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ORIGINAL ARTICLE

Spatiotemporal Variations of Precipitation in Bangladesh Revealed by Nationwide Rain Gauge Data

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Abstract

Bangladesh is under the strong influence of the South Asian monsoon. Extensive damages caused by frequent severe flood events in this country call for a study of nationwide precipitation climatology. Here, we examine spatiotemporal variations of precipitation in Bangladesh using rain gauge data at 35 stations for the period 2003–2016. The annual precipitation amount in Bangladesh is 2263 mm, and it shows large spatial variations. The annual precipitation amount is large in the southeastern coastal region of the country and the region close to the Meghalaya Plateau, and it is small in the west central region. 17% and 73% of the annual precipitation amount are observed in the pre-monsoon season (March to May) and monsoon season (June to September), respectively. The pattern of the diurnal variation of precipitation differs depending on regions of Bangladesh. In the northern region of the country, the precipitation maximum occurs in the late night to early morning in both the pre-monsoon and monsoon seasons. The late night to early morning maximum of precipitation is associated with the large horizontal convergence of low-level water vapor flux. The Himalaya Mountains and the Meghalaya Plateau together with more nighttime moisture transport due to the strengthened nighttime low-level wind seem to play roles in enhancing nighttime precipitation. In the southwestern region of the country, the precipitation maximum is observed in the early evening in the pre-monsoon season, which is associated with the large convective instability in the afternoon, and it is observed in the early afternoon in the monsoon season. In the southeastern region of the country, the diurnal variability of precipitation is smallest in the pre-monsoon season compared with other regions of the country in the pre-monsoon and monsoon seasons and the precipitation maximum occurs in the late night to early morning in the monsoon season.

Keywords Bangladesh · Precipitation · Spatiotemporal variations · Pre-monsoon season · Monsoon season

1 Introduction

Bangladesh is a South Asian deltaic country with three main rivers, the Ganges, the Brahmaputra, and the Meghna, running through it. Its topography is mostly flat except for some portions of northeastern and southeastern regions of the country where the elevation is higher than 100 m above the sea level. Bangladesh is under the strong influence of the South Asian monsoon and experiences frequent severe flood events which cause lots of losses of lives and properties.

Bangladesh is a country with much rains. The Mawsynram region of Meghalaya state in northeast India is one of the rainiest places in the world. The northeastern region of Bangladesh, which is adjacent to the Meghalaya Plateau, and the southeastern coastal region of the country adjacent to the Chittagong Hill Tracts receives considerable amounts of rain. The rainy season in and around Bangladesh can be divided into pre-monsoon season (MAM: March, April, and May), monsoon season (JJAS: June, July, August, and September), and post-monsoon season (ON: October and November) (Islam and Uyeda 2007). Using the rain gauge data from 1998 to 2002, Islam and Uyeda (2007) showed that average daily precipitation rates are 5.30, 15.14, and 4.56 mm/day in the pre-monsoon, monsoon, and post-monsoon seasons, respectively.

Although the precipitation amount is much smaller in the pre-monsoon season than in the monsoon season,

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investigations of pre-monsoon precipitating systems are important because they result in the first precipitation after the end of the dry winter season (December to February) and they are convective (Romatschke and Houze 2011). In the pre-monsoon season, especially in April, the high thermal instability and vertical wind shear are present over Bangladesh (Yamane and Hayashi 2006), which favors the generation of precipitating convective systems. In the northeastern region of Bangladesh, precipitating systems in the pre-monsoon season exhibit an extremely convective nature (Romatschke et al. 2010). In the regions which include the Meghalaya Plateau region, pre-monsoon convection seems to be more sensitive to synoptic forcing than monsoon convection (Romatschke and Houze 2011).

In the monsoon season, on the other hand, strong moist low-level southwesterly winds prevail over the Bay of Bengal, which is related to the thermal contrast between South Asia and the Indian Ocean (Li and Yanai 1996). In Bangladesh, the summer monsoon begins earliest in the extreme southeastern part of the country with a mean start date of 2 June, and it begins latest in the extreme northwestern part of the country with a mean start date of 15 June (Ahmed and Karmakar 1993). The Meghalaya Plateau plays significant roles in producing heavy precipitation in the northeastern region of the country (Sato 2013). It is known that monsoon intraseasonal oscillations modulate precipitating systems in and around Bangladesh (Ohsawa et al. 2000; Goswami and Mohan 2001). An analysis of precipitation in Bangladesh during the 1995 summer monsoon season by Ohsawa et al. (2000) shows that the north-south oscillation of the monsoon trough dominates the precipitation.

The diurnal variation of precipitation is an important ingredient of the water cycle at any location (Ohsawa et al. 2001). Many observational studies have been conducted to examine the diurnal variation of precipitation in India and some part of Bangladesh which shares a border with India (Prasad 1970; Ohsawa et al. 2001; Terao et al. 2006). Prasad (1970) showed that the precipitation maximum at Cherrapunji located in the Meghalaya Plateau occurs in the late night to early morning. He conjectured that the low-level convergence produced by nocturnal katabatic winds may be responsible for the precipitation maximum. Ohsawa et al. (2001) found the late night to early morning precipitation maximum at stations on the windward side of the Meghalaya Plateau. Through a case study using a mesoscale numerical model, Kataoka and Satomura (2005) showed that the Meghalaya Plateau or the dammed deep cold air mass in the concave area northeast of Bangladesh acts to raise air with high equivalent potential temperature to the level of free convection and trigger strong convective systems in the nighttime, thus leading to the late night to early morning precipitation maximum. Using the rain gauge and rawinsonde data in 2000, Terao et al. (2006) showed that the nocturnal low-level jet is one of the causes for the late night to early morning precipitation maximum in the northeastern region of the country through the intensified wind which blows against the southern side of the Meghalaya Plateau.

Many studies of precipitation in Bangladesh and surrounding areas have used satellite data (e.g., Islam and Uyeda 2008). Satellite-estimated precipitation data have fine spatial resolutions but contain some biases and uncertainties (Dai et al. 2007; Islam and Uyeda 2008; Zhou et al. 2008; Yuan et al. 2012). Islam and Uyeda (2008) showed that the Tropical Rainfall Measuring Mission (TRMM) data overestimate the pre-monsoon precipitation and underestimate the monsoon precipitation in Bangladesh. Tarek et al. (2017) showed that in Bangladesh, TRMM data are well matched with rain gauge data for average precipitation values on an annual basis, but the deviation is significant for daily peak precipitation values. A recent study of comparing six satellite-retrieved precipitation products with rain gauge data in Bangladesh (Islam 2018) reveals that the satellite-retrieved precipitation products are good in detecting the precipitation occurrence but not so good in estimating the precipitation amount. It seems that the precipitation in Bangladesh could be better characterized using nationwide rain gauge data rather than satellite data. It is noted that studies of the diurnal variation of precipitation in Bangladesh have been performed focusing on the northeastern region of the country (or focusing on the region of the Meghalaya Plateau and its surrounding) or using short-term data (e.g., Islam et al. 2005). Since the diurnal variation of precipitation can vary depending on regions (Yang and Slingo 2001), diurnal variations in other regions of Bangladesh deserve an investigation with long-term precipitation data. The characteristics of the diurnal variation of precipitation in the monsoon season can be to some extent different from those in the pre-monsoon season. This also deserves an investigation.

Bangladesh is a densely populated country where people mostly depend on agriculture. Moreover, the country is very vulnerable to flooding. A long-term precipitation analysis study using data at 12 stations in Bangladesh (Endo et al. 2015) shows increasing trends in the annual precipitation amount and the number of wet days. Bari et al. (2017) found an increasing trend in precipitation seasonality at some locations of northern Bangladesh. A recent study by Basher et al. (2018) reveals that all the indices of precipitation extremes in northeast Bangladesh are in a decreasing trend in both the pre-monsoon and monsoon seasons, implying that the region might suffer from water stress in the future if the decreasing trend continues. For better weather forecasting, climate change assessment, agricultural planning, water resource management, and so on, it is necessary, as a first step, to document a reliable climatology of precipitation in Bangladesh.

In this study, spatial and temporal variations of precipitation in Bangladesh, particularly focusing on its diurnal variation, are examined using 14-year nationwide rain gauge data and reanalysis data. In section 2, the data used in this study are described. In section 3, the results are presented and discussed. In section 4, summary and conclusions are given.

2 Data

The Bangladesh Meteorological Department (BMD) has 35 meteorological stations which are distributed all over the country (Fig. 1). For this study, the BMD 3-h accumulated precipitation amount data collected from 2003 to 2016 are used. Exceptions are at Cox's Bazar (21.43°N, 91.93°E), Chittagong (22.27°N, 91.82°E), and Hatiya (22.43°N, 91.10°E) stations located in the southeastern coastal region whose data are available from 2004, 2004, and 2008, respectively. The 3-h accumulated precipitation amount data for the 14-year period are used to document and analyze diurnal, monthly, and yearly precipitation climatology in the country.

The ERA5 reanalysis data with 0.25°×0.25° horizontal grid resolution (European Centre for Medium-Range Weather Forecasts 2019) are used to examine large-scale thermodynamic and dynamic characteristics associated with the features of precipitation in Bangladesh. For this, fields of velocity, water vapor flux and its divergence and vertical profiles of equivalent potential temperature are analyzed.

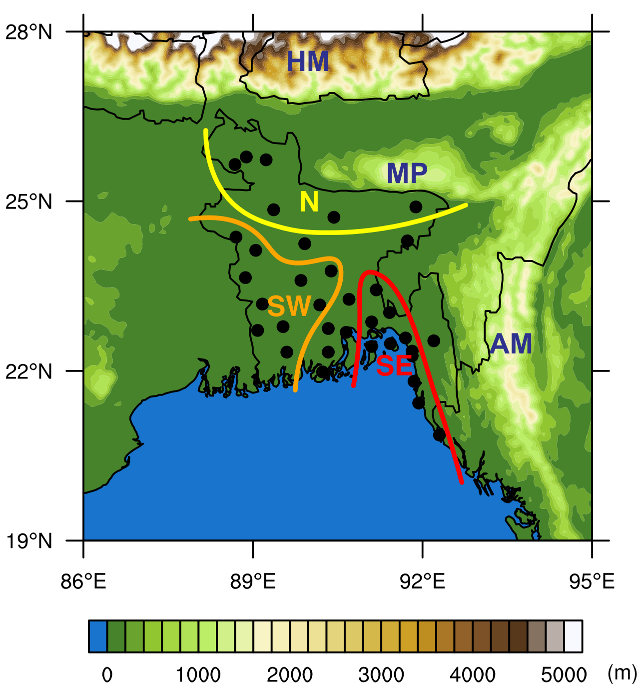

Fig. 1 Terrain height (color shading) and locations of 35 meteorological stations (closed circles). Three regions are indicated: northern (N) region, southwestern (SW) region, and southeastern (SE) region. HM, MP, and AM represent the Himalaya Mountains, the Meghalaya Plateau, and the Arakan Mountains, respectively

3 Results and Discussion

3.1 Yearly and Monthly Variations of Precipitation

The variation of annual precipitation amount from 2003 to 2016 is examined (Fig. 2). The averaged annual precipitation amount in Bangladesh is 2263 mm, with its standard deviation of 341 mm. The deviation of the annual precipitation amount from its average value (2263 mm) varies from 425 mm in 2015 to −840 mm in 2016. The interannual variability with a 3- or 4-year oscillation period is clearly seen from 2003 to 2014. In 2016, the precipitation amount is distinctly smaller compared with the other 13 years.

The Indian Ocean Dipole (IOD) is regarded as a large-scale phenomenon that is partially responsible for the interannual variability of precipitation amount in Bangladesh, especially for the western region (Ahmed et al. 2017). Fujinami et al. (2011), however, suggested that the monsoon precipitation, which occupies a large portion of annual precipitation, is modulated by the submonthly-scale intraseasonal oscillation which belongs to internal variability of monsoon. Causes for the interannual variability shown in Fig. 2 are not clear, but it appears to be associated with large-scale phenomena such as IOD, intraseasonal oscillation of monsoon, and so on. Studies on this issue are needed.

The monthly precipitation amount (Fig. 3) increases with time, peaks in July, and then decreases. July is the rainiest month (488 mm). 17% and 73% of the annual precipitation amount are observed in the pre-monsoon season (MAM) and monsoon season (JJAS), respectively. The precipitation amount in the monsoon season is more than four times larger than that in the pre-monsoon season. The contribution of the post-monsoon season (ON) to the annual precipitation amount is 8.7%. December to February is characterized as a dry season.

The annual precipitation amount is considerably large in the southeastern coastal region of Bangladesh and the region close to the Meghalaya Plateau (Fig. 4a). The rainiest place in

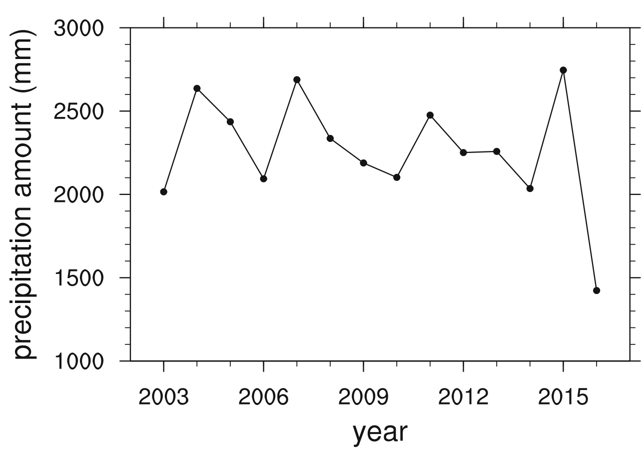

Fig. 2 Temporal variation of annual precipitation amount averaged over Bangladesh

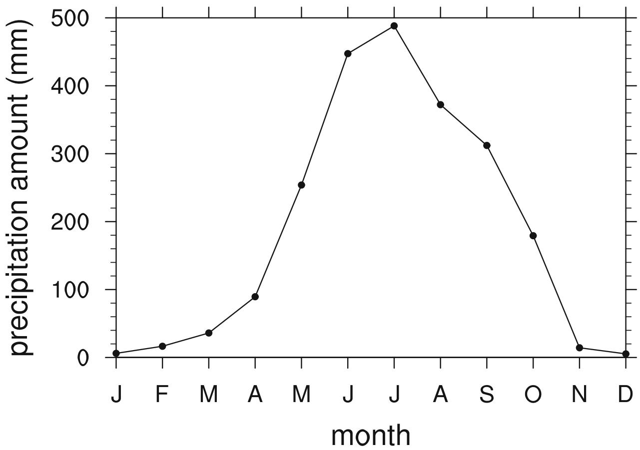

Fig. 3 Monthly precipitation amounts averaged over Bangladesh and the period 2003–2016

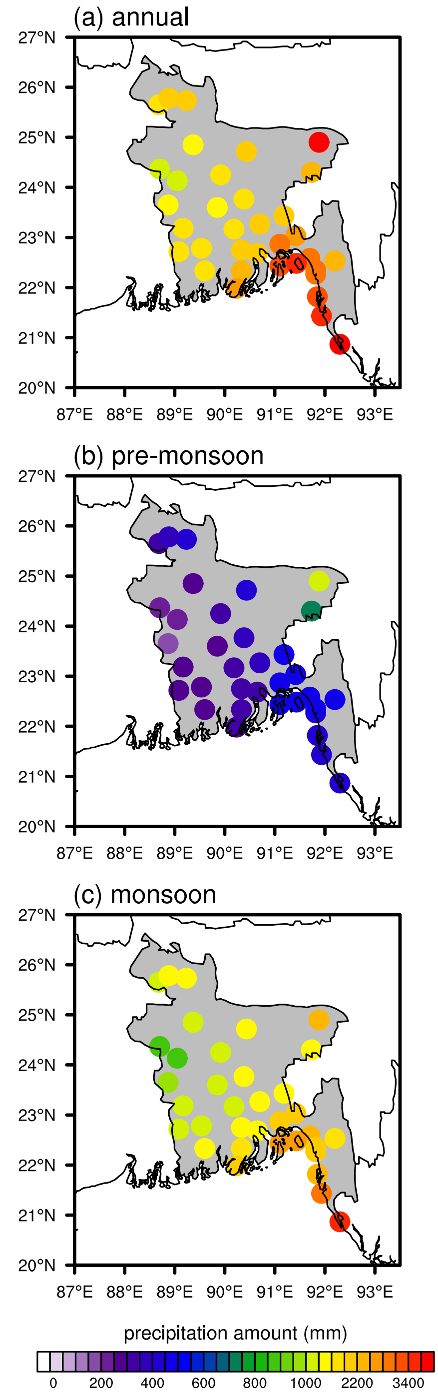

Fig. 4 Spatial distributions of **a** annual, **b** pre-monsoon season, and **c** monsoon season precipitation amounts averaged over the period 2003–2016

Bangladesh is Teknaf (20.87°N, 92.30°E) with an annual precipitation amount of 4261 mm. In the west central region of the country, the annual precipitation amount is smallest. Rajshahi (24.37°N, 88.70°E) has the least annual precipitation amount (1252 mm).

In the pre-monsoon season, the precipitation amount is largest in the northeastern region of the country and it is larger in the southeastern region of the country than in the southwestern region (Fig. 4b). Sylhet (24.90°N, 91.88°E) near the Meghalaya Plateau is the rainiest place in the pre-monsoon season. In the monsoon season, the precipitation amount varies from 896 mm at Ishurdi (24.13°N, 89.05°E) in the west central region of the country to 3539 mm at Teknaf in the southeastern coastal region (Fig. 4c). Relatively large precipitation is observed in the northeastern region near the Meghalaya Plateau.

The water vapor flux $q\boldsymbol{u}$, where q is the water vapor mixing ratio and $\boldsymbol{u}$ is the horizontal velocity, is calculated to examine differences in large-scale flow and moisture between the pre-monsoon and monsoon seasons in association with precipitation amount. The 900-hPa water vapor flux vector and its magnitude in the pre-monsoon and monsoon seasons are presented in Fig. 5a, b. Differences in water vapor flux between the pre-monsoon and monsoon seasons are clearly seen. In the pre-monsoon season, the relatively weak low-level southwesterly wind is prevalent over Bangladesh, and it transports moisture from the Bay of Bengal to inland area (Fig. 5a). In addition, the Arabian Sea serves as another moisture source for precipitation in Bangladesh, although its contribution is smaller than that of the Bay of Bengal (Tanoue et al. 2018). The water vapor flux is large in the northeastern region of the country. This is associated with the large precipitation amount there (Fig. 4b). In the monsoon season, on the other hand, the strong low-level southwesterly wind from the Bay of Bengal enters the southern coast of the country with abundant moisture, indicating that the moisture source for monsoonal precipitation comes mainly from the Bay of Bengal. The southwesterly wind, then, turns to southerly wind, which is attributable to the blocking and deflecting effects of the Arakan Mountains (Wu et al. 2014), and the southerly wind becomes dominant over the country. The water vapor flux is large in the southeastern region of the country, which is associated with the large precipitation amount there (Fig. 4c).

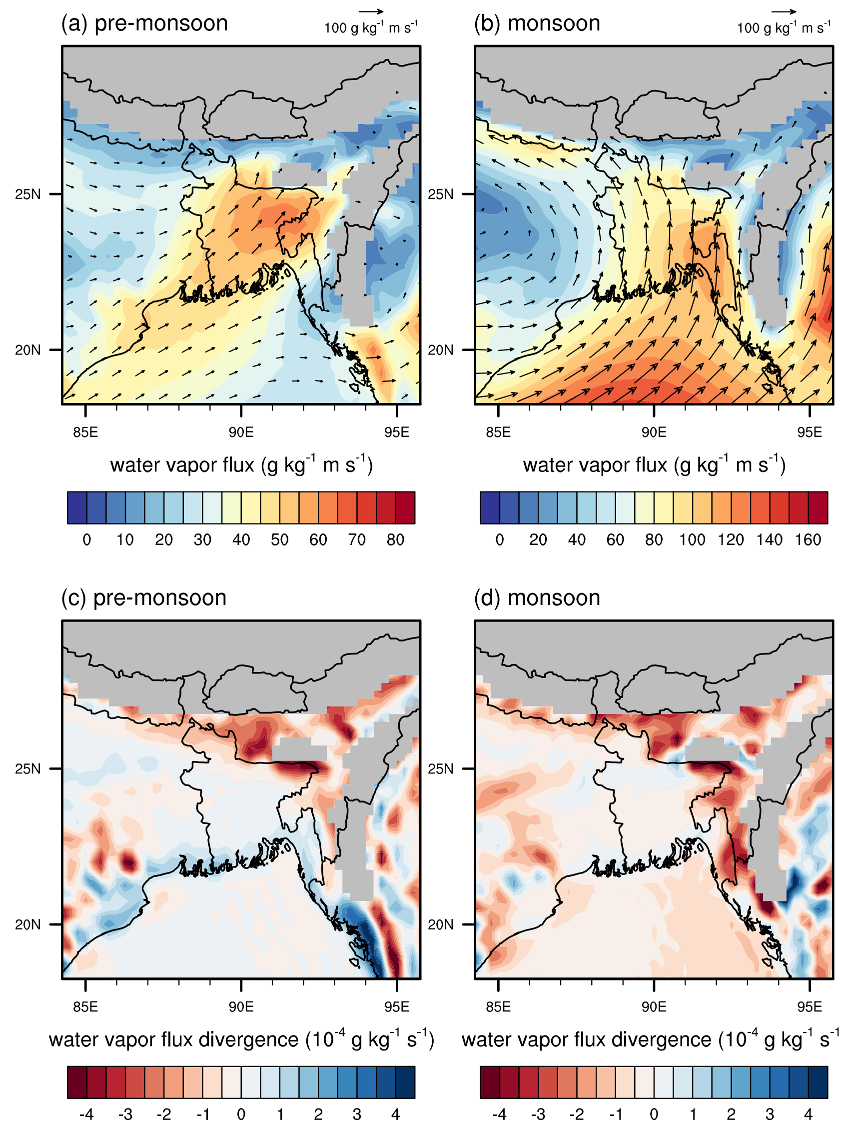

Fig. 5 Fields of water vapor flux vector and its magnitude (color shading) at 900-hPa level averaged over the period 2003–2016 in the **a** pre-monsoon season and **b** monsoon season. **c** and **d** are the same as **a** and **b**, respectively, except for the divergence of water vapor flux

Figure 5c, d shows the divergence of water vapor flux, that is, $\nabla\cdot(q\boldsymbol{u})$, at 900 hPa. In the pre-monsoon season, as expected from Fig. 5a, the water vapor flux convergence is large in the Meghalaya Plateau region, which is closely related to the large precipitation amount in the northeastern region of Bangladesh (Fig. 4b). A weak divergence of water vapor flux is found in the southeastern region although the precipitation amount in this region is larger compared to that in the southwestern region. This may be related to the large diurnal variability of the water vapor flux divergence in this region, which will be shown in the following subsection (see Fig. 8). In the monsoon season, the region of the Arakan Mountains exhibits a large water vapor flux convergence. This is closely related to the large precipitation amount in the southeastern region of the country (Fig. 4c).

The annual precipitation amount is distinctly smaller in 2016 (Fig. 2). As an attempt to find causes for this, we analyzed the annual, pre-monsoon, and monsoon precipitation amounts and the 900-hPa water vapor flux in the pre-monsoon and monsoon seasons for the year 2016 (figures not shown) and compared the results with those of Figs. 4 and 5. In 2016, the annual precipitation amount is decreased at all stations in comparison with Fig. 4a. This implies that the distinctly smaller annual precipitation amount in 2016 could be associated with large-scale phenomena. The noticeable reduction of precipitation amount in the monsoon season in 2016 is mainly responsible for the distinctly smaller annual precipitation amount in 2016. The water vapor transport from the Bay of Bengal is noticeably reduced in 2016. However, it is unclear what caused the noticeable reduction in the water vapor transport, needing a further investigation.

3.2 Diurnal Variation of Precipitation

The precipitation data at each station are analyzed to find the time of day at which the precipitation amount is largest. The stations whose precipitation peaks appear at similar times are grouped to investigate the diurnal variation of precipitation. In this way, Bangladesh is divided into three regions: northern (N), southwestern (SW), and southeastern (SE) regions (Fig. 1). The number of stations included is 6 in the N region, 10 in the SW region, and 11 in the SE region. The 3-h accumulated precipitation amounts averaged over stations in each region in the pre-monsoon and monsoon seasons are calculated. Their diurnal variations are presented in Fig. 6.

In the pre-monsoon season (Fig. 6a, c, e), the degree of the diurnal variability of precipitation is large in the N and SW regions but small in the SE region. In the N region, the precipitation amount is largest in 00–03 LST and smallest in 15–18 LST. On the contrary, the pattern is almost opposite in the SW region: the precipitation amount is largest in 18–21 LST and smallest in 03–06 LST. In the monsoon season (Fig. 6b, d, f), the precipitation amount is larger in the SE region than in the N and SW regions and the degree of the diurnal variability of precipitation in the SW region is larger than that in the N region. The pattern of the diurnal variation of precipitation in the SE region is similar to that in the N region: the precipitation amount is largest in 03–06 LST and smallest in 18–21 LST. In the SW region, the precipitation amount is largest in 12–15 LST and smallest in 21–24 LST. These results from Fig. 6 imply that mechanisms or factors responsible for the diurnal variation of precipitation are different depending on regions of Bangladesh.

To quantify a diurnal variability of precipitation in each region and each season, D is defined as (1) and is calculated using the data used to plot Fig. 6.

$$D = \frac{P_{\max} - P_{\min}}{P_{\mathrm{m}}} \quad (1)$$

where $P_{\max}$, $P_{\min}$, and P_{m} are the daily maximum (largest), minimum (smallest), and mean precipitation amounts, respectively. The calculated D values in the N, SW, and SE regions in the pre-monsoon and monsoon seasons are given in Table 1. Compared with the N and SE regions, the SW region experiences the largest diurnal variability of precipitation in both the pre-monsoon and monsoon seasons. In the pre-monsoon season, the diurnal variability of precipitation is larger in the SW region than in the SE region. This seems to be associated with the larger diurnal variation of convective instability in the SW region than in the SE region, as will be shown in Fig. 7c, e.

Next, we attempt to associate the features of the diurnal variations of precipitation in Bangladesh with large-scale thermodynamic and dynamic characteristics. The vertical profiles of equivalent potential temperature at different local times are presented in Fig. 7. Two features are pronounced in Fig. 7. One prominent feature is that in both the pre-monsoon and monsoon seasons, the atmosphere is conditionally unstable (i.e., the equivalent potential temperature decreases with height) below ~600–650 hPa and stable (i.e., the equivalent potential temperature increases with height) above it. The other prominent feature is that the atmosphere is more conditionally unstable in the pre-monsoon season than in the monsoon

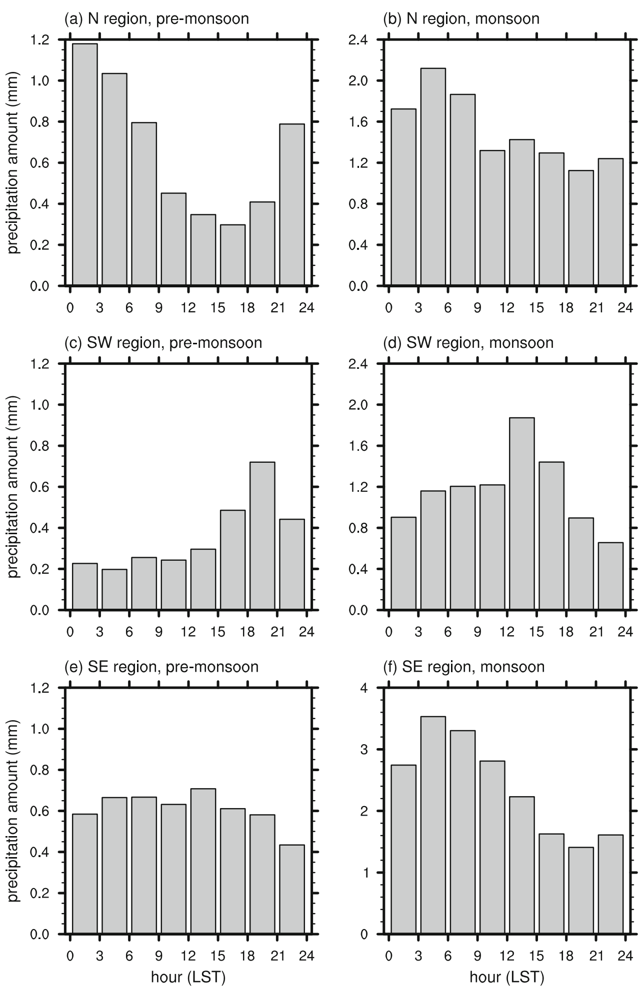

Fig. 6 Diurnal variations of 3-h accumulated precipitation amount averaged over stations in the **a** northern (N), **c** southwestern (SW), and **e** southeastern (SE) regions in the pre-monsoon season and those in the **b** N, **d** SW, and **f** SE regions in the monsoon season. Note that the *y*-axis limits in the plots of the pre-monsoon and monsoon seasons are different

Table 1 Diurnal variability of precipitation D in each region and each season

Season	Region N	SW	SE
Pre-monsoon	1.33	1.46	0.45
Monsoon	0.66	1.04	0.88

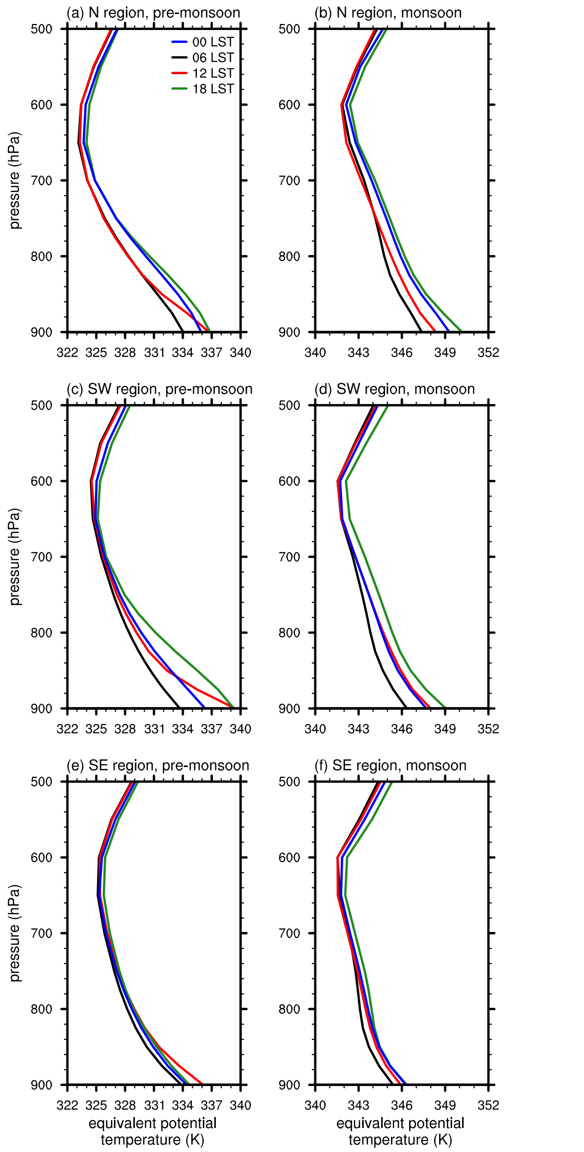

Fig. 7 Vertical profiles of equivalent potential temperature at 00, 06, 12, and 18 LST averaged over stations in the **a** northern (N), **c** southwestern (SW), and **e** southeastern (SE) regions in the pre-monsoon season and those in the **b** N, **d** SW, and **f** SE regions in the monsoon season

season. This implies that the pre-monsoonal precipitation is more convective in nature than the monsoonal precipitation.

In the pre-monsoon season, the diurnal variation of equivalent potential temperature below ~700 hPa is larger in the SW region than in the N and SE regions (Fig. 7a, c, e). The effect of this large diurnal variation of equivalent potential temperature is to some extent reflected in the large diurnal variability of precipitation (Fig. 6c). In the SW region, the atmosphere is noticeably conditionally unstable below ~830 hPa at 12 LST compared with other times. The large convective instability could be a cause for the precipitation maximum in the early evening in the SW region (Fig. 6c). The SE region experiences the least diurnal variation of equivalent potential temperature.

In the monsoon season, the diurnal variation of equivalent potential temperature is small compared with the pre-monsoon season in all of the three regions. As in the pre-monsoon season, the diurnal variation of equivalent potential temperature in the monsoon season is smallest in the SE region among the three regions. It is, however, interesting to note that the diurnal variability of precipitation in the SE region is about two times larger in the monsoon season ($D = 0.88$) than in the pre-monsoon season ($D = 0.45$), indicating that factors other than conditional instability would be responsible for the larger diurnal variability of precipitation in the monsoon season.

The 950-hPa horizontal velocity and water vapor flux divergence are examined (Fig. 8). The 950-hPa level rather than the 900-hPa level as in Fig. 5 is chosen to get a more glimpse of the influences of the high mountains in and near Bangladesh. Over Bangladesh, the low-level wind is stronger at all times in the monsoon season than in the pre-monsoon season. In the pre-monsoon season, the convergence of water vapor flux in the N region is largest at 00 LST, which is associated with the precipitation maximum in 00–03 LST (Fig. 6a). It becomes weak at 12 and 18 LST, even with the divergence of water vapor flux being present at 12 LST in part of the N region, which is associated with the precipitation minimum in 15–18 LST (Fig. 6a). Similar features are also evident in the monsoon season, but with slightly different times of the precipitation maximum/minimum (Figs. 6b and 8b). There is a divergence of water vapor flux in part of the SW region at 00 LST in the pre-monsoon season (Fig. 8a), which is connected with the precipitation minimum in 03–06 LST (Fig. 6c). In the monsoon season, the convergence of water vapor flux in the N region is largest at 00 LST. At 12 LST, the convergence of water vapor flux overall becomes weak over Bangladesh except for the southwestern region of the country, with the divergence of water vapor flux appearing in part of the northwestern region of the country. In the SW region, the convergence of water vapor flux is largest at 12 LST (Fig. 8f) and this is associated with the precipitation maximum in 12–15 LST (Fig. 6d). In the SE region, the convergence of water vapor flux is generally large in the nighttime compared with that in the daytime (Fig. 8b, d, f, h), overall consistent with the precipitation maximum 03–06 LST (Fig. 6f). It is observed from Fig. 8 that in both the pre-monsoon and monsoon seasons, the low-level wind over Bangladesh is stronger in the nighttime than in the daytime. This leads to more nighttime moisture transport, especially from the Bay of Bengal in the monsoon season.

In the nighttime, the downslope wind produced by cooling over the high terrain of the Himalaya Mountains meets with the approaching low-level moist unstable airflow and causes nighttime or early morning precipitation maxima near the

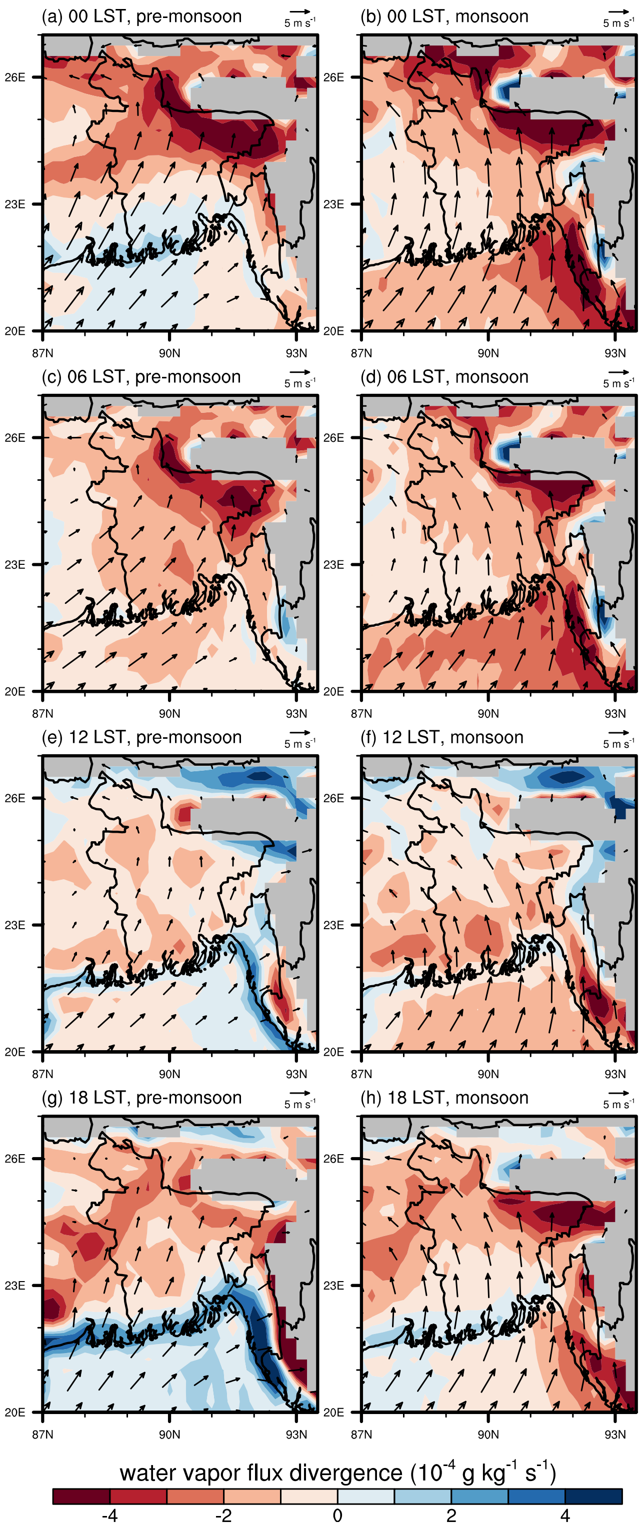

Fig. 8 Fields of horizontal wind vector and the divergence of water vapor flux (color shading) at 950 hPa level averaged over the period 2003–2016: **a** 00 LST, **c** 06 LST, **e** 12 LST, and **g** 18 LST in the pre-monsoon season and **b** 00 LST, **d** 06 LST, **f** 12 LST, and **h** 18 LST in the monsoon season

Himalayan foot (Romatschke et al. 2010; Houze 2014). The northwestern region of Bangladesh is located close to the Himalayan Foothills. So, this mechanism could to some extent explain the late night to early morning maximum of precipitation in the northwestern region of the country. However, further investigations are needed to confirm this mechanism. It should be noted that in the nighttime, the converging wind due to the Himalaya Mountains, which is accompanied by more moisture transport due to the strengthened nighttime low-level wind, plays an important role in enhancing nighttime precipitation in the northwestern region of Bangladesh. Similarly, the Meghalaya Plateau and more nighttime moisture transport could contribute to the nighttime maximum of precipitation in the northeastern region of the country.

Kataoka and Satomura (2005) reported an interesting numerical modeling result that the katabatic mountain wind does not play a major role in the diurnal variation of precipitation in the northeastern region of Bangladesh. Although the result is obtained through a case study, it is in contradiction with the speculation that in the northeastern region of the country, the katabatic mountain wind plays a major role in the diurnal variation of precipitation (Prasad 1970; Ohsawa et al. 2000). Further numerical modeling studies with numerous cases would help to find to what extent the katabatic mountain wind (the downslope wind) contributes to the late night to early morning precipitation maximum in the northeastern region of Bangladesh.

Fujinami et al. (2017) showed that in the monsoon season, the reduced vertical mixing in the stable boundary layer in the nighttime accelerates the low-level jet towards the Meghalaya Plateau, which acts to intensify nighttime precipitation. This is largely in line with our result.

The averaged spatiotemporal characteristics of precipitation found in this study may be to some or large extent affected by extreme variations of large-scale circulation. To examine whether our conclusions are the same even after excluding extreme large-scale events, the analysis is performed in which the years with strong IOD, La Niña, and El Niño are excluded. It is found that the analysis ends up with the results that are very similar to those calculated from the whole 14-year period, because the positive and negative deviations in these years cancel each other out (not shown).

4 Summary and Conclusions

This study examined observed spatial and temporal variations of precipitation in Bangladesh. For this, the rain gauge data in 3-h intervals at 35 stations for the period 2003–2016 and the reanalysis data were used. The annual precipitation amount is 2263 mm, and its spatial variation is large. The pre-monsoon and monsoon seasons have 17% and 73% of the annual precipitation amount, respectively.

In the northern region of Bangladesh, the precipitation peaks in the late night to early morning in both the pre-monsoon and monsoon seasons. This is associated with the large horizontal convergence of low-level water vapor flux. On the other hand, in the southwestern region of the country, the precipitation peaks in the early evening in the pre-monsoon season and peaks in the afternoon in the monsoon season. The early evening maximum of precipitation in the pre-monsoon season is associated with the large convective instability in the late afternoon.

It was speculated that the Himalaya Mountains and the Meghalaya Plateau play roles in enhancing nighttime precipitation in the northern region of the country. However, we could not present the detailed processes and mechanisms only with the rain gauge data and the reanalysis data. Numerical studies with high-resolution cloud-resolving models will help to find involved processes and mechanisms. Bangladesh is affected by tropical cyclones which bring heavy rains in the country. It would be interesting to examine to what extent tropical cyclones take part in the amount and spatial distribution of precipitation.

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