Characteristics of Low Pressure Systems Associated with Intraseasonal Oscillation of Rainfall over Bangladesh during Boreal Summer

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ABSTRACT

Characteristics of low pressure systems (LPSs) responsible for submonthly-scale (7–25 days) intraseasonal oscillation (ISO) in rainfall over Bangladesh and their impact on the amplitude of active peaks are investigated for 29 summer monsoon seasons. Extreme and moderate active peaks are obtained based on the amplitude of 7–25-day-filtered rainfall series. By detecting the LPSs that formed over the Indian monsoon region, it was found that about 59% (62%) of extreme (moderate) active peaks of rainfall are related to LPSs. These LPSs have horizontal scale of about 600 km and vertical scale of about 9 km. For the extreme active peak, the locations of the LPS centers are clustered significantly over and around Bangladesh, accompanied by the maximum convergence in the southeast sector of the LPSs. After their formation, they tend to remain almost stationary over and around Bangladesh. In contrast, for the moderate active peak, the LPS centers are located over the Ganges Plain around 85°E, and the maximum convergence of the LPSs occurs around their centers. This difference in the convergence fields is closely associated with the geographical features to the north and east of Bangladesh and the horizontal scale of the LPSs. These features suggest that the amplitude of the active peaks in the submonthly-scale ISO is modulated by small differences in the locations of the LPS centers. These findings suggest that improved predictions of both genesis location and the tracks of the LPSs are crucial to forecasting seasonal rainfall over Bangladesh.

1. Introduction

During the summer monsoon season (June–September), Bangladesh often receives heavy rainfall and the maximum seasonal rainfall is in excess of 6000 mm (Matsumoto et al. 1996). Bangladesh is characterized by very flat lowland (less than 10 m above sea level), but the Shillong Plateau and Chittagong Hill Tracts, situated near the northeast and east-southeast borders with India, respectively, rise up to ~2000 m above sea level (Fig. 1). As the southwesterly/southerly monsoonal flow from the Bay of Bengal dominates during this season, these higher-elevation regions act as orographic barriers against the prevailing winds. Thus, these geographical features are closely associated with both the spatial distribution of seasonal mean rainfall and the development of individual precipitation systems over Bangladesh (e.g., Kripalani et al. 1996; Ohsawa et al. 2000, 2001; Islam et al. 2005; Kataoka and Satomura 2005; Terao et al. 2006; Murata et al. 2008; Rafiuddin et al. 2010). Heavy rainfall during this season often causes disastrous floods over the flat lowland of Bangladesh (e.g., Matsumoto et al. 1996; Chowdhury 2003; Murata et al. 2008). To aid the prediction of heavy rainfall that leads to flooding over Bangladesh, it is necessary to have precise understanding of the processes and precipitation systems causing the heavy rainfall.

In the South Asian monsoon region, intraseasonal oscillations (ISOs) are a dominant mode of rainfall/convective variability. Many previous studies have shown

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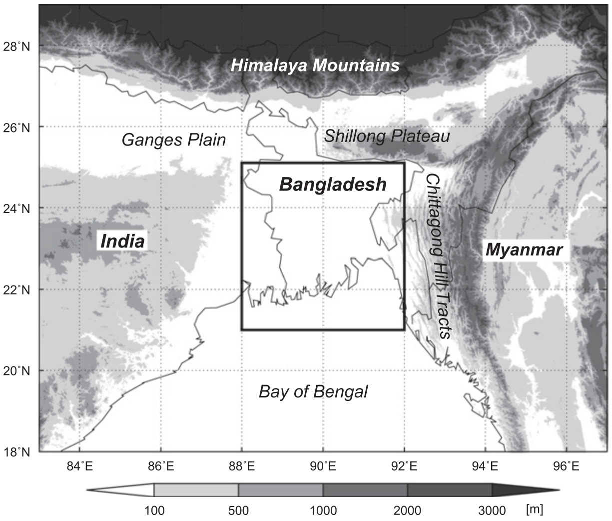


FIG. 1. Topography in and around Bangladesh. The boxed region denotes the area used in calculating the area-averaged rainfall time series.

two dominant spectral peaks: one with a period of 30–60 days (e.g., Yasunari 1979, 1980; Hartmann and Michelsen 1989; Singh et al. 1992; Annamalai and Slingo 2001) and the other with a period of 7–25 days, which in this study is referred to as a submonthly-scale ISO (e.g., Krishnamurti and Bhalme 1976; Yasunari 1979; Chen and Chen 1993; Annamalai and Slingo 2001; Hoyos and Webster 2007). A few studies have addressed specifically the ISO of rainfall/convection over Bangladesh. Ohsawa et al. (2000) examined the ISO of rainfall over Bangladesh for the summer of 1995 and found that the 7–25-day variation is dominant, whereas the 30–60-day variation is weak. Murata et al. (2008) presented distinct submonthly rainfall variability at Cherrapunjee (located on the southern slopes of the Shillong Plateau; 25.25°N, 91.73°E) in the 2004 monsoon season. Recently, Fujinami et al. (2011) reported similar findings over Bangladesh when using long-term data from a network of 25 rain gauges obtained between 1981 and 2000. These results indicate that the rainfall variation over and around Bangladesh is dominated by the submonthly-scale ISO. These ISO activities are also strongly related to interannual variability of the total summer monsoon rainfall in India and Bangladesh (Goswami and Mohan 2001; Fujinami et al. 2011). Fujinami et al. (2011) found that the interannual variability of the total summer monsoon rainfall in Bangladesh is correlated significantly with the submonthly rainfall variance, suggesting that the ISO activity controls the interannual variability of the total summer monsoon rainfall. They also examined probable effects of the submonthly-scale ISO on the interannual variability of summer rainfall and showed that high-amplitude active peaks occur more frequently during wet monsoon years than during dry monsoon years. However, it is still unclear which processes enhance the amplitude of the active peaks.

Monsoon lows and depressions, classified by the India Meteorological Department based on their maximum surface wind speeds (Raghavan and Rajesh 2003), are the main rain-producing systems over the Indian monsoon region. In this study, these systems are referred to collectively as low pressure systems (LPSs). Most LPSs form over the head of the Bay of Bengal and then move northwestward, accompanied by maximum rainfall in their southwest sectors. Their typical horizontal scale is a few thousand kilometers. These characteristic features have been well documented in many previous studies (e.g., Mooley 1973; Krishnamurti et al. 1975; Godbole 1977; Sikka 1977; Mooley and Shukla 1989). LPS activity is related strongly to the active and break phases of the ISOs (Yasunari 1981; Murakami et al. 1984; Goswami et al. 2003). Goswami et al. (2003) showed that the frequency of occurrence of LPSs is ~3.5 times higher during the active phase of an ISO than during its break phase, and that the tracks of the LPSs exhibit strong spatial clustering along the monsoon trough during the active phase of the monsoon. Recently, Krishnamurthy and Ajayamohan (2010) revealed that the number of LPS days during the active period is ~1.7 times greater than that during the break period. These results indicate that the spatial and temporal clustering of LPSs plays an essential role in increasing (decreasing) rainfall over central India during active (break) phases. As Bangladesh adjoins the head of the Bay of Bengal, the area in which the LPSs form most frequently, such systems are expected to augment the country's rainfall. However, no previous studies have addressed the relationship between the activity of the LPSs and the ISO over Bangladesh.

The objectives of this study are to 1) reveal the relationship between LPS activity and the submonthly-scale ISO of rainfall over Bangladesh during the summer monsoon season (June–September), 2) reveal the characteristics of the LPSs related to the ISO in Bangladesh, and 3) explain how the amplitude of active peaks in the ISO is modulated by the LPSs. Section 2 describes the datasets and analysis methods used in this study. The spatiotemporal structure of rainfall and atmospheric circulation associated with the submonthly-scale ISO over Bangladesh is presented in section 3. The detailed characteristics of LPSs related to the ISO and their impact on the amplitude of active peaks are discussed in section 4. In section 5, other processes that enlarge the amplitude of active peaks are discussed. In addition, the detailed structure of the LPSs is also discussed here, in comparison with monsoon depressions over India. Finally, the results are summarized in section 6.

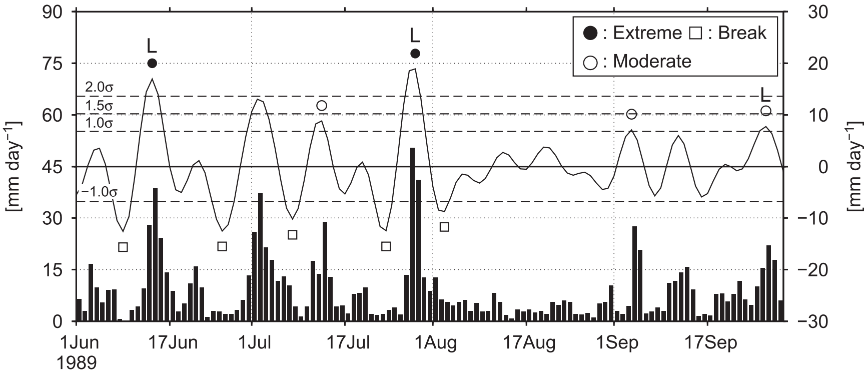


FIG. 2. Time series of area-averaged rainfall in APHRODITE dataset (black bars; left axis) and 7–25-day-filtered rainfall anomaly (solid line; right axis) from 1 Jun to 30 Sep 1989. Black and white circles denote extreme and moderate active peaks of the ISO in this study, respectively. The "L" indicates the extreme and moderate active peaks associated with LPS events. Black squares denote break peaks. Dashed lines indicate the criteria (±1.0σ, +1.5σ, and +2.0σ of climatological 7–25-day rainfall variance) used to select the peaks.

2. Data and analysis method

a. Dataset

The Asian Precipitation–Highly-Resolved Observational Data Integration Toward Evaluation of Water Resources (APHRODITE) dataset (Yatagai et al. 2009, 2012) was used to analyze the rainfall variations over Bangladesh. APHRODITE is a daily rainfall product on a 0.25° × 0.25° grid based on rain gauge observations. The period analyzed in this study is from June to September covering 29 years (1979–2007). To examine the temporal variation of rainfall over Bangladesh, the rainfall data obtained from an area encompassed by the coordinates 21°–25°N, 88°–92°E (rectangular box in Fig. 1) were averaged. Rain gauge stations were distributed uniformly over Bangladesh during the study period (Yatagai et al. 2009); thus, the area-averaged rainfall series does not depend on a specific region. This dataset was also used to depict the spatiotemporal structure of rainfall associated with the submonthly-scale ISO over Bangladesh. However, because this dataset is restricted to land areas, data from the Tropical Rainfall Measuring Mission (TRMM) 3B42 rainfall product, on a 0.25° × 0.25° grid, were also used for the case study in section 4.

To examine the spatiotemporal structure of atmospheric circulation associated with the submonthly-scale ISO over Bangladesh, we used Japanese 25-year Reanalysis Project (JRA-25) data on a 1.25° × 1.25° grid (Onogi et al. 2007). In accordance with APHRODITE, the period from June to September for 29 years (1979–2007) is used for the analysis. Moreover, we detected and tracked LPSs that formed over the Indian monsoon region during the study period by using the reanalysis data. The detailed procedure is described in section 4.

b. Definition of active and break peaks

To remove annual cycles, daily rainfall anomalies were computed by subtracting a 121-day (about 4 months) running mean from the original time series for each year. Submonthly (7–25 days) fluctuations were then extracted by applying a Lanczos filter (Duchon 1979) to the anomaly series throughout the entire year. This method is similar to that described by Fujinami et al. (2011). As an example, Fig. 2 presents the daily rainfall time series for the 1989 monsoon season (black bar) and the 7–25-day-filtered rainfall (solid line). The daily rainfall time series exhibits clear active and break cycles on the submonthly time scale, particularly during June, July, and September. Active and break peaks of the 7–25-day-filtered rainfall time series correspond well with those of the unfiltered time series. To extract the active peaks of the ISO, the 29-summer climatological standard deviation based on the 7–25-day-filtered anomalies (1.0σ: ~6.8 mm day^{-1}) was used as a criterion. As the purpose of this study is to clarify the process that causes high-amplitude active peaks of the ISO, positive extremes that exceeded +2.0σ were selected as extreme active peaks (filled circles in Fig. 2). To demonstrate the distinct difference between the active peaks, we also extracted moderate active peaks defined as those lying between +1.0σ and +1.5σ (open circles in Fig. 2). Note that active peaks between +1.5σ and +2.0σ (e.g., the active peak in early July 1989) were not included in either classification. In total, 49 extreme and 58 moderate active peaks were identified over the 29 years. The mean daily rainfall is 47.1 and 22.0 mm day^{-1} for the extreme and moderate active peaks, respectively. Additionally, 148 break peaks, defined as negative extremes of less than −1.0σ, were also identified to show general

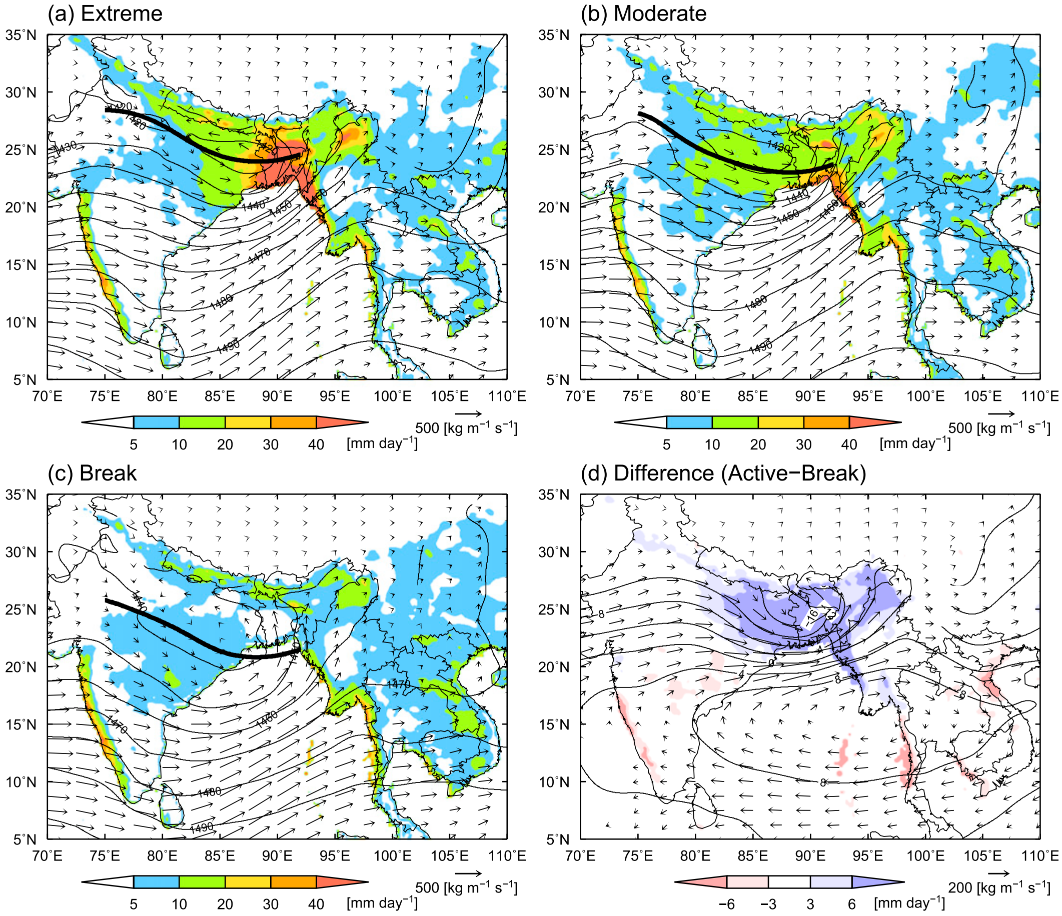


FIG. 3. Composites of APHRODITE rainfall (shading), 850-hPa geopotential height (contour), and vertically integrated (from the surface to 100 hPa) moisture flux vectors for the (a) extreme active, (b) moderate active, and (c) break peaks. The thick solid lines indicate the axis of the monsoon trough from India to Bangladesh. (d) Composite differences between active and break peaks. Only 95% statistically significant vectors are plotted.

features of the submonthly-scale ISO over Bangladesh (open squares in Fig. 2).

3. Synoptic features of submonthly-scale ISO over Bangladesh

To investigate the spatiotemporal structure of rainfall and atmospheric circulations associated with the submonthly-scale ISO over Bangladesh, composite analyses were conducted for extreme active, moderate active, and break peaks. Figure 3 shows composites of the total atmospheric circulation fields and rainfall for each peak. The position of the monsoon trough was identified using the 850-hPa streamfunction. In the extreme active peak, heavy rainfall ($\geq$30 mm day^{-1}) is observed over both Bangladesh and the high-elevation regions of the Shillong Plateau and Chittagong Hill Tracts (Fig. 3a). The monsoon trough is located along the foot of the Himalayas in the low-level troposphere and has its eastern end over Bangladesh. In this synoptic situation, southwesterly moisture flow dominates from the Bay of Bengal to Bangladesh. In the moderate active peak, the area of heavy rainfall is restricted to the Shillong Plateau and Chittagong Hill Tracts (Fig. 3b). Note that rainfall of more than 10 mm day^{-1} still can be observed over the entire country. The atmospheric circulation features show close similarity to those of the extreme active peak. In contrast, in the break peak, the rainfall amount exhibits a significant decrease over and around Bangladesh (Fig. 3c). The monsoon trough shifts southward and its eastern end is located over the head of the Bay of Bengal. The wind direction over Bangladesh becomes southerly/southeasterly, instead of southwesterly, owing to the shift of the monsoon trough. The features of the synoptic-scale circulation in both the active and break peaks are similar to those obtained by Ohsawa et al. (2000) and Fujinami et al. (2011). Figure 3d shows the composite differences between the active (147 peaks defined as positive extremes that exceed $+1.0\sigma$) and break peaks. The vectors where either the zonal or meridional moisture flux component surpasses the 95% confidence level, according to a Student's t test, are plotted. The circulation anomalies show a remarkable westerly moisture flux anomaly around 20°–25°N, accompanied by a cyclonic circulation anomaly over northern Bangladesh and an anticyclonic circulation anomaly over the Bay of Bengal. Thus, these results suggest that the westerly component toward Bangladesh plays an important role in increasing rainfall over Bangladesh.

Although these composites demonstrate obvious differences between the active and break peaks, our focus in this study is the differences between the active peaks. Figure 4 shows the composite differences between the extreme and moderate active peaks. As shown in Fig. 3, a remarkable positive rainfall anomaly is observed over northeastern India, all of Bangladesh, and western Myanmar. The circulation anomalies show a wavelike pattern with a ridge axis at about 83°E and a trough axis at about 90°E. A striking feature is a local cyclonic circulation anomaly centered on northern Bangladesh, enhancing westerly moisture flux anomalies over the head of the Bay of Bengal and Bangladesh. Associated with the local cyclonic circulation anomaly, moisture flux convergence is also enhanced remarkably over Bangladesh (not shown). The composite differences between the extreme and moderate active peaks reconfirm that the intensity of the westerly component is an important factor for increasing rainfall over Bangladesh. To understand the mechanism that causes the enhancement of local cyclonic circulation over Bangladesh, the following section focuses on the activity of the LPSs.

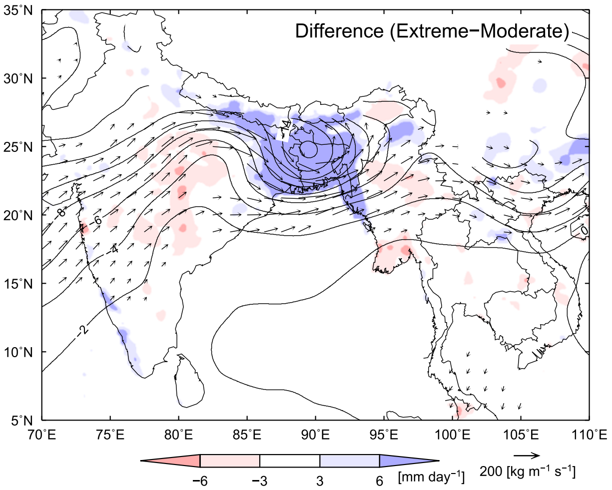


FIG. 4. Composite differences of APHRODITE rainfall (shading), 850-hPa geopotential height, and vertically integrated (from the surface to 100 hPa) moisture flux vectors between extreme and moderate active peaks. Only 95% statistically significant vectors are plotted.

4. Relationship between LPS activity and submonthly-scale ISO over Bangladesh

a. *Procedure for identifying LPSs*

In this section, the relationship between LPS activity and active peaks of submonthly rainfall variability over Bangladesh is examined. In the present study, an LPS means a cyclonic circulation with a closed contour of geopotential height in the low-level troposphere. We attempt here to detect and track LPSs that formed over the Bay of Bengal and adjoining land areas, during the 29-yr study period (1979–2007), using reanalysis data.

Some previous studies have used long-term data of the genesis and tracks of lows and depressions that formed over the Indian monsoon region (e.g., Goswami et al. 2003; Krishnamurthy and Ajayamohan 2010). These data were derived from a sea level pressure analysis of daily weather reports published by the India Meteorological Department. Although we also tried to detect LPSs based on the distribution of sea level pressure using an objective criterion, small-scale LPSs, which significantly affect rainfall variation over Bangladesh (shown in section 4b), were not detected well. Takahashi and Yasunari (2008) used the 700-hPa relative vorticity to identify tropical storms and weaker tropical cyclones around the Indochina domain. However, the Indian monsoon region is characterized by strong meridional cyclonic shear in the lower troposphere, which is due to the westerlies (easterlies) to the south (north) of the monsoon trough (see Fig. 3). As the region of strong cyclonic shear is usually accompanied by large positive vorticity, it is difficult to distinguish closed LPSs from the cyclonic shear. Therefore, we detected LPSs using a combination of relative vorticity and geopotential height at 850 hPa. The procedures are as follows. 1) A candidate LPS center is identified by satisfying a criterion of a minimum 850-hPa geopotential height. That criterion is defined by the difference from surrounding grids, the thresholds of which are 2 and 1 gpm for the surrounding 8 and 16 grids, respectively. 2) If the 850-hPa relative vorticity of the candidate center is more than $6.0 \times 10^{-5}\,\mathrm{s}^{-1}$, it is identified as a legitimate LPS. 3) To track the LPS, a search area is defined as a range of six grids (about 800 km) to the west side and three grids (about 400 km) to the east, south, and north sides from the LPS center. If, on the following day, an LPS appears within the search area, it is considered the same one as detected previously. 4) Only LPSs formed within the genesis region are detected and are tracked within the tracking region (each region is shown in Fig. 5). These regions cover a dense area of the genesis and track of LPSs described by previous studies

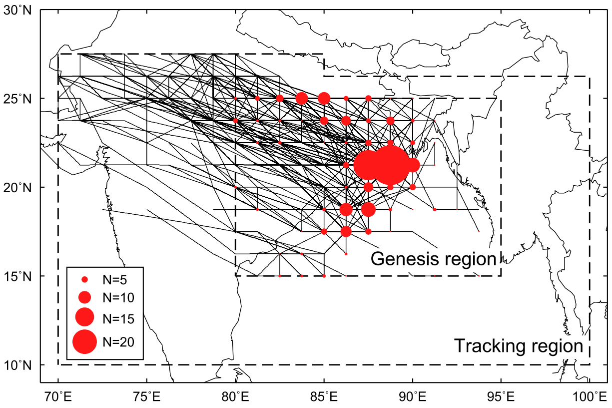


FIG. 5. Distributions of genesis points (red circles) and tracks (solid lines) of all LPSs identified during June–September (JJAS) for the period 1979–2007. The size of red circles denotes the number of geneses in each grid point. The inner and outer domains bounded by dashed lines indicate the regions used to detect and track the LPSs, respectively (see the text for details).

(e.g., Fig. 1 of Krishnamurthy and Ajayamohan 2010). Some LPSs have also been seen over the Arabian Sea in these previous studies; however, they are not expected to affect directly the rainfall over Bangladesh. Figure 5 shows the distribution of the genesis point and track of the all the LPSs identified during the 29 summer monsoon seasons according to this procedure. The size of the red circles indicates the number of LPS geneses at each grid point. During this period, 274 LPSs were identified with a seasonal average of 9.4 and an average lifetime of 4.9 days. Most of these LPSs were generated over the head of the Bay of Bengal and moved northwestward. This distribution captures well the characteristics of the classical LPSs, such as monsoon lows and depressions. In addition, the small-scale systems that are the focus of this study are also identified successfully by our method. To examine the activity of the LPSs related to submonthly rainfall variability over Bangladesh, we defined an LPS case as a day on which at least one LPS existed between day −1 and day +1 of a peak day. As a result, 29 out of 49 extreme (36 out of 58 moderate) active peaks were identified as LPS cases. This result indicates that about 60% of the selected peaks are related to the LPSs in both active peaks.

b. *Case study*

Figure 6 shows an example of an LPS related to an extreme active peak in the summer of 2003 using TRMM rainfall, 850-hPa geopotential height, and wind vectors. The date of the extreme active peak was 21 June. This LPS formed over southwestern Bangladesh on 17 June with a weak cyclonic circulation, and remained almost stationary until its termination on 22 June. Interestingly, in general, tropical disturbances (such as tropical depressions, tropical storms, and typhoons) develop over the sea and weaken after landfall, whereas this LPS formed over the coastal region and attained its maximum strength over land. In the initial stage of the LPS (17–19 June), heavy rainfall occurred mainly in the low-level monsoon westerly region over the Bay of Bengal. In the mature stage (20–22 June), heavy rainfall was observed in the southeast sector of the LPS, corresponding to the region of strong southwesterly winds from the LPS. The low-level southwesterly winds toward the coastal mountains of Myanmar cause intense convection on the windward side via orographic lifting (e.g., Xie et al. 2006; Houze et al. 2007). Therefore, this result suggests that the heavy rainfall in the southeast sector of the LPS was induced by the physical interaction between the southwesterly winds and the mountainous terrain to the southeast of Bangladesh. Note that high rainfall of more than 30 mm day^{-1} can also be observed near the LPS center (i.e., over Bangladesh) on 21–22 June. Moreover, as an important characteristic, this LPS had a horizontal scale of about 500 km throughout its lifetime.

As mentioned in section 1, LPSs such as monsoon lows and depressions typically have horizontal scale of 1000–3000 km and move northwestward exhibiting maximum rainfall in their southwest sectors. When these LPSs move toward central India, associated southerly/southeasterly winds dominate over Bangladesh (see Fig. 2 of Krishnamurthy and Ajayamohan 2010). This situation is similar to that during the break peak in our results (Fig. 4c); thus, Bangladesh receives little rainfall during their northwestward passage. On the other hand, we found that one LPS is closely related to heavy rainfall over Bangladesh. The LPS examined here has obviously different characteristics from the monsoon lows and depressions described in previous studies. However, this result is derived from the analysis of a single heavy rainfall event over Bangladesh. Therefore, the statistical characteristics of LPSs associated with active peaks over Bangladesh are analyzed in section 4c.

c. *Statistical characteristics*

1) LPS LOCATION

Figure 7 shows a distribution of the appearance frequency of LPS centers associated with extreme and moderate active peaks for 29 years, together with a histogram with respect to longitude. The frequency is obtained by counting the number of LPS centers detected between day −1 and day +1 of peak days for each grid point. In total, 85 and 92 LPSs were counted in the extreme and moderate active peaks, respectively. In both active peaks, the LPS centers are located mainly along

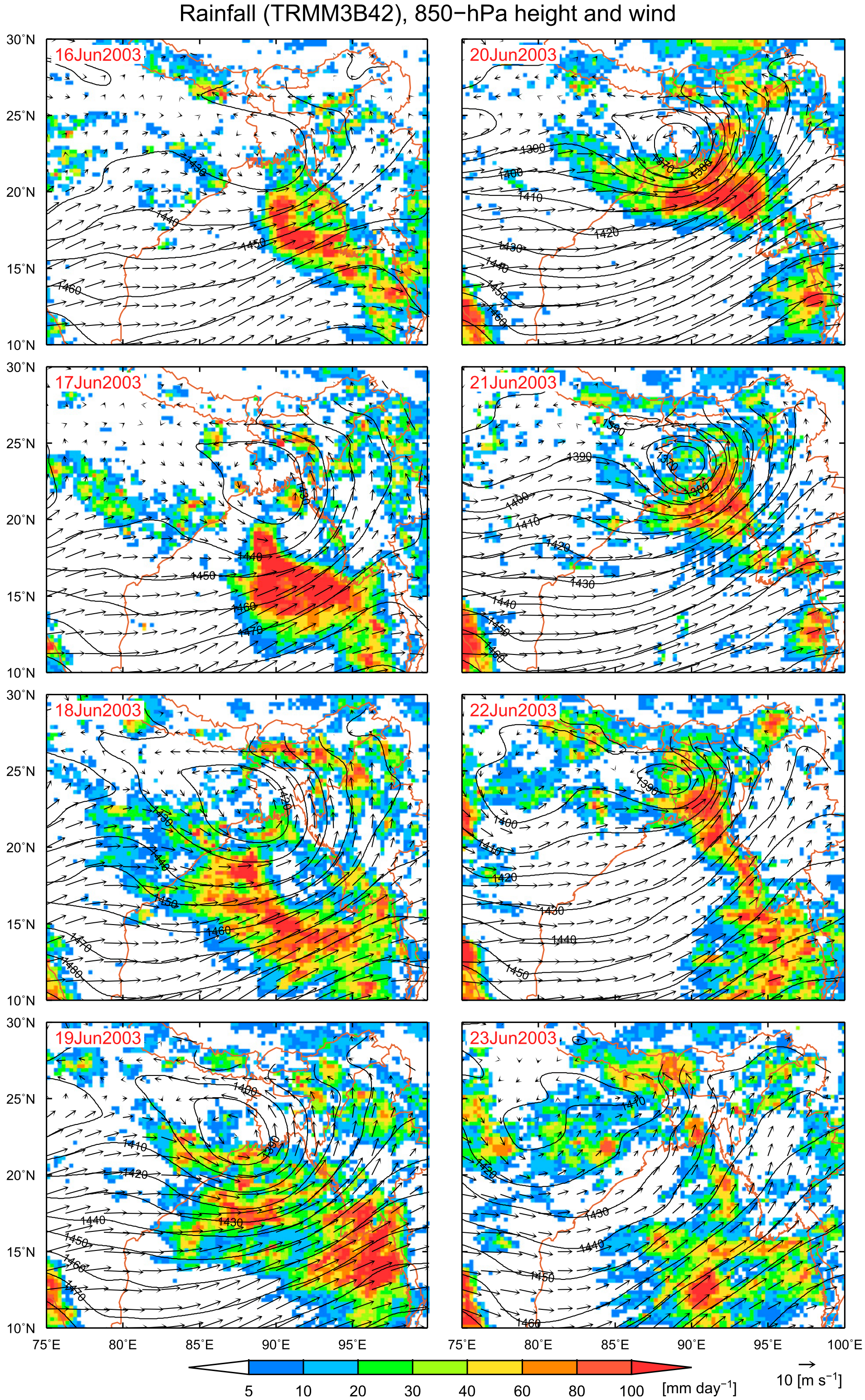


FIG. 6. Time evolution of an LPS associated with an extreme active peak based on TRMM 3B42 rainfall (shading), 850-hPa geopotential height (contour), and wind vectors during 16–23 Jun 2003. The date of 21 Jun corresponds to the extreme active peak. The dates of 17 and 22 Jun correspond to the genesis and termination of the LPS, respectively, identified using our method (see the text).

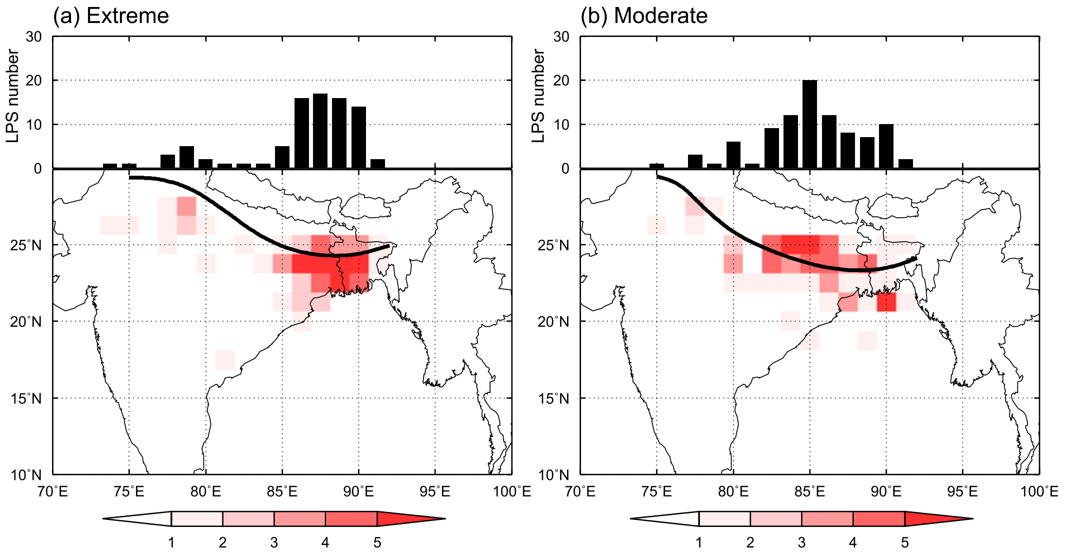


FIG. 7. (bottom) Distribution of the frequency of LPS centers in each grid point and (top) its histogram with respect to longitude for the (a) extreme and (b) moderate active peaks. The thick solid line indicates the axis of the monsoon trough from India to Bangladesh.

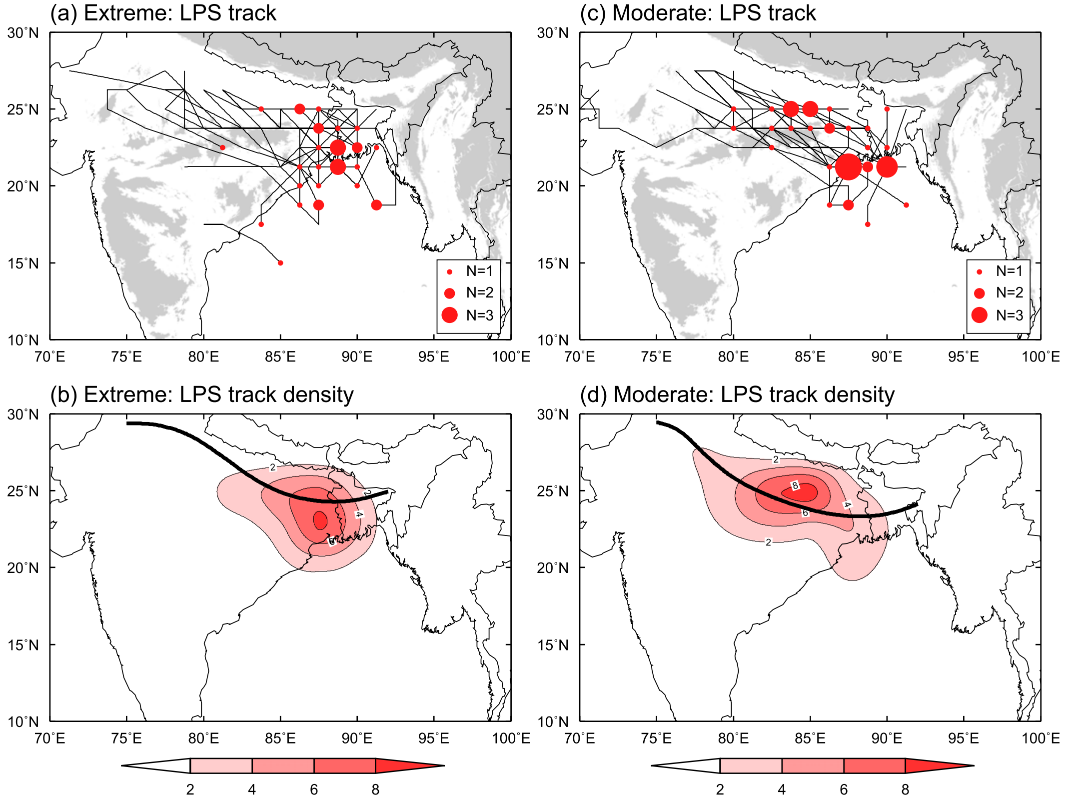
the monsoon trough, which extends from northwestern India to Bangladesh. However, the longitudinal distributions show a considerable difference between the extreme and moderate active peaks. In the extreme active peak, the LPS centers are clustered over and around Bangladesh (Fig. 7a). The maximum frequency appears over Bangladesh at grid points of 23.75°N, 90°E and 23.75°N, 88.75°E. In terms of location, this result supports that the LPS shown in Fig. 6 is a typical example of the extreme active peak. In the moderate active peak, the centers are concentrated over the Ganges Plain around 25°N, 85°E (Fig. 7b). The high-frequency area shifts slightly to the northwest side of that of the extreme active peak. The locational difference between the extreme and moderate active peaks contributes to form the local cyclonic circulation anomaly over Bangladesh shown in Fig. 4. We also examined the location of LPS centers when active peaks in the submonthly-scale ISO lay between $+1.5\sigma$ and $+2.0\sigma$ (not shown). Despite a lower percentage of LPS cases (~40%), the frequency with respect to longitude showed a maximum at 86.25° and 87.5°E, which is between the extreme and moderate active peaks. Therefore, these results suggest strongly that the small difference in the location of LPS centers has significant impact on the amplitude of active peaks over Bangladesh.

2) LPS TRACK

Figure 8 shows the distributions of LPS tracks and genesis points associated with extreme and moderate active peaks. To show their spatial distributions more quantitatively, Fig. 8 also shows the frequencies that were computed on 2.5° × 2.5° grid boxes by counting the number of LPS within a given grid box. In both active peaks, the LPS tracks and genesis points are concentrated around the monsoon trough. In the extreme active peak, most of the LPSs formed over the head of the Bay of Bengal and around Bangladesh (Fig. 8a). The distribution of LPS frequency shows the highest frequency around Bangladesh, indicating that it is rare for an LPS to move northwestward like a monsoon depression (Fig. 8b). This result is consistent with that of the case study shown in Fig. 6. In the moderate active peak, the LPSs occur most commonly over the northern tip of the Bay of Bengal (Fig. 8c), and they tend to move northwestward to the Ganges Plain. A relatively large number of LPSs are also formed over the Ganges Plain around 25°N, 85°E, which tend to remain almost stationary. The characteristics of these LPS tracks are reflected in the high-frequency area in Fig. 8d. The difference in the distribution between the extreme and moderate active peaks suggests that the LPSs related to the extreme active peak are distinct from those related to the moderate active peak.

3) SPATIAL STRUCTURE OF LPSS

To understand the processes responsible for increasing the amplitude of active peaks, we examined the spatial structures of LPSs associated with the extreme and moderate active peaks. Figure 9 shows the composite structures of the LPSs for each active peak, which are obtained by superposing the individual LPS centers at the origin of the coordinate system. In the extreme and moderate active peaks, 85 and 92 samples were used to construct the composites, respectively. Figures 9a and 9c show the composites of 850-hPa geopotential height



(a) Extreme: LPS track

(c) Moderate: LPS track

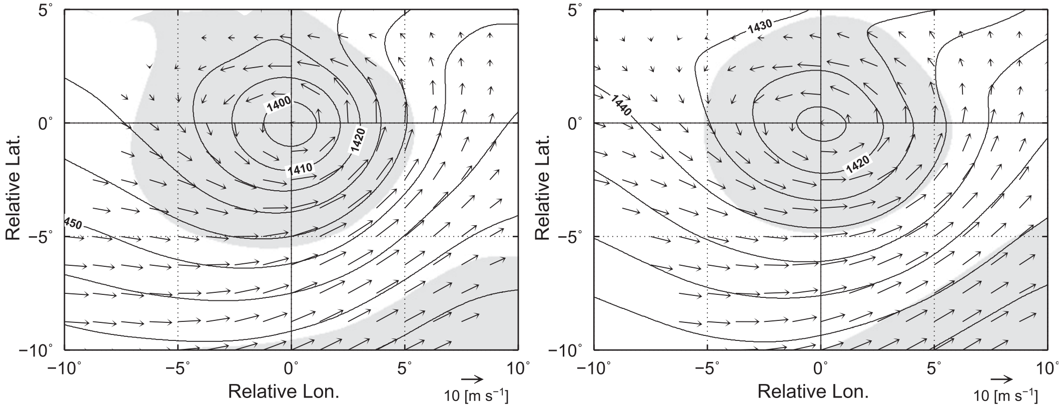
(b) Extreme: LPS track density

(d) Moderate: LPS track density

FIG. 8. (a) As in Fig. 5, but for the extreme active peak. (b) Distribution of the frequency of the LPS tracks for the extreme active peak, which is computed on 2.5° × 2.5° grid boxes by counting the number of LPS within a given grid box. (c),(d) As in (a),(b), but for the moderate active peak. The gray shading in the top panels shows an elevation higher than 500 m. The thick solid lines in the bottom panels indicate the axis of the monsoon trough from India to Bangladesh.

and wind vectors. In both active peaks, closed cyclonic circulations are clearly identified to the north of the predominant westerly/southwesterly monsoon. A typical horizontal scale of these LPSs is estimated from the size of the outermost closed contour. In the extreme active peak, the horizontal scale of the LPS is estimated to be 600–700 km (Fig. 9a). The low-level winds associated with the LPS have a maximum speed of 13–14 m s^{-1} in the southeast sector. In the moderate active peak, the horizontal scale is estimated to be about 600 km, which is almost the same size as in the extreme active peak (Fig. 9c). The maximum wind speed is also seen in the southeast sector, but it is weak compared with that in the extreme active peak ($\sim$10 m s^{-1}). In both active peaks, it is highly probable that the maximum winds in the southeast sector are caused by the superposition of the large-scale monsoon westerlies and the LPS's own flows. As well as the maximum wind speed, the LPSs exhibit stronger central vorticity in the extreme active peak than in the moderate active peak (not shown). Although the horizontal scale in the extreme active peak seems to be slightly larger than that of the moderate active peak, both of these LPSs are much smaller than the monsoon depressions described by previous studies (e.g., Krishnamurti et al. 1975; Godbole 1977). The similar horizontal scale of the LPS between the extreme and moderate active peaks emphasizes the importance of their locations for the modulation of the amplitude of active peaks.

Figures 9b and 9d show the composites of vertically integrated (from the surface to 100 hPa) moisture flux and its divergence for each active peak. A striking feature in the extreme active peak is the remarkable convergence field in the southeast sector of the LPS (Fig. 9b). In the composite map, Bangladesh corresponds to the east side of the LPS. Thus, the spatially localized feature of the strong convergence is influenced undoubtedly by the surrounding mountainous terrain, such as the Shillong Plateau and Chittagong Hill Tracts. This result is consistent with the maximum rainfall in the southeast sector of the LPSs during the mature phase shown in Fig. 6. A relatively large convergence is also located in the northeast sector away from the center of the LPS, which is likely caused by the orographic effect to the northeast of Bangladesh (i.e., the Shillong


(a) Extreme: 850−hPa z and wind

(c) Moderate: 850−hPa z and wind

(b) Extreme: qv and div(qv)

(d) Moderate: qv and div(qv)

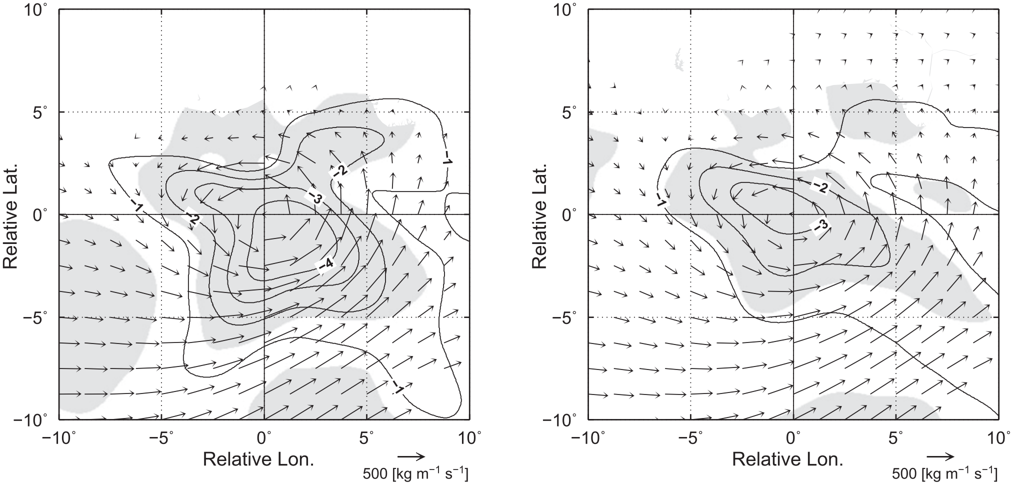


FIG. 9. Horizontal structures of the composite LPS. (a) 850-hPa geopotential height (contour) and wind vectors for the extreme active peak. (b) As in (a), but for vertically integrated (from the surface to 100 hPa) moisture flux and its divergence (contour). The contours for moisture flux divergence are shown at −4.0, −3.0, −2.0, and −1.0. The unit is $1 \times 10^{-4}\,\mathrm{kg\,m^{-2}\,s^{-1}}$. (c),(d) As in (a),(b), but for the moderate active peak. In all panels, the vectors and shaded areas indicate that the anomaly is statistically significant at the 99% confidence level.

Plateau). In the moderate active peak, a remarkable convergence field is formed around the LPS center, but the intensity is weak compared with that of the extreme active peak (Fig. 9d). As Bangladesh corresponds to the east side of the LPS in the composite map, the convergence around the center seems to be due to the effect of surface friction rather than surrounding terrain. Note also that weak convergence fields are observed over the southeast and northeast side of the LPS, suggesting orographic rainfall on the windward slopes of the Shillong Plateau and Chittagong Hill Tracts. Thus, the difference in the moisture flux divergence field between the extreme and moderate active peaks suggests that these geographical features and the horizontal scale of the LPSs are essential factors that enhance the convergence of the LPSs. The submonthly-scale ISO of rainfall over Bangladesh is caused by the low-level zonal wind fluctuations associated with the north–south shift of the monsoon trough (e.g., Ohsawa et al. 2000; Fujinami et al. 2011). That is, when the southeasternmost portion of the monsoon trough is situated over Bangladesh during the active phase of the ISO, the strong meridional cyclonic shear and abundant moisture provide favorable environmental conditions for inducing rainfall in this region. Under this synoptic situation, the LPSs have a role in further enhancing the moisture convergence locally and in enlarging the amplitude of active peaks over Bangladesh.

Figure 10 shows the vertical cross sections of each variable in the extreme active peak, which are based on zonal vertical planes passing through the LPS center described in Fig. 9. In the vertical structure of meridional wind (Fig. 10a), a cyclonic circulation associated with the LPS is identified from the surface up to the 300-hPa level, which prevails particularly in the lower troposphere

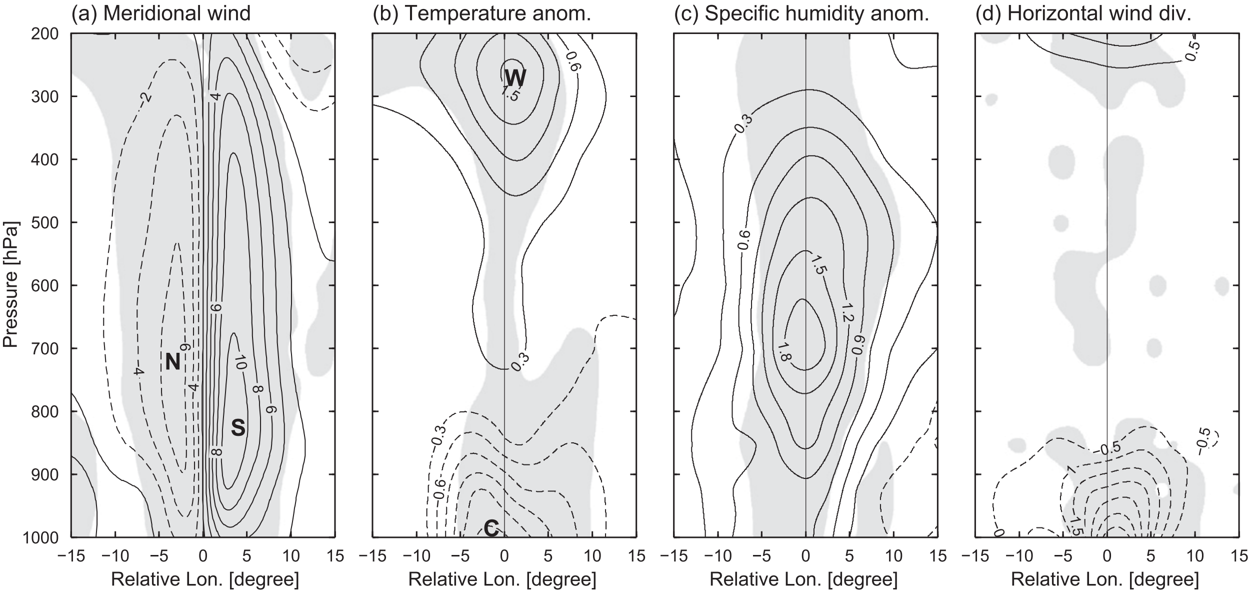


FIG. 10. Vertical cross sections of the composite LPS for the extreme active peak along the longitude of the LPS center shown in Fig. 9. (a) Meridional wind. The contour interval is 2 m s^{-1}. (b) Temperature anomaly. The contour interval is 0.3 K. (c) Specific humidity anomaly. The contour interval is 0.3 kg kg^{-1}. (d) Horizontal wind divergence. The contour interval is 0.5 × 10^{-5} s^{-1}. In all panels, the shaded areas indicate that the anomaly is statistically significant at the 99% confidence level.

below the 600-hPa level. The vertical structure of the zonal wind also shows an associated cyclonic circulation extending to about 300 hPa (not shown). These results indicate that the vertical scale of the LPS is about 9 km. Figure 10b shows the vertical structure of temperature anomaly defined as a departure from the 29-yr summer mean at each pressure level. The thermal structure shows clearly a cold core in the lower troposphere and a warm core in the upper levels. The reversal of the thermal structure occurs between the 800- and 700-hPa levels. Figure 10c shows the vertical structure of the specific humidity anomaly. A deep moist layer is observed from the surface up to the 300-hPa level, in accordance with the depth of the cyclonic circulation in Fig. 10a. The maximum anomaly appears in the middle troposphere near the 700-hPa level. This moisture distribution seems to be caused by the vertical advection of water vapor due to the organized convection. Figure 10d shows the vertical structure of horizontal wind divergence. A striking feature is the strong convergence in the lower troposphere from the surface up to about 850 hPa. The low-level convergence is stronger on the east side of the LPS center than on the west side. This is consistent with the vertically integrated moisture flux convergence in Fig. 9, indicating again the effects of the geographical features around Bangladesh. In the moderate active peak, the LPS shows vertical structures similar to the extreme active peak, except for the divergence field with maximum convergence around the LPS center (not shown). These structures of the LPS are compared with monsoon depressions over India and discussed in the following section.

5. Discussion

a. *Regional-scale rainfall distribution and associated mesoscale processes in LPS and non-LPS cases*

In the previous section, we found that about 60% of the selected active peaks are related to LPSs, and that location is an important factor in determining the amplitude of the active peaks. However, about 40% of them occur without LPSs (hereafter referred to as a non-LPS case). This means that the non-LPS case also contributes to increasing rainfall over Bangladesh. Figure 11 shows the distributions of mean rainfall and 925-hPa wind in the extreme and moderate active peaks. In the extreme LPS case, heavy rainfall (≥50 mm day^{-1}) is observed over most of Bangladesh and high-elevation regions such as the Shillong Plateau and Chittagong Hill Tracts (Fig. 11a). Low-level winds are mainly southwesterly/southerly over Bangladesh, in association with cyclonic circulation over the west of the country. In contrast, in the extreme non-LPS case, the heavy rainfall is limited to the regions around the Shillong Plateau and Chittagong Hill Tracts (Fig. 11b). Low-level winds are predominantly westerly/southwesterly over Bangladesh, suggesting orographically induced rainfall on the windward slopes of these high-elevation regions. Corresponding to large-scale geographical features, high rainfall ($\geq$20 mm day^{-1}) is also observed along the foot of the Himalayas. Note that the rainfall over Bangladesh decreases compared with the extreme LPS case, although more than 30 mm day^{-1} is still observed over the entire country. This indicates the importance of LPSs for increasing rainfall over the lowland area of Bangladesh. In the moderate LPS case, high rainfall is located mainly over southern Bangladesh, accompanied by a cyclonic circulation around 85°E (Fig. 11c), whereas in the non-LPS case it appears over the northeast and southeast of Bangladesh (Fig. 11d). Comparing the non-LPS cases (Figs. 11b,d), the westerly/southwesterly winds are stronger in the extreme active peak than in the moderate active peak. Using a regional atmospheric model, Sato (2013) indicated that during the active period in June–July 2004, the southwesterly wind speed in the lower troposphere is a crucial factor with regard to heavy rainfall over the Shillong Plateau. Our results also suggest that the intensity of the low-level winds is one of the important factors for enhancing the amplitude of active peaks over Bangladesh.

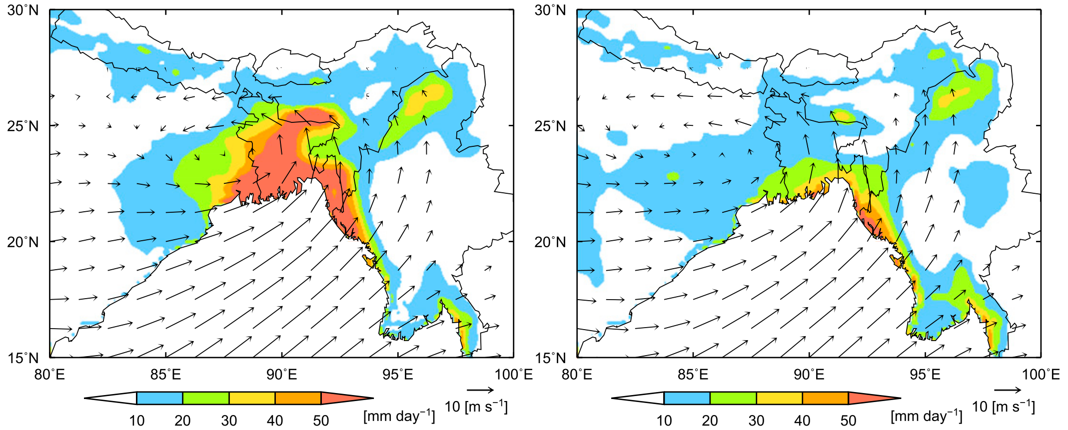
The diurnal cycle during the active phase of submonthly-scale ISO also plays an important role in heavy rainfall over Bangladesh. Ohsawa et al. (2000) showed that during the active phases in 1995, convective activity over Bangladesh has a clear diurnal cycle with its peak during the late night–early morning hours. Using a nonhydrostatic cloud-resolving model, Kataoka and Satomura (2005) found that late night–early morning precipitation maxima in northeastern Bangladesh on 15–18 June 1995 were associated with squall-line precipitation systems, triggered near the southern foot of the Shillong Plateau, which moved southward. Recently, Sato (2013) reported that the simulated diurnal cycle of rainfall around the Shillong Plateau becomes more stimulated during the active phase with a late night–early morning peak. He also showed that the low-level jet develops around the 900-hPa level over windward areas such as Bangladesh during the midnight–early morning hours, suggesting that the diurnal cycle of the low-level jet contributes to the ISO as well as the diurnal cycle of rainfall. Our results in this study also show similar synoptic features in the non-LPS case (Figs. 11b,d). Thus, the same processes are expected to be responsible for the non-LPS active peaks over Bangladesh. However, the rainfall and circulation fields in the extreme active peak show remarkable differences between the LPS and non-LPS cases (Figs. 11a,b), suggesting that different mesoscale processes are responsible for increasing the rainfall over Bangladesh. We did not examine the mesoscale processes associated with the LPS case in this study; however, this issue is important in understanding the processes that cause heavy rainfall over Bangladesh.

b. *Vertical structure of LPSs over Bangladesh and Indian monsoon depression*

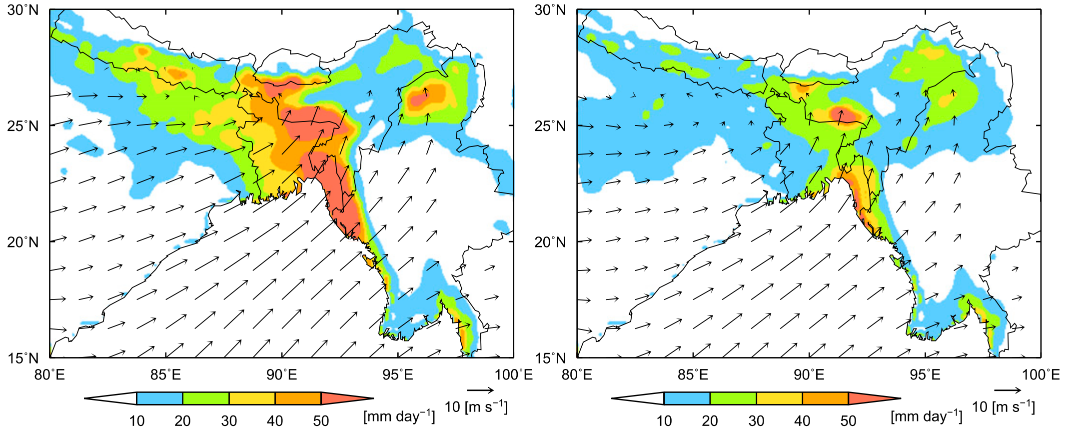
In the previous section, we demonstrated that the LPSs associated with active peaks over Bangladesh have different horizontal scales and rainfall (and moisture flux convergence) distributions from the monsoon depressions over India. In contrast, the vertical scale of the LPS, which is about 9 km (Fig. 10a), agrees roughly with that of the monsoon depressions obtained by Krishnamurti et al. (1975) and Godbole (1977). The cold/warm core structure (Fig. 10b) also resembles well that of the monsoon depressions described by the above two studies, but their results show the cold core center near the 800-hPa level and not at the surface level. Krishnamurti et al. (1975) noted that this thermal structure is peculiar to the monsoon depressions over India, by comparing them with other tropical disturbances. Murakami (1977) examined the vertical structures of monsoon lows over the inland and coastal areas of northern India, but his results did not show an obvious cold core in the lower troposphere for either region. He mentioned that this discrepancy probably reflects the difference between the monsoon depressions and the relatively weak monsoon lows. These results indicate that the LPSs related to the extreme active peaks over Bangladesh have a vertical structure similar to that of the monsoon depressions. In contrast, a remarkable difference in the vertical structures between Bangladesh and India is found in the divergence field. As shown in Fig. 10d, the LPSs over Bangladesh have stronger convergence on the east side of the LPS center in the lower troposphere, whereas the monsoon depressions over India, obtained by Godbole (1977), present strong convergence on the west side of the depression center from the surface up to the 400-hPa level. He also mentioned that the presence of the pronounced convergence (and rainfall) on the west side contributes to the northwestward propagation of the depressions. Therefore, the difference in the convergence/rainfall distribution of the LPSs may also be related to their direction of propagation (i.e., as a suppressive effect on northwestward movement).

c. *Genesis and development processes of LPSs over Bangladesh*

The formation processes of the LPSs are also an important issue because the LPSs provide more rainfall over the flat lowland of Bangladesh during the extreme active peak (Fig. 11). The time evolution of the LPS has been shown in Fig. 6. According to this case study, a low-level monsoon westerly seems to flow into Bangladesh along the Chittagong Hill Tracts and Shillong Plateau during the formative stage (16–18 June 2003). That is, these orographic features seem to act in the formation


(a) Extreme (LPS case)

(c) Moderate (LPS case)


(b) Extreme (non−LPS case)

(d) Moderate (non−LPS case)

FIG. 11. Spatial distribution of mean rainfall in APHRODITE dataset (shading) and 925-hPa wind vectors for the (left) extreme and (right) moderate active peaks. (a),(c) LPS case. (b),(d) Non-LPS case.

and development of the vortex over the Bangladesh region in front of their windward slopes. In contrast, if the low-level wind flows against these areas of mountainous terrain, forced lifting along their windward slopes is expected to be more dominant without any formation of a vortex (i.e., non-LPS case). Hence, whether a vortex-type LPS is formed over and near Bangladesh may be controlled by a slight difference in the low-level wind direction toward the surrounding regional-scale terrain, such as the Shillong Plateau and Chittagong Hill Tracts. Fujinami et al. (2011) reported that the submonthly rainfall ISO over Bangladesh is caused by the low-level zonal wind fluctuations over and around Bangladesh, associated with the westward-propagating submonthly-scale ISO. In the active ISO phase, an anticyclonic anomaly from the western Pacific is located over the Bay of Bengal (see Fig. 7 of Fujinami et al. 2011; Fig. 10 of Fujinami et al. 2014). This synoptic situation enhances the westerly/southwesterly flow over and around Bangladesh, which provides a favorable environment for inducing high rainfall within this region, together with the surrounding regional mountains. In this study, we found that LPSs bring high rainfall on submonthly time scales over Bangladesh (e.g., Figs. 2 and 6), suggesting that the genesis and development of the LPSs are also controlled by the submonthly-scale ISO. To illustrate the phase relationship between the submonthly-scale ISO and an LPS for a typical case, Fig. 12 shows the time evolution of the atmospheric circulation related to the ISO during 24–29 July 1989. The date of 29 July corresponds to the extreme active peak of rainfall over Bangladesh (Fig. 2). The red circles in Fig. 12 indicate the central positions of the LPS responsible for the active peak. This LPS formed over the head of the Bay of Bengal on 26 July and disappeared over Bangladesh on 29 July. The horizontal scale of the LPS is estimated to be about 500 km (not shown), consistent with statistical characteristics shown in this study. Figure 12 shows a remarkable westward propagation, as seen in previous studies (Fujinami et al. 2011, 2014). On 24 July, an anticyclonic circulation appears over the westernmost Pacific around

20°N, 120°E and moves westward to the Indian subcontinent by 29 July. On 26 July, when the anticyclonic anomaly moves into the Bay of Bengal, the LPS is generated simultaneously with the enhancement of westerly flow over the head of the Bay of Bengal. After 26 July, the LPS moves gradually northward under the strong westerly anomaly because of the anticyclonic circulation around 15°N. Saha et al. (1981) suggested that most Indian monsoon depressions could be attributed to the redevelopment of westward-propagating residual lows of typhoons, tropical storms, or other tropical disturbances from the westernmost Pacific. In Fig. 12, such a westward-propagating low/depression can be found over western India on 24–26 July, inducing the break phase over Bangladesh. The LPS over Bangladesh is indeed triggered by the anomalous high (not low) related to the submonthly-scale ISO that propagates westward in a similar manner. Fujinami et al. (2011) also revealed that the submonthly-scale ISO is closely associated with the north–south shift of the monsoon trough. That is, when the anticyclonic circulation anomaly appears over the Bay of Bengal, the monsoon trough axis shifts northward and deepens along the Ganges Plain. This situation is likely to create strong meridional shear of low-level westerlies and cyclonic vorticity in this region, contributing to the genesis and development of the LPS. Additionally, as mentioned above, the orographic features around Bangladesh (i.e., the Shillong Plateau and Chittagong Hill Tracts) appear to provide favorable conditions for the genesis and development of such a vortex over Bangladesh. Thus, large-scale intraseasonal dynamics for LPS genesis and development probably differ from Indian monsoon depressions. Recently, Fujinami et al. (2014) found that robust circulation signals on the same time scale appear in midlatitudes. It was reported that in the active phase, a cyclonic anomaly appears over and around the Tibetan Plateau throughout the troposphere, which contributes to the enhancement of the westerly flow in conjunction with the anticyclonic anomaly over the Bay of Bengal. Therefore, using long-term data, we need to investigate which factors of the submonthly-scale ISO determine LPS or non-LPS cases in active peaks, and how the subtropical–midlatitude interaction affects the genesis and development of LPSs.

6. Summary

The relationship between the LPS activity and the submonthly-scale (7–25 days) ISO of rainfall over Bangladesh during the summer monsoon season (June–September) has been investigated using APHRODITE and TRMM 3B42 rainfall, and JRA-25 reanalysis data. By detecting and tracking the LPSs formed over the Indian monsoon region over a period of 29 years (1979–2007), we found that about 59% (62%) of extreme (moderate) active peaks are related to the LPSs. The characteristics of LPSs for extreme and moderate active peaks are summarized as follows.

In the extreme active peak, the locations of LPS centers are clustered significantly over and around Bangladesh. These LPSs are formed mainly over the head of the Bay of Bengal and around Bangladesh, and they tend to remain almost stationary throughout the lifetime. The composite structures of the LPSs indicate that the horizontal scale of the systems is about 600 km. Moreover, as an important characteristic, the maximum moisture convergence occurs on the southeast side of the LPSs. This is likely caused by interaction between the topography to the north and east of Bangladesh and the prevailing southwesterly winds from the LPSs. In contrast, in the moderate active peak, the LPS centers are concentrated over the Ganges Plain around 25°N, 85°E. Most of the LPSs are formed over the northern tip of the Bay of Bengal and the Ganges Plain, and they tend to move northwestward and remain almost stationary, respectively. The horizontal scale of the LPSs is similar to that of the extreme active peaks. The maximum moisture convergence occurs around the LPS center, whereas the intensity of the convergence on the southeast side (corresponding to Bangladesh) is relatively weak. Therefore, we conclude that the modulation of the amplitude of active peaks in the submonthly-scale ISO over Bangladesh is caused by small differences in the locations of the LPS centers. This result also indicates that these LPSs have significantly different structures from the monsoon depressions over India.

The vertical structures of the LPSs over Bangladesh show that the associated cyclonic circulation extends up to about 9 km (~300 hPa). The temperature fields are characterized by a well-defined cold core in the lower troposphere and a warm core in the upper levels. These vertical fields are similar to those of monsoon depressions. The most remarkable contrast is found in the field of horizontal wind divergence. In the extreme active peak, the LPS has stronger convergence, particularly on the east side in the lower troposphere, whereas the monsoon depressions show a maximum on the west side. This contrast seems to be responsible for the difference in the propagation characteristics compared with the monsoon depression.

The submonthly-scale ISO of rainfall over Bangladesh is dominated by the north–south shift of the monsoon trough; however, this study reveals the important

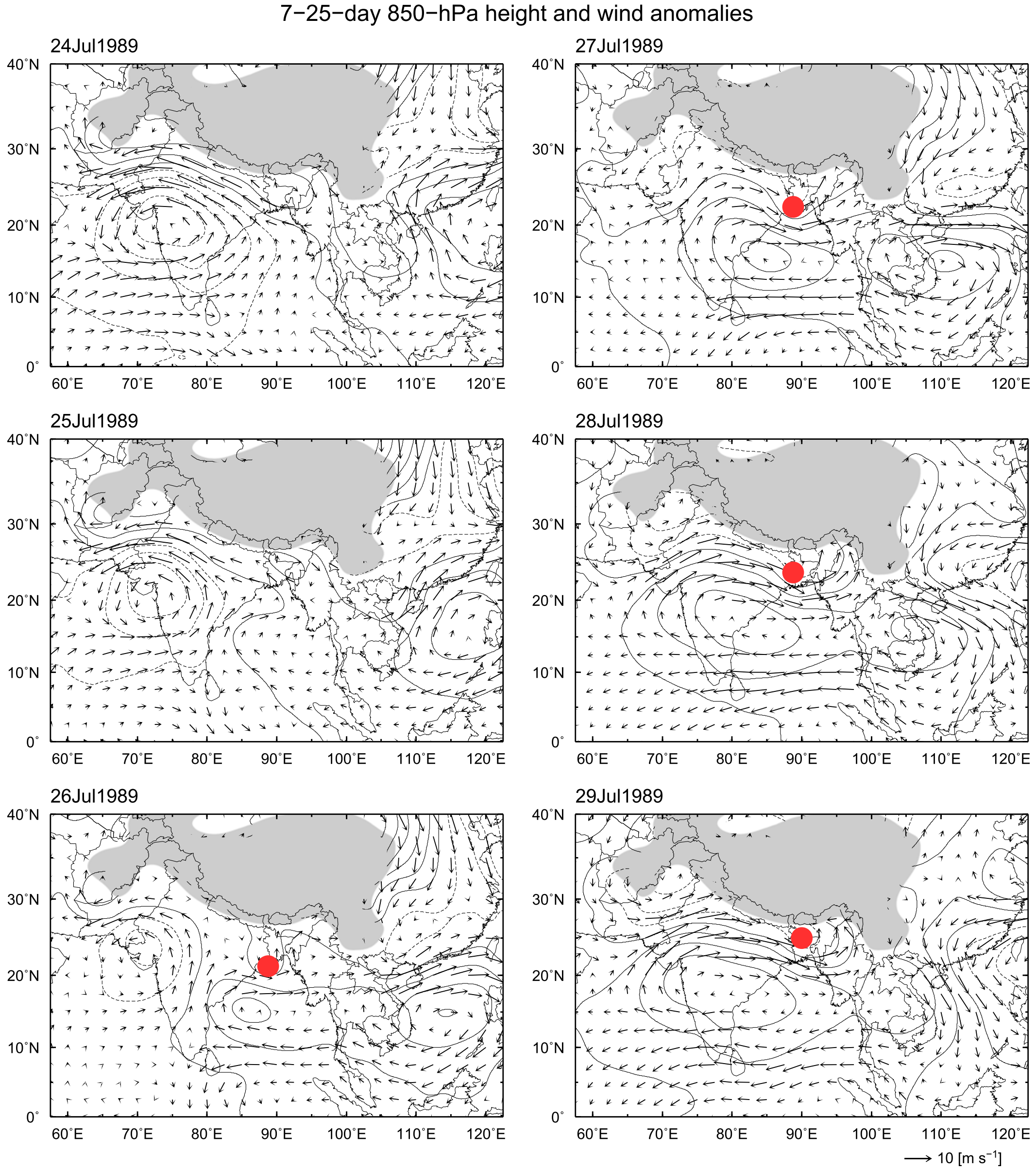


FIG. 12. Time evolution of 7–25-day-filtered 850-hPa geopotential height (contour) and wind vectors during 24–29 Jul 1989. The date of 29 Jul corresponds to the extreme active peak over Bangladesh. The red circles indicate the central positions of the LPS identified by our method. Solid (dashed) contours represent positive (negative) values. The contour interval is 10 gpm. Shading denotes areas at an altitude of more than 1500 m.

role that the LPSs have in enhancing the amplitude of the active peaks. Furthermore, among the extreme active peaks, heavy rainfall over the lowland area of Bangladesh is more likely in the presence of an LPS than in its absence. Therefore, the prediction of the genesis and tracks of the LPSs is a crucial aspect in the prediction of seasonal rainfall over Bangladesh, and it is an important challenge for future research. Because of their small scale, a numerical simulation by regional and cloud-resolving models would be necessary for such a study.

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REFERENCES

Annamalai, H., and J. M. Slingo, 2001: Active/break cycles: Diagnosis of the intraseasonal variability of the Asian summer monsoon. *Climate Dyn.,* **18,** 85–102, doi:10.1007/s003820100161.

Chen, T. C., and J. M. Chen, 1993: The 10–20-day mode of the 1979 Indian monsoon—Its relation with the time variation of monsoon rainfall. *Mon. Wea. Rev.,* **121,** 2465–2482, doi:10.1175/1520-0493(1993)121<2465:TDMOTI>2.0.CO;2.

Chowdhury, M. R., 2003: The El Niño-Southern Oscillation (ENSO) and seasonal flooding—Bangladesh. *Theor. Appl. Climatol.,* **76,** 105–124, doi:10.1007/s00704-003-0001-z.

Duchon, C. E., 1979: Lanczos filtering in one and two dimensions. *J. Appl. Meteor.,* **18,** 1016–1022, doi:10.1175/1520-0450(1979)018<1016:LFIOAT>2.0.CO;2.

Fujinami, H., and Coauthors, 2011: Characteristic intraseasonal oscillation of rainfall and its effect on interannual variability over Bangladesh during boreal summer. *Int. J. Climatol.,* **31,** 1192–1204, doi:10.1002/joc.2146.

——, T. Yasunari, and A. Morimoto, 2014: Dynamics of distinct intraseasonal oscillation in summer monsoon rainfall over the Meghalaya–Bangladesh–western Myanmar region: Covariability between the tropics and mid-latitudes. *Climate Dyn.,* **43,** 2147–2166, doi:10.1007/s00382-013-2040-1.

Godbole, R., 1977: The composite structure of the monsoon depression. *Tellus,* **29A,** 25–40, doi:10.1111/j.2153-3490.1977.tb00706.x.

Goswami, B. N., and R. S. A. Mohan, 2001: Intraseasonal oscillations and interannual variability of the Indian summer monsoon. *J. Climate,* **14,** 1180–1198, doi:10.1175/1520-0442(2001)014<1180:IOAIVO>2.0.CO;2.

——, R. S. Ajayamohan, P. K. Xavier, and D. Sengupta, 2003: Clustering of synoptic activity by Indian summer monsoon intraseasonal oscillations. *Geophys. Res. Lett.,* **30,** 1431, doi:10.1029/2002GL016734.

Hartmann, D. L., and M. L. Michelsen, 1989: Intraseasonal periodicities in Indian rainfall. *J. Atmos. Sci.,* **46,** 2838–2862, doi:10.1175/1520-0469(1989)046<2838:IPIIR>2.0.CO;2.

Houze, R. A., D. C. Wilton, and B. F. Smull, 2007: Monsoon convection in the Himalayan region as seen by the TRMM Precipitation Radar. *Quart. J. Roy. Meteor. Soc.,* **133,** 1389–1411, doi:10.1002/qj.106.

Hoyos, C. D., and P. J. Webster, 2007: The role of intraseasonal variability in the nature of Asian monsoon precipitation. *J. Climate,* **20,** 4402–4424, doi:10.1175/JCLI4252.1.

Islam, M. N., T. Terao, H. Uyeda, T. Hayashi, and K. Kikuchi, 2005: Spatial and temporal variations of precipitation in and around Bangladesh. *J. Meteor. Soc. Japan,* **83,** 21–39, doi:10.2151/jmsj.83.21.

Kataoka, A., and T. Satomura, 2005: Numerical simulation on the diurnal variation of precipitation over northeastern Bangladesh: A case study of an active period 14–21 June 1995. *SOLA,* **1,** 205–208, doi:10.2151/sola.2005-053.

Kripalani, R. H., S. Inamdar, and N. A. Sontakke, 1996: Rainfall variability over Bangladesh and Nepal: Comparison and connections with features over India. *Int. J. Climatol.,* **16,** 689–703, doi:10.1002/(SICI)1097-0088(199606)16:6<689::AID-JOC36>3.0.CO;2-K.

Krishnamurthy, V., and R. S. Ajayamohan, 2010: Composite structure of monsoon low pressure systems and its relation to Indian rainfall. *J. Climate,* **23,** 4285–4305, doi:10.1175/2010JCLI2953.1.

Krishnamurti, T. N., and H. N. Bhalme, 1976: Oscillations of monsoon system. Part I: Observational aspects. *J. Atmos. Sci.,* **33,** 1937–1954, doi:10.1175/1520-0469(1976)033<1937:OOAMSP>2.0.CO;2.

——, M. Kanamitsu, R. Godbole, C.-B. Chang, F. Carr, and J. H. Chow, 1975: Study of a monsoon depression (I): Synoptic structure. *J. Meteor. Soc. Japan,* **53,** 227–239.

Matsumoto, J., M. R. Rahman, T. Hayashi, and N. Monji, 1996: Rainfall distribution over the Indian subcontinent during the 1987 and 1988 severe floods in Bangladesh. *Bull. Dept. Geogr. Univ. Tokyo,* **28,** 25–44.

Mooley, D. A., 1973: Some aspects of Indian monsoon depressions and the associated rainfall. *Mon. Wea. Rev.,* **101,** 271–280, doi:10.1175/1520-0493(1973)101<0271:SAOIMD>2.3.CO;2.

——, and J. Shukla, 1989: Main features of the westward-moving low pressure systems which form over the Indian region during the summer monsoon season and their relation to the monsoon rainfall. *Mausam,* **40,** 137–152.

Murakami, M., 1977: On the structure of monsoon lows over the inland area of northern India. *J. Meteor. Soc. Japan,* **55,** 442–448.

Murakami, T., T. Nakazawa, and J. He, 1984: On the 40–50 day oscillations during the 1979 Northern Hemisphere summer. Part I: Phase propagation. *J. Meteor. Soc. Japan,* **62,** 440–468.

Murata, F., T. Terao, T. Hayashi, H. Asada, and J. Matsumoto, 2008: Relationship between atmospheric conditions at Dhaka, Bangladesh, and rainfall at Cherrapunjee, India. *Nat. Hazards,* **44,** 399–410, doi:10.1007/s11069-007-9125-2.

Ohsawa, T., T. Hayashi, Y. Mitsuta, and J. Matsumoto, 2000: Intraseasonal variation of monsoon activities associated with the rainfall over Bangladesh during the 1995 summer monsoon season. *J. Geophys. Res.,* **105,** 29 445–29 459, doi:10.1029/2000JD900499.

——, H. Ueda, T. Hayashi, A. Watanabe, and J. Matsumoto, 2001: Diurnal variations of connective activity and rainfall in tropical Asia. *J. Meteor. Soc. Japan,* **79,** 333–352, doi:10.2151/jmsj.79.333.

Onogi, K., and Coauthors, 2007: The JRA-25 Reanalysis. *J. Meteor. Soc. Japan,* **85,** 369–432, doi:10.2151/jmsj.85.369.

Rafiuddin, M., H. Uyeda, and M. N. Islam, 2010: Characteristics of monsoon precipitation systems in and around Bangladesh. *Int. J. Climatol.,* **30,** 1042–1055, doi:10.1002/joc.1949.

Raghavan, S., and S. Rajesh, 2003: Trends in tropical cyclone impact: A study in Andhra Pradesh, India. *Bull. Amer. Meteor. Soc.,* **84,** 635–644, doi:10.1175/BAMS-84-5-635.

Saha, K., F. Sanders, and J. Shukla, 1981: Westward propagating predecessors of monsoon depressions. *Mon. Wea. Rev.,* **109,** 330–343, doi:10.1175/1520-0493(1981)109<0330:WPPOMD>2.0.CO;2.

Sato, T., 2013: Mechanism of orographic precipitation around the Meghalaya Plateau associated with intraseasonal oscillation and the diurnal cycle. *Mon. Wea. Rev.,* **141,** 2451–2466, doi:10.1175/MWR-D-12-00321.1.

Sikka, D. R., 1977: Some aspects of the life history, structure and movement of monsoon depressions. *Pure Appl. Geophys.,* **115,** 1501–1529, doi:10.1007/BF00874421.

Singh, S. V., R. H. Kriplani, and D. R. Sikka, 1992: Interannual variability of the Madden–Julian Oscillations in Indian summer monsoon rainfall. *J. Climate,* **5,** 973–979, doi:10.1175/1520-0442(1992)005<0973:IVOTMJ>2.0.CO;2.

Takahashi, H. G., and T. Yasunari, 2008: Decreasing trend in rainfall over Indochina during the late summer monsoon:

Impact of tropical cyclones. *J. Meteor. Soc. Japan,* **86,** 429–438, doi:10.2151/jmsj.86.429.

Terao, T., M. N. Islam, T. Hayashi, and T. Oka, 2006: Nocturnal jet and its effects on early morning rainfall peak over northeastern Bangladesh during the summer monsoon season. *Geophys. Res. Lett.,* **33,** L18806, doi:10.1029/2006GL026156.

Xie, S., H. Xu, N. H. Saji, Y. Wang, and W. T. Liu, 2006: Role of narrow mountains in large-scale organization of Asian monsoon convection. *J. Climate,* **19,** 3420–3429, doi:10.1175/JCLI3777.1.

Yasunari, T., 1979: Cloudiness fluctuations associated with the Northern Hemisphere summer monsoon. *J. Meteor. Soc. Japan,* **57,** 227–242.

——, 1980: A quasi-stationary appearance of 30 to 40 day period in the cloudiness fluctuations during the summer monsoon over India. *J. Meteor. Soc. Japan,* **58,** 225–229.

——, 1981: Structure of an Indian summer monsoon system with around 40-day period. *J. Meteor. Soc. Japan,* **59,** 336–354.

Yatagai, A., O. Arakawa, K. Kamiguchi, H. Kawamoto, M. I. Nodzu, and A. Hamada, 2009: A 44-year daily gridded precipitation dataset for Asia based on a dense network of rain gauges. *SOLA,* **5,** 137–140, doi:10.2151/sola.2009-035.

——, K. Kamiguchi, O. Arakawa, A. Hamada, N. Yasutomi, and A. Kitoh, 2012: APHRODITE: Constructing a long-term daily gridded precipitation dataset for Asia based on a dense network of rain gauges. *Bull. Amer. Meteor. Soc.,* **93,** 1401–1415, doi:10.1175/BAMS-D-11-00122.1.