the time evolution of the 200-hPa AAC (Figs. 12a–c) shows that the AAC in the upper troposphere moves not westward but southward from the Tibetan Plateau on the onset of CARSs. It corresponds to a southward extension of the Tibetan high. Wang and Xie (1996) showed that the vertical easterly shear tended to trap Rossby waves in the lower troposphere. A plausible cause of the barotropic structure over central India is that the upper tropospheric AAC generated as a response to the diabatic heating over northeast India is superimposed on the lower-tropospheric AAC that propagated from the western North Pacific. It cannot be produced in the model of Wang and Xie (1997) because topography was not included in their model. The barotropic structure over central India during CARSs has been described during the break in the Indian summer monsoon (Ramaswamy 1962). There are studies that considered barotropic instability as a mechanism to control a revival of the Indian summer monsoon after the break events (Rao 1971; Govardhan et al. 2017). Figures 8a and 10a show a structure similar to a stationary Rossby wave pattern (Hoskins and Karoly 1981). However, the mean easterly flow in the upper troposphere over the south of the Tibetan Plateau will not form a stationary Rossby wave train.

Why do CARSs occur when the AAC is located south of northeast India? Figures 8d and 10d show the anomalous moisture convergence at the northern portion of the AAC. It can be seen that the area is consistent with the excessive rainfall area (Figs. 6 and 7). Figure 9b suggests that the westerly moisture transport over central India enhances water vapor convergence over northeast India together with the moisture transport from the Bay of Bengal during CARSs. In the climatological condition, the westerly moisture transport does not exist due to convergence over the Indian monsoon trough that extends from the northern Bay of Bengal to northwest India (Fig. 9a).

Murata et al. (2008) compared radiosonde soundings at Dhaka, Bangladesh, with daily rainfall at Cherrapunji during the monsoon in 2004, and showed that westerly wind dominated over the Bengal plain during the CARSs there. Figure 13 uses JRA-55 grid data corresponding to the location of Dhaka during 1958–2005.
and shows the correlation between the 925-hPa level horizontal wind and daily rainfall at Cherrapunji. The curve of the cumulative frequency distribution shows that nearly half of the period was an easterly phase. This situation corresponds with typical monsoon conditions when the Indian monsoon trough is intensified along the Ganges plain (Fig. 9a). However, the heavy daily rainfall was concentrated in the westerly phase of 5–10 m s
superscript 1, and occupies less than 20% of the overall period. For the meridional wind component, the southerly wind component was dominant throughout the monsoon period, and the heavy daily rainfall appeared in the southerly phase of 5–15 m s
superscript 1. This result implies that the westerly phase or southwesterly wind is a favorable condition for CARSs. As a small piece of additional evidence, there is a short story in which a boatman living in the Bengal plain recognizes a change in wind direction from easterly to westerly as a sign of an ARS.1

b. Relationship with the break spell of the Indian core region

The composite of the ARSs at Cherrapunji (Fig. 6) shows the opposite tendency to that of the composite of the ARSs over the Indian core region (e.g., Pai et al. 2016). The AAC at the 850-hPa level (Fig. 8b) over central India during CARSs weakens the airflow toward the Western Ghats, as well as the monsoon trough over the Ganges plain and the northern Bay of Bengal (Fig. 9), and suppresses the generation of monsoon depressions or lows, which are the main contributor to rainfall over the Indian core region. This perspective regarding the Indian monsoon break is similar to that of Krishnamurti and Ardanuy (1980), and implies that the onset of CARSs has the potential to predict break spells over the Indian core region. The CARSs overlap with 61% of break spells and only 2% of active spells in the Indian core region in the list shown in Pai et al. (2016).

However, Hartmann and Michelsen (1989) shows that a 30–60-day periodicity is dominant over the Indian core region, although years with a dominance of a 10–20-day periodicity are also included (Kulkarni et al. 2011). The 30–60-day mode exhibits remarkable northward propagation from the equatorial Indian Ocean to central India (Sikka and Gadgil 1980; Yasunari 1980). Recently, Hatsuzuka and Fujinami (2017) investigated the condition that low pressure systems (LPSs) with a wavelength of around 6000 km develop over Bangladesh. The LPSs tended to occur when an anomalous cyclonic circulation in 30–60-day mode was located over central India and the northern Bay of Bengal, while an AAC in 10–20-day mode was located over the northern Bay of Bengal. The westward propagation of the AAC from the northern Bay of Bengal toward central India was unclear in the LPS cases. Their result implies that combination of 10–20-day and 30–60-day modes produces the difference in the dominant frequencies between northeast and central India. CARSs may include more non-LPS cases as they showed that convection over Meghalaya Plateau is more active in the non-LPS cases.

c. Contribution of CARSs to extreme rainfall

Northeast India corresponds to the maximum rainfall area in the Indian subcontinent including not only the Meghalaya Plateau but also the adjoining areas of

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1 The short story “Boatman Tarini” written by Tarashankar Bandyopadhyay, a twentieth-century Bengali novelist.
the Himalayan range. Xie et al. (2006) pointed out the importance of narrow mountain ranges in the Indian subcontinent for the Indian monsoon circulation. In general, diabatic heating due to convective activity is an important factor in intensifying the monsoon circulation.

Daily rainfall equaling the record-breaking levels at Mumbai (Jenamani et al. 2006) is sometimes observed at Cherrapunji (Figs. 3 and 13; Guhathakurta 2007). Interestingly, however, such extreme daily rainfall exceeding 500 mm does not occur during on 1 or 2 consecutive HRDs and is included in longer CARSs (Table 1). As in the findings of Goswami et al. (2010), the fact implies that synoptic conditions during ARSs are important for heavy rainfall at Cherrapunji. The influence of the AACs on moisture flux convergence seems to produce persistent orographic lifting and result in large cumulative rainfall (Fig. 9). However, the composite of OLR does not represent well the heavy rainfall during CARSs (Fig. 8c). The orographic heavy rainfall may be difficult to be detect by OLR. Hamada et al. (2015) found that the extreme rainfall events with maximum near-surface rainfall rates had relatively low echo-top heights in the statistical analysis of TRMM observations, and pointed out the weak linkage between the heaviest rainfall and tallest storms.

The cumulative rainfall during CARSs has high correlation with the total monsoon rainfall (Fig. 4). The world record precipitation from 3 to 15 days was observed at Réunion Island in the southwestern Indian Ocean, and the records from 10 to 15 days were caused by the three approaches of Cyclone “Hyacinthe” in January 1980 (Chaggar 1984; Kiguchi and Oki 2010). On the other hand, the world record precipitation for more than 1-month time scales at Cherrapunji is based on the climatological long monsoon season during June–September including high-frequency CARSs with the dominance of 10–20-day periodicity.

Both total rainfalls during a CARS and frequency of CARSs contribute to the cumulative rainfall (Fig. 5). There is a linear relationship between the length and total rainfall of an ARS (Table 1). Figure 11 shows that AACs with a greater zonal scale tend to produce longer and more intense CARS. The AACs over the western North Pacific have been identified as an important component because they exert a great influence on the dynamics of East Asia monsoon through the production of a Pacific–Japan pattern (Nitta 1987). Longer persistent AACs, with a greater zonal scale, have been observed as a specific feature in post–El Niño summers, and various hypotheses have been proposed to explain the dynamics, such as wind–evaporation–SST feedback (Wang et al. 2000) or an Indian Ocean capacitor effect (Xie et al. 2009). The findings of this study provide evidence for the effect of AACs in the western North Pacific on the Indian summer monsoon. Some severe floods in Bangladesh (Hofer and Messerli 2006) occurred in post–El Niño summers. Terao et al. (2013) investigated the relationship between the rainfall over Bangladesh and western North Pacific monsoon, and focused on the post–El Niño summers of 1983, 1988, and 1998. Further investigations of the relationship between the AACs over the western North Pacific and CARSs are necessary for better forecasting of intense CARSs.

6. Conclusions

The synoptic conditions of active rainfall spells (ARSs) at Cherrapunji (CARSs), northeast India, were investigated. The town is famous for the extreme high rainfall that occurs over time scales greater than 1 month. The data that were predominantly used in this study were the daily rainfall data from 1902–2005 and the JRA-55 reanalysis data from 1958–2005. The CARSs correlated with the monsoon break spells over the Indian core region. Although several studies described excess rainfall in the northern part of India during the Indian monsoon break, research focusing on the intraseasonal variation over northeast India have been limited.

The CARSs start when an AAC is over the Bay of Bengal. The orographic rainfall at Cherrapunji intensifies when a westerly wind prevails in the northern portion of the AAC and enhances moisture flux convergence over northeast India. The AAC propagates westward from the South China Sea, and the same AAC suppresses convection over central India and the Western Ghats. In the upper troposphere, the Tibetan high tends to extend southward with the onset of CARSs. While the synoptic conditions during the Indian monsoon break have been described in terms of a northward shift of the Indian monsoon trough, the westward-propagating synoptic system plays an important role in the occurrence of CARSs: this implies the possibility of forecasting CARSs by monitoring the AAC over the South China Sea and the western North Pacific. A linear relationship was found between the length of a CARS and the total rainfall during the spell. Longer and heavier CARSs occurred when zonally larger AAC existed over the South China Sea and the western North Pacific. These findings provide evidence that AACs in the western North Pacific control the severity of CARSs and have an effect on the Indian summer monsoon.

Cherrapunji is a calcium-rich area geologically, and there are several limestone caves that have a potential to reconstruct the paleo monsoon climate. For example,
Myers et al. (2015) compared the stalagmite record of recent 50 years at Mawmluh cave in Cherrapunji with indices that represent Pacific decadal variabilities. The fact that the rainfall at Cherrapunji occurs during the break in the Indian core region may improve the interpretation, although it is still uncertain whether the same mechanism can be applicable on longer (interannual to centennial) time scales.

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