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CLIMATOLOGICAL CHARACTERISTICS OF MONSOON SEASONAL TRANSITIONS OVER BANGLADESH

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Abstract Climatological characteristics of monsoon seasonal transitions in Bangladesh, focusing on onset and withdrawal phases, were examined using pentad and 20-day mean wind, moisture flux, and precipitable water distributions obtained from Japanese 25-year re-analysis data from 1979 to 2003 and rainfall data from the Bangladesh Meteorological Department (BMD) from 1948 to 2008. Analysis of the pentad and 20-day mean horizontal wind at 850 hPa, the total column water vapor flux, and the precipitable water distribution around Bangladesh showed that the onset and withdrawal of the summer monsoon season in Bangladesh occurred between pentad 31 (May 31–June 4) and pentad 32 (June 5–9), and between pentad 56 (October 3–7) and pentad 57 (October 8–12), respectively. Changes in wind at 850 hPa, total column water vapor flux, precipitable water, and rainfall distribution associated with monsoon onset and withdrawal phases are described by consecutive 20-day mean maps. The annual cycle of 5-day mean rainfall is also presented for each BMD station. High rainfall occurred in the northeast region (Sylhet) during the pre-monsoon season and in the southeast region (Teknaf) during the monsoon season. The central west region (Ishurdi) received relatively less rainfall in all seasons. In the post-monsoon season, rainfall amounts did not differ much among the stations.

Key words: South Asian monsoon, pre-monsoon, monsoon onset, monsoon withdrawal, post-monsoon

1. Introduction

The term “monsoon” refers to the seasonal reversal of wind direction between winter and summer. Among monsoon phenomena worldwide, one of the most fascinating is the South Asian summer monsoon, which causes a number of interesting changes in atmospheric circulation when it occurs over the Indian subcontinent (e.g., Matsumoto 1992).

Bangladesh has flat topography, and a large part of the country is occupied by one of the largest deltas in the world, the Ganges-Brahmaputra-Meghna river delta. The elevation is generally less than 10 m above sea level. Only in the southeast, which borders Myanmar, does the elevation exceed 200 m. In the northeast, the southern slope of the Meghalaya Plateau, the rainiest place in the world (Murata *et al.* 2007), is located approximately 10 km from the border of northeastern Bangladesh.

Bangladesh is situated in the tropical monsoon region and receives relatively abundant rainfall. The Bangladesh Meteorological Department (BMD) divides the seasons in Bangladesh into pre-monsoon (March–May), monsoon (June–September), post-monsoon (October–November), and winter (December–February). The onset of the Asian summer monsoon is a key indicator characterizing the abrupt transition from dry season to rainy season and the subsequent seasonal march (Ding and Sikka 2006). Various methods to determine the onset and withdrawal dates of the Asian summer monsoon have been proposed, including by Das (1968, 1987), Mooley and Shukla (1987), Ananthakrishnan and Soman (1988), Ahmed and Karmakar (1993), Murakami and Matsumoto (1994), Matsumoto (1997), Pant and Rupa Kumar (1997), Wang and LinHo (2002), Zhang *et al*. (2002), Webster (2006), and Htway and Matsumoto (2010).

The monsoon onset date is crucial for a tropical monsoon country such as Bangladesh. Rainfall amounts during the pre- to post-monsoon periods seriously affect agriculture, and the impacts of the summer monsoon have pronounced economic effects in the Indian Peninsula (Gadgil and Rupa Kumar 2006). Hence, accurate prediction of the dates of monsoon onset and retreat would help farmers select the most suitable crops and planting dates (Das 1987).

Ahmed and Karmakar (1993) analyzed the mean onset and withdrawal dates of the summer monsoon over Bangladesh. Their statistical analysis determined that the monsoon first arrived in southeastern Bangladesh on June 2 and then moved northwards, reaching the northwest region on June 15. Conversely, the withdrawal of the summer monsoon started earlier in northwestern Bangladesh on September 30 and finished in southeastern Bangladesh on October 17. Matsumoto (1997) determined the mean onset and withdrawal of the summer rainy season over the Indochina Peninsula and adjacent regions including Bangladesh using pentad mean rainfall data and presented seasonal circulation changes related to the rainy season onset and withdrawal. The earliest onset of the summer rainy season was found in early April in the Assam region over northeast India.

However, descriptions of monsoon seasonal transitions in Bangladesh are still insufficient. To address this issue, this study first describes circulation changes associated with the onset and withdrawal of the summer monsoon in Bangladesh by examining the pentad and 20-day mean horizontal wind at 850 hPa, total column water vapor flux, and precipitable water distribution around Bangladesh. Then, the climatological annual cycle of pentad mean rainfall at each station and regional differences in each season are described.

2. Data and Methods

The space-time structure of the atmospheric circulation field was investigated using Japanese 25-year re-analysis (JRA-25) data with a spatial resolution of 1.25° by 1.25° (latitude-longitude grid) and a time interval of 6 hours (Onogi *et al*. 2007). These data were provided by the Japan Meteorological Agency and the Central Research Institute of Electric Power Industry (http//jra.kishou.go.jp/). This study used climatological pentad mean data of horizontal wind at 850 hPa, precipitable water, and total column water vapor flux over a 25-year period from 1979 to 2003.

Daily rainfall data at 35 stations in Bangladesh were provided by the BMD (Table 1 and Fig. 1). The data period depended on the station. The station network in Bangladesh has developed gradually. The longest records were for 61 years from 1948 to 2008 at 10 stations, and the shortest records were

Table 1 List of 35 BMD stations

Station	Latitude (N)	Longitude (E)	Elevation (m)	Data period used in this study	Mean annual precipitation (mm)
Barisal	23°43’	90°22’	2.10	1949-2008	2111.6
Bhola	22°41’	90°39’	4.30	1966-2008	2265.0
Bogra	24°51’	89°22’	17.90	1948-2008	1719.7
Chandpur	23°14’	90°42’	4.88	1964-2008	2018.0
Chittagong (City)	22°21’	91°49’	33.20	1999-2008	2951.6
Chittagong (AP)	22°13’	91°48’	5.50	1949-2008	2856.5
Chuadanga	23°39’	88°49’	11.58	1989-2008	1524.1
Comilla	23°26’	91°11’	7.50	1948-2008	2257.7
Cox’s Bazar	21°27’	91°58’	2.10	1948-2008	3612.8
Dhaka	23°47’	90°23’	8.45	1953-2008	2062.8
Dinajpur	25°39’	88°41’	37.58	1948-2008	1851.1
Faridpur	23°36’	89°51’	8.10	1948-2008	1883.2
Feni	23°02’	91°25’	6.40	1973-2008	2967.9
Hatiya	22°27’	91°60’	2.44	1966-2008	3128.3
Ishurdi	24°09’	89°20’	12.90	1961-2008	1457.3
Jessore	23°12’	89°20’	6.10	1948-2008	1610.4
Khepupara	21°59’	90°14’	1.83	1974-2008	2775.4
Khulna	22°47’	89°32’	2.10	1948-2008	1725.2
Kutubdia	21°49’	91°51’	2.74	1977-2008	2769.9
Madaripur	23°10’	90°11’	7.00	1977-2008	2030.5
Maijdee Court	22°52’	91°60’	4.87	1951-2008	2988.8
Mongla	22°28’	89°36’	1.80	1991-2008	1948.6
Mymensingh	24°44’	90°25’	18.00	1948-2008	1741.3
Patuakhali	22°20’	90°20’	1.50	1973-2008	2684.7
Rajshahi	24°22’	88°42’	19.50	1964-2008	1555.2
Rangpur	25°44’	89°16’	32.61	1958-2008	2075.1
Rangamati	22°38’	92°09’	68.89	1957-2008	2402.8
Sandwip	22°29’	91°26’	2.10	1966-2008	3507.5
Satkhira	22°43’	89°05’	3.96	1948-2008	1683.7
Sitakunda	22°38’	91°42’	7.30	1977-2008	2984.4
Srimangal	24°18’	91°44’	21.95	1948-2008	2206.3
Syedpur	25°45’	88°55’	39.60	1991-2008	2217.9
Sylhet	24°54’	91°53’	33.53	1956-2008	3963.0
Tangail	24°15’	89°56’	10.20	1987-2008	1898.7
Teknaf	20°52’	92°18’	5.00	1977-2008	3884.5

for 10 years from 1999 to 2008 at one station (Table 1). The climatological pentad mean amounts of rainfall were calculated from the daily data. When missing data in a particular pentad exceeded 2 days, the data for that pentad were excluded from the calculation of the mean data. The 20-day mean data were calculated from the pentad data.

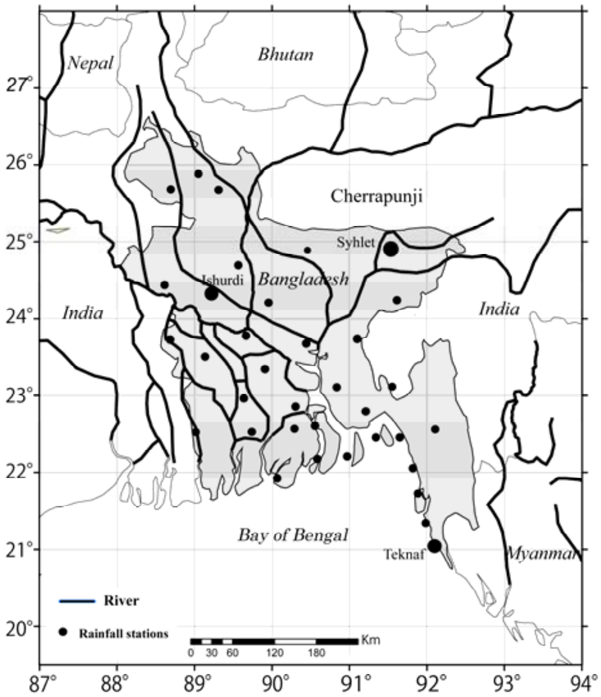

Fig. 1 Geographic location of Bangladesh and the 35 observation stations. Dots denote locations of the 35 BMD rain gauge stations. Larger dots mark stations specifically noted in Fig. 4 with related descriptions.

3. Results

Seasonal transitions in atmospheric circulation associated with summer monsoon onset and withdrawal in Bangladesh

Inspection of all pentad mean wind at 850 hPa and total column water vapor flux maps revealed that the first systematic intrusion of southerly wind and vapor flux from the Bay of Bengal (BoB) into the inland region of Bangladesh occurred at pentad 32 (June 5–9: hereafter abbreviated as P32) (not shown). Therefore, we considered that monsoon onset in Bangladesh occurred between P31 and P32. Southerly wind and vapor flux intruded from the BoB to Bangladesh almost continuously during the monsoon season until P56 (October 8–12) and then suddenly weakened in P57 (not shown). These results suggest that monsoon withdrawal from Bangladesh occurred between P56 and P57. Although determined in a somewhat subjective manner, both dates agree closely with the monsoon onset and withdrawal dates in central Bangladesh estimated by Ahmed and Karmakar (1993) based on surface wind and rainfall observations. To avoid the influence of short time-scale disturbances, we present consecutive 20-day mean maps prior to and after the monsoon onset and withdrawal, respectively.

Figure 2 shows the 20-day mean wind at 850 hPa, total column water vapor flux, and precipitable water during the monsoon onset. Before the monsoon onset, the wind at 850 hPa (Fig. 2a, top) and middle and total column water vapor flux (Fig. 2a, middle) around Bangladesh were both directed east from the northern part of the Indian subcontinent. The core of the strong westerly wind at 850 hPa was located south of 15°N and east of 90°E over the BoB and blew east to east-southeastward (Fig. 2a, top). Both the total column water vapor flux and the precipitable water amount were smaller over the (a)Pre-monsoon (b) Monsoon I

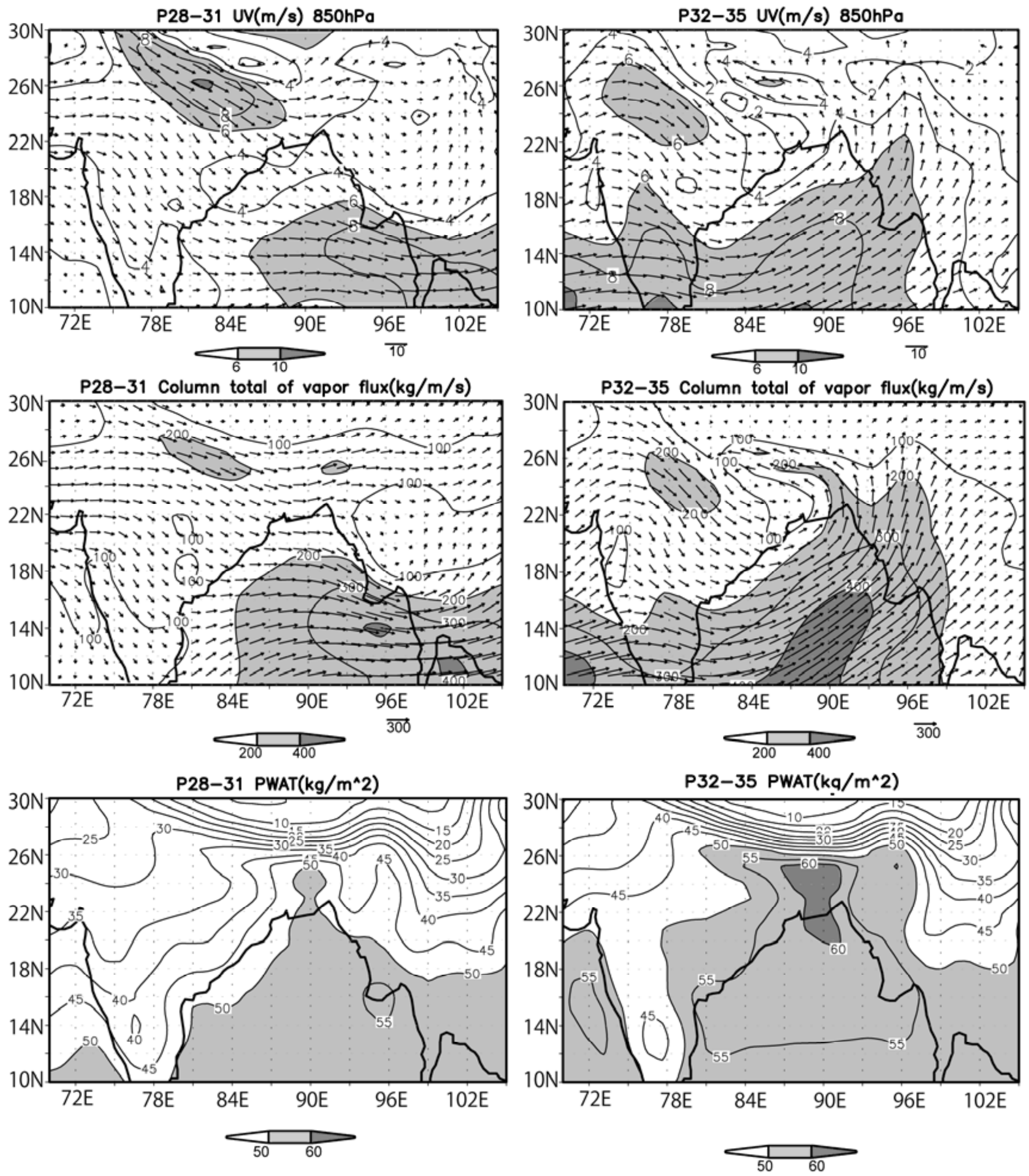

Fig. 2 Twenty-day mean distribution of horizontal wind at 850 hPa (top), water vapor flux (middle), and precipitable water (bottom) in the pre-monsoon (a) and monsoon I (b) periods. Top: contour interval is 2 ms $^{-1}$. Light and dark shading indicate winds stronger than 6 and 10 ms $^{-1}$, respectively. Middle: contour interval is 100 kg m $^{-1}$ S $^{-1}$. Light and dark shading indicate values higher than 200 and 400 kg m $^{-1}$ S $^{-1}$, respectively. Bottom: contour interval is 5 kg m $^{-2}$. Light and dark shading indicate values higher than 50 kg m $^{-2}$ and 60 kg m $^{-2}$, respectively.

(c) Monsoon II (d) Post-monsoon

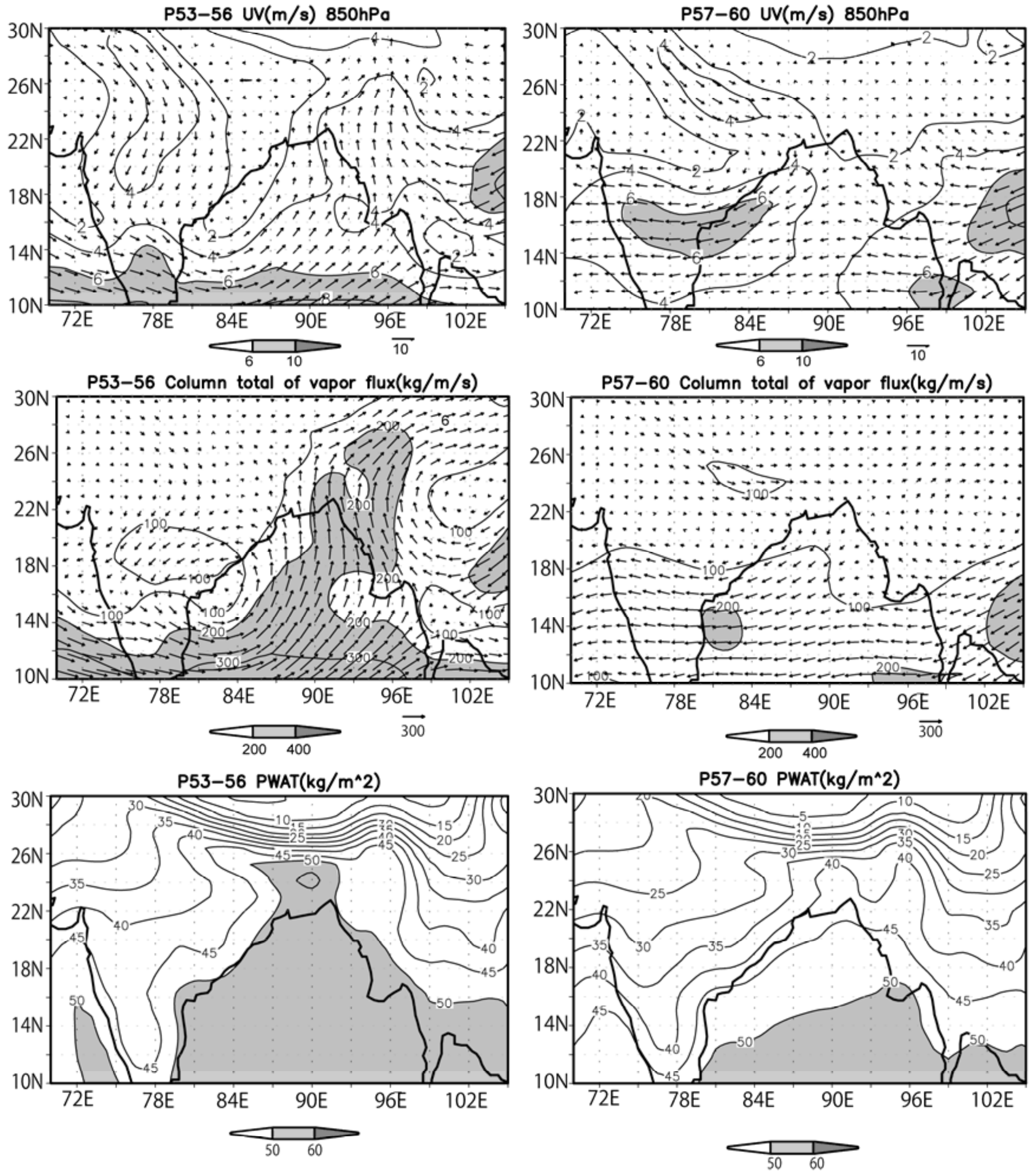

Fig. 2 (continued) For monsoon II (c) and post-monsoon (d) periods.

Arabian Sea than in the BoB (Fig. 2a, top and middle). However, a tongue-shaped region of high precipitable water amount stretched to Bangladesh from the BoB (Fig. 2a, bottom).

After the monsoon onset, the southwesterly flow at 850 hPa (Fig. 2b, top) and northward total column water vapor flux (Fig. 2b, middle) were directed toward the inland region of Bangladesh from the BoB. The core of strong westerly wind over the BoB expanded both northward to the Bangladesh southeastern border region with Myanmar and westward to the Arabian Sea. This indicated that the monsoon circulation was established in the southern part of the northern Indian Ocean (Fig. 2b, top and middle). The highest precipitable water amount (greater than 60 kg m^{-2}) was located over Bangladesh (Fig. 2b, bottom).

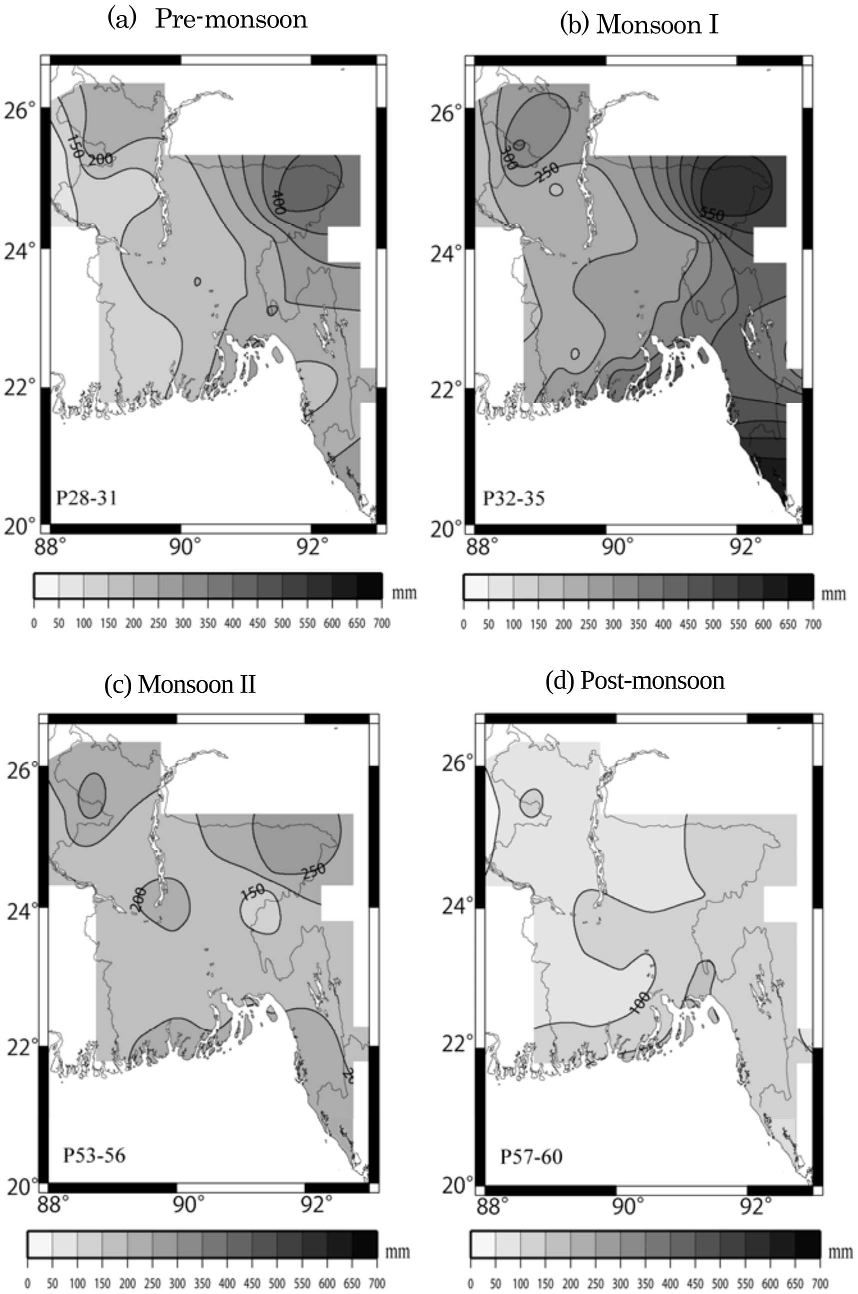

Fig. 3 Spatial distribution of 20-day mean rainfall over Bangladesh. (a) Pre-monsoon, pentads 28–31 , (b) monsoon I, pentads 32–35, (c) monsoon II, pentads 53–56, (d) post-monsoon, pentads 57–60.

The rainfall distribution also showed obvious changes in monsoon onset and withdrawal phases. During the pre-monsoon season (Fig. 3a), the rainfall peak was located in northeastern Bangladesh at Sylhet, while it was located in the southeastern tip of Bangladesh at Teknaf after the monsoon onset (Fig. 3b). In addition, the rainfall amount almost doubled after the monsoon onset (Figs. 3a and 3b).

The southerly 850 hPa wind and northward total column water vapor flux flowed almost continuously from the BoB to Bangladesh during the monsoon season, although they weakened in some pentads in September (e.g. in P52 and P53, not shown). The final systematic intrusions from the BoB to Bangladesh were found at P56. Before P56, both 850 hPa and column total water vapor flux were directed northward (Fig. 2c, top and middle), similar to the situation after monsoon onset (Fig. 2b, top and middle). Interestingly, part of the northward flow over the Indochina Peninsula appeared to originate not from the BoB, but from the South China Sea via the Indochina Peninsula, implying a mutual effect of summer southwesterlies in the Indian Ocean and winter northeasterlies in the Pacific Ocean. The highest precipitable water peak was located over Bangladesh (Fig. 2c, bottom).

After the monsoon withdrawal, both 850 hPa wind and northward total column water vapor flux were weakened around Bangladesh (Fig. 2d, top and middle). Westerly flow vanished not only in and around Bangladesh, but also in almost the whole Indian Ocean and Indian subcontinent region (Fig. 2d). Precipitable water also decreased both in Bangladesh and in the northern BoB, and its peak region shifted to the southern BoB. Rainfall decreased dramatically, particularly in the inland region of Bangladesh after the monsoon withdrawal (Figs. 3c and 3d).

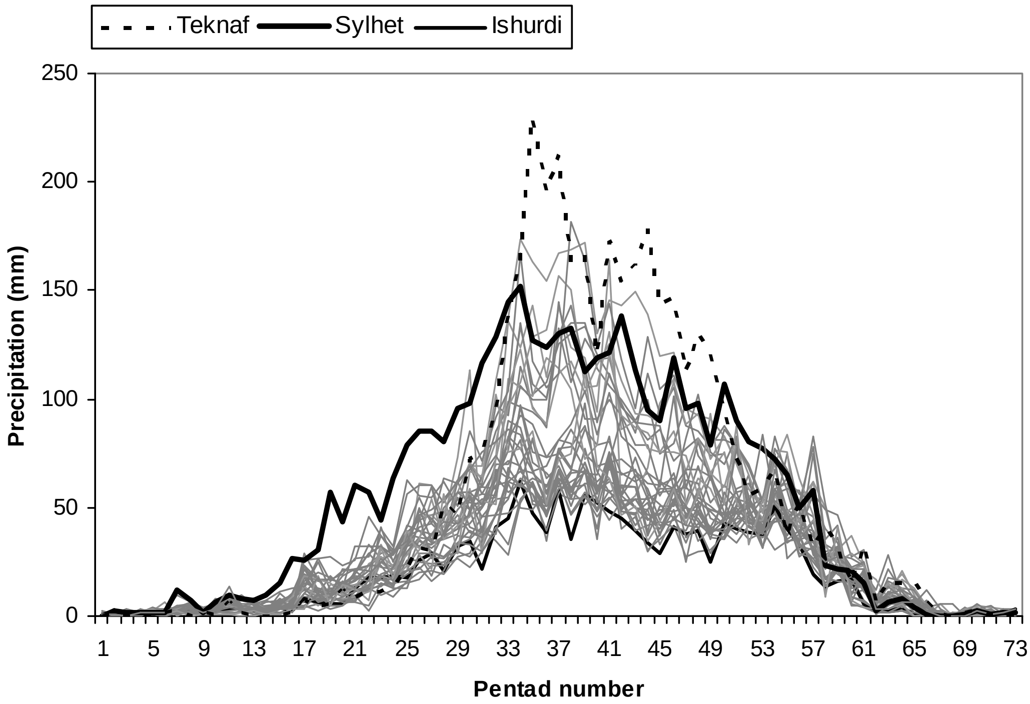

Fig. 4 Annual variations in pentad mean precipitation at 35 BMD rain gauge stations. The thick dotted line, heavy thick line, and medium thick line represent Teknaf, Sylhet, and Ishurdi, respectively. Gray lines are for other stations.

Annual rainfall variations

To highlight the climatological annual variations in rainfall, the pentad mean rainfall at 35 BMD stations is plotted in Fig. 4. Monsoon onset and withdrawal periods are also shown for reference. We mainly focus on the data for three rainfall stations: Teknaf, Sylhet, and Ishurdi, indicated by the thick lines in Fig. 4, because they showed characteristic seasonal rainfall variations.

The mean annual total precipitation at Sylhet was the highest in Bangladesh, followed by that at Teknaf (Table 1). Although both stations were located in heavy rainfall areas in Bangladesh, the former was in the northeast inland region, while the latter was in the southeast coastal region (Fig. 1). The seasonal precipitation changes were apparently different at these two stations. Those at Sylhet were characterized by pronounced pre-monsoon rainfall, while those at Teknaf were characterized by outstanding monsoon rainfall with a sharp increase during the monsoon onset phase and relatively low pre-monsoon rainfall, particularly in the earlier phase (Fig. 4). Rainfall variations at Ishurdi in central west Bangladesh are also shown; this station had the lowest annual precipitation (Table 1) in Bangladesh. In all seasons, the precipitation at Isurdi was in the lowest group within Bangladesh (Fig. 4).

Although rainfall sharply increased after the monsoon onset at Teknaf and some other stations, in general, rainfall increased gradually in the pre-monsoon season at most stations in Bangladesh. Sylhet was unique being the only station to show such pronounced pre-monsoon rainfall. Hoque *et al*. (2008, 2010) investigated heavy rainfall and flood-prone areas around northeastern Bangladesh using rain gauge, discharge, and RADARSAT image data. The high pre-monsoon rainfall in Sylhet seemed to be related to the formation of these flood-prone areas.

At most stations, including Sylhet, the rainfall curves show that the rainfall peak in the monsoon season occurred early in the season from P34 to P41. In the latter phase of the monsoon, in particular after P45, the mean rainfall gradually decreased at most of the stations. After the monsoon withdrawal in the post-monsoon season, rainfall gradually decreased, although at some stations such as Sylhet, a small rainfall peak appeared at P57. In the post-monsoon season, the regional differences in rainfall were smaller than those in the pre-monsoon and monsoon seasons.

4. Conclusions

The climatological characteristics of monsoon seasonal transitions in Bangladesh, particularly onset and withdrawal phases, were examined using pentad and 20-day mean wind, moisture flux, and precipitable water distributions obtained from JRA-25 data from 1979 to 2003 and rainfall data from the BMD from 1948 to 2008. Analysis of the pentad and 20-day mean horizontal wind at 850 hPa, total column water vapor flux, and precipitable water distribution around Bangladesh showed that the onset and withdrawal of the summer monsoon season in Bangladesh occurred between pentad 31 (May 31–June 4) and pentad 32 (June 5–9), and between pentad 56 (October 3–7) and pentad 57 (October 8–12), respectively. The main changes in 850 hPa wind, total column water vapor flux, precipitable water, and rainfall distribution associated with the monsoon onset and withdrawal phases were described by consecutive 20-day mean maps.

The annual cycle of 5-day mean rainfall at each BMD station was also presented. Large amounts of rainfall fell in the northeast region (Sylhet) in the pre-monsoon season and in the southeast region (Teknaf) during the monsoon season. Relatively less rainfall occurred in the central west region

(Ishurdi) in the monsoon season. In the post-monsoon season, rainfall amounts did not differ much among the stations.

This study presented mean conditions. Further study is needed to reveal the interannual variations and long-term changes in monsoon seasonal transitions in Bangladesh.

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