Effects of the South Asian Monsoon Intraseasonal Modes on Genesis of Low Pressure Systems over Bangladesh

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ABSTRACT

The quasi-biweekly oscillation (QBW) is a dominant intraseasonal mode in summer rainfall over Bangladesh. Active phases of the QBW are often accompanied by low pressure systems (LPSs) such as vortex-type lows. This study investigated the effects of two intraseasonal modes, the QBW and the boreal summer intraseasonal oscillation (BSISO), on the genesis of LPSs over Bangladesh during 29 summer monsoon seasons. Daily lag composites of convection and low-level atmospheric circulation were constructed for active-phase cases with LPSs (LPS case) and without LPSs (non-LPS case) based on rainfall in the QBW over Bangladesh. In the QBW mode, a westward propagation of an anticyclonic anomaly from the western Pacific to the Bay of Bengal (BoB) is common in both cases. However, the anticyclonic center in the LPS case is located slightly to the east of that in the non-LPS case, which results in stronger cyclonic vorticity over and around Bangladesh. In contrast, the BSISO mode shows an opposite phase between the two cases: a cyclonic (anticyclonic) anomaly propagating northward from the equator to the BoB in the LPS case (non-LPS case). In the LPS case, the cyclonic anomaly in the BSISO mode enhances the westerly (easterly) flow over the BoB (Bangladesh) in the active phase, resulting in the enhancement of cyclonic vorticity over the northern BoB and Bangladesh, in cooperation with the QBW mode. These results suggest that both the QBW and BSISO modes have significant influence on the environmental conditions for LPS genesis over Bangladesh.

1. Introduction

Rainfall and tropospheric atmospheric circulation both exhibit pronounced intraseasonal oscillations (ISOs) in the South/Southeast Asian region during the boreal summer. These ISOs can be divided into two types based on time scale (e.g., Yasunari 1979; Annamalai and Slingo 2001): one with a period of 25–60 days and the other with a period of 10–20 days, which are referred to here as the boreal summer intraseasonal oscillation (BSISO) and quasi-biweekly oscillation (QBW), respectively. These two ISO modes have differing spatiotemporal structures. The BSISO mode exhibits northward propagation of convection and circulation anomalies from the equatorial Indian Ocean (e.g., Yasunari 1981; Murakami et al. 1984; Kemball-Cook and Wang 2001; Lawrence and Webster 2002; Jiang et al. 2004; Wang et al. 2006), whereas the QBW mode is characterized by westward propagation of convection and circulation anomalies from the western Pacific (e.g., Krishnamurti and Ardanuy 1980; Chen and Chen 1993; Yokoi and Satomura 2005; Hoyos and Webster 2007; Kikuchi and Wang 2009; Fujinami et al. 2014).

The area around Bangladesh exhibits a distinct QBW during summer monsoon rainfall (e.g., Ohsawa et al. 2000; Murata et al. 2008; Fujinami et al. 2011, 2014; Sato 2013; Hatsuzuka et al. 2014). Fujinami et al. (2011)

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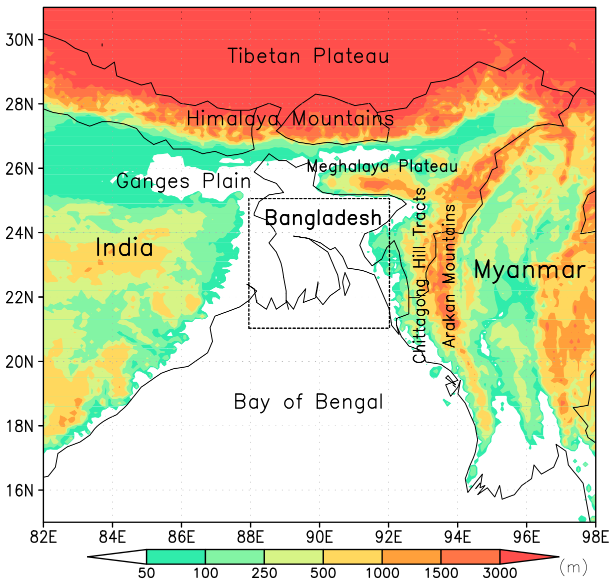

FIG. 1. Geographical features in and around Bangladesh. The boxed region (only over land) denotes the area used to calculate a representative rainfall time series for Bangladesh.

found that the rainfall spectrum in Bangladesh has a pronounced peak at about 14 days, while no statistically significant peak appears within the 30–60-day period. They also reported that the interannual variability of the total summer monsoon rainfall over Bangladesh is correlated significantly with the 7–25-day rainfall variance, suggesting that the QBW controls the interannual variability of the total seasonal rainfall in the country. Recently, Hatsuzuka et al. (2014) found that a vortex-type low pressure system (LPS) is often observed in the active phase of the QBW over Bangladesh. The typical horizontal scale of these LPSs is ~600 km, which is considerably smaller than the so-called Indian monsoon depressions (e.g., Krishnamurti et al. 1975; Godbole 1977), and most of these systems occur over and around Bangladesh. During the 29 summer monsoon seasons considered by Hatsuzuka et al. (2014), it was revealed that about 60% of the extreme and moderate active peaks were related to such vortex-type LPSs and that small differences in their central locations caused modulation of the amplitude of the active peaks. Furthermore, they reported that heavy rainfall over the lowland area of Bangladesh was more likely when the LPS was present (LPS case) than during its absence (non-LPS case), under extreme active peaks. Thus, it is evident that LPS activity profoundly affects ISO activity and total summer rainfall over Bangladesh. Contrastingly, in non-LPS cases, rainfall is significantly enhanced around the mountainous areas such as the Meghalaya Plateau and Chittagong Hill Tracts (Fig. 1) because of the orographic lifting of moist air over the windward areas of the mountains. However, the processes that determine the occurrence of LPS and non-LPS cases in the active phase of the QBW over Bangladesh remain unclear.

Previous studies have revealed that the distinct QBW in rainfall over Bangladesh is caused by the interaction between the low-level zonal wind fluctuation around the Ganges Plain and the topographical features around Bangladesh (Fujinami et al. 2011, 2014). In the active (break) phase of the QBW over Bangladesh, a low-level westerly/southwesterly (easterly/southeasterly) dominates along the plain. The strong westerly/southwesterly flow enhances the orographic lifting of low-level moisture over the windward area of the Meghalaya Plateau and Chittagong Hill Tracts during the active phase, which results in a significant increase in rainfall over the country. Recently, Fujinami et al. (2014) demonstrated that the QBW-scale low-level zonal wind fluctuation is controlled by a westward-moving $n = 1$ equatorial Rossby wave with a wavelength of ~6000 km. However, their analyses were based on all active peaks without consideration of LPS and non-LPS cases. Hatsuzuka et al. (2014) suggested that the LPS over Bangladesh might be triggered by a westward-propagating anticyclonic anomaly in the QBW mode. However, this conjecture was based on the analysis of a single LPS event. Thus, a more rigorous statistical analysis is necessary to elucidate the relationship between the QBW mode and LPS formation over Bangladesh.

Some studies have focused on the relationship between the BSISO mode and the formation of tropical cyclones over the north Indian Ocean (e.g., Kikuchi and Wang 2010; Yanase et al. 2012). Tropical cyclones are intense systems with maximum wind speeds exceeding 17 m s^{-1}, and they generally occur under conditions of weak vertical shear during the pre- and postmonsoon seasons. These studies reported that the formation of tropical cyclones is enhanced during the active convective phases of the BSISO mode. With regard to LPSs during the mature monsoon season (e.g., monsoon lows and depressions), previous studies have reported similar findings to those above regarding tropical cyclones [i.e., high genesis frequencies over the Bay of Bengal (BoB) and adjoining land areas during the active phases of the BSISO mode; e.g., Yasunari 1981; Goswami et al. 2003; Krishnamurthy and Shukla 2007; Krishnamurthy and Ajayamohan 2010]. In contrast, few studies have addressed the relationship with the QBW mode. For instance, Saha et al. (1981) reported that most of the monsoon depressions that form over the BoB are associated with the redevelopment of westward-propagating residual lows from the western Pacific, suggesting that their genesis is affected by the QBW mode that propagates westward in a similar manner. Goswami et al. (2003) showed, based on their ISO index containing the two dominant periods of the BSISO and QBW modes, that the occurrence frequency of LPSs is ~3.5 times higher in the active phase than during the break phase and that the remarkable difference in LPS occurrence is due to modulation of the large-scale monsoon circulation by the ISO. As mentioned above, the area around Bangladesh exhibits a distinct QBW during summer monsoon rainfall, whereas the BSISO signal is very weak. However, in the low-level circulation fields, the BSISO mode also has some signals over the country [e.g., Fig. 8 of Hoyos and Webster (2007)]. This implies that it is probable that the BSISO mode could modulate the structure of atmospheric circulation associated with the active phases of rainfall over Bangladesh or induce favorable conditions for LPS genesis in this region. Therefore, to understand fully the processes that determine the LPS and non-LPS cases in the active phase of the QBW over Bangladesh, the effects of the QBW and BSISO modes should be investigated.

The objectives of this study were 1) to reveal the spatiotemporal structures of the atmospheric circulation in the QBW and BSISO modes based on LPS and non-LPS cases in the active peak of the QBW mode over Bangladesh and 2) to show how the two ISO modes affect the environmental conditions for LPS genesis. The findings of this study further the understanding of the formation processes of LPSs under the influence of these two ISO modes. The remainder of this paper is organized as follows. Section 2 describes the datasets and analysis methods used in this study. Section 3 presents the spatiotemporal structures of the atmospheric circulation and convection related to the two ISO modes based on LPS and non-LPS cases. The impacts of two ISO modes on the environmental conditions for LPS genesis are also discussed in this section. Section 4 discusses the interaction between the BSISO and QBW modes and some environmental factors associated with LPS genesis. Finally, the results are summarized in section 5.

2. Data and analysis method

a. Dataset

The APHRODITE rainfall dataset was used to analyze the rainfall variations associated with the ISO over Bangladesh from 1979 to 2007 (29 years). The APHRODITE dataset is a high-resolution ($0.25° \times 0.25°$) daily rainfall product over land based on rain gauge observations (Yatagai et al. 2009, 2012). To examine the large-scale atmospheric circulation, the Japanese 25-year Reanalysis Project (JRA-25) and Japan Meteorological Agency Climate Data Assimilation System (JCDAS) datasets on a $1.25° \times 1.25°$ grid (Onogi et al. 2007) were used. The JRA-25 dataset covers the period from 1979 to 2004, and JCDAS data are available from January 2005 to January 2014. Because the JCDAS is based on the same assimilation system as the JRA-25, the two products provide a homogeneous dataset for the period 1979–2007. Daily interpolated outgoing longwave radiation (OLR) data on a $2.5° \times 2.5°$ grid were also used as a proxy for large-scale convective activity (Liebmann and Smith 1996).

b. Method

The data processing and analysis methods used in this study were similar to those of Hatsuzuka et al. (2014). To remove annual cycles, daily anomalies of rainfall, OLR, and the reanalysis data were computed by subtracting a 121-day (about 4 months) running mean from the original time series for each year. Then, a Lanczos filter (Duchon 1979) was applied to the daily anomalies to extract the two ISO signals (i.e., the BSISO and QBW). A 25–60-day band was chosen as the BSISO because the major spectral peak of the BSISO appears at the higher frequency at around 30 days compared with that of the eastward-propagating Madden–Julian oscillation (MJO) (Wang et al. 2006). A 7–25-day band was applied for the QBW because a statistically significant peak often appears at around 10 days in each year, although the ensemble spectrum shows a peak at around 14 days (Fujinami et al. 2011). To check the dependence of the results on the bandwidth of the filter, other bandwidths (i.e., a 30–60-day band for the BSISO and a 10–20-day band for the QBW) were applied to the OLR and reanalysis data; however, the results were little different. A representative rainfall time series for Bangladesh was created by averaging over the region 21°–25°N, 88°–92°E, which encompasses a large area of Bangladesh (Fig. 1). As an example, Fig. 2 presents the daily rainfall time series for the 1979 monsoon season (black bars) and the 7–25-day-filtered rainfall anomaly (solid line) with the power spectrum of each time series. Both time series show a clear 7–25-day variation with a significant spectrum peak at about 18 days. Based on the 7–25-day rainfall anomalies, positive extremes that exceeded the 29-summer climatological one standard deviation ($\sigma = \sim 6.3\,\mathrm{mm\,day^{-1}}$) were defined as active peaks (filled circles in Fig. 2). In total, 148 active peaks were identified during the 29 summer monsoon seasons (June–September).

This study used LPS data obtained by Hatsuzuka et al. (2014), who detected the locations of LPS centers that formed over the BoB and adjoining land areas during the 29 summer monsoon seasons. Using JRA-25 data, they have developed a method for identifying not only large-scale LPSs such as Indian

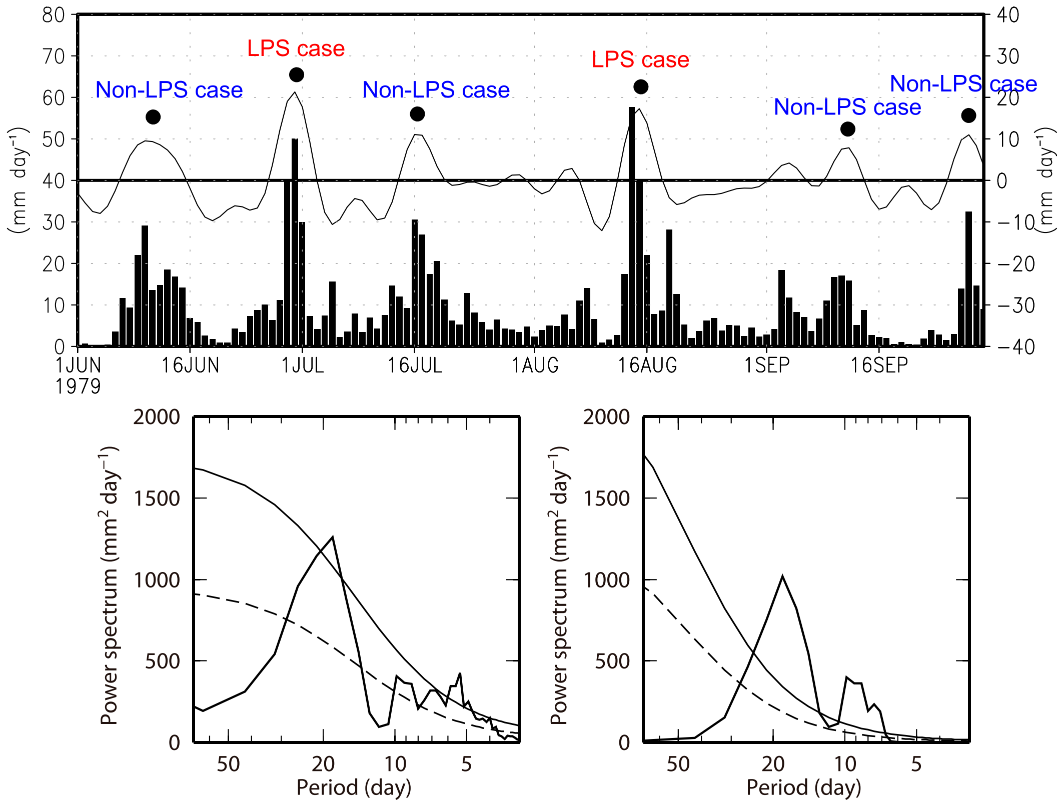

FIG. 2. Time series of area-averaged daily rainfall (black bars; left *y* axis) and 7–25-day-filtered rainfall anomaly (solid line; right *y* axis) from 1 Jun to 30 Sep 1979. Closed circles denote selected active peaks for the rainfall anomaly series. (bottom left) The power spectrum of the daily rainfall time series (with only the seasonal cycle of rainfall removed). Dashed line indicates red-noise spectrum and solid line shows 90% significance level. (bottom right) As in (bottom left), but for the 7–25-day-filtered rainfall anomaly.

monsoon depressions but also small-scale systems (~600 km) that bring heavy rainfall over Bangladesh. The Indian monsoon region is characterized by strong meridional cyclonic shear in the lower troposphere. Therefore, to distinguish vortex-type LPSs from cyclonic shear (e.g., monsoon trough), a combination of relative vorticity and geopotential height at 850 hPa was used in the identification of the LPSs. An LPS center was identified when a grid of minimum 850-hPa geopotential height satisfied the following two criteria: 1) the difference between the center and surrounding 8 (16) grids was smaller than -2 (-1) gpm, and 2) the 850-hPa relative vorticity of the center was more than $6.0 \times 10^{-5}\,s^{-1}$. A full description of the identification procedure is provided in section 4 of Hatsuzuka et al. (2014). Here, an LPS case was defined as a day on which at least one LPS existed between day -1 and day $+1$ of an active peak day. In the summer of 1979 (Fig. 2), two of six active peaks were classified as LPS cases. The remaining active peaks occurred without LPSs (non-LPS case). In total, 82 (66) active peaks were classified as LPS (non LPS) cases during the 29 summer monsoon seasons. In this study, daily lag composites of convection and atmospheric circulation were constructed relative to these active peaks.

3. Results

a. Synoptic-scale features

To illustrate the spatiotemporal structure of the atmospheric circulation for the LPS and non-LPS cases associated with the QBW over Bangladesh, Fig. 3 shows the temporal sequence of composites for the total 850-hPa wind vectors and zonal wind speed from day -3 to day 0. Active rainfall peaks in the QBW mode over Bangladesh are referred to as day 0. Because Indian monsoon depressions form in regions with strong horizontal shear of the zonal wind, several studies have suggested that barotropic dynamics play an important role in the formation of these depressions (e.g., Shukla 1977; Goswami et al. 1980; Lindzen et al. 1983). Hence, this study also focuses attention on the horizontal shear of the zonal wind as an environmental factor responsible for LPS genesis. In the LPS case (Fig. 3a), a cyclonic

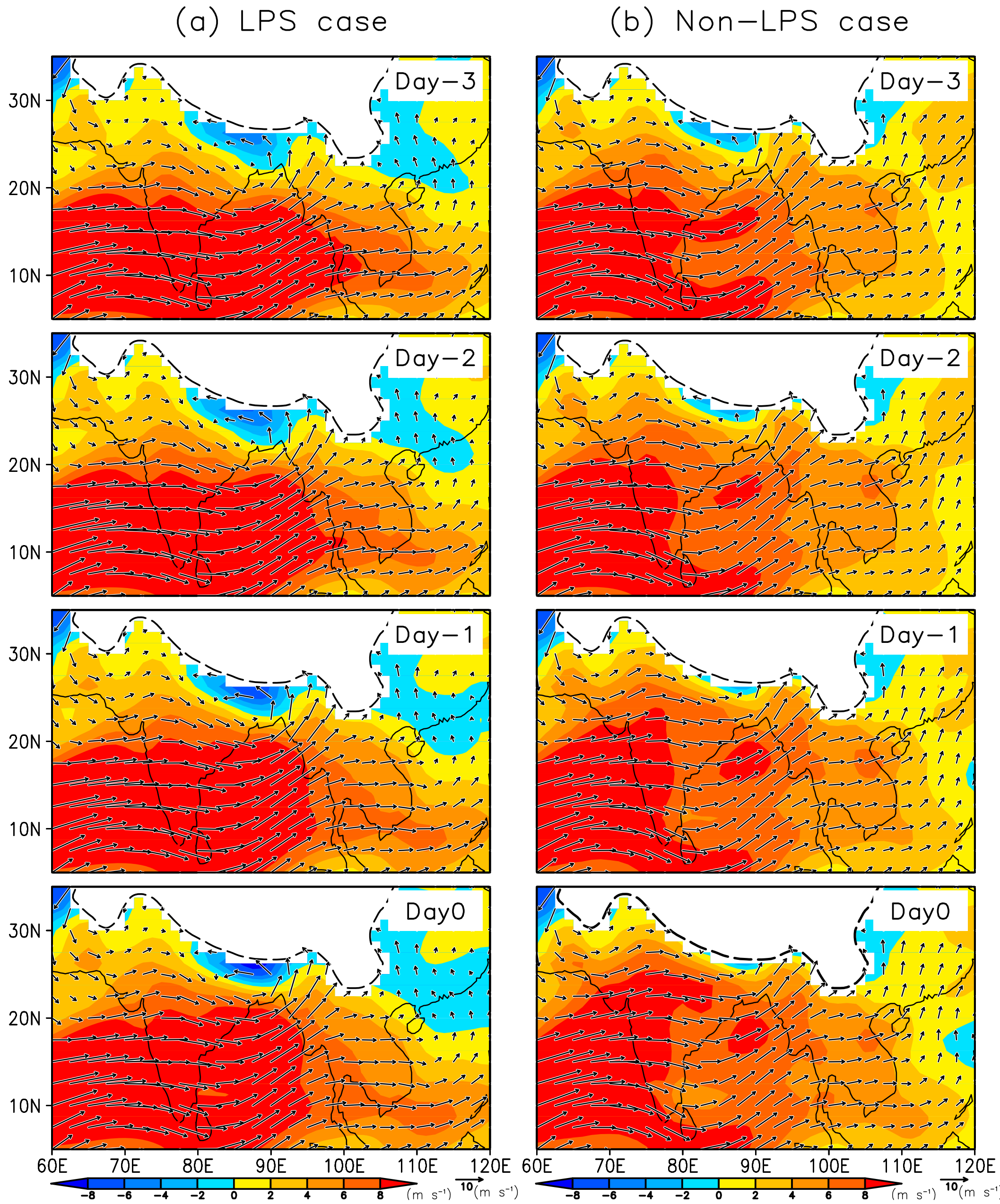

FIG. 3. Composites of total 850-hPa wind (vectors) and zonal wind speed (shading) from day −3 to day 0 for (a) LPS and (b) non-LPS cases based on 7–25-day rainfall variation in Bangladesh. Day 0 corresponds to the active rainfall peak in Bangladesh. The thick dashed line indicates the topographic 1500-m contour line.

circulation is observed over Bangladesh, reflecting the presence of the LPS. During this period, a monsoonal westerly flow prevails from the equator to around 20°N. The monsoon trough (approximately the zero line of the zonal wind speed) is located over the Ganges Plain and southwesterly/southerly winds dominate over Bangladesh. In this synoptic situation, a strong meridional cyclonic shear of zonal winds is observed over the head of the BoB and Bangladesh, which results in favorable environmental conditions for LPS genesis. In the non-LPS case (Fig. 3b), the monsoonal westerlies over the BoB are much weaker than in the LPS case. The monsoon trough is located along the foot of the Himalayas; hence, stronger westerly winds are observed around the Ganges Plain. This synoptic situation leads to a weaker meridional shear of zonal winds over the head of the BoB and Bangladesh.

Figure 4 shows the composite differences of the 850-hPa wind vectors and relative vorticity between the

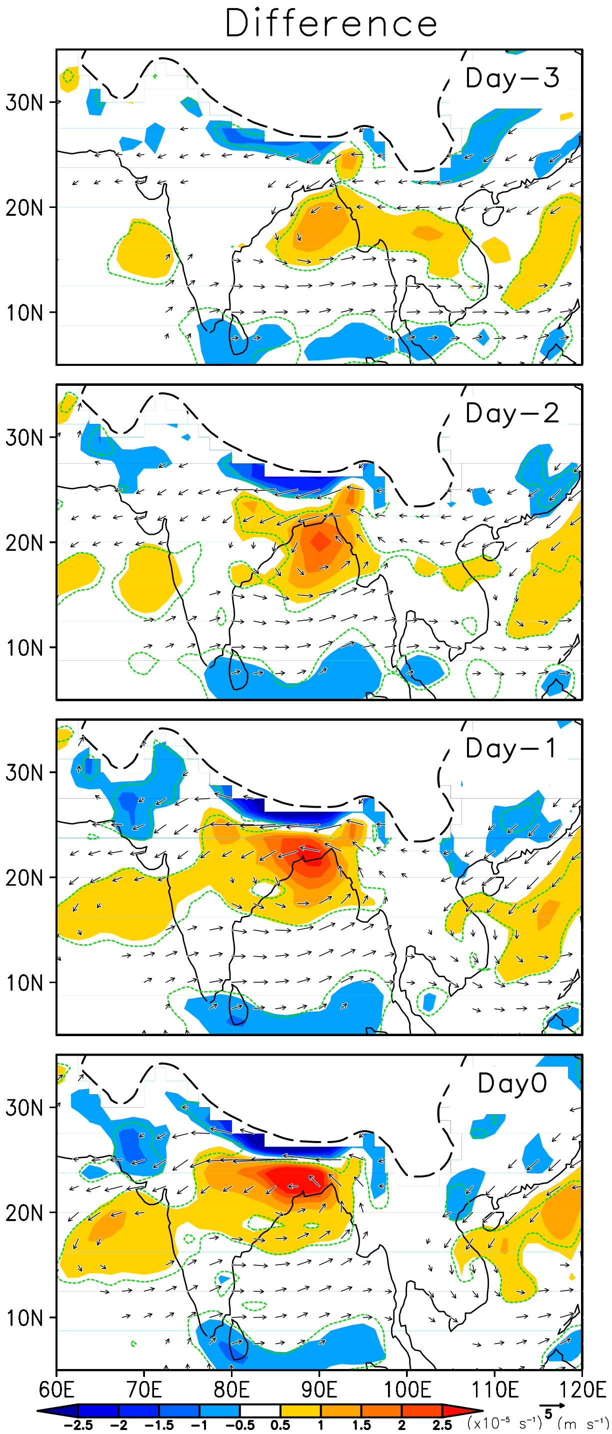

FIG. 4. Composite difference of 850-hPa wind (vectors) and relative vorticity (shading) between LPS and non-LPS cases. Vectors denote only 95% statistically significant difference. The green dashed line shows the 95% significance level for the relative vorticity difference. The thick dashed line indicates the topographic 1500-m contour line.

LPS and non-LPS cases. On day −3, a significant positive (cyclonic) vorticity anomaly appears over the BoB between the westerly and easterly anomalies. On day −2, the cyclonic vorticity anomaly is enhanced over the northern BoB, which then gradually moves northward with expansion to Bangladesh and northern India by day 0. These composite results indicate that environmental conditions more favorable for LPS genesis are created in the LPS case than in the non-LPS case. Although the significant positive difference in the relative vorticity around the BoB includes the effects of the LPS itself, the horizontal scale of the LPS (~600 km) is much smaller than that area. Significant westerly and easterly anomalies associated with the positive vorticity anomaly also appear broadly from India to the South China Sea. Thus, these significant differences between LPS and non-LPS cases cannot be explained fully only by the effects of the LPS. In addition, because the LPSs occur most frequently on day −1, they seem to have an insignificant effect on the cyclonic vorticity anomaly on days −3 and −2. Therefore, this study considered the synoptic-scale situations on days −3 and −2 as the environmental fields responsible for LPS genesis. The following subsections show the impacts of the two ISO modes on the environmental fields related to LPS genesis.

b. *QBW mode*

Figure 5 shows the temporal sequence of composites of the 850-hPa circulation and OLR anomalies related to the QBW mode for the LPS case. The composite anomalies exhibit a westward-propagating feature from the western Pacific. On day −5, Bangladesh is dominated by suppressed convection accompanied by a local anticyclonic circulation anomaly. Active convection and cyclonic anomalies are located over the BoB, and they move gradually northward from day −5 to day −2. Note that the cyclonic anomaly moves westward from the South China Sea and that it reaches the BoB by day −5 (not shown). Alternatively, an anticyclonic anomaly over the western Pacific starts to move westward toward the Indochina Peninsula from day −5. On day −2, when the anticyclonic anomaly is located over the South China Sea, a westerly/southwesterly flow is significantly enhanced over the BoB because of an increase in the pressure gradient between the cyclonic and anticyclonic anomalies. Simultaneously, a narrow cyclonic circulation deepens around Bangladesh, in conjunction with an active convection anomaly over Bangladesh. On day 0, when the convection/rainfall reaches a maximum over Bangladesh, the anticyclonic anomaly is centered on the western coast of the Indochina Peninsula, and the westerly/southwesterly flow is further enhanced around Bangladesh.

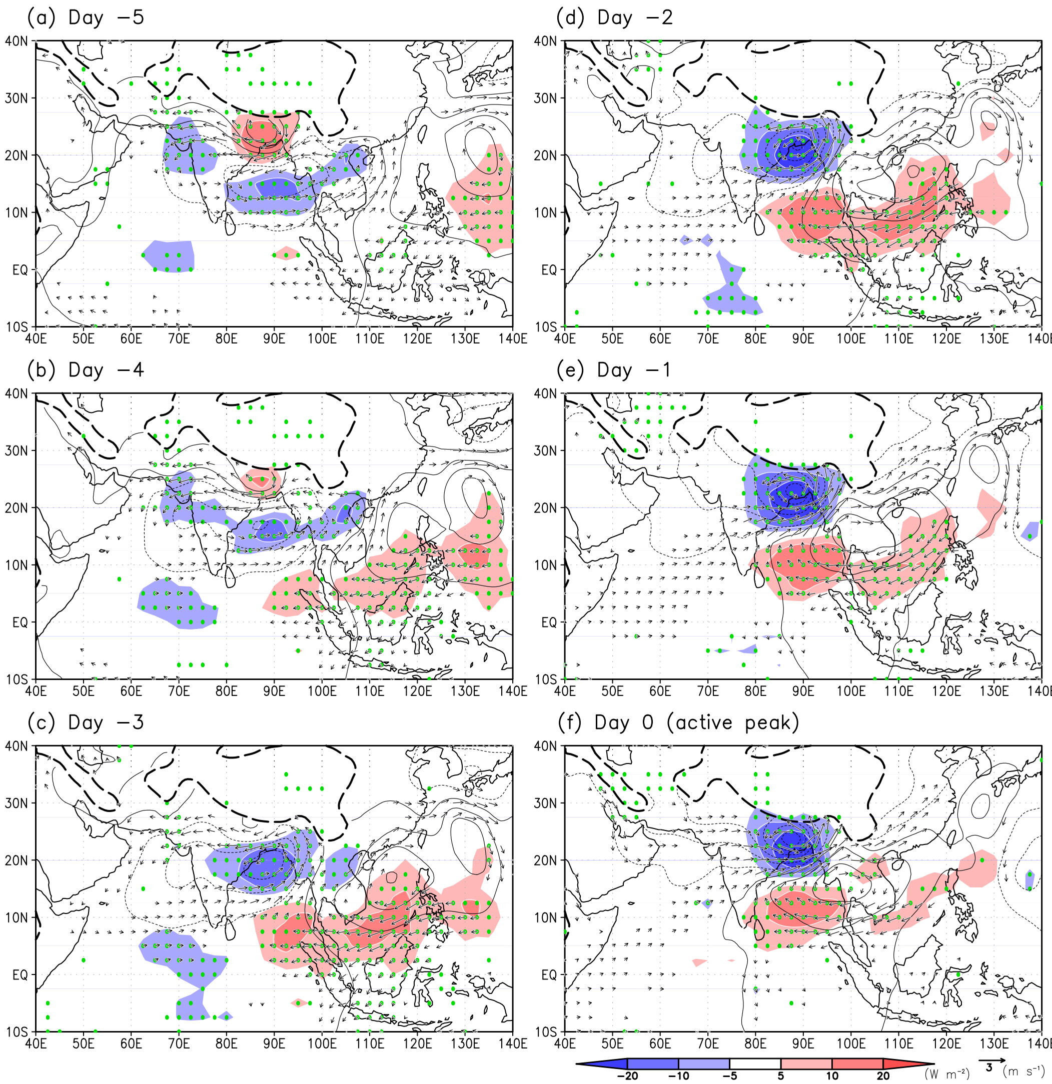

FIG. 5. Composites of 7–25-day-filtered 850-hPa geopotential height (contour), wind (vectors), and OLR (shading) anomalies from day −5 to day 0 for LPS case based on 7–25-day rainfall variation in Bangladesh. Day 0 corresponds to the active rainfall peak in Bangladesh. The contour interval is 2 m. Only 95% statistically significant vectors are plotted. The green circles denote statistically significant grids at the 95% confidence level for the OLR anomalies. The thick dashed line indicates the topographic 1500-m contour line.

The time sequence of composites for the non-LPS case is shown in Fig. 6. In the non-LPS case, as in the LPS case, the QBW mode is characterized by the westward propagation of atmospheric circulation and convection. From day −5 to day −2, an anticyclonic circulation anomaly moves westward along 15°N from the western Pacific to the western coast of the Indochina Peninsula. On day −2, convection is enhanced over Bangladesh simultaneously with the enhancement of a westerly/southwesterly flow over the head of BoB and Bangladesh. By day 0, the anticyclonic anomaly moves into the BoB, and the westerly flow and convection are further enhanced over and around Bangladesh. In addition, statistically significant circulation signals are also observed over the midlatitudes from day −1 to day 0. As shown by Fujinami et al. (2014), the airflow from the midlatitudes intrudes over Bangladesh along the southwestern periphery of the Tibetan Plateau, which seems to be related to the enhancement of the westerly flow over Bangladesh.

As discussed in the introduction, previous studies have revealed that the anticyclonic circulation anomaly of the QBW mode provides strong low-level westerly/southwesterly winds over and around Bangladesh in the active phase (Fujinami et al. 2011, 2014). The prevailing low-level flow transports abundant moisture to the

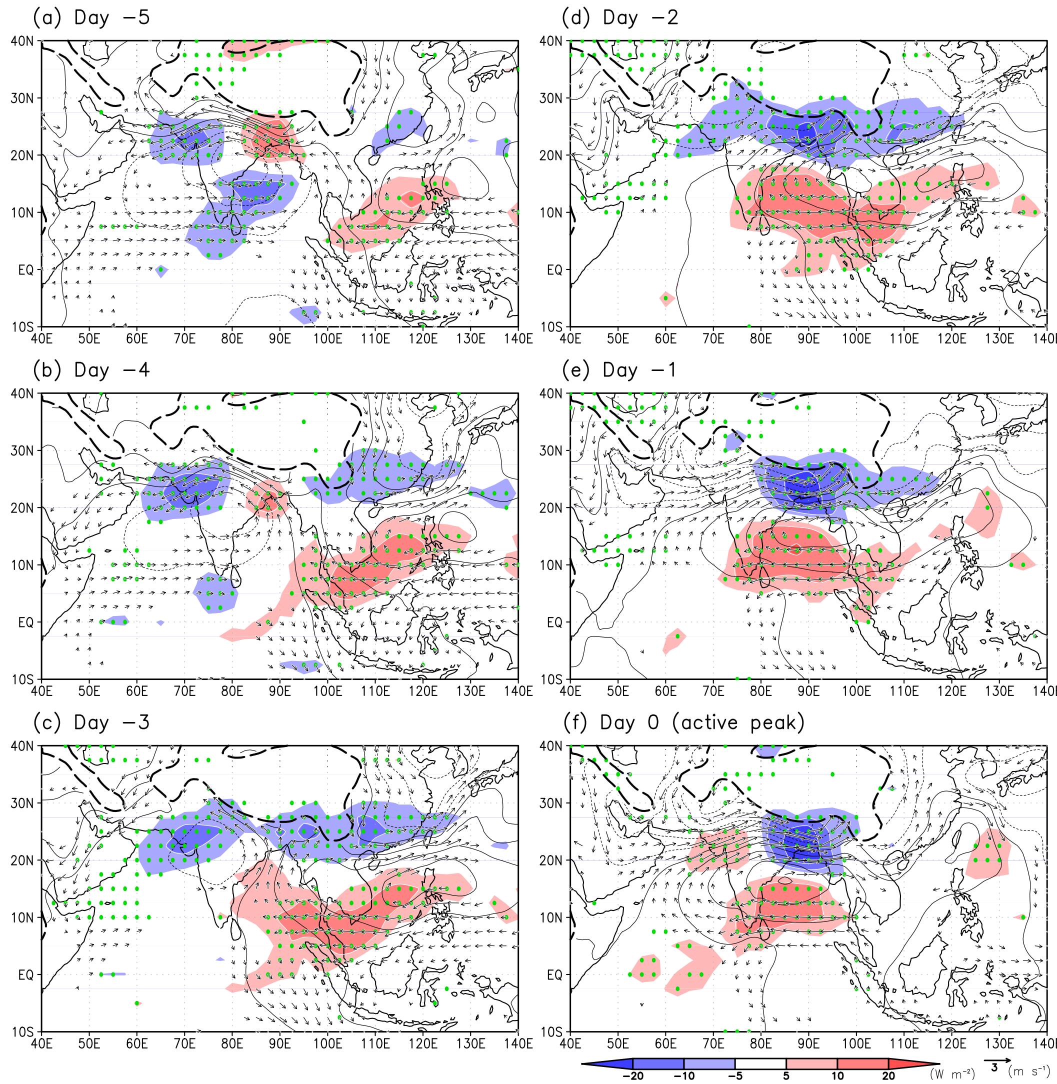

FIG. 6. As in Fig. 5, but for the non-LPS case.

windward areas of the Meghalaya Plateau and Chittagong Hill Tracts, which triggers forced lifting of the moist air and results in a large increase in rainfall over the country. The results of this study for both the LPS and non-LPS cases also demonstrate that the westward-propagating anticyclonic anomaly is closely associated with the active peaks of rainfall over Bangladesh. However, the central position of the anticyclonic anomaly is slightly different between the LPS and non-LPS cases. For instance, on day −2, the anticyclonic center is located over the South China Sea in the LPS case (Fig. 5d). This situation brings the westerly/southwesterly anomaly over the BoB, which enhances the horizontal shear of zonal wind over and around Bangladesh where the LPSs occur most frequently. In contrast, in the non-LPS case (Fig. 6d), the anticyclonic center is located over the Indochina Peninsula, and the westerly/southwesterly anomaly dominates over northern India and Bangladesh. This acts to weaken the low-level cyclonic shear around the genesis region of the LPSs. To highlight the difference in environmental conditions between the two cases, Fig. 7 shows the composites of the 7–25-day-filtered 850-hPa wind and relative vorticity anomalies on day −2. In the LPS case (Fig. 7a), a large positive vorticity anomaly dominates over and around Bangladesh. This means that the QBW mode provides favorable environmental conditions for LPS genesis in the LPS case. In contrast, in the non-LPS case (Fig. 7b), the low-level cyclonic vorticity is mainly enhanced along the foot of the Himalayas, in association with the enhancement of westerly/southwesterly flow from northern India to Bangladesh. Hatsuzuka et al. (2014) noted that the LPS that occurred on 26 July

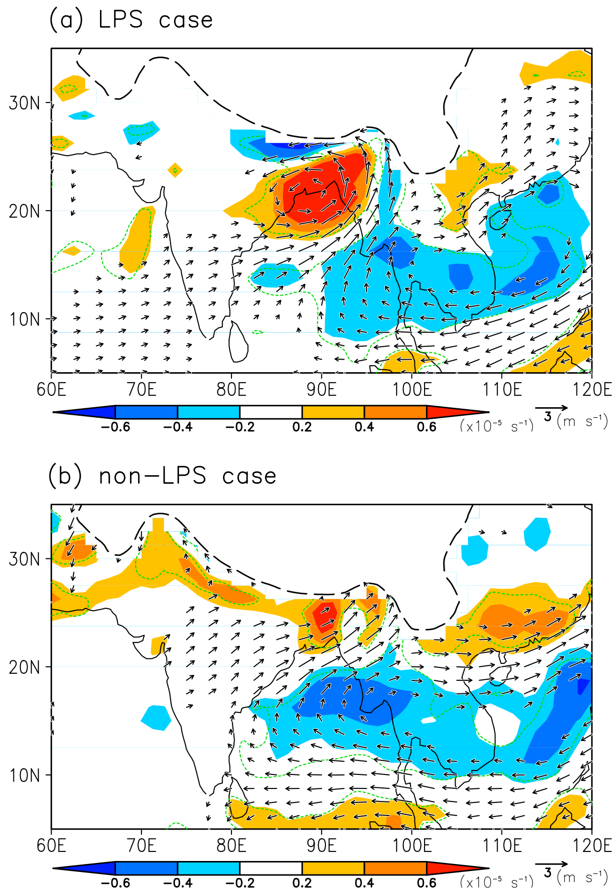

FIG. 7. Composite difference of 7–25-day-filtered 850-hPa wind (vectors) and relative vorticity (shading) anomalies between (a) LPS and (b) non-LPS cases on day −2. Vectors denote only 95% statistically significant difference. The green dashed line shows the 95% significance level for the relative vorticity difference. The thick dashed line indicates the topographic 1500-m contour line.

1989 was related to the westward propagation of the anticyclonic anomaly in the QBW mode [Fig. 12 of Hatsuzuka et al. (2014)]. In their case study, an anticyclonic anomaly was located over the South China Sea one day before its occurrence (25 July). On 26 July, the anticyclonic anomaly intruded into the BoB and enhanced the westerly flow over the northern tip of the BoB. These spatial features are similar to the composite structures on day −2 and day −1 in the LPS case. Unlike those of the non-LPS case, a remarkable westerly anomaly was absent over Bangladesh on these days. Thus, the case study by Hatsuzuka et al. (2014) seems to provide a typical example of the relationship between the QBW mode and LPS genesis. These results suggest that modulation of the low-level circulation by the QBW mode affects the environmental conditions for LPS genesis over Bangladesh. The differences in the spatial patterns of the QBW mode between the LPS and non-LPS cases are discussed further in section 4.

c. BSISO mode

To illustrate the relationship between the BSISO mode and QBW in rainfall over Bangladesh, Fig. 8 shows the temporal sequence of composites for the 25–60-day-filtered 850-hPa circulation and OLR anomalies for the LPS and non-LPS cases. Note that day 0 corresponds to the active rainfall peak in the QBW mode over Bangladesh. The BSISO mode is characterized by the northward propagation of the anomalies from the equatorial Indian Ocean in both LPS and non-LPS cases. However, interestingly, the BSISO mode exhibits an opposite phase between the two cases. In the LPS case (Fig. 8a), an active convection anomaly appears over the equatorial Indian Ocean on day −20, which then moves northward. On day −5, the active convection anomaly covers a broad area from central India to the BoB, accompanied by a cyclonic circulation anomaly. Simultaneously, a following suppressed convection anomaly starts to develop over the equatorial Indian Ocean. On day 0, the convection is further enhanced over the head of the BoB. Note that the enhanced convection significantly weakens by day +5 without intruding into Bangladesh (not shown). In contrast, the BSISO mode in the non-LPS case (Fig. 8b) shows the northward propagation of the suppressed convection. From day −20 to day −5, the suppressed convection shifts from the equatorial Indian Ocean to the Indian subcontinent. On day 0, the suppressed convection signals are observed broadly from northwestern India to the western Pacific, accompanied by anticyclonic anomalies centered around 85° and 120°E. In both cases, the convection signals are weak over Bangladesh on day 0. This result indicates that the BSISO mode does not directly produce the convection/rainfall related to the QBW over Bangladesh. However, a significant contrast in the circulation anomaly between the LPS and non-LPS cases is observed over the BoB and Bangladesh, suggesting that the BSISO mode has considerable effect on the modulation of the environmental conditions for LPS genesis.

To illustrate the spatial pattern of circulation associated with the BSISO mode for the LPS and non-LPS cases more clearly, Fig. 9 presents the time–latitude cross sections of the 850-hPa zonal wind anomaly averaged over 80°–95°E. Lag day 0 corresponds to the active rainfall peak in the QBW mode over Bangladesh. As shown in Fig. 8, a northward propagation signal is evident from the equator to Bangladesh but with opposite signs between the LPS and non-LPS cases. In the LPS case (Fig. 9a), a statistically significant westerly (easterly)

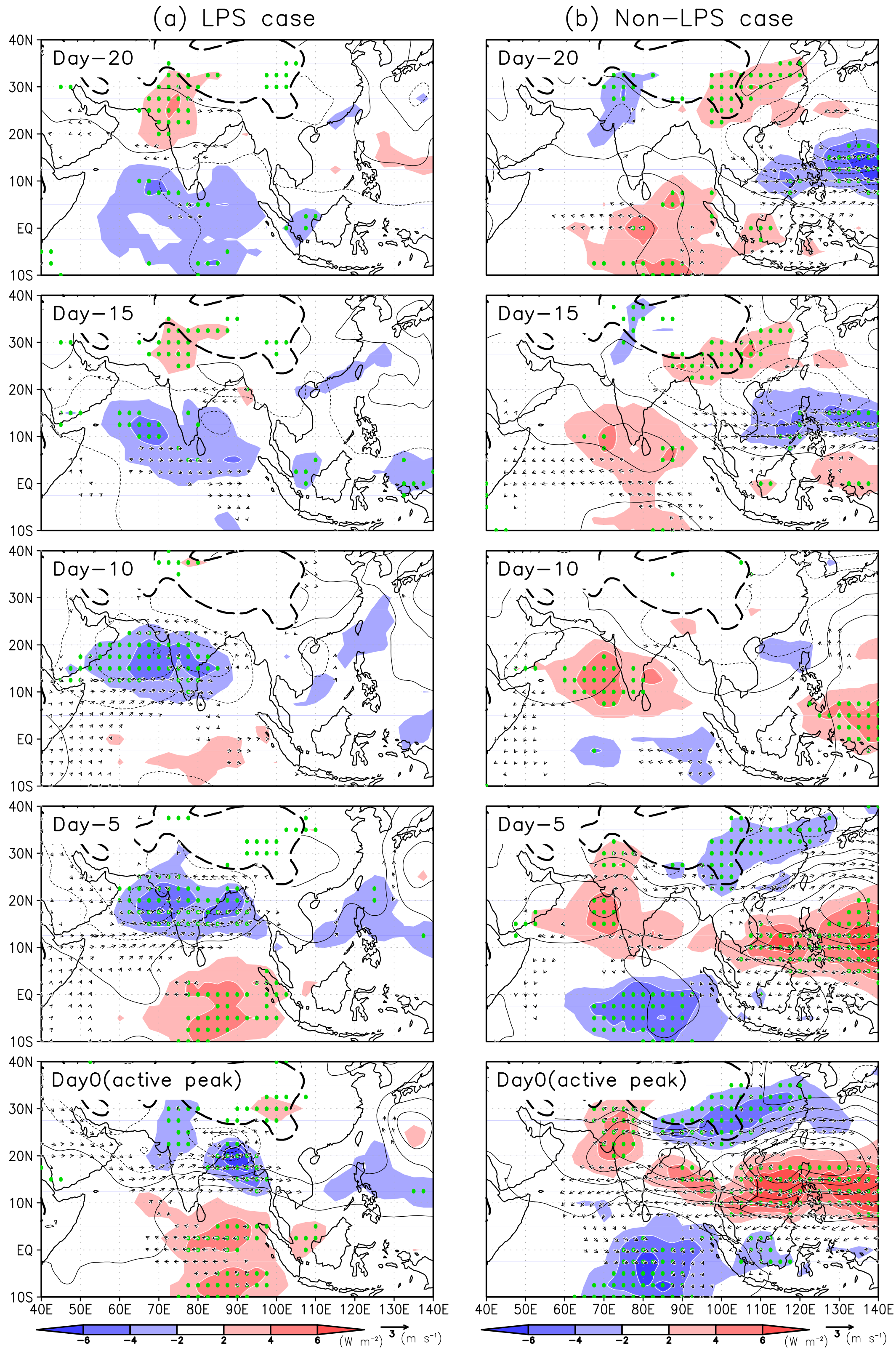

FIG. 8. Composites of 25–60-day-filtered geopotential height (contour), wind (vectors), and OLR (shading) anomalies from day −20 to day 0 for (a) LPS and (b) non-LPS cases based on 7–25-day rainfall variation in Bangladesh. Day 0 corresponds to the active peak of the 7–25-day rainfall variation in Bangladesh. The contour interval is 1 m. Only 95% statistically significant vectors are plotted. The green circles denote statistically significant grids at the 95% confidence level for the OLR anomalies. The thick dashed line indicates the topographic 1500-m contour line.

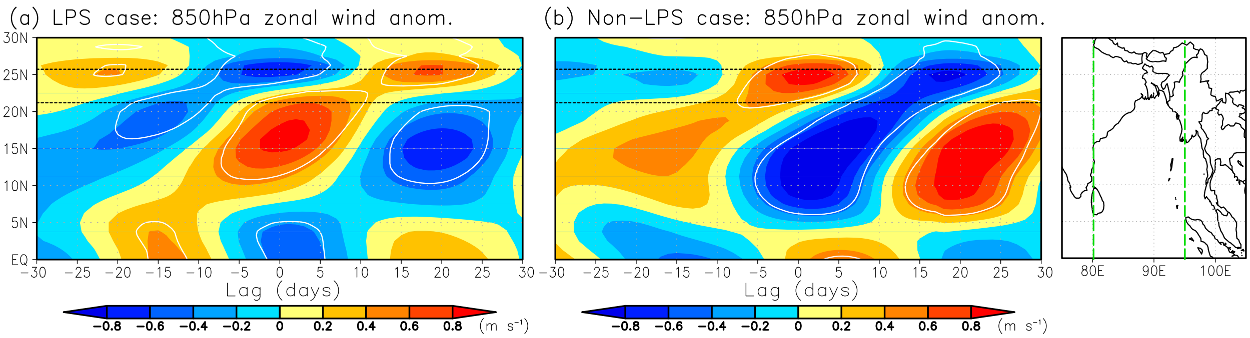

FIG. 9. Time–latitude cross section of 25–60-day-filtered 850-hPa zonal wind anomaly averaged between 80° and 95°E for (a) LPS and (b) non-LPS cases. Lag 0 corresponds to the active peak of the 7–25-day rainfall variation in Bangladesh. The white contour shows the 95% significance level. Bangladesh is located roughly within the two dashed lines. A map is shown to the right of (b).

anomaly appears over the BoB (northern Bangladesh) from at least day −5 to day +5. This situation enhances the meridional cyclonic shear of the zonal wind over the northern BoB and Bangladesh, which provides favorable environmental conditions for LPS genesis. Conversely, in the non-LPS case (Fig. 9b), a significant easterly (westerly) anomaly is observed over the BoB (Bangladesh) during almost the same period. In this situation, the anticyclonic shear of the zonal wind is enhanced over the northern BoB and Bangladesh, which leads to environmental conditions unfavorable for LPS genesis.

Figure 10 shows the occurrence frequency of the active rainfall peaks in the QBW mode over Bangladesh as a function of the phase of the BSISO. The BSISO phases are represented by the amplitude of the 25–60-day-filtered 850-hPa relative vorticity averaged over 15°–25°N, 80°–95°E, which covers the region from the northern BoB to Bangladesh. To focus on the activity of the BSISO before LPS genesis, the results presented here are only for day −5 because the LPSs occur most frequently on day −1. In Fig. 10a, about 65% of the total active peaks in the LPS cases (54 out of 82) occur in the positive (cyclonic) phase of the BSISO. In contrast, about 60% of the total active peaks in the non-LPS cases (40 out of 66) occur in the negative (anticyclonic) phase (Fig. 10b). The frequency distributions from day −4 to day 0 also show similar percentages as day −5 in both LPS and non-LPS cases (not shown). This phase preference of the BSISO mode in the two cases is consistent with the results of the composites shown in Figs. 8 and 9. Thus, these results strongly suggest that the phase of the BSISO has an important role in determining the LPS or non-LPS cases in the active peak of the QBW over Bangladesh.

d. *Impact of the two ISO modes on LPS genesis*

To understand how these two ISO modes affect the synoptic-scale environment for LPS genesis, Fig. 11 shows the composite differences of the 850-hPa wind vectors and zonal wind speed between the LPS and non-LPS cases for the total field, BSISO mode, and QBW mode. The overall patterns of anomalies are similar from day −3 to day 0 in each field. In the total field (Fig. 11a), the spatial pattern is characterized by a westerly anomaly over the BoB and an easterly anomaly over Bangladesh. The favorable environment for LPS genesis is created between these westerly and easterly anomalies, where the low-level cyclonic vorticity is

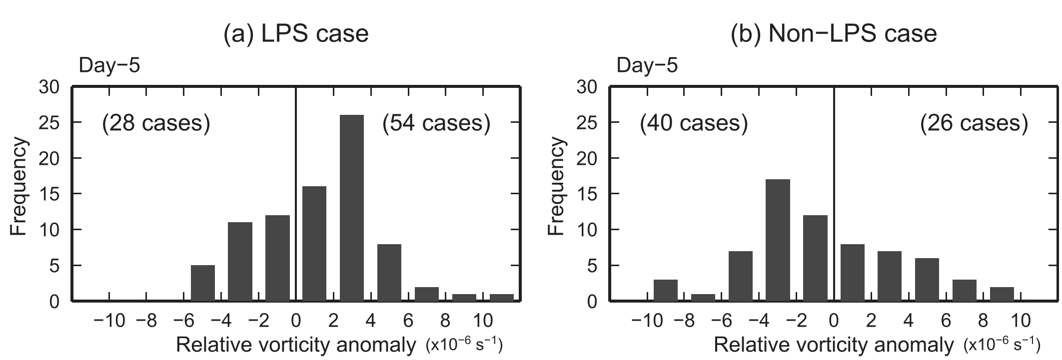

FIG. 10. Occurrence frequency of active peaks for (a) LPS and (b) non-LPS cases as a function of amplitude of 25–60-day-filtered 850-hPa relative vorticity on day −5 averaged over 15°–25°N, 80°–95°E.

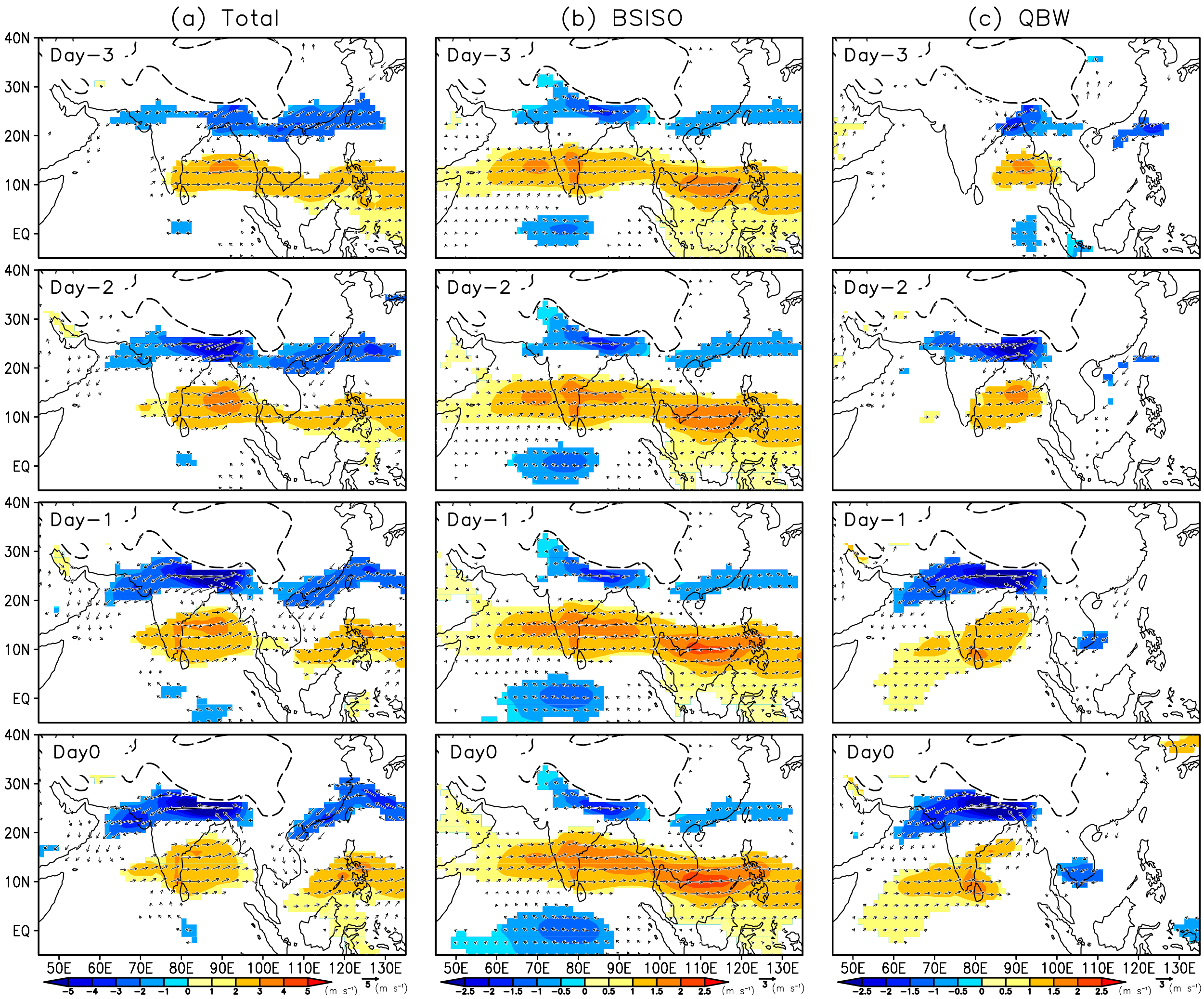

FIG. 11. Composite difference of (a) total 850-hPa wind (vectors) and zonal wind speed (shading) between LPS and non-LPS cases from day −3 to day 0. Day 0 corresponds to the active peak of the 7–25-day rainfall variation in Bangladesh. Vectors and shaded areas denote only 95% statistically significant difference. (b) As in (a), but for BSISO mode. (c) As in (a), but for QBW mode.

enhanced (Fig. 4). Such circulation features are also observed over the South China Sea and the western Pacific. The spatial pattern of the composite difference in the total field is similar to that of the BSISO mode (Fig. 11b). By comparing Figs. 11a and 11b, it is found that the westerly anomaly over the BoB, associated with the BSISO mode, could explain approximately half the total difference. The easterly anomaly over Bangladesh is also explained by the BSISO mode, but with a lower percentage for the total difference. Although, in the QBW mode, the spatial pattern of the atmospheric circulation is almost in phase between the LPS and non-LPS cases, it has been noted that the central position of the anticyclonic anomaly is slightly different between the two cases (Figs. 5 and 6). In Fig. 11c, the composite difference of the QBW mode shows a statistically significant westerly (easterly) anomaly over the BoB (Bangladesh), enhancing the low-level cyclonic vorticity over the northern BoB. In addition, Fig. 11 indicates that the contribution of the QBW mode to the total difference is comparable with that of the BSISO mode over the BoB and Bangladesh. This result suggests again that the locational difference in the anticyclonic anomaly in the QBW mode has an impact on the environmental conditions for LPS genesis.

This study demonstrated that the LPS genesis over Bangladesh is fostered by the cyclonic circulation anomaly of the BSISO mode. This result is consistent with the results of previous studies showing the relationship between the genesis of Indian monsoon depressions and the BSISO mode (e.g., Yasunari 1981; Goswami et al. 2003; Krishnamurthy and Ajayamohan 2010). With regard to the QBW mode, Krishnamurti et al. (1977) and Saha et al. (1981) have suggested that Indian monsoon depressions are initiated by the redevelopment of westward-propagating residual lows from the western Pacific. Furthermore, Goswami et al. (2003) reported that the frequency of occurrence of LPSs increases significantly under the enhanced cyclonic circulation during the active phase over the BoB in both the 30–60- and the 10–20-day modes. However, unlike the Indian monsoon depressions, this study suggests that LPS genesis over Bangladesh is induced by the anticyclonic circulation of the QBW mode in combination with the cyclonic circulation of the BSISO mode. The cyclonic circulation of the BSISO mode can be found from the Indian subcontinent through the BoB from approximately day −5 (Figs. 8a and 9a). On that day, the anticyclonic anomaly of the QBW mode is still located over the western Pacific (Fig. 5a). Then, the anticyclonic anomaly of the QBW mode moves westward toward the BoB, and in turn, the low-level cyclonic vorticity becomes enhanced around Bangladesh on day −2 and day −1 (Figs. 5d,e). Thus, the QBW mode likely acts as a trigger for LPS genesis under the favorable cyclonic environment arranged by the BSISO mode. In addition, the regional-scale mountain topography around Bangladesh (i.e., the Meghalaya Plateau and Chittagong Hill Tracts) might help enhance the low-level cyclonic vorticity within this region (Fig. 1). Therefore, these results suggest that the combination of the BSISO and QBW modes is important for LPS genesis over Bangladesh. Using composite analysis, this study revealed a robust feature of atmospheric circulation associated with the two ISO modes. However, the fact remains that some LPSs occur when the BSISO-related low-level vorticity is anticyclonic over the BoB (Fig. 10a). This is likely due to a greater contribution of the QBW mode or environmental factors other than the low-level zonal wind shear to the environmental conditions for LPS genesis, which should be studied in future work.

4. Discussion

a. Interaction between the QBW and BSISO modes

In the previous section, it was reasoned that locational differences in the anticyclonic anomaly of the QBW mode have a significant impact on the environmental conditions for LPS genesis. For instance, on day −1, the anticyclonic circulation center is located over the Indochina Peninsula in the LPS case (Fig. 5e), whereas it is located over the BoB in the non-LPS case (Fig. 6e). The northern pathway for the circulation anomalies of the QBW mode (~15°N) generally corresponds to the dominant area of zonal wind fluctuation in the BSISO mode (e.g., Goswami and Mohan 2001; Lawrence and Webster 2002; Hoyos and Webster 2007). The horizontal scale of the BSISO mode is also much larger than that of the QBW mode, which extends from the Arabian Sea to the western Pacific. This means that the BSISO mode could act as a large-scale background condition for the QBW mode and thus affect its spatial structure and evolution. To address this possibility, this study examined the preferred spatial structure of the QBW mode under the two different phases of the BSISO mode. The 25–60-day-filtered 850-hPa zonal wind averaged over 10°–20°N, 60°–110°E (the rectangle shown in Figs. 12a,b) was used as a reference of the BSISO mode, where the zonal wind variance of the BSISO mode dominates [see Fig. 10d of Fujinami et al. (2011)]. Based on the reference time series, positive and negative extremes that exceeded the 29-summer climatological one standard deviation and their previous day and following day were selected as westerly and easterly phases of the BSISO mode, respectively. In total, 189 westerly days and 174 easterly days were used to compile the composites. Figures 12a and 12b show the composites of the 850-hPa wind anomaly for the westerly and easterly phases of the BSISO mode. The westerly and easterly phases correspond to cyclonic and anticyclonic circulation anomalies in the BSISO from northern India to Bangladesh, respectively. Figures 12c and 12d present the composites of the 850-hPa wind and geopotential height anomalies of QBW mode in the westerly and easterly phases of the BSISO mode, respectively. Interestingly, in the westerly phase of the BSISO, the QBW mode exhibits an anticyclonic circulation centered on the Indochina Peninsula (Fig. 12c), consistent with the features of the LPS case (Fig. 5e). As shown in Figs. 5 and 6, this anticyclonic anomaly also shows a westward-propagating feature from the western Pacific to the BoB (not shown). Moreover, a cyclonic circulation anomaly can be found over Bangladesh in the BSISO westerly phase, reflecting the presence of an LPS there. A remarkable anticyclonic anomaly also appears centered on the Arabian Sea in the BSISO westerly phase (Fig. 12c). However, this anticyclonic anomaly seems to be derived from a sudden development over the Arabian Sea rather than the westward propagation (not shown), suggesting that it might not be part of the QBW mode. In contrast, during the easterly phase of the BSISO, the anticyclonic circulation in the QBW mode is dominant over the BoB (Fig. 12d), consistent with the features of the non-LPS case (Fig. 6e). However, no statistically significant anomalies are shown in the midlatitudes, unlike the non-LPS case. These results are also consistent with the results found for the summer of 1979 by Chen and Chen (1993), indicating that the cyclonic anomaly of the

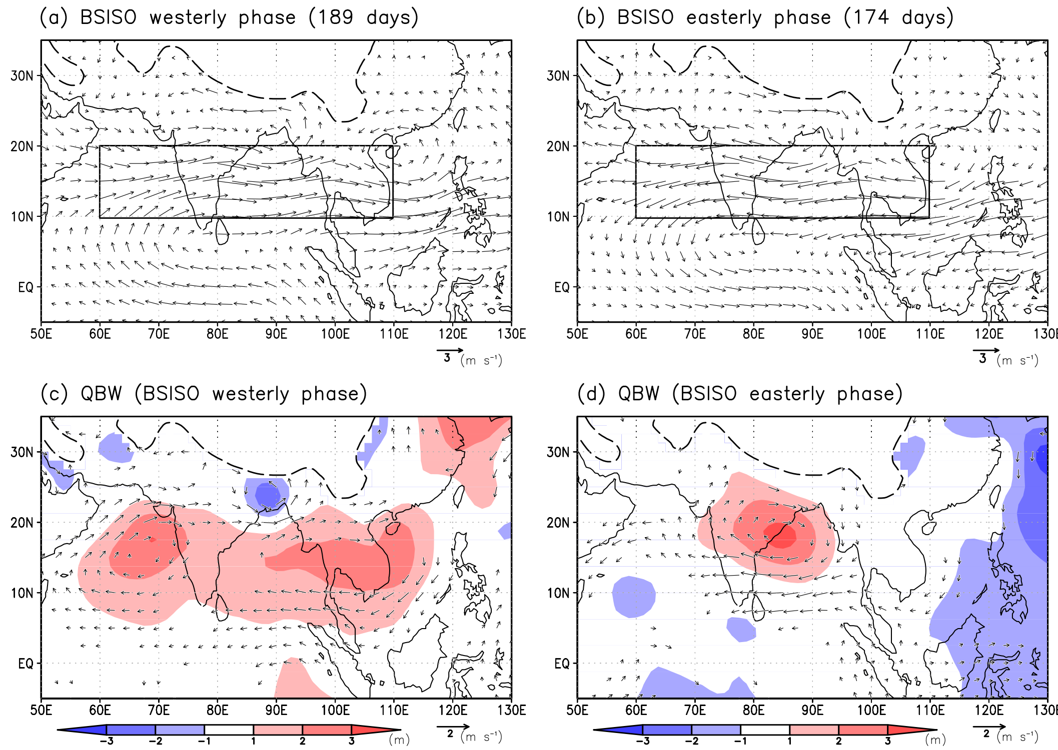

FIG. 12. (a) Composite of 25–60-day-filtered 850-hPa wind anomaly (vectors) for the westerly phase of the BSISO. The boxed region indicates the area in which the zonal wind is averaged to generate the BSISO index. (b) As in (a), but for the easterly phase of the BSISO. (c) Composite of 7–25-day-filtered 850-hPa geopotential height (shading) and wind (vectors) anomalies for the westerly phase of the BSISO. (d) As in (c), but for the easterly phase of the BSISO. Only 95% statistically significant vectors are plotted. The thick dashed line indicates the topographic 1500-m contour line.

10–20-day mode is reinitiated around Bangladesh by the 30–60-day monsoon trough over the northern BoB (i.e., westerly phase over the BoB). Conversely, no cyclonic anomaly of the 10–20-day mode appears around Bangladesh when the 30–60-day monsoon ridge is located over the northern BoB (i.e., easterly phase over the BoB). In addition, during the transition phase from the westerly (easterly) to easterly (westerly) anomalies, the QBW mode exhibits a remarkable cyclonic circulation anomaly centered on the BoB (figure not shown). Thus, this finding suggests that the BSISO mode might control the phase preference of the QBW mode around the BoB and Bangladesh region. Further studies are needed to elucidate such a climatological relationship between the QBW and BSISO modes over South Asia.

Fujinami et al. (2014) reported that the midlatitude circulation around the Tibetan Plateau, in conjunction with equatorial waves, helps induce the distinct QBW in rainfall over Bangladesh. In the results of this study, midlatitude circulation signals are not evident in the LPS case (Fig. 5), whereas the non-LPS case shows that airflow from the midlatitudes does intrude over Bangladesh along the southwestern periphery of the Tibetan Plateau from day −1 to day 0 (Figs. 6e,f). The enhanced westerly flow along the Ganges Plain probably weakens the meridional shear of zonal winds around Bangladesh, which results in conditions unfavorable for LPS genesis in the non-LPS case. Therefore, this result suggests that the environmental conditions for LPS genesis are influenced by tropical–midlatitude interaction along with BSISO–QBW interaction, although further analysis is needed to elucidate the physical mechanism behind such interactions.

b. *Other environmental factors for LPS genesis over Bangladesh*

The present study has demonstrated that low-level shear is an important environmental factor for LPS genesis over Bangladesh. However, previous studies have also considered factors such as high sea surface temperature, convective instability, high relative humidity in the midtroposphere, and weak vertical wind shear with regard to the provision of favorable environment conditions for tropical cyclone genesis (e.g., Gray 1979). These environmental factors are usually considered when diagnosing the formation of strong

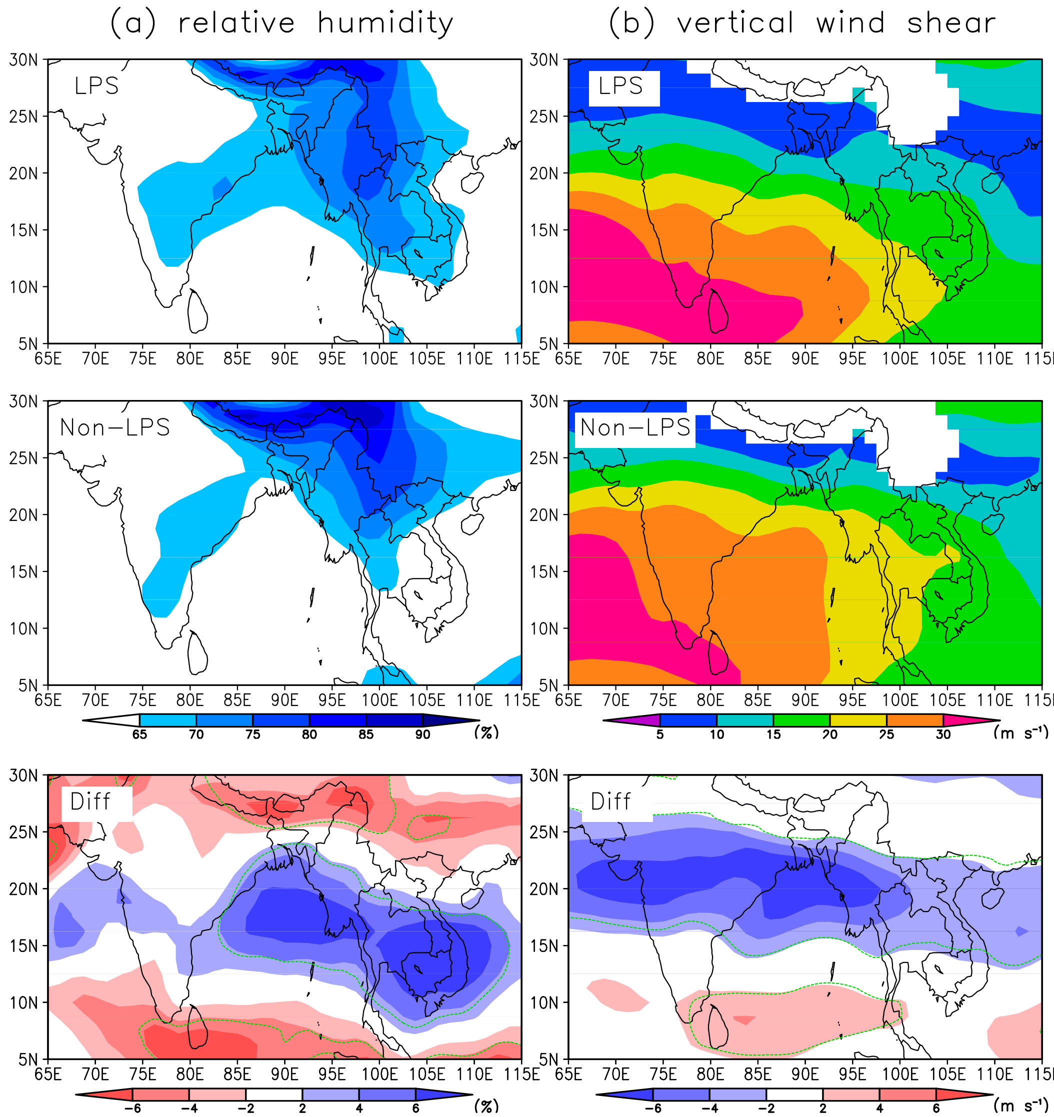

FIG. 13. Composites of total (a) 600-hPa relative humidity and (b) vertical zonal wind shear between 850 and 200 hPa on day −2 for (top) LPS cases, (middle) non-LPS cases, and (bottom) the difference between the LPS and non-LPS cases. The green dashed line shows the 95% significance level.

systems such as hurricanes and typhoons that occur and develop over the oceans. Because the LPSs over Bangladesh have vortex structures similar to such tropical cyclones (i.e., a cyclonic circulation extending through the entire depth of the troposphere with a warm core at its upper level), it is speculated that LPS genesis might be associated with not only low-level cyclonic vorticity but also the other environmental factors mentioned above. Here, the effects of three of the above environmental factors were examined, excluding sea surface temperature because most of the LPSs form over land or over the sea near land. Figure 13 shows composites of total fields associated with the environmental factors on day −2 for the LPS and non-LPS cases and the difference between the two cases. In Fig. 13a, the 600-hPa relative humidity shows a remarkably high value along the southern slope of the Himalayas and over the southeastern Tibetan Plateau in both LPS and non-LPS cases, which is related to the orographically induced convection over the mountainous regions. The composite difference shows a significant positive anomaly over the BoB and southern Bangladesh, where the LPSs occur most frequently. As greater low-level cyclonic vorticity in that area leads to greater convective activity, this result is consistent with the result presented in Fig. 4. Moreover, it was demonstrated that the two ISO modes provide larger low-level cyclonic vorticity over the BoB in the LPS case (Figs. 11b,c), suggesting that these ISO modes also contribute to the high level of midtropospheric humidity. In Fig. 13b, vertical wind shear is defined as the magnitude of the difference between the zonal winds at 200 and 850 hPa. During the monsoon season, easterly vertical shear is climatologically significant south of 20°N, whereas vertical shear is weak from the head of the BoB to Bangladesh, which is where the LPSs occur most frequently. The composite difference shows a significant negative anomaly over the BoB, southern Bangladesh, and central India, suggesting that vertical shear also contributes to the favorable conditions for LPS genesis. However, the low-level atmospheric circulation associated with the two ISO modes, together with the total field, shows almost no statistically significant difference in the regions of the negative vertical shear anomaly (Fig. 11). Thus, the difference in the vertical wind shear might be due to the influence of the upper-level atmospheric circulation. In contrast, atmospheric instability in the lower troposphere (defined as the difference of equivalent potential temperature between 850 and 500 hPa) exhibits no statistically significant difference between the LPS and non-LPS cases over the northern BoB and Bangladesh; however, in both cases, it shows convective instability that favors LPS genesis (not shown). This is probably due to the warm and humid air in the low-level troposphere from the BoB to Bangladesh. Thus, these results provide further confirmation that environmental conditions that are more favorable are created in the LPS case than the non-LPS case. Furthermore, it has also been suggested that the two ISO modes contribute to the high midlevel humidity as well as the strong low-level cyclonic vorticity.

Only a handful of studies have investigated the physical mechanisms responsible for the genesis and growth of monsoon depressions. Sikka (1977) argued that barotropic dynamics play a significant role in the early stages of the development of monsoon depressions, but the latter stages of development, as well as the maintenance of the depression, are related intimately with the baroclinic and conditional instability of the second kind (CISK) dynamics. The results of this study also suggest that LPS genesis over Bangladesh is related to the barotropic process rather than baroclinic dynamics because the vertical wind shear is weaker in the LPS case compared with the non-LPS case (Fig. 13b). Recently, Ditchek et al. (2016) examined the statistical association of monsoon disturbance genesis and environmental conditions using a genesis index that they developed. They found that genesis frequency decreases in the region of strong vertical shear, suggesting again that baroclinic instability might not be a primary mechanism of genesis. As this study focused on LPS genesis, it is considered that such dynamics might have an important role in the growth stages of the systems. In addition, they revealed that genesis over the BoB is fostered by humid, vorticity-rich, and convectively unstable environments. The results also denoted the same tendency as Ditchek et al. (2016), suggesting that similar mechanisms likely govern the genesis of Indian monsoon depressions and LPSs over Bangladesh. However, the details of the dynamics of the genesis and growth of LPSs are not the subject of this study, and they should be investigated in future work.

5. Summary

This study investigated the effects of two ISO modes (i.e., the BSISO and QBW modes) on LPS genesis over Bangladesh for 29 summer monsoon seasons. The main results were obtained from composite analyses of atmospheric circulation based on LPS and non-LPS cases in the active rainfall peak of the QBW mode over Bangladesh. To summarize the relationship between the two ISO modes in LPS and non-LPS cases, schematic drawings are provided in Fig. 14.

In the QBW mode, the westward propagation of a low-level anticyclonic anomaly from the western Pacific is common in both cases. It should be noted that the anticyclonic center in the LPS case is located slightly to the east of that in the non-LPS case. This locational difference provides stronger low-level cyclonic shear over and around Bangladesh in the LPS case. In contrast, the BSISO mode shows an opposite phase between the two cases. In the LPS (non LPS) case, a cyclonic (anticyclonic) anomaly moves northward from the equator to the BoB. In the LPS case, the cyclonic anomaly in the BSISO mode enhances a westerly (easterly) flow over the BoB (northern Bangladesh), resulting in enhancement of the meridional cyclonic shear of zonal winds over the northern BoB and Bangladesh. It was also suggested that the two ISO modes contribute to the high level of midtropospheric humidity around the LPS genesis region, as well as the strong low-level cyclonic vorticity. Thus, in the LPS case, the two ISO modes provide favorable environmental conditions for LPS genesis. Conversely, in the non-LPS case, the westerly flow is enhanced from northern India to Bangladesh in association with the anticyclonic anomalies of the two ISO modes. The enhanced westerly flow leads to the enhancement of orographic lifting of low-level moisture on the windward slopes of mountains such as the Meghalaya Plateau and Chittagong Hill Tracts, which results in a large increase in rainfall in the area. Thus, these results suggest that the phase relationship between the two ISO modes controls the selection of the LPS or

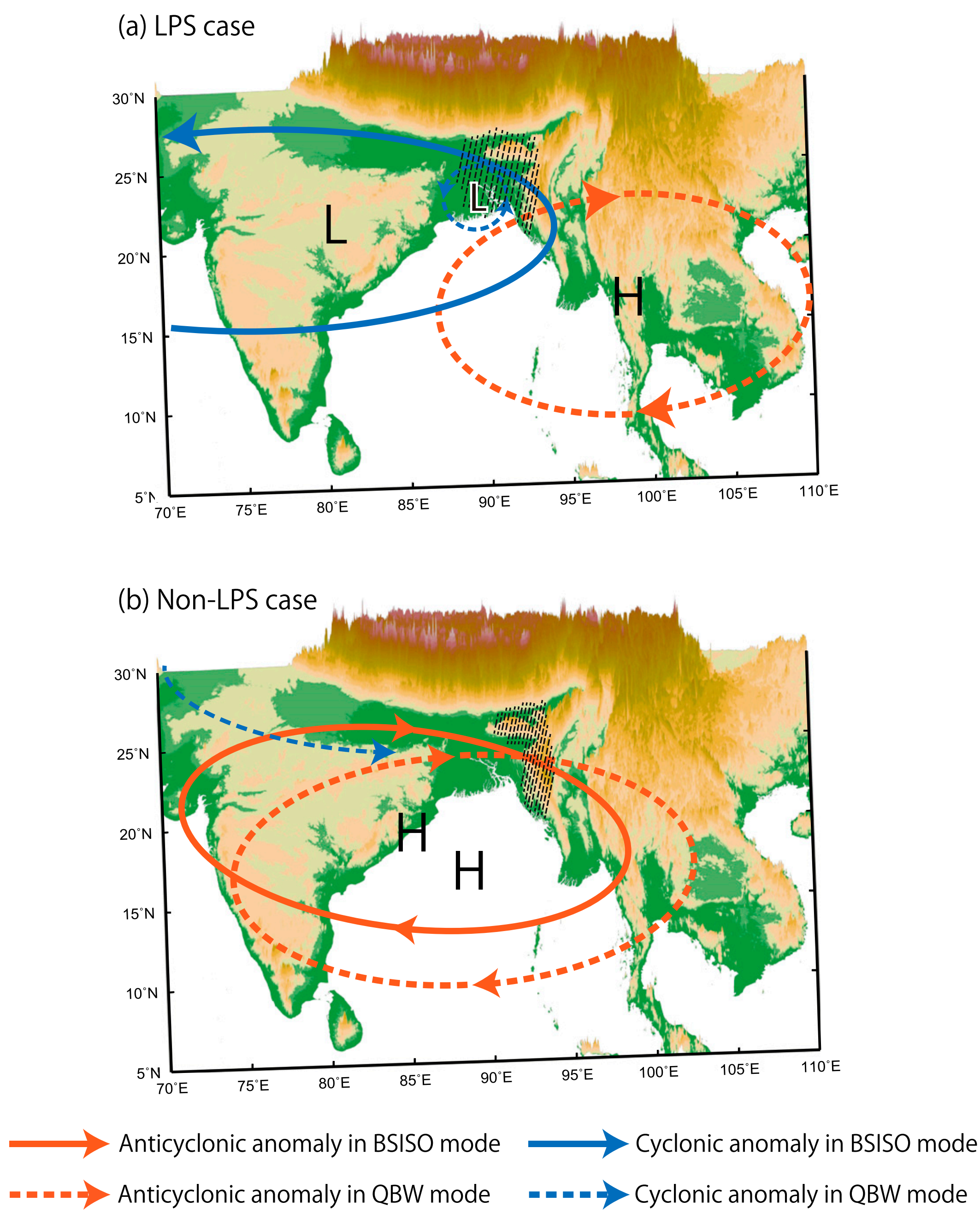

FIG. 14. Schematic illustration of the relationship between BSISO mode (solid arrows) and QBW mode (dashed arrows) on day −1 when LPSs occur most frequently: (a) LPS case and (b) non-LPS case. Symbols L and H represent the center of anticyclonic (orange arrows) and cyclonic (blue arrows) anomaly associated with the ISO modes, respectively.

non-LPS case in the active peak over Bangladesh. Such a relationship also suggests that the monitoring and prediction of the behaviors of these ISOs would aid the prediction of LPS genesis around the Bangladesh region. Because of their small scale and the complex features of the terrain around Bangladesh, numerical simulation by regional and cloud-resolving models would be necessary for furthering the understanding of LPS formation processes.

Additionally, the results of this study suggest that the QBW mode might be phase locked by the BSISO mode over the BoB. The model results of Wang and Xie (1997) demonstrated that a westward-propagating Rossby wave emanates from the equatorial eastward-propagating

Kelvin–Rossby wave packet when it approaches the date line from the western Indian Ocean. Thus, the BSISO could be considered a system composed of the equatorial eastward, off-equatorial westward, and northward-propagating modes. Further studies are needed to understand fully the complex behavior and dynamics of the BSISO.

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