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# Characteristic intraseasonal oscillation of rainfall and its effect on interannual variability over Bangladesh during boreal summer

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**ABSTRACT:** Intraseasonal oscillation (ISO) of rainfall during the summer monsoon season (June–August) and its plausible effect on interannual variation (IAV) of total summer monsoon rainfall over Bangladesh are examined using daily rainfall data from 25 rain-gauge stations for 20 years (1981–2000). Submonthly scale (7–25 days) ISO is a dominant mode of summer rainfall fluctuation over Bangladesh. In the active (suppressed) ISO phases, a cyclonic (anticyclonic) circulation anomaly develops at the low-level troposphere from northeastern India to Bangladesh, and an anticyclonic (cyclonic) circulation anomaly appears over the Bay of Bengal, accompanied by the enhancement of westerly/southwesterly (easterly/southeasterly) moisture flux anomalies over Bangladesh. The IAV of total summer monsoon rainfall is significantly correlated with that of the rainfall variance, mainly in the submonthly scale, suggesting that the ISO activity controls the IAV of the total summer monsoon rainfall. Moreover, the spatial patterns of atmospheric circulation and convection associated with the ISO and the IAV are quite similar to each other around the monsoon trough, especially from northeastern India to Bangladesh. In wet monsoon years, more frequent strong submonthly scale ISOs and a larger number of rainy days related to the active ISO phase are evident compared with that of dry monsoon years. Climatologically, Bangladesh is one of the most predominant areas of submonthly scale ISO; however, 30–60-day ISO is not prominent. These characteristic features probably allow the submonthly scale ISO to modulate the total seasonal rainfall and the spatial patterns of circulation and convection over and near Bangladesh. Copyright © 2010 Royal Meteorological Society

KEY WORDS Asian summer monsoon; Bangladesh; rainfall; intraseasonal oscillation; interannual variation

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## 1. Introduction

Bangladesh is one of the heaviest rainfall areas in the world. In the summer monsoon season (June–August), southwesterly/southerly winds from the ocean bring abundant moisture to Bangladesh. Geographically, the country encompasses the flat lowland (less than 10 m above sea level) confluence zone of the Ganges, Brahmaputra, and Meghna rivers and is surrounded to the north, west, and east by high-elevation areas (the Himalaya Mountains/Tibetan Plateau, Chota Nagpur Plateau, and Chittagong Hill Tracts, respectively), as shown in Figure 1. Southern Bangladesh faces the Bay of Bengal, from which southerly moist winds easily intrude over the country. To the northeast of Bangladesh and south of the Himalaya Mountains, the Shillong Plateau stands at ∼2000 m above sea level, extending east to west. These geographic features and prevailing southwesterly/southerly winds strongly affect the spatial distribution of seasonal mean rainfall as well as individual precipitation systems over Bangladesh (e.g. Kripalani *et al.*, 1996; Ohsawa *et al.*, 2000; Ohsawa *et al.*, 2001; Islam *et al.*, 2005; Kataoka and Satomura, 2005; Terao *et al.*, 2006; Islam and Uyeda, 2007; Murata *et al.*, 2008; Terao *et al.*, 2008). Heavy rains often lead to flood disasters over the flat, low-elevation lands of Bangladesh (e.g. Chowdhury, 2003; Murata *et al.*, 2008). Therefore,

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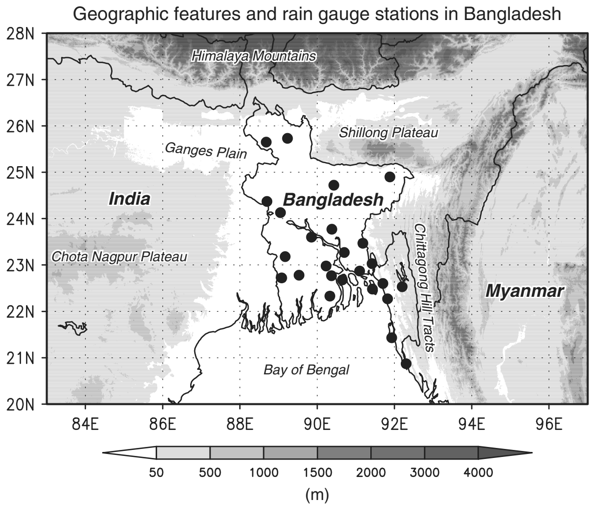


Figure 1. Geographic features in and around Bangladesh. Closed circles denote the locations of the 25 rain-gauge stations used in this study. Shading denotes areas more than 50 m in surface altitude.

it is important to examine the detailed space–time characteristics of variations in rainfall and convection over Bangladesh.

Intraseasonal oscillations (ISOs) of rainfall/convection and associated atmospheric circulations are prominent phenomena over the Asian summer monsoon region. The ISOs can be divided into two types according to timescales: those of 30–60 days, the so-called Madden–Julian Oscillation (MJO; Madden and Julian, 1972, 1994), and those of ∼6–25 days, or submonthly timescales (e.g. Vincent *et al*., 1998; Fukutomi and Yasunari, 2002, 2005; Fujinami and Yasunari 2004, 2009; Hoyos and Webster, 2007). The submonthly timescale contains the 10–20-day or quasi-biweekly timescales reported in previous studies (e.g. Krishnamurti and Ardanuy, 1980; Chen and Chen, 1993; Chatterjee and Goswami, 2004). The ISOs of the two timescales differ in their spatiotemporal structures; the 30–60-day ISO is associated with northward propagation of convection from the equatorial Indian Ocean, whereas the submonthly scale ISO is a westward propagating feature from the western Pacific (e.g. Yasunari, 1979; Krishnamurti and Ardanuy, 1980; Chen and Chen, 1993; Annamalai and Slingo, 2001; Hoyos and Webster, 2007). Only a few studies have addressed the ISO of rainfall/convection over Bangladesh. Ohsawa *et al*. (2000) presented a detailed study on the ISO of rainfall in Bangladesh for summer 1995 and showed that the submonthly scale ISO was dominant in summer monsoon rainfall in that year. Rainfall variation in Bangladesh is closely associated with the north–south oscillation of the monsoon trough. Rainfall increases when the axis of the monsoon trough is located at the foot of the Himalayas, whereas it decreases when the axis is located to the south of Bangladesh. Murata *et al*. (2008) showed that submonthly variability in rainfall dominated at Cherrapunjee (located on the southern slope of the Shillong Plateau in India near the Bangladesh border) in the 2004 monsoon season, and the variation strongly affected river levels around Sylhet (located in northeastern Bangladesh near the Indian border). The MJO-scale ISO was not dominant during the 2 years examined in those studies. Hartmann and Michelsen (1989) investigated the dominant periodicity of intraseasonal rainfall variation over India, using daily precipitation data from 3700 rain-gauge stations for 70 years. They reported that MJO-scale periodicity predominated over most parts of India south of 23 °N, whereas spectral peaks around submonthly timescales were limited to northern India where the MJO-scale signal did not dominate. These studies suggest that submonthly variation is more common than MJO-scale variation over Bangladesh.

With regard to interannual variation (IAV), although many studies have examined the IAV of summer monsoon rainfall over India, few have addressed the relationship between this parameter and monsoon variability over Bangladesh (e.g. Goswami *et al*., 1999; Krishnamurthy and Shukla, 2000). Kripalani *et al*. (1996) examined the IAV of summer (June–September) rainfall over Bangladesh using data from 14 rain-gauge stations from 1901 to 1977. They noted that, as a whole, the summer rainfall over Bangladesh and India showed no relationship. Only the summer rainfall variation over northeastern India, close to Bangladesh, had statistically significant positive correlation with that over Bangladesh. They also found that the summer rain over Bangladesh had no significant correlation with the El Niño–Southern Oscillation (ENSO) signal, which could act as an external forcing to influence seasonal mean rainfall over the Asian monsoon region. Ahmed *et al*. (1996) examined the relationship between rainfall variation over Bangladesh and that over El Niño using data from 1950 to 1992 obtained at four rain-gauge stations in Bangladesh. They reported that rainfall amount showed a negative or decreasing tendency during El Niño events in pre-monsoon, monsoon, post-monsoon, and winter seasons. Chowdhury (2003) also investigated the relationship between the IAV of rainfall over Bangladesh and ENSO for about 40 years (from the 1960s to 1990s). He found that although the summer monsoon rainfall in Bangladesh showed a decreasing (increasing) tendency during strong El Niño (La Niña) years, the quantitative correspondence between the strength of ENSO and the summer rainfall anomaly over Bangladesh was very weak. One reason for the small number of studies on IAV over Bangladesh may be the lack of reliable rainfall datasets available for climatological research. Cash *et al*. (2008) pointed out that results on the IAV of monsoon rainfall in Bangladesh can vary depending on the dataset used [e.g. Global Precipitation Climatology Project (GPCP), Climate Prediction Center-Merged Analysis of Precipitation (CMAP), or gauge-based gridded precipitation data]. Therefore, long-term precipitation data from densely situated gauge stations are needed to represent the IAV, as well as the ISOs, of summer monsoon rainfall.

The relationship between the ISOs and the IAV of the summer monsoon is an interesting topic in Asian monsoon studies. Krishnamurthy and Shukla (2000) noted that seasonal mean monsoon rainfall over India consists of a large-scale persistent rainfall anomaly (related to an external forcing such as sea surface temperature anomalies) and a fluctuating intraseasonal component (i.e. internal monsoon variability). The nature of the intraseasonal variability does not differ between wet and dry years. In contrast, Goswami and Mohan (2001) reported that higher occurrence frequency of active (break) conditions could result in stronger (weaker) than normal seasonal mean precipitation over the Indian summer monsoon region. Furthermore, Goswami *et al.* (2003) showed that the occurrence frequency of a westward moving monsoon low-pressure system was ∼3.5 times higher in the active phase of the monsoon than during the break phase and that the tracks of these synoptic systems were strongly spatially clustered along the monsoon trough during the active phase of the monsoon. Hoyos and Webster (2007) suggested that propagation characteristics of ISO on 25–80-day and 4–20-day timescales, coupled with local effects of orography and land–atmosphere feedbacks, modulate and determine the locations of summer mean precipitation patterns over the Asian monsoon region. They also noted that, over the Indian Ocean, the cumulative effect of the 25–80-day rainfall variability was directly connected to a proportion of the interannual modulation of the summer rainfall, constituting one of the most important sources of internally generated interannual variability. For Bangladesh, however, no previous study has addressed how ISOs relate to the IAV of summer rainfall.

The objectives of this study were to (1) reveal a robust feature of the ISO of rainfall over Bangladesh from June to August (JJA) based on 20-year (1981–2000) daily precipitation data from 25 rain-gauge stations; (2) reveal the typical space–time structure of atmospheric circulation related to the ISO in Bangladesh; and (3) attempt to explain how the IAV of summer mean rainfall is modulated by the ISO activity over and around Bangladesh. Section 2 describes the datasets and analysis methods used in this study. The generalised characteristics of the ISO over Bangladesh and distinctive space–time structure of atmospheric circulation associated with the ISO are discussed in Section 3. Section 4 presents the spatial pattern of atmospheric circulation and large-scale convection related to the IAV of summer rainfall over Bangladesh. Probable effects of the ISOs on the IAV of summer rainfall are discussed in Section 5. Finally, the results are summarised in Section 6.

## 2. Data and analysis method

Rainfall data observed at 25 rain-gauge stations across Bangladesh and provided by the Bangladesh Meteorological Department (BMD) were the primary datasets used to analyse rainfall variation (Figure 1). Daily averaged values were available for 20 years (1981–2000). For all stations, missing data accounted for less than 2% of the total observation times during the study period. In this study, the rain-gauge data for each of the 25 stations were simply averaged for each day (defined as the ‘all Bangladesh daily rainfall’ and abbreviated as ABDR), similar to the method described by Ohsawa *et al.* (2000). Local-scale spatial variations in rainfall series for each station could be filtered out using this procedure. These data were used as an index representing temporal variation in rainfall over the whole of Bangladesh. The space–time structures of the atmospheric circulation fields associated with ISO and IAV in the ABDR were also investigated using Japanese 25-year reanalysis (JRA25) data on a 1.25° latitude–longitude grid (Onogi *et al.*, 2007). Streamfunction and moisture flux vectors integrated from the surface to 100 hPa were mainly used in this study. Such relatively fine-resolution reanalysis data are useful for studying Bangladesh because it is a small country surrounded by areas of complex terrain. Daily interpolated outgoing longwave radiation (OLR) data on a 2.5° latitude–longitude grid were also used as a proxy for large-scale convective activity (Liebmann and Smith, 1996).

Daily anomalies of rainfall, OLR, and the reanalysis data were computed by subtracting the first three harmonics of the annual cycle (about 120 days) for each year. Submonthly (7–25 days) perturbations were then computed by applying a Lanczos filter (Duchon, 1979) to the detrended anomalies. As an example, Figure 2 shows the time series of ABDR in summer 1993 (black bar) and 7–25-day filtered rainfall (solid line). The ABDR time series for 1993 shows clear intraseasonal variation on submonthly timescales. The active and break peaks of the 7–25-day filtered ABDR series correspond well with those of the unfiltered ABDR series. Submonthly scale intraseasonal variance was calculated based on the 7–25-day filtered ABDR series and used as the index for the ISO activity. In this study, an active phase was defined as a period in which the 7–25-day ABDR value exceeded zero within one cycle of the ISO and its peak value in that cycle exceeded more than 1.0 standard deviation of the climatological mean 7–25-day rainfall variance (shown by shading in Figure 2).

Composites and daily-lag composites were used to investigate the temporal-phase relationships of ABDR fluctuation, circulation fields, and OLR. Regression analysis was also used to examine the spatial pattern of circulation and OLR fields associated with the IAV of Bangladesh monsoon rainfall.

## 3. Intraseasonal variability over Bangladesh

### 3.1. Characteristic features of ISO over Bangladesh

To show the dominant period of ISO in rainfall for the 20 years, spectrum analysis was performed using the fast-Fourier transform (FFT) technique. The FFT analyses used the detrended ABDR data (the first three harmonics of the annual cycle were removed) between 15 May and

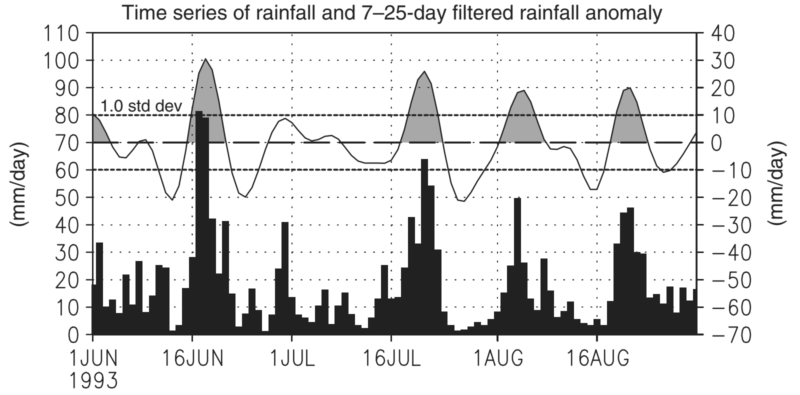


Figure 2. Time series of rainfall (black bars; left axis) and 7- to 25-day filtered rainfall anomaly (solid line; right axis) from 1 June to 31 August 1993. Periods with grey shading are active phases of the ISO in this study. Dotted lines denote the 20-summer (JJA) climatological 1.0 standard deviation. The dashed line is the zero line for the filtered anomaly. See the text for the definition of the active phase.

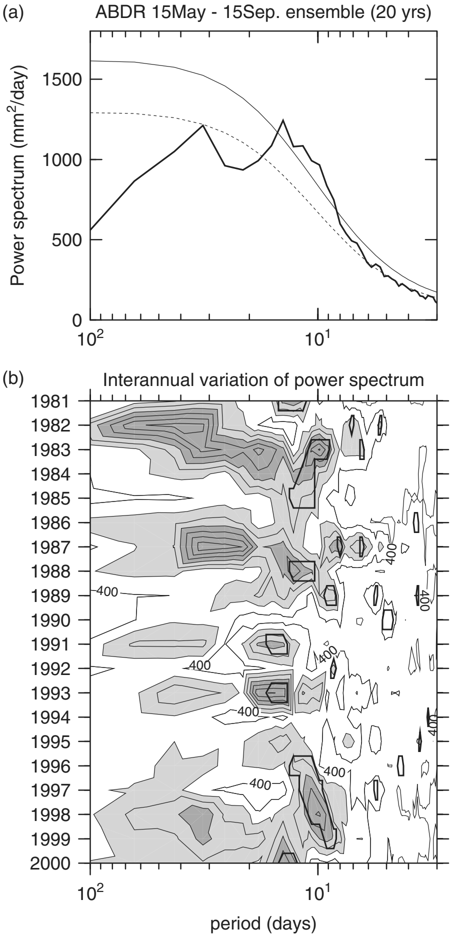


Figure 3. (a) The 20-summer ensemble spectrum of the ABDR time series from 15 May to 15 September (124 days). A red noise spectrum (dashed curve) and its 95% level of significance (solid curve) based on a lag-1 autocorrelation are also shown. (b) Interannual variation of the ABDR spectrum from 1981 to 2000. The contour interval is 400 mm$^2$ day$^{-1}$. The thick solid line shows the 95% level of significance. Areas having a power spectrum >800 (1600) mm$^2$ day$^{-1}$ are lightly (darkly) shaded.

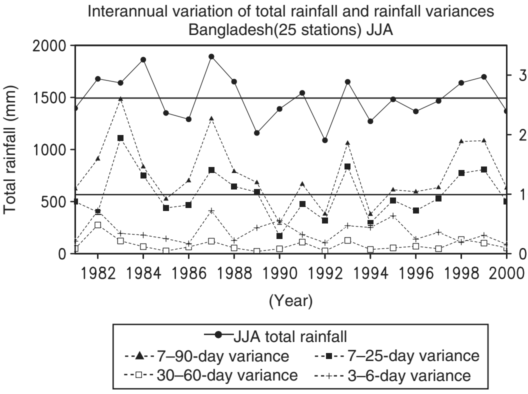


Figure 4. Interannual variations of total ABDR (solid line with closed circles; left axis), 7- to 90-day ABDR variance (dashed line with closed triangles; right axis. The unit is mm$^2$ day$^{-2}$), 7- to 25-day ABDR variance (dashed line with closed squares), 30- to 60-day ABDR variance (dashed line with open squares), and 3- to 6-day ABDR variance (dashed line with plus signs) for June–August.

15 September (124 days). Cosine tapering was applied to 10% of the time series at either end. A 3-point running mean in the frequency domain was applied to the raw spectra to reduce estimate errors. Figure 3 shows the 20-summer ensemble spectrum of the ABDR. A pronounced peak appears at a period of about 14 days, and the peak exceeds the 95% confidence level (Figure 3(a)). A peak around the 30–40-day period can also be seen but is not statistically significant. Figure 3(b) presents the IAV of the ABDR power spectrum for the 20 years. Periods of 7–25 days are common in most of the years, whereas large IAV appears in peak periodicity of 30–40 days. Note that a statistically significant peak often appears at around 10 days in each year, although the ensemble spectrum shows a peak spectrum at around 14 days. Thus, submonthly scale ISO is the predominant mode of summer rainfall fluctuation over Bangladesh.

Figure 4 shows the IAV of total ABDR and intraseasonal and higher frequency (3–6-day) rainfall variances during JJA. Note that the IAV of total summer monsoon rainfall is well correlated with intraseasonal variance of the ABDR, suggesting that the ISO activity could control the IAV of summer monsoon rainfall over Bangladesh. The relationship of the IAV of summer monsoon rainfall and 7–90-day ABDR variance (i.e. the all-period range of ISOs) has a correlation coefficient of 0.74. Correlation values larger than 0.56 are statistically significant at the 99% confidence level. This high correlation is not necessarily natural because the seasonal total rainfall usually consists of a large-scale persistent rainfall anomaly, an intraseasonal component, and a higher frequency component. Furthermore, the 7–25-day variance accounts for 60–90% of total intraseasonal variance, except in 1982 and 1990. The correlation between the IAV of summer monsoon rainfall and the 7–25-day (30–60-day) variance is 0.65 (0.59). Throughout the study period, the 30–60-day ABDR variance is very small compared with the 7–25-day variance, except in 1982; the 7–25-day variance is ~10 times larger than the 30–60-day variance in the 20-year average. Besides the ISOs, westward moving synoptic-scale monsoon lows and depressions are main rain-producing systems with typical timescales of 3–5 days over the Indian monsoon region. The occurrence frequency of westward moving synoptic-scale disturbances was nearly 3.5 times higher in the active phase of the monsoon than that during the break phase (Goswami *et al.*, 2003). This implies that high-frequency (3–6-day) synoptic-scale rainfall systems also significantly affect rainfall variation over Bangladesh and, in turn, contribute to the IAV of total summer monsoon rainfall there. However, in Bangladesh, statistically significant peaks are not found in the high-frequency period range in more than half of the 20 years (Figure 3(b)), implying that synoptic-scale lows and depressions on the 3–6-day period are not common rain-producing systems in Bangladesh, unlike in India. In addition, the correlation between the IAV of summer monsoon rainfall and the 3–6-day variance is low, with a correlation coefficient of 0.36 (*cf* Figure 4). These results suggest that 7–25-day ISO activity is essential to modulate total summer rainfall and to understand the IAV of summer monsoon rainfall over Bangladesh. Nearly simultaneous increases in the variances of both timescale bands in wet monsoon years suggest that the amplitude of the 7–25-day ISO may be modulated by the envelope of convection in 30–60-day bands, with greater amplitude during the active phase of the 30–60-day ISO. That is, a possible dynamical process may exist by which submonthly scale ISO can be superimposed on the active phase of the 30–60-day ISO, whereas inactive 30–60-day ISO phases do not suppress the submonthly ISO activity significantly.

### 3.2. Space–time structure of atmospheric circulation and convection fields

Our focus here is to understand the space–time structure of atmospheric circulation and large-scale convection

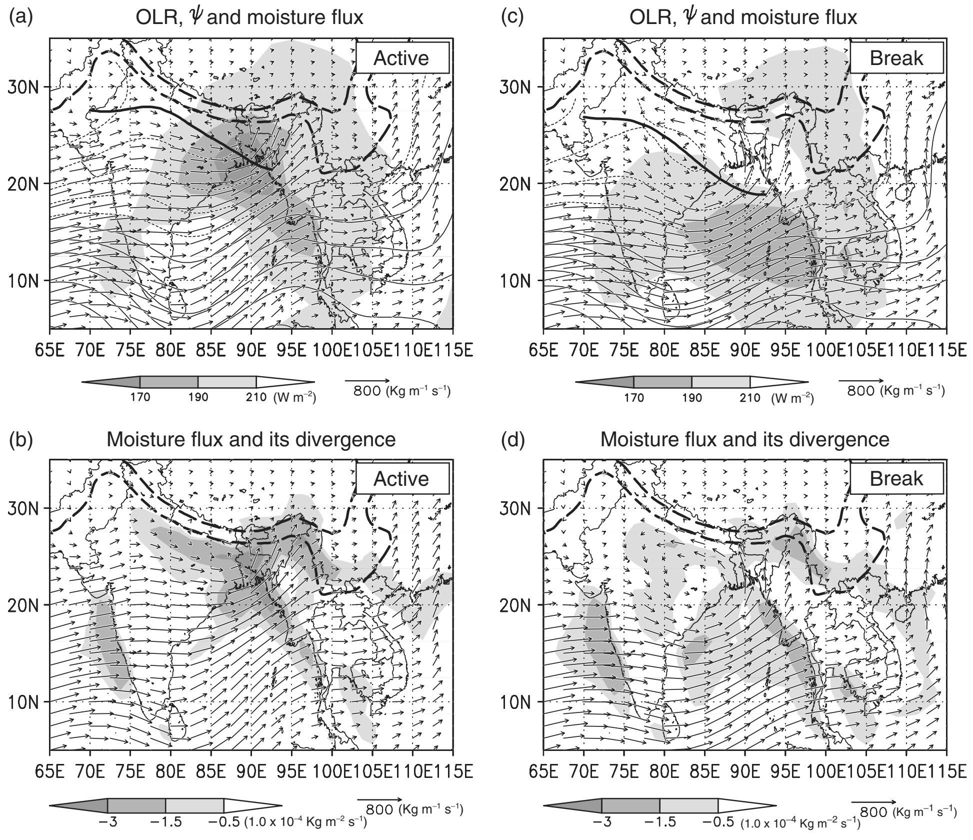


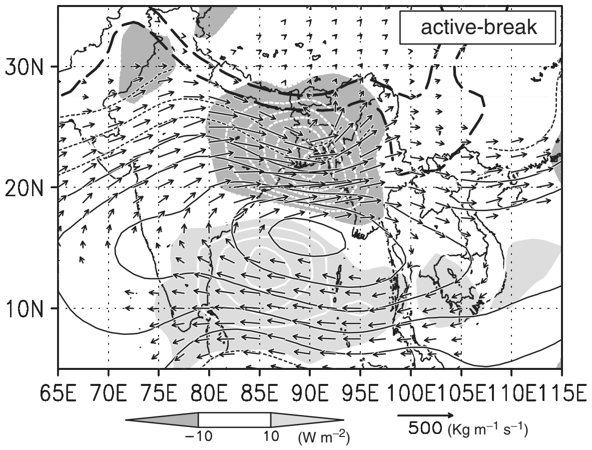
Figure 5. Composites of the (a) total OLR (shadings), 925-hPa streamfunction ($\psi$), and vertically integrated (from the surface to 100 hPa) moisture flux vectors in a peak active phase of 7- to 25-day rainfall variation over Bangladesh. The contour interval for $\psi$ is $2 \times 10^6$ m$^2$ s$^{-1}$. The topographic contour lines for 1000 and 3000 m are also shown (thick dashed lines). (b) As in (a), but for vertically integrated moisture flux and its divergence (shading). Convergence areas less than $-0.5 \times 10^{-4}$ Kg m s$^{-1}$ are shaded. (c), (d) As in (a) and (b), but for a peak break phase. Thick solid lines in (a) and (c) indicate the axis of the monsoon trough from India to Bangladesh.

associated with submonthly scale rainfall variation over Bangladesh using composite analyses. On the basis of the 7–25-day ABDR anomalies, positive and negative extremes that exceeded the 20-summer climatological 1.0 standard deviation (~10 mm day$^{-1}$) were selected as active and break peaks for the composites. In total, 78 peak active and 84 peak break phases were identified during the 20-summer monsoon seasons. This represents a sufficient number of samples from multi-year data to reveal generalised and robust features of the space–time structure associated with ISO over Bangladesh. The composite active and break peaks of total ABDR showed rainfall values of 46.6 and 6.9 mm day$^{-1}$, respectively.

Figure 5 shows composites of the total atmospheric circulation fields and large-scale convective activity for the peak active and break phases. In the active phase (Figure 5(a)), the monsoon trough is located from northwestern India to Bangladesh in the low-level troposphere, providing westerly/southwesterly moisture flow over Bangladesh. In this synoptic situation, the low-level southwesterlies blow towards the high mountain regions to the northeast and east of Bangladesh (Figure 1). The southwesterlies seem to stagnate in windward areas such as Bangladesh and northeastern India, forming a remarkable convergence field there. The centre of active convection is found over Bangladesh and the head of the Bay of Bengal, corresponding to the centre of large moisture flux convergence (Figure 5(b)). The centre of 925-hPa positive vorticity is also located over Bangladesh (not shown). In contrast, in the break period (Figure 5(c)), the monsoon trough shifts southward and extends from central Pakistan to the head of the Bay of Bengal. The wind direction over Bangladesh is southerly/southeasterly rather than westerly/southwesterly due to the shift of the monsoon trough. In this case, the incoming southerly moisture flow from the Bay of Bengal can easily flow out from the flat lowland of northwestern Bangladesh over the Ganges Plain. In fact, the easterly flow dominates along the Ganges Plain. Thus, this circulation change induces a significant decrease in moisture flux convergence over Bangladesh. A maximum area of cloudiness moves to the Bay of Bengal along 15 °N, accompanied by an increase in moisture flux convergence. These atmospheric features of the monsoon trough and associated wind fields are very similar to those found for summer 1995 by Ohsawa *et al.* (2000).

Figure 6 shows the composite differences between the active and break peaks. The statistical significance of the difference at each grid point was estimated using Student's *t*-tests. In OLR and moisture flux divergence fields, shaded areas are nearly in accordance with the areas of 99% confidence (Figure 6(a) and (b)). Associated with the submonthly rainfall ISO over Bangladesh, convection anomalies show a negative sign (i.e. enhanced convection) over northeastern India, all of Bangladesh, and northwestern Myanmar, with a positive sign (i.e. suppressed convection) over the southern Bay of Bengal. The active rainfall/convection is associated with the deepening of the monsoon trough from the northern fringe of India to northern Bangladesh and the enhancement of anticyclonic circulation over the Bay of Bengal. The circulation features enhance westerly moisture flux anomalies around 20°–25 °N and moisture flux convergence over and near Bangladesh.

(a) OLR, $\psi$ and moisture flux



(b) Moisture flux and its divergence

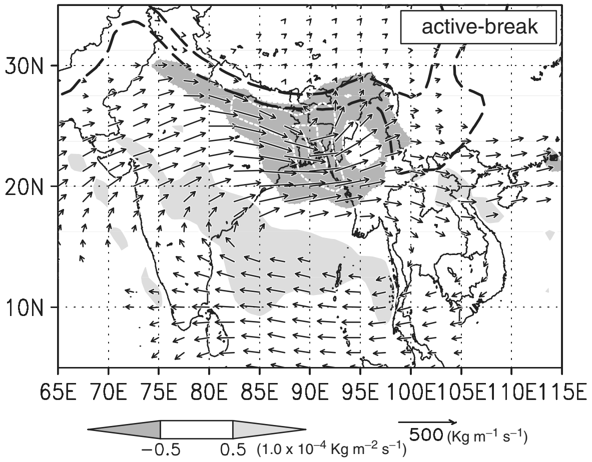


Figure 6. Composite differences of (a) OLR (shadings), 925-hPa streamfunction ($\psi$), and vertically integrated (from the surface to 100 hPa) moisture flux vectors between peak active and break phases of 7- to 25-day rainfall variation over Bangladesh. The contour interval for $\psi$ is $5 \times 10^5$ m$^2$ s$^{-1}$. The contour interval for OLR is 10 W m$^{-2}$, and the zero contours are omitted. Only moisture flux vectors that show 99% statistically significant difference are plotted. The topographic contour lines for 1000 and 3000 m are also shown (thick dashed lines). (b) As in (a), but for vertically integrated moisture flux and its divergence (shading). Contours for moisture flux divergence are shown at −3.5, −2.5, −0.5, 0.5, 2.5, and 3.5. The unit is $1 \times 10^{-4}$ kg m s$^{-1}$.

To further illustrate the time evolution, Figure 7 shows daily-lag composites of 925-hPa streamfunction, moisture flux, and OLR fields from day −4 to day +3 based on the 7–25-day rainfall variation over Bangladesh. Active rainfall peaks over Bangladesh are referred to as day-0 phases, whereas day −5 and day +5 correspond to break peaks, indicating that one cycle of the composite variation is 10 days. This is because, as seen in Figure 3(b), statistically significant peaks often appear at around 10 days in each year, and therefore, a large number of composite samples have an ~10-day period. In each phase, 78

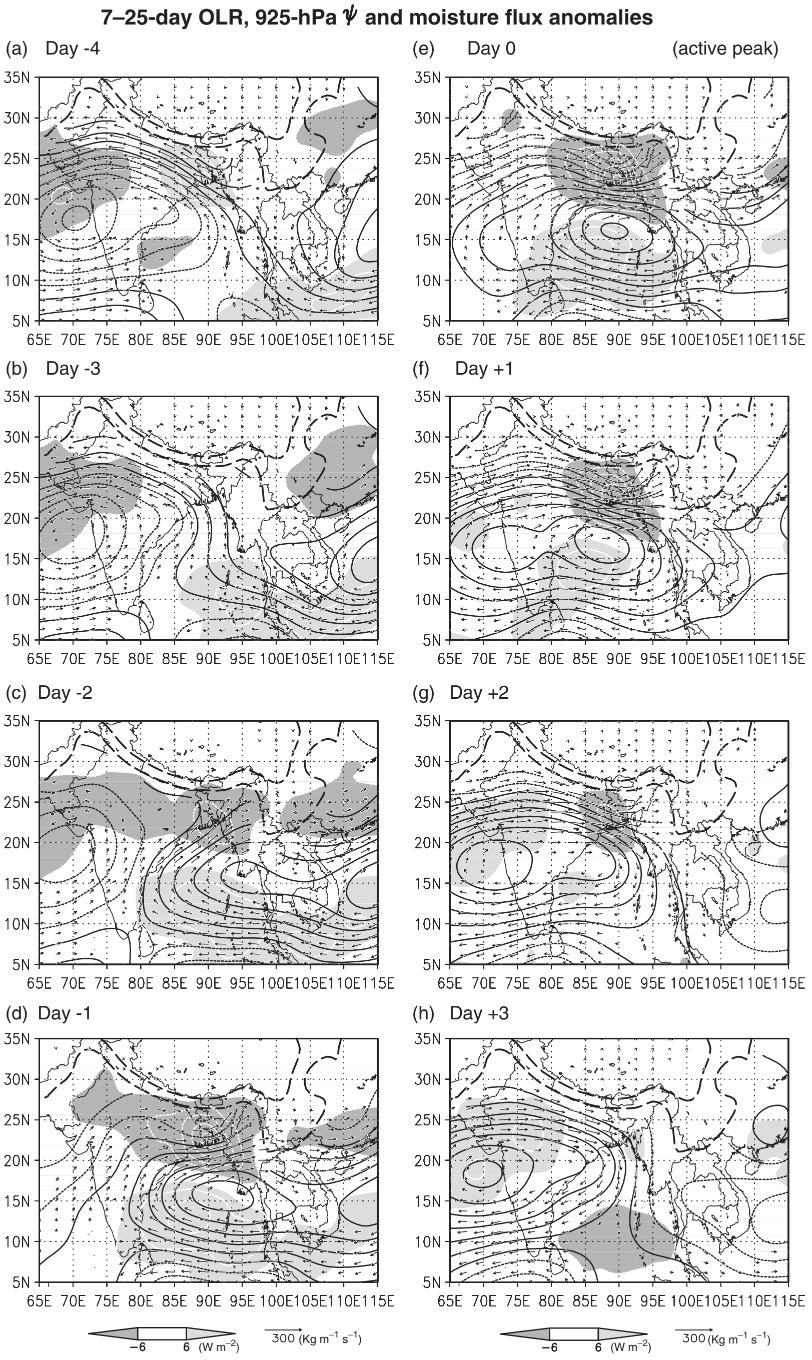


Figure 7. Composites of 7- to 25-day filtered OLR, 925-hPa streamfunction ($\psi$), and vertical integrated moisture flux anomalies from day −4 to day +3 based on the ABDR variation. Day 0 corresponds to the active peak of 7- to 25-day ABDR variation. OLR anomalies less than −6 (6) W m$^2$ are darkly (lightly) shaded. The contour interval for OLR is 6 W m$^{-2}$ (white contours). Solid black (dashed) contours represent positive (negative) $\psi$ values. The contour interval is $2 \times 10^5$ m$^2$ s$^{-1}$. Only 99% statistically significant vectors are plotted.

samples were used to construct the daily-lag composites. Shaded areas of OLR nearly correspond to areas of 99% confidence. On day −4, suppressed convection is shown over Bangladesh and northeastern India, accompanied by southeasterly moisture flux anomalies. Bangladesh is located under the northeastern part of a cyclonic anomaly centred on the western coast of India and under the southwestern part of a local anticyclonic circulation over northern Bangladesh. An anticyclonic circulation appears over the South China Sea around 115 °E, 15 °N from day −4 and moves westward to the west of India by day +3 via the Indochina Peninsula and the Bay of Bengal. These atmospheric structures are very similar to the so-called synoptic-scale 10–20-day ISO (e.g. Chen and Chen, 1993; Annamalai and Slingo, 2001; Hoyos and Webster, 2007; Yokoi and Satomura, 2008). In addition, a negative streamfunction anomaly is centred on the equator, south of the anticyclonic anomaly over the Bay of Bengal (not shown). The negative streamfunction anomaly moves westward in synchrony with the anticyclonic anomaly around 15 °N, as also noted by Chen and Chen (1993) and Chatterjee and Goswami (2004). On day −2, when the anticyclonic anomaly moves into the eastern part of the Bay of Bengal from the Indochina Peninsula, a cyclonic anomaly starts to develop around Bangladesh. Simultaneously, the active convection anomaly appears over Bangladesh, northeastern India, and western Myanmar due to the enhancement of southwesterly/westerly moisture inflow. The anticyclonic anomaly moves westward, with its centre reaching the western part of the Indian subcontinent by day +2. On day +1, the anticyclonic circulation seems to split to the east and west of the Deccan Plateau, a large plateau located to the southwest of the Chota Nagpur Plateau. This split is indicative of the effect of the plateau on the shape of the anticyclonic circulation anomaly around India. Interestingly, the centre of the cyclonic circulation in and near Bangladesh remains at almost the same location from day −2 to +2. Like the cyclonic circulation, the convection anomaly over Bangladesh remains almost stationary from day −2 to +2. The standing feature of the cyclonic circulation and convection likely suggests that the terrain features around Bangladesh, especially to its northeast and east, are essential to enhance cyclonic circulation and convection. If the southwesterly flow, which varies on submonthly timescales, is affected by the mountain ranges and then converges over Bangladesh, the convergence area (i.e. the cyclonic circulation) does not necessarily move during the southwesterly wind phase. In contrast, suppressed convection anomalies over the Bay of Bengal, located around the south/southwestern part of the anticyclonic circulation where easterly anomalies dominate, move westward from day −3 to −1 and reach the southwestern Bay of Bengal. On day +2, a cyclonic anomaly emerges over the South China Sea and moves westward across the Indochina Peninsula. After day +4, as the cyclonic circulation anomaly moves westward along 15 °N, the easterly moisture flux component becomes dominant over Bangladesh, northeastern India, and northwestern Myanmar. Suppressed convection is observed in these regions under the atmospheric condition.

Ohsawa *et al.* (2000) noted that ∼20-day variation over Bangladesh in summer 1995 was associated with the northward propagation of synoptic-scale 10–20-day ISO. However, the northward propagation signal is not evident in our results for both convection and circulation anomalies. The northward propagation of the 10–20-day mode seemed to be remarkable, especially in a case with heavy rainfall from 7 June to 5 July 1995. However, in other cases in 1995, the northward movement was not evident [Figures 7 and 13 of Ohsawa *et al.* (2000)]. The latitude–time cross sections of OLR along 90 °E from 0 to 30 °N in JJA for the other years of the period 1981–2000 show that well-organised northward propagation is very rare on submonthly timescales (not shown). In contrast, the 30–60-day signal often exhibits well-organised northward propagation from the equator to around 20 °N (figures not shown, e.g. Yasunari, 1979; Wang *et al.*, 2006).

## 4. Interannual variability over Bangladesh

This section presents the spatial structure of atmospheric circulation and convection associated with the IAV of the ABDR. As shown in Figure 4, the IAV of ABDR corresponds well with the submonthly scale variance of the ABDR, suggesting that the submonthly scale ISO activity could modify the spatial pattern of IAV over and around Bangladesh. Linear regression coefficients for estimating the streamfunction, moisture flux, and OLR values at each grid point from the interannual ABDR series are shown in Figure 8. A value equal to 1.0 standard deviation of the interannual ABDR series was input to the regression equation to produce the grid-point values. The overall pattern of anomalies in Figure 8 is characterised by a cyclonic anomaly from northern India to Bangladesh and an anticyclonic anomaly centred on the Bay of Bengal. A striking feature is the statistically significant westerly/southwesterly moisture flux anomalies over northeastern India, Bangladesh, and northwestern Myanmar, accompanied by active convection anomalies. The spatial pattern around Bangladesh is very similar to that of submonthly scale ISO. Statistically significant convection and moisture flux signals in the IAV are also observed over northwestern India, Pakistan, and southern China. No statistically significant convection anomalies are shown over India south of 20 °N, consistent with the findings of Kripalani *et al.* (1996). A weak relationship is also found in the correlation between ABDR and 'all India monsoon rainfall' (AIMR, available at ftp://www.tropmet.res.in/pub/data/rain/iitm-regionrf.txt) (Table I). These results indicate that the IAV of summer rainfall over Bangladesh has little relationship to the IAV of the Indian summer monsoon.

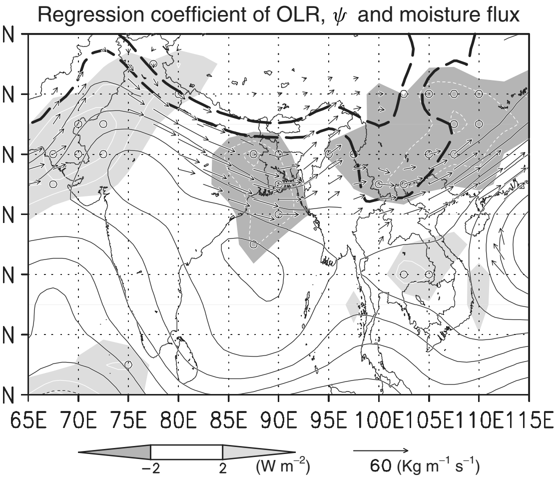


Figure 8. Regressions of OLR, 925-hPa streamfunction, and vertically integrated moisture flux vector in JJA for 1980–2000 against the standardised interannual time series of JJA total ABDR. OLR values less (greater) than −2 (2) W m$^{-2}$ are darkly (lightly) shaded. Open circles indicate locally statistically significant grids for OLR at the 95% significance level. The contour interval for OLR is 1 W m$^{-2}$ (white contours). Only 95% statistically significant moisture flux vectors are plotted. The contour interval for $\psi$ is $6 \times 10^4$ m$^2$ s$^{-1}$. The topographic contour lines for 1000 and 3000 m are also shown (thick dashed line).

Table I. Simultaneous correlation of interannual variations between all Bangladesh daily rainfall (ABDR) and the all India monsoon rainfall (AIMR), meridional thermal gradient (MTG), Niño-3 SST, and Indian Ocean dipole (DMI) mode indices for June–August. Correlation values larger than 0.56 are statistically significant at the 99% confidence level.

| AIMR | MTG | Niño-3 SST | DMI |
|---|---|---|---|
| −0.22 | −0.01 | −0.16 | 0.33 |

In the IAV of the total ABDR series (Figure 4), 3- to 5-year variation is observed for the period from 1981 to 1991 and after 1996, whereas a 2- to 3-year signal appears from 1991 to 1996. The 2- to 5-year period of variation is common in ENSO signals. However, Bangladesh summer monsoon rainfall has almost no correlation with the Niño-3 SST index (available at http://www.cpc.noaa.gov/data/indices/sstoi.indices), which represents ENSO variability, for JJA. As in the Niño-3 SST index, no relationship exists between Bangladesh summer monsoon rainfall and the meridional thermal gradient (MTG) index, a large-scale monsoon index defined by Kawamura (1998), for JJA. The correlation coefficient is −0.16 in the Niño-3 SST and almost zero in the MTG (Table I). The MTG, defined as the difference in area-averaged upper tropospheric (200–500 hPa) thickness between the Tibetan Plateau (50°–100 °E, 20°–40 °N) and the Indian Ocean (50°–100 °E, 0°–20 °N) regions, has shown good correlation with ENSO and another large-scale monsoon index proposed by Webster and Yang (1992) (Kawamura, 1998; Kawamura *et al.*, 2005). The correlation coefficient between the MTG and Niño-3 SST indices during the 20 years of our study is 0.68, which exceeds the 99% confidence level. Moreover, an Indian Ocean dipole event can be an effective external forcing of the summer Asian monsoon as well as ENSO (e.g. Saji *et al.*, 1999; Ashok *et al.*, 2001, 2004). However, the simultaneous relationship between ABDR and the Indian Ocean dipole mode index (DMI, available at http://www.jamstec.go.jp/frsgc/research/d1/iod/) is also weak (Table I). These results likely suggest that total summer monsoon rainfall in Bangladesh is modulated by internal monsoon variability, such as intraseasonal variation, rather than by large-scale persistent anomalies due to external forcing such as by SST anomalies.

However, further detailed study using long-term data is needed to clarify why the IAV of rainfall in Bangladesh has little simultaneous relationship with the Indian summer monsoon, large-scale Asian monsoon circulation, and external forcing induced by tropical SST anomalies such as ENSO and Indian Ocean dipole events.

## 5. Discussion

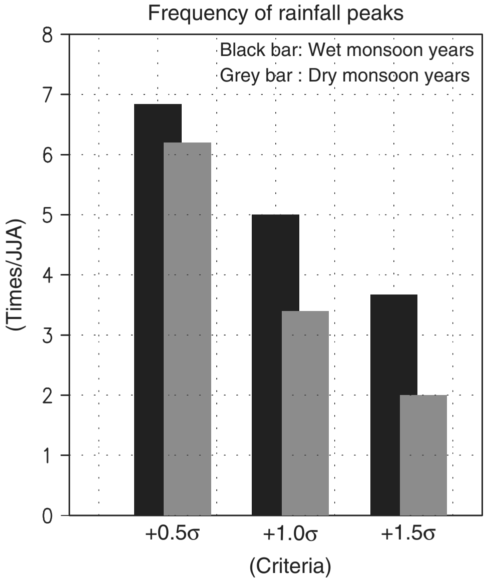


Figure 9. Average occurrence frequency of rainfall peaks of 7- to 25-day variation during JJA for six wet monsoon years (black bars) and five dry monsoon years (grey bars) based on three different criteria ($+0.5\sigma$, $+1.0\sigma$, and $+1.5\sigma$ of climatological 7- to 25-day ABDR variance). The frequency was counted when a rainfall peak exceeded each criterion in wet and dry monsoon years, respectively. The 20-summer (JJA) climatological 1.0 standard deviation (~10 mm day$^{-1}$) of 7- to 25-day variation is $+1.0\sigma$.

The similarity of the spatial patterns between the IAV and ISO indicates that more frequent occurrence of strong active conditions of the ISO produces a wet monsoon year over Bangladesh. Figure 9 shows the average frequency of occurrence of rainfall peaks in the submonthly ISO in JJA for six wet monsoon years (1982, 1984, 1987, 1988, 1993, and 1999) and five dry monsoon years (1985, 1986, 1989, 1992, and 1994). The IAV of total summer rainfall of these years exceed $0.7\sigma$, except for 1985, in which the IAV failed to reach the value by only a narrow margin. The frequencies were counted based on three separate criteria (i.e. $+0.5\sigma$, $+1.0\sigma$, and $+1.5\sigma$ of climatological 7–25-day ABDR variance) to ascertain the differences in the properties of rainfall peaks in wet and dry monsoon years. The value of $+1.0\sigma$ corresponds to ~10 mm day$^{-1}$. The frequencies did not differ largely between wet and dry monsoon years when small amplitude peaks ($>+0.5\sigma$) were included. However, the difference in the frequency of the rainfall peaks became larger as the amplitude increased. The differences for $+1.0\sigma$ and $+1.5\sigma$ are statistically significant at the 95% level. Thus, high-amplitude active peaks of the ISO occur more frequently in wet monsoon years than in dry monsoon years. In addition, on average, 29 active-phase days were observed in the wet monsoon years, and 19 active-phase days were found in the dry monsoon years (e.g. the periods shown by grey shading in Figure 2); this difference in the number of days is also statistically significant at the 99% level. In contrast, no statistically significant difference exists in the average frequency of break peaks (defined as peaks that exceed $-1.0\sigma$ of climatological 7–25-day ABDR variance) between the wet and dry monsoon years (not shown). These results indicate that the characteristic spatial pattern of the active

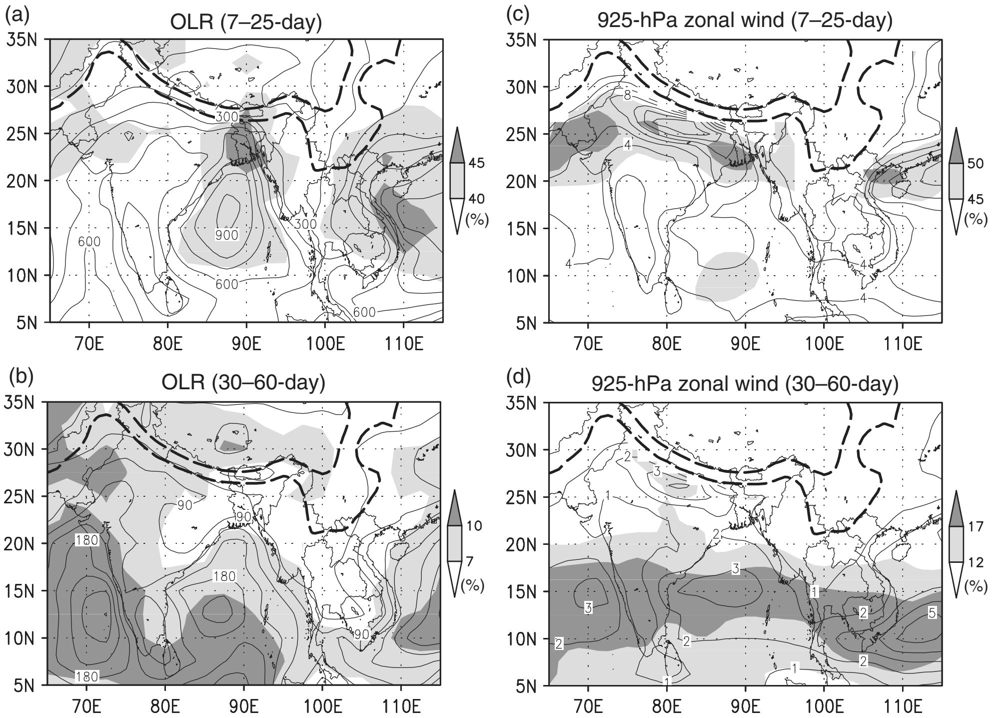


Figure 10. (a) Variance of 7- to 25-day filtered OLR for JJA (solid line). Shading represents the percentage of the total variance (with the seasonal cycle of OLR removed) explained by the 7- to 25-day band. The contour interval is 150 $W^2$ $m^{-4}$. The topographic contour lines for 1000 and 3000 m are also shown (thick dashed line). (b) As in (a), but for 30- to 60-day filtered OLR. The contour interval is 30 $W^2$ $m^{-4}$. (c), (d) As in (a) and (b), but for the 925-hPa zonal wind component (u). The contour intervals are 2 and 1 $m^2$ $s^{-2}$ for (c) and (d), respectively.

phase (Figures 6 and 7) appears more frequently in wet monsoon years, and in turn, contributes to modulating the spatial pattern of the IAV over and near Bangladesh.

The 7–25-day ISO variance is more than ~10 times larger than the 30–60-day ISO variance in the 20-year average. This is a peculiar feature of the ISO over Bangladesh. Hartmann and Michelsen (1989) showed that the MJO-scale (30–60-day) period was predominant over most parts of India, except in a few areas of northern India. Whereas the 30–60-day ISO is important for defining the observed mean seasonal rainfall and circulation pattern over India and the Bay of Bengal (e.g. Goswami and Mohan, 2001; Hoyos and Webster, 2007), the submonthly scale ISO also contributes to the mean monsoon circulation and rainfall/convection pattern. In Myanmar, the 30–60-day variance of rainfall fluctuation dominates in most of the coastal region during summer, whereas the 10–20-day ISO has larger variance in the inland region (Yokoi *et al*., 2007; Yokoi and Satomura, 2008). Compared with these results, Bangladesh is probably one of the most dominant regions of the submonthly scale ISO of rainfall in the South/Southeast Asian monsoon region. This suggestion is confirmed by OLR and low-level zonal wind fields. Figure 10 shows the spatial distributions of filtered OLR and zonal wind ($u$) variances on intraseasonal timescales and the percentage of total variances explained by the filtered variances. A local maximum of OLR variance is observed over the Bay of Bengal in both the 7–25-day and the 30–60-day bands (Figure 10(a) and (b)). Large percentages of the explained variance in both bands are also found in this region. Notably, just over Bangladesh, a local maximum of the 7–25-day explained variance ($\geq$45%) and a local minimum ($\leq$6%) of the 30–60-day explained variance are shown. In the variance of 925-hPa zonal wind, a zonally oriented maximum of the 7–25-day filtered $u$ variance extends from northern India to western Bangladesh, south of the Himalayas, where the explained variance exceeds 45% (Figure 10(c)). The 30–60-day explained variance of 925-hPa $u$ is relatively larger to the south of 20 °N compared with the 7–25-day variance. The spatially localised feature of the large percentage variance of 7–25-day filtered OLR may be related to geographic features of Bangladesh, as shown in Figure 1. The common signals spread into northeastern India close to Bangladesh. Thus, these results strongly support that the activity of submonthly scale ISO modulates the mean seasonal rainfall and circulation pattern only in the area over and near Bangladesh.

The southeasternmost portion of the monsoon trough is situated over Bangladesh in the active phase of the ISO, and hence southwesterly moisture flow dominates over Bangladesh (Figure 5(a)). When the southwesterly flow reaches high-elevation regions such as the Shillong Plateau and Chittagong Hill Tracts, orographical lifting induces rainfall on the windward slopes of these geographic features. Moreover, the westerly/southwesterly flow stagnates in windward areas such as Bangladesh and northeastern India, forming a remarkable convergence field. Thus, the orographical barrier effect of large-scale high-elevation regions to the north and east of Bangladesh also seems to spread to windward areas. Additionally, the southeastern part of the monsoon trough is accompanied by a local maximum of cyclonic vorticity over Bangladesh. The strong meridional cyclonic shear and abundant moisture could create a favourable environment for inducing precipitation system formation over all of Bangladesh. Although we did not examine what process enlarges the amplitude of ISO-related active peaks in this study, this issue is important for understanding the process of IAV in seasonal mean rainfall over Bangladesh. This process likely depends on which precipitation system dominates in the active phase of the ISOs. Ohsawa *et al.* (2001) pointed out that, in the active phase of the submonthly scale ISO in 1995, convective activity over Bangladesh presented clear diurnal variation with its peak during late night–early morning hours, providing rainfall over the whole of Bangladesh. Using a non-hydrostatic 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 that were triggered near the southern foot of the Shillong Plateau and moved southward. Rafiuddin *et al.* (2010) reported detailed statistics of summer monsoon precipitation systems over Bangladesh using 6-year radar data. They classified the precipitation systems into three types according to shape: line type, arc type, and scattered type. Interestingly, the scattered-type systems, composed of groups of poorly organised small individual systems, dominated over Bangladesh during the summer monsoon season. About half of the systems were of the scattered type with wide areal coverage [referred to as SWAC in Rafiuddin *et al.*'s (2010) study]. In a SWAC, small echoes grew and disappeared continuously. Almost all SWACs developed during the monsoon period and contributed greatly to monsoon rainfall in this region, suggesting again that synoptic-scale disturbances such as a monsoon low are not common rain-producing systems over Bangladesh. The mesoscale disturbances may be contained within the intraseasonal envelope of convection in Bangladesh.

In addition to the features of mesoscale precipitation systems in active ISO phases, we should also examine the dynamical relationship between the submonthly scale ISO and the 30–60-day ISO, and how external forcings (i.e. ENSO and Indian Ocean dipole mode) can affect precipitation systems and ISOs over Bangladesh. We also need to investigate why the submonthly scale ISO exhibits such a strong signal over Bangladesh.

## 6. Summary

The ISO of rainfall during the summer monsoon season (June–August) and its possible effect on the IAV of total summer monsoon rainfall over Bangladesh were examined using daily rainfall data from 25 rain-gauge stations for 20 years (1981–2000). The space–time structures of atmospheric circulation and large-scale convection fields related to the ISO and the IAV of the ABDR were also investigated using Japanese 25-year reanalysis (JRA25) and interpolated OLR data. The analysis using multi-year rain-gauge data from a dense observation network revealed robust and characteristic features of the ISO climatology in Bangladesh. Results are summarised as follows:

1. An ISO of 7–25 days (submonthly scale) appears in the ABDR time series in almost all of the 20 years (1981–2000). The variance shows a large IAV. In contrast, the activity of 30–60-day ISO is weak and spectral peaks occasionally appear in this period range. The 7–25-day filtered ABDR variance is always very large compared with the 30–60-day variance. Thus, submonthly scale ISO can be regarded as a dominant intraseasonal mode of rainfall fluctuation over Bangladesh during the summer monsoon season.
2. The IAV of the intraseasonal rainfall variances shows significant correlation with the IAV of total summer monsoon rainfall, suggesting that the ISO activity could modulate total summer monsoon rainfall. In wet monsoon years, the ISO activities on both intraseasonal periods tend to become enhanced simultaneously. The activity of high-frequency variation (3–6-day) has little relationship to the IAV of the intraseasonal variance and total summer monsoon rainfall.
3. Submonthly timescale ISO in ABDR is closely associated with the north–south shift of the monsoon trough. In the peak active (break) phase of the 7–25-day ISO over Bangladesh, total atmospheric circulation fields show the monsoon trough to be located from northern India to Bangladesh (from northwestern India to the northern part of the Bay of Bengal) in the low-level troposphere, enhancing westerly/southwesterly (southerly/southeasterly) moisture flow and increasing (decreasing) its convergence over Bangladesh. Hence, the active (suppressed) convection centre is observed over Bangladesh and the head of the Bay of Bengal.
4. The time evolution of atmospheric circulation and convention anomalies associated with submonthly scale ABDR ISO reveals that the changes in atmospheric circulation over the Bay of Bengal are associated with the so-called synoptic-scale 10–20-day ISO that originates around the western Pacific and then moves westward to India. Over and near Bangladesh, the active convection anomaly shows sudden enhancement when the westward moving anticyclonic circulation anomaly appears over the eastern Bay of Bengal around 15 °N and southwesterly moisture inflow begins to be enhanced over Bangladesh. Then, convection/precipitation is further enhanced and the cyclonic circulation anomaly deepens over Bangladesh. In the peak active phase, active convection anomalies appear over northeastern India, all of Bangladesh, and western Myanmar, whereas suppressed convection anomalies occur over the southern Bay of Bengal, accompanied by a cyclonic anomaly from northeastern India to northwestern Myanmar, centred on northern Bangladesh, and an anticyclonic circulation anomaly over the central Bay of Bengal. Note that despite

the continuous westward migration of convection and circulation anomalies over the Bay of Bengal, the convection anomalies and cyclonic anomalies over Bangladesh remain in almost the same location from the initiation to termination of the active ISO phase.

5. The spatial pattern of atmospheric circulation and convection related to the IAV of total summer ABDR is characterised by a cyclonic anomaly from northern India to Bangladesh and an anticyclonic anomaly centred on the Bay of Bengal, accompanied by an active convection anomaly from northeastern India to all of Bangladesh. Westerly/southwesterly moisture flux anomalies are evident under such circulation fields. Note that the spatial pattern is quite similar to that of submonthly scale ISO over and near Bangladesh. Also, interestingly, no or weak correlations were found with the IAV of some climate indices such as all India monsoon rainfall, a large-scale monsoon index, Niño-3 SST, and the Indian Ocean DMI.
6. The similarity of the spatial patterns of the IAV and ISO indicates that the occurrence of the strong active ISO condition results in a wet monsoon year over Bangladesh. A higher occurrence frequency of strong submonthly scale ISOs and larger number of rainy days related to the active ISO phase are evident in wet monsoon years compared with dry monsoon years. In addition, Bangladesh is characterised by a local maximum of 7–25-day explained variance (i.e. the percentage of total variance explained by the filtered variance) and a local minimum of 30–60-day explained variance in the South/Southeast Asian monsoon region. The characteristic features of ISOs over Bangladesh likely allow the submonthly scale ISO to modify the seasonal mean rainfall and spatial pattern of circulation and convection over and near Bangladesh.

In the Asian monsoon region, ISOs are important phenomena in the regional water cycle. To the north of Bangladesh, convective activity also exhibits remarkable submonthly scale ISO over the Tibetan Plateau and its leeward areas (e.g. Fujinami and Yasunari, 2004, 2009). Mid-latitude waves such as Rossby waves regulate southerly moisture inflow to the Tibetan Plateau area, and hence, a remarkable ISO appears. Interestingly, statistically significant moisture flux anomalies related to the ISO of rainfall over Bangladesh can also be found over the Tibetan Plateau (Figures 6 and 7). How these ISOs interact between the mid-latitudes and subtropics, and how ISOs regulate the water cycle of the Himalayas and Tibetan Plateau are also important problems for future research.

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## References

Ahmed ASMS, Munim AA, Begum QN, Choudhury AM. 1996. El-Nino Southern Oscillation and rainfall variation over Bangladesh. *Mausam* **47**: 157–162.

Annamalai H, Slingo JM. 2001. Active/break cycles: diagnosis of the intraseasonal variability of the Asian summer monsoon. *Climate Dynamics* **18**: 85–102.

Ashok K, Guan Z, Yamagata T. 2001. Impact of the Indian Ocean Dipole on the relationship between the Indian monsoon rainfall and ENSO. *Geophysical Research Letters* **28**: 4499–4502.

Ashok K, Guan Z, Saji NH, Yamagata T. 2004. Individual and combined influences of ENSO and the Indian Ocean Dipole on the Indian summer monsoon. *Journal of Climate* **17**: 3141–3155.

Cash BA, Rodo X, Kinter JL, Fennessy MJ, Doty B. 2008. Differing estimates of observed Bangladesh summer rainfall. *Journal of Hydrometeorology* **9**: 1106–1114, DOI: 10.1175/2008jhm928.1.

Chatterjee P, Goswami BN. 2004. Structure, genesis and scale selection of the tropical quasi-biweekly mode. *Quarterly Journal of the Royal Meteorological Society* **130**: 1171–1194, DOI: 10.1256/Qj.03.133.

Chen TC, Chen JM. 1993. The 10-20-day mode of the 1979 Indian monsoon – Its relation with the time-variation of monsoon rainfall. *Monthly Weather Review* **121**: 2465–2482.

Chowdhury MR. 2003. The El Nino-Southern Oscillation (ENSO) and seasonal flooding – Bangladesh. *Theoretical and Applied Climatology* **76**: 105–124.

Duchon CE. 1979. Lanczos filtering in one and two dimensions. *Journal of Applied Meteorology* **18**: 1016–1022.

Fujinami H, Yasunari T. 2004. Submonthly variability of convection and circulation over and around the Tibetan Plateau during the boreal summer. *Journal of the Meteorological Society of Japan* **82**: 1545–1564, DOI:10.2151/jmsj.82.1545.

Fujinami H, Yasunari T. 2009. The effects of midlatitude waves over and around the Tibetan Plateau on submonthly variability of the East Asian summer monsoon. *Monthly Weather Review* **137**: 2286–2304, DOI: 10.1175/2009MWR2826.1.

Fukutomi Y, Yasunari T. 2002. Tropical-extratropical interaction associated with the 10–25-day oscillation over the western Pacific during the Northern summer. *Journal of the Meteorological Society of Japan* **80**: 311–331.

Fukutomi Y, Yasunari T. 2005. Southerly surges on submonthly time scales over the eastern Indian Ocean during the southern hemisphere winter. *Monthly Weather Review* **133**: 1637–1654.

Goswami BN, Mohan RSA. 2001. Intraseasonal oscillations and interannual variability of the Indian summer monsoon. *Journal of Climate* **14**: 1180–1198.

Goswami BN, Krishnamurthy V, Annamalai H. 1999. A broad-scale circulation index for the interannual variability of the Indian summer monsoon. *Quarterly Journal of the Royal Meteorological Society* **125**: 611–633.

Goswami BN, Ajayamohan RS, Xavier PK, Sengupta D. 2003. Clustering of synoptic activity by Indian summer monsoon intraseasonal oscillations. *Geophysical Research Letters* **30**: 1431, DOI: 10.1029/2002GL016734.

Hartmann DL, Michelsen ML. 1989. Intraseasonal periodicities in Indian rainfall. *Journal of the Atmospheric Sciences* **46**: 2838–2862.

Hoyos CD, Webster PJ. 2007. The role of intraseasonal variability in the nature of Asian monsoon precipitation. *Journal of Climate* **20**: 4402–4424, DOI: 10.1175/JCLI4252.1.

Islam MN, Terao T, Uyeda H, Hayashi T, Kikuchi K. 2005. Spatial and temporal variations of precipitation in and around Bangladesh. *Journal of the Meteorological Society of Japan* **83**: 21–39.

Islam MN, Uyeda H. 2007. Use of TRMM in determining the climatic characteristics of rainfall over Bangladesh. *Remote Sensing of Environment* **108**: 264–276, DOI: 10.1016/j.rse.2006.11.011.

Kataoka A, Satomura T. 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.

Kawamura R. 1998. A possible mechanism of the Asian summer monsoon-ENSO coupling. *Journal of the Meteorological Society of Japan* **76**: 1009–1027.

Kawamura R, Uemura K, Suppiah R. 2005. On the recent change of the Indian summer monsoon-ENSO relationship. *SOLA* **1**: 201–204, DOI: 10.2151/sola.2005-052.

Kripalani RH, Inamdar S, Sontakke A. 1996. Rainfall variability over Bangladesh and Nepal: Comparison and connections with features over India. *International Journal of Climatology* **16**: 689–703.

Krishnamurthy V, Shukla J. 2000. Intraseasonal and interannual variability of rainfall over India. *Journal of Climate* **13**: 4366–4377.

Krishnamurti TN, Ardanuy P. 1980. 10 to 20-day westward propagating mode and breaks in the monsoons. *Tellus* **32**: 15–26.

Liebmann B, Smith CA. 1996. Description of a complete (interpolated) outgoing longwave radiation dataset. *Bulletin of the American Meteorological Society* **77**: 1275–1277.

Madden RA, Julian PR. 1972. Description of global-scale circulation cells in the tropics with a 40–50 day period. *Journal of the Atmospheric Sciences* **29**: 1109–1123.

Madden RA, Julian PR. 1994. Observations of the 40- to 50-day tropical oscillation – A review. *Monthly Weather Review* **122**: 814–837.

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

Ohsawa T, Hayashi T, Mitsuta Y, Matsumoto J. 2000. Intraseasonal variation of monsoon activities associated with the rainfall over Bangladesh during the 1995 summer monsoon season. *Journal of Geophysical Research–Atmospheres* **105**: 29445–29459.

Ohsawa T, Ueda H, Hayashi T, Watanabe A, Matsumoto J. 2001. Diurnal variations of connective activity and rainfall in tropical Asia. *Journal of the Meteorological Society of Japan* **79**: 333–352.

Onogi K, Tsutsui J, Koide H, Sakamoto M, Kobayashi S, Hatsushika H, Matsumoto T, Yamazaki N, Kamahori H, Takahashi K, Kadokura S, Wada K, Kato K, Oyama R, Ose T, Mannoji N, Taira R. 2007. The JRA-25 reanalysis. *Journal of the Meteorological Society of Japan* **85**: 369–432.

Rafiuddin M, Uyeda H, Islam MN. 2010. Characteristics of monsoon precipitation systems in and around Bangladesh. *International Journal of Climatology*. (in press), DOI: 10.1002/joc.1949.

Saji NH, Goswami BN, Vinayachandran PN, Yamagata T. 1999. A dipole mode in the tropical Indian Ocean. *Nature* **401**: 360–363.

Terao T, Islam MN, Hayashi T, Oka T. 2006. Nocturnal jet and its effects on early morning rainfall peak over northeastern Bangladesh during the summer monsoon season. *Geophysical Research Letters* **33**: L18806, DOI: 10.1029/2006gl026156.

Terao T, Islam MN, Murata F, Hayashi T. 2008. High temporal and spatial resolution observations of meso-scale features of pre- and mature summer monsoon cloud systems over Bangladesh. *Natural Hazards* **44**: 341–351, DOI: 10.1007/s11069-007-9128-z.

Vincent DG, Fink A, Schrage JM, Speth P. 1998. High- and low-frequency intraseasonal variance of OLR on annual and ENSO timescales. *Journal of Climate* **11**: 968–986.

Wang B, Webster PJ, Kikuchi K, Yasunari T, Qi YJ. 2006. Boreal summer quasi-monthly oscillation in the global tropics. *Climate Dynamics* **27**: 661–675, DOI 10.1007/s00382-006-0163-3.

Webster PJ, Yang S. 1992. Monsoon and ENSO – Selectively interactive systems. *Quarterly Journal of the Royal Meteorological Society* **118**: 877–926.

Yasunari T. 1979. Cloudiness fluctuations associated with the northern hemisphere summer monsoon. *Journal of the Meteorological Society of Japan* **57**: 227–242.

Yokoi S, Satomura T. 2008. Geographical distribution of variance of intraseasonal variations in western Indochina as revealed from radar reflectivity data. *Journal of Climate* **21**: 5154–5161, DOI: 10.1175/2008jcli2153.1.

Yokoi S, Satomura T, Matsumoto J. 2007. Climatological characteristics of the intraseasonal variation of precipitation over the Indochina Peninsula. *Journal of Climate* **20**: 5301–5315, DOI: 10.1175/2007jcli1357.1.