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Spatial and temporal analysis of a 17-year lightning climatology over Bangladesh with LIS data

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Abstract Using NASA's TRMM Lightning Imaging Sensor (LIS) data from 1998 to 2014, this paper presents a 17-year lightning climatology of Bangladesh, at $0.5^\circ \times 0.5^\circ$ spatial resolution. Diurnal, seasonal, monthly and annual variations in the occurrence of lightning flashes were explored. The diurnal regime of lightning is dominated by afternoon/evening events. Overall, peak lightning activity occurs in the early morning (0200 LST) and evening (1900 LST). The distribution of lightning flash counts by season over Bangladesh land-mass is as follows: pre-monsoon (69.2%), monsoon (24.1%), post-monsoon (4.6%) and winter (2.1%). Flash rate density (FRD) hotspots were primarily located in the north and north-eastern parts of Bangladesh, with a maximum of 72 fl $\text{km}^{-2} \text{year}^{-1}$. Spatially, the distribution of FRD increases from

the Bay of Bengal in the south to relatively higher elevations (of the Himalayan foothills) in the north. A spatial shift in FRD hotspots occurs with change in season. For example, in monsoon season, hotspots of lightning activity move in a south-westerly direction from their pre-monsoon location (i.e. north-eastern Bangladesh) towards West Bengal in India. South and south-eastern parts of Bangladesh experience high lightning activity during post-monsoon season due to regional orographic lifting and low-pressure systems (i.e. cyclone) in the Bay of Bengal. To the best of our knowledge, this is the first study focused on LIS-based lightning climatology over Bangladesh. This baseline study, therefore, is an essential first step towards effective management of lightning-related hazards in Bangladesh.

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1 Introduction and background

Thunderstorm and associated lightning activity is the manifestation of mesoscale instability of the atmosphere (Goodman and MacGorman 1986; Kandalgaonkar et al. 2003; Williams 2005). Lightning activity may be used to understand various meteorological phenomena and events such as estimation of convective rainfall (Petersen and Rutledge 1998), deep convection in a unstable atmosphere (Petersen et al. 1996) and distribution of local severe thunderstorms (Chaudhuri and Middey 2013).

Lightning activity across the world is expected to increase in response to projected increase in global temperature (Williams 1992, 1994, 2005). A subtle change in the average wet-bulb temperature of the globe of 1 °C could enhance lightning activity by up to 40% (Nath et al. 2009; Reeve and Toumi 1999), with devastating consequences for humans and property (Holle 2016). Moreover, lightning is regarded a major source of natural forest fires in the mid-latitudes (Price and

Rind 1994). Further, fatalities from lightning could rise as the frequency and intensity of lightning increases (Zhang et al. 2011). Consequently, research on lightning activity received renewed interest around the world.

Satellite-based lightning data is essential for understanding lightning characteristics at various spatial and temporal scales (Albrecht et al. 2016; Yuan et al. 2016; Cecil et al. 2015; Dai et al. 2009; Ranalkar and Chaudhari 2009; Kandalgaonkar et al. 2005; Kodama et al. 2005; Qie et al. 2003; Bond et al. 2002; Boccippio et al. 2000). Establishing the contribution of lightning activity to hazardous weather, as well as its impact on property and humans, is a prominent theme of studies utilising satellite-based lightning data (e.g. Cardoso et al. 2014). From many existing works, it is clear that satellite data provides opportunity to enhance our understanding of lightning activity. This is particularly relevant for developing countries where lightning-related casualties are often high and near real-time weather forecasting is unavailable due to limitations in resources and technical expertise.

Whilst many studies have been conducted in the Indian region to characterise spatial and temporal variation of lightning, and model relationships between lightning and various meteorological parameters, most have focused on India (Tinmaker et al. 2010, 2014, 2015; Murugavel et al. 2014; Siingh et al. 2014; Chaudhuri and Middey 2013; Tinmaker and Chate 2013; Tinmaker and Ali 2012; Kumar and Kamra 2012a, b; Nath et al. 2009; Lal and Pawar 2009; Ranalkar and Chaudhari 2009; Kandalgaonkar et al. 2003, 2005, 2010). Using lightning data, predominantly from TRMM's (Tropical Rainfall Measuring Mission) Lightning Imaging Sensor (LIS), these studies indicate that northeast parts of Indian subcontinent are a lightning hotspot with unique spatial and temporal attributes. Further, several studies highlight Bangladesh as one of the most vulnerable countries in the region to local severe storms and associated lightning activity.

Unfortunately, studies on long-term lightning climatology, including spatial and temporal aspects of it, are lacking in Bangladesh. Instead, studies of lightning-related phenomena, notably thunderstorm frequency, exist (Saha and Quadir 2016; SMRC 2010; Karmakar and Alam 2005; Karmakar 2001; Chowdhury and De 1995). Where lightning activity was studied, the data used was often related to short timespan—typically, not exceeding 10 years—and they were largely focused on India (and not on Bangladesh)—hence the need for this study.

Tinmaker and Ali (2012), for example, investigated space-time variation of lightning flash rate density over northeast India for a period of 10 years (1998–2007) with LIS data. They reported 55 flashes $\text{km}^{-2} \text{year}^{-1}$ with the maximum occurring during pre-monsoon season. Ranalkar and Chaudhari (2009) estimated 40 flashes $\text{km}^{-2} \text{season}^{-1}$ during pre-monsoon, over northeast India. Siingh et al. (2014) also stressed that northeast India, including Bangladesh, is one of the

most lightning-prone regions in Indian subcontinent due to orography and local meteorological factors. In addition, their study noted that lightning flash in the region increases with an increase of aerosol concentration in the atmosphere which they believe related to industrialisation and rapid urban expansion. Kumar and Kamra (2012a) made a similar observation. Using satellite data from 1995 to 2011, Murugavel et al. (2014) noted that the genesis of thunderstorm and lightning is not only controlled by convective available potential energy (CAPE) but orography and prevailing local meteorological conditions also play significant role over Indian region, particularly in northeast India. It appears, from these studies, that eastern, central and bordering northern regions of Bangladesh experience relatively high rate of lightning activity in different seasons. Whilst the studies conducted in India provide baseline information on characteristics of lightning activity in the Indian subregion, they do not provide specific local-level lightning information. Such information is essential for formulating public policies on lightning hazard awareness and safety. Since lightning constitutes more than 25% of total causality in Bangladesh (Mashreky et al. 2012), an accurate long-term lightning climatology is critical to reliable weather forecasts (Kandalgaonkar et al. 2010) and lightning safety education (Roeder et al. 2015).

Owing to its unique orographic pattern and geographical location (21° to 26° N), it is anticipated that lightning activity in Bangladesh would differ from that of the rest of Indian subcontinent as local factors (e.g. low elevation or slope) differ (Siingh et al. 2014; Tinmaker and Chate 2013; Nath et al. 2009). For instance, Bourscheidt et al. (2009) observed that terrain slope influences occurrence of thunderstorm and lightning more than altitude. Moreover, lightning activity varies considerably across various spatial and temporal scales (Qie et al. 2003; Williams et al. 2000). Consequently, existing regional studies not accurately depict localised weather phenomenon in Bangladesh.

With an estimated population of more than 150 million (BBS 2012), Bangladesh is vulnerable to various natural hazards, of which floods and cyclones are the most devastating. Because of the extensive scale of damage associated with floods and cyclones, natural hazards such as lightning often receive little attention (Ono and Schmidlin 2011). Between 2009 and 2014, a total of 1,350,094 (21.9% of total) households were affected by tornado, thunderstorm and hail (collectively referred to as local severe storms), whereas 1,503,742 households (24.4% of total) were inflicted by floods (BBS 2016), in the same period. Further, it is estimated that local severe storms resulted in a loss of 26,710 million (14.5% of total loss due to natural hazards) Bangladeshi Taka (1 US\$ = 78 BDT) whilst the damage from floods was 23% (42,807.19 million BDT). Clearly, the impacts of thunderstorms and potentially lightning are significant. It is surprising that government agencies in Bangladesh, including Bangladesh Meteorological

Department (BMD), lack data related to lightning. Following the shocking deaths of 89 people across the country in 2 days (12 and 13 May) in 2016, the government of Bangladesh declared lightning a natural disaster and mandated the collection of information on lightning-related injury and fatality. Hence, there is a need for a robust lightning database to inform public policy on lightning safety and mitigation. Further, characterisation of lightning activity at a range of spatial and temporal scales is essential in managing this naturally occurring phenomenon. Consequently, this study strives to fill a significant void in the scientific literature for a region with a large population that is highly vulnerable to lightning-related hazards (Dewan et al. 2017).

In this context, the objective of this study was to develop a lightning climatology for Bangladesh, based on 17-year (1998–2014) LIS data from TRMM. Specifically, this research aimed to quantify spatial and temporal characteristics of lightning activity over Bangladesh landmass and explore meteorological explanations for variation in lightning activity.

2 Study area

Bangladesh is located between 88.05° E to 92.74° E longitudes and 20.45° to 26.63° N latitudes (Fig. 1). Its topography is characterised by extreme lowlands, with most of the land below 10 m above mean sea level (Ohsawa et al. 2000). Pre-monsoon (March–May), monsoon (June–September), post-monsoon (October–November) and winter (December–February) are four distinct seasons of Bangladesh. Southwest and northeast monsoons have major influence on the country's climate, resulting in marked seasonality in rainfall and temperature (Salahuddin et al. 2006).

3 Methods and materials

LIS is specifically designed to capture lightning flashes between 35° N and 35° S latitude, and data from this sensor is particularly suitable for studying average lightning activity over large areas (Christian et al. 2003). The LIS is an instrument aboard the TRMM satellite that was launched into space in 1997. Compared to the Optical Transient Detector (OTD) sensor, LIS has a smaller field of view (FOV) but offers greater detection efficiency (Bond et al. 2002), reaching 88% at night-time (Cecil et al. 2014). With a spatial resolution of 4–7 km over a large area (approximately 600 km × 600 km), LIS captures total flash count—including both cloud-to-cloud and cloud-to-ground lightning flashes. Further, with an orbital inclination of 35°, a low altitude of 350 km, and a total dwell time of approximately 90 s, the sensor is able to capture individual storms within its FOV. The LIS is highly

useful in identifying the spatial distribution of lightning, recording the time of events and measuring the radiant energy of lightning flashes (Qie et al. 2003; Kandalgaonkar et al. 2003).

In this study, LIS data covering 17 years (January 1998 to December 2014) was downloaded from National Aeronautics and Space Administration (NASA) website (<http://thunder.nsstc.nasa.gov/lisib/lisearch.html>). Hierarchical Data Format (HDF) reading software (<https://www.hdfgroup.org>) was used to access the lightning data. Custom IDL scripts were used to compute lightning climatology for Bangladesh.

Two types of analyses were conducted. First, lightning flash counts (FC) were analysed to examine annual, monthly and diurnal patterns of flash activity in Bangladesh over the study period (1998–2014). For convenience, 90 min LIS time resolution was interpolated to 1 h by taking starting and ending times of the flashes into account which results total flashes occurred in the same time for all years, i.e. 1998 to 2014. Overall, a total of 83,641 flashes were estimated to have occurred within the territory of Bangladesh, of which 71,535 flashes (86%) occurred over land and the rest was over the Bay of Bengal. This agrees with our general understanding that lightning activities are predominantly distributed over land (Zipser 1994). To characterise diurnal lightning activity, only flashes that occurred on Bangladesh's land area were taken into account and reported here. To explore monthly variation in lightning flashes, mean monthly flash counts (aggregated over 17 years) and associated confidence intervals (CI) were also computed.

The second part of the analysis considered flash rate density (hereafter, FRD), expressed in units of flashes per km² per year (fl km⁻² y⁻¹), was calculated according to the method detailed in Cecil et al. (2014). FRD was computed by dividing scaled flash counts by the product of view time and area of each grid cell. Also, FRD can be multiplied by total seconds of a month, season or year to obtain an estimate for a desired timescale. Various detection efficiencies were applied depending on the local solar time of a given flash activity (refer to Table 2 in Cecil et al. (2014) for details). FRD was computed at different temporal scales—annual, monthly and seasonal—and then gridded at 0.5° × 0.5° spatial resolution. Lastly, FC and FRD were summarised according to local standard time (hereafter, LST), months, season and year.

4 Results

a. Diurnal variation of lightning flashes

Diurnal variation of lightning flashes over Bangladesh during 1998–2014 shows two prominent peaks with the first maxima occurring between 0100 and 0300 LST and the second manifesting between 1800 and 2200 LST. Further, a subdued peak is

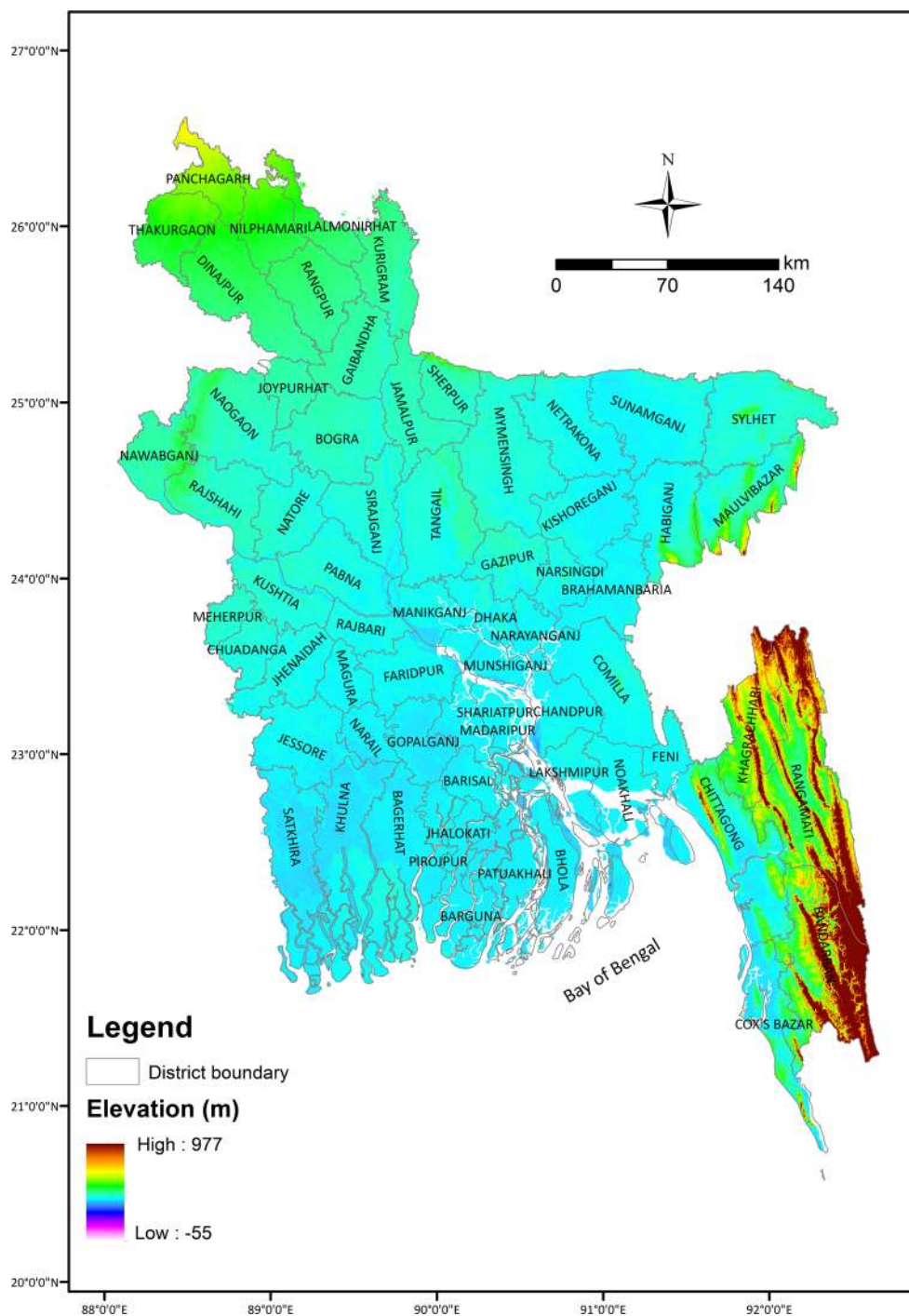


Fig. 1 The study area (district names draped over surface elevation, source: Shuttle Radar Topographic Mission (SRTM))

evident at 1400 LST (Fig. 2). Generally, lightning activity is higher in the early evening and low from morning to afternoon and can be characterised by afternoon–evening maxima. A 24-h distribution of lightning activity by 6-h periods showed the following pattern: 29.68% (early morning—0000 to 0559 LST), 10.69% (late morning—0600 to 1159 LST), 23.20% (afternoon—1200 to 1759 LST) and 36.41% (evening—1800

to 2355 LST). This implies lightning activity in Bangladesh is characterised by early morning and evening maxima.

To evaluate the influence of season on diurnal lightning activity, 17 years' worth of data (1998–2014) was summarised according to four seasons: pre-monsoon, monsoon, post-monsoon and winter. Total flash counts for these four seasons over land were computed as 49,526 (69.2%), 17,245 (24.1%),

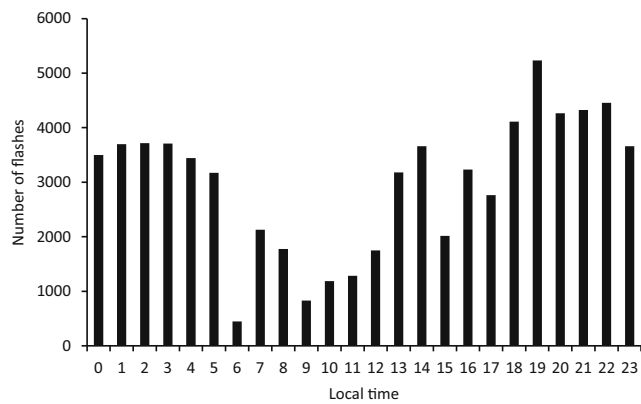


Fig. 2 Diurnal variation of lightning flash counts over Bangladesh, 1998–2014

3284 (4.6%) and 1480 (2.1%), respectively. The pre-monsoon period diurnal cycle (Fig. 3a) resembled the annual diurnal cycle (Fig. 2), with a bimodal distribution. Similar to annual pattern, the double maxima occurred in the early morning (0200 LST) and evening (1900 LST). For monsoon season, lightning activity peaks at 0100, 1800 and 2000 LST (Fig. 3b). Post-monsoon season has one strong peak at 1300 LST, but activity remains strong until late afternoon (e.g. 1600–1700 LST) (Fig. 3c). During winter, lightning activity is greatly

diminished (Fig. 3d). However, there is one prominent peak at 1900 LST (Fig. 3d). A comparison of diurnal variation across seasons reveals that most activity is of afternoon–evening type. Specifically, lightning activity is predominantly nocturnal-type in pre-monsoon and monsoon, afternoon-type in post-monsoon and evening type in winter.

Monthly diurnal cycle over 17 years (Fig. 4a–l) indicates that March has one prominent peak at 1800 LST and April has double maxima during 0300 to 0400 LST and 1900 to 2200 LST. On the other hand, May has a strong peak (1900 LST), but activity is evenly distributed throughout the day. In June, a prominent peak occurs at midnight (0000 LST) and in the early evening (e.g. 2000 LST). July has a strong peak in lightning at 1600 LST with a gradual decrease afterwards, whereas in August and September peak activity occurs at 0100 LST and 1800 LST, respectively. It is also observed from the study period that lightning activity was significantly low during 0600 LST relative to other time of the day. In post-monsoon season, October has the highest activity from 1300 to 1700 LST. In November, lightning activity occurred almost exclusively during the afternoon hours (1300 to 1600 LST). Most of the events in December and February occur in the afternoon and evening. However January has one prominent peak at 0800 LST with a secondary peak at 1800 LST (Fig. 4a).

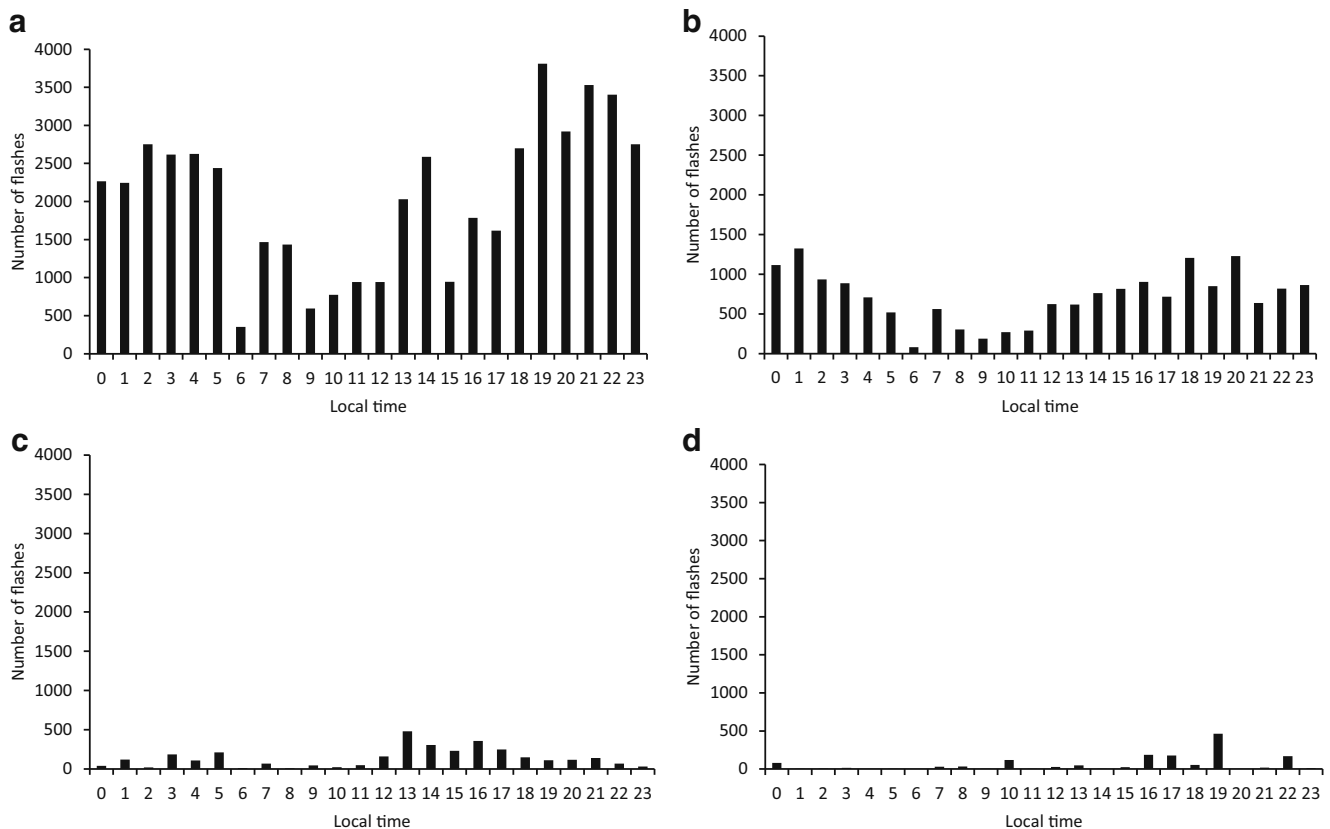


Fig. 3 a–d Seasonal variation of lightning flash counts according to season: **a** pre-monsoon, **b** monsoon, **c** post-monsoon and **d** winter

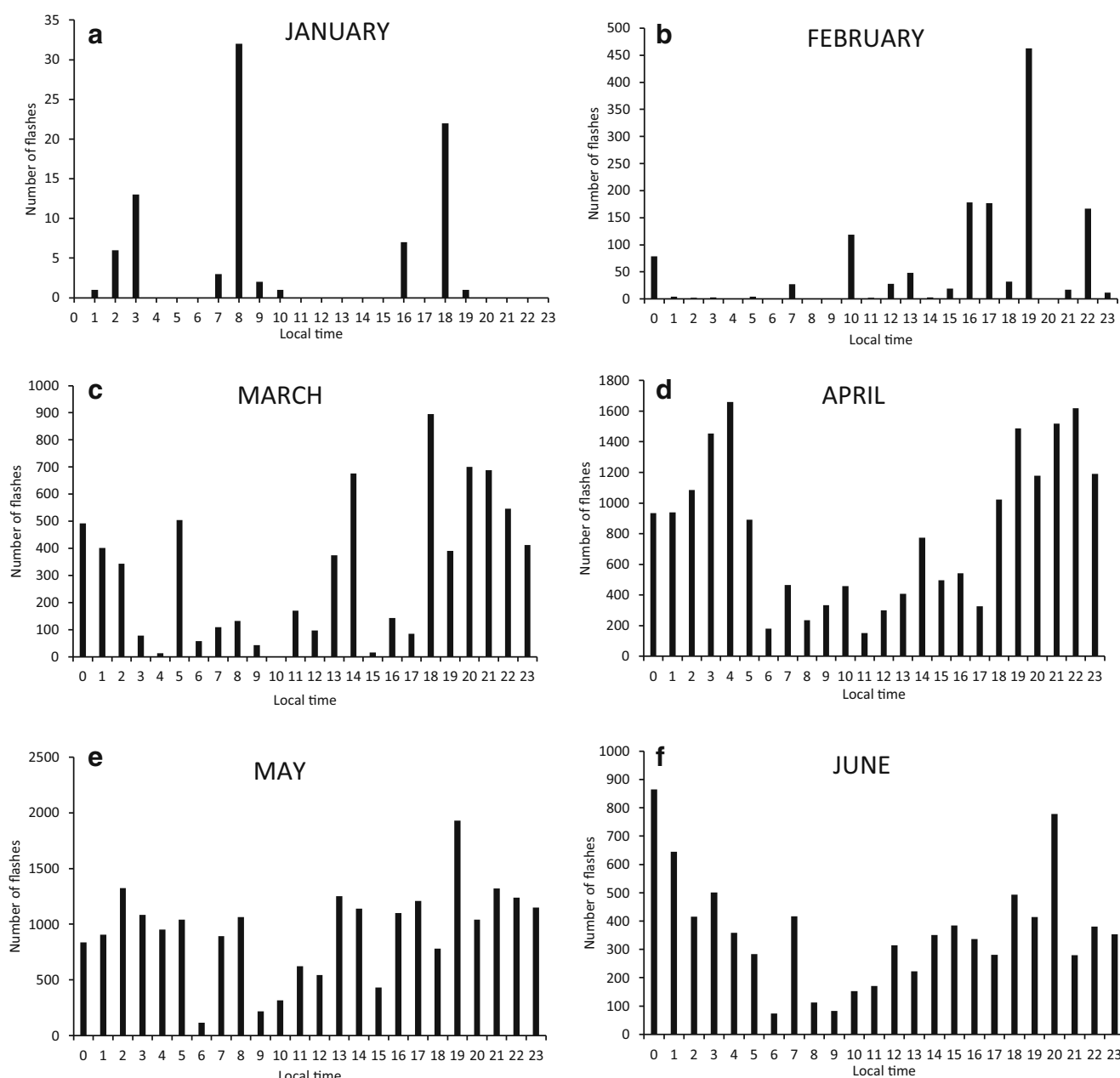


Fig. 4 a–f Diurnal variation of monthly lightning flash counts, 1998–2014

The intra-annual distribution of lightning is unimodal (Fig. 5)—rising steadily from January to May and then descending through December. The highest variability in lightning flashes occurs between March and May, with a peak in May (Mean \pm CI = 1324 \pm 230).

b. Spatial variation in total lightning climatology

Analysis of spatial variation in total lightning activity over Bangladesh suggests that FRD hotspots are located to

the north and north-east of the country (Fig. 6). Specifically, the greatest activity is concentrated between the latitudes of 24.75° to 25.50° N and longitudes of 89.75° to 92.50° E wherein mean FRD is 62 fl km⁻² year⁻¹. Whilst most of the country is associated with low FRD, a few pockets of moderate to high FRD exist. One of them is located from 26.00° to 26.50° N and 87.75° to 90.00° E longitudes with a mean FRD of 40 fl km⁻² year⁻¹. A similar pocket lies between 24.00° to 25.00° N and 90.50° to 92.00° E with a mean FRD of 40 fl km⁻² year⁻¹. The central part and hilly areas of southeast Bangladesh have

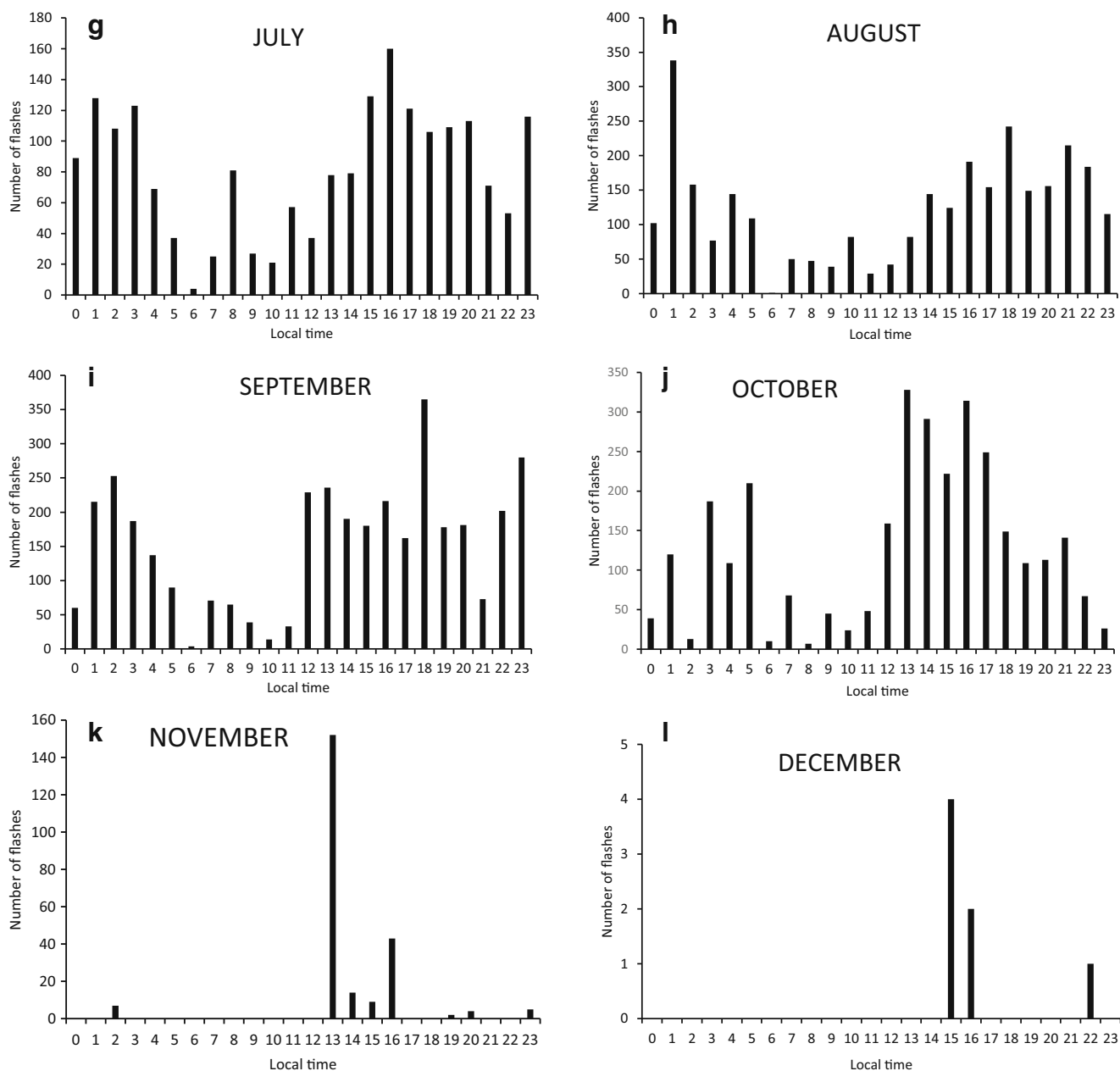


Fig. 4 (continued)

moderate lightning activity over the study period, with a value of $36 \text{ fl km}^{-2} \text{ year}^{-1}$.

The analysis of monthly area-averaged FRD demonstrates that the flash rate density has two peaks (Fig. 7), one is large whilst the other is relatively small. The first peak is in May, representing pre-monsoon season and the other is in September (towards the end of monsoon season). From its lowest points in December and January, FRD begins to rise in February ($0.55 \text{ fl km}^{-2} \text{ month}^{-1}$), before peaking in May ($8 \text{ fl km}^{-2} \text{ month}^{-1}$). After April/May, it declines until August before peaking again in September with a mean of $1.4 \text{ fl km}^{-2} \text{ month}^{-1}$. Error bars (Fig. 7) indicate that April has the largest standard error.

c. Seasonal variation in total lightning climatology

Figure 8a shows the spatial distribution of lightning activity over Bangladesh during pre-monsoon of 1998–2014. FRD of this season ranges from a minimum of 0.26 to a maximum of $57 \text{ fl km}^{-2} \text{ season}^{-1}$ with a mean of $17 \text{ (fl km}^{-2} \text{ season}^{-1})$. The distribution of FRD increases from south to north as one moves to relatively higher elevations from the Bay of Bengal. Northern district of Jamalpur (centred at 89.77° E and 25.22° N), Gaibandha (89.54° E and 25.29° N) and north-eastern districts of Sunamganj (91.34° E and 24.92° N), Sylhet (92.05° E and 25.03° N)

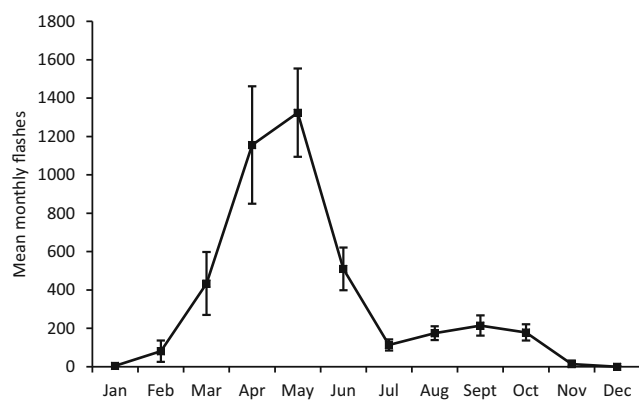


Fig. 5 Annual variations of monthly mean flash counts over Bangladesh. The vertical bars are confidence intervals (CI)

and Netrokona (90.76° E and 24.99° N), in particular, experience high lightning activity during pre-monsoon compared to other parts of the country. The mean FRD of these locations is 46 fl km⁻² season⁻¹. Apart from aforementioned districts, Kishoreganj (centred at 90.87° E and 24.38° N), Habiganj (91.43° E and 24.36° N), Maulvibazar (91.84° E and 24.43° N), Narshingdi (90.72° E and 23.97° N) and Sherpur (90.07° E and 25.12° N) also experience high lightning activity with mean of 33 fl km⁻² season⁻¹.

Figure 8b indicates the spatial pattern of FRD during monsoon. Overall, FRD ranges from 0.8 to 11 fl km⁻² season⁻¹. Compared with pre-monsoon months, lightning activity shows a longitudinal expansion/shift towards West Bengal of India despite the fact that Sunamganj (91.26° E, 25.02° N) in the north-east had the highest FRD of 11 fl km⁻² season⁻¹. Northwest districts of Panchagarh (88.64° E, 26.30° N) and Nilphamari (88.89° E, 26.15° N) also experience high FRD with a mean value of 11 fl km⁻² season⁻¹. During this season, regionally, FRD within Bangladesh increases with increasing latitude.

During post-monsoon, a completely different spatial pattern of FRD occurs as hilly areas of southeast and a coastal district of Bangladesh observed high lightning activity in terms of FRD. The highest FRD was estimated to be 5 fl km⁻² season⁻¹ at Rangamati District (centred at 92.29° E and 23.26° N). On the other hand, a coastal district of Patuakhali (90.80° E and 21.67° N) ranked second with a FRD of 4 fl km⁻² season⁻¹. The mean FRD of this season ranges from 0.3 to 2.7 fl km⁻² season⁻¹. But the central part of the country experiences moderate lightning activity during post-monsoon season. Further, a longitudinal shift/expansion to the east, relative to pre-monsoon season, is also evident.

In winter, lightning activity hotspots seemed to have moved back to the locations that has higher activity in pre-monsoon season. FRD in winter ranges from 0 to 4 fl km⁻² season⁻¹ (Fig. 8d), with the highest lightning activity recorded in

Sylhet region. Lightning activity is mostly concentrated at the following locations: northeast districts of Sylhet (92.05° E and 25.03° N), Sunamganj (91.34° E and 24.92° N) and Maulvibazar (91.84° E and 24.43° N); central districts of Rajbari (89.66° E and 23.74° N), Faridpur (89.84° E and 23.56° N), Manikganj (89.93° E and 23.89° N) and Kushtia (89.14° E and 23.89° N) and the coastal districts of Bagerhat (89.71° E and 21.99° N), Satkhira (89.12° E and 22.66° N) and Khulna (89.37° E and 22.78° N) (Fig. 8d). Moderate lightning activity also occurred in the district of Rangpur (89.22° E and 25.68° N), Lalmonirhat (89.36° E and 25.93° N) and Dinajpur (88.70° E and 25.84° N). The rest of the country experienced little lightning activity during winter.

5 Discussion

5.1 Lightning at diurnal timescale

The *diurnal* statistics and inter-seasonal diurnal variability typically agrees with earlier studies in the Indian region (Kumar and Kamra 2012a, b; Kandalgaonkar et al. 2003, 2010) and Nigeria (Oladipo and Mornu 1985), which found that peak lightning activity usually occurs during afternoon–evening hours (Fig. 3a–e). The analysis further noted that early morning hour of 0600 LST has particularly low lightning activity across various timescales. This result is in agreement with the study of Qie et al. (2003). Note that the hourly frequency of local severe storms also exhibits the same diurnal cycle in Bangladesh (Yamane et al. 2010a). A range of factors may be related to this type of diurnal activity. These include diurnal solar cycle leading to destabilisation of the atmosphere and development of convection, particularly during pre- and monsoon seasons (e. g. Williams 1994; Kumar and Kamra 2012a; Patra et al. 1998; Tinmaker and Chate 2013; Nath et al. 2009; Manohar and Kesarkar 2003). In the north- and south-eastern Bangladesh, topographic forcing of the Shillong Plateau and Chittagong hills allow convection and associated lightning to develop (e.g. see Romatschke et al. 2010; Medina et al. 2010). Thus, topography in conjunction with favourable synoptic system may lead to convective development (Romatschke and Houze 2011a, b; Medina et al. 2010; Zuidema 2003; Qie et al. 2003), giving rise to the increase of thunderstorms (Tyagi 2007) and lightning (Kodama et al. 2005). Romatschke et al. (2010) demonstrated that deep convective cores over land in South Asia occur between noon and midnight whilst wide convective cores have midnight to morning peak which is clearly associated with solar heating and topography, with terrain and land surface characteristics being the most important in triggering intense convection, particularly in the Meghalaya Plateau region (Choudhury et al. 2016; Romatschke and Houze 2011a, b). Ohsawa et al. (2000, 2001) indicated that local convective activity has a clear

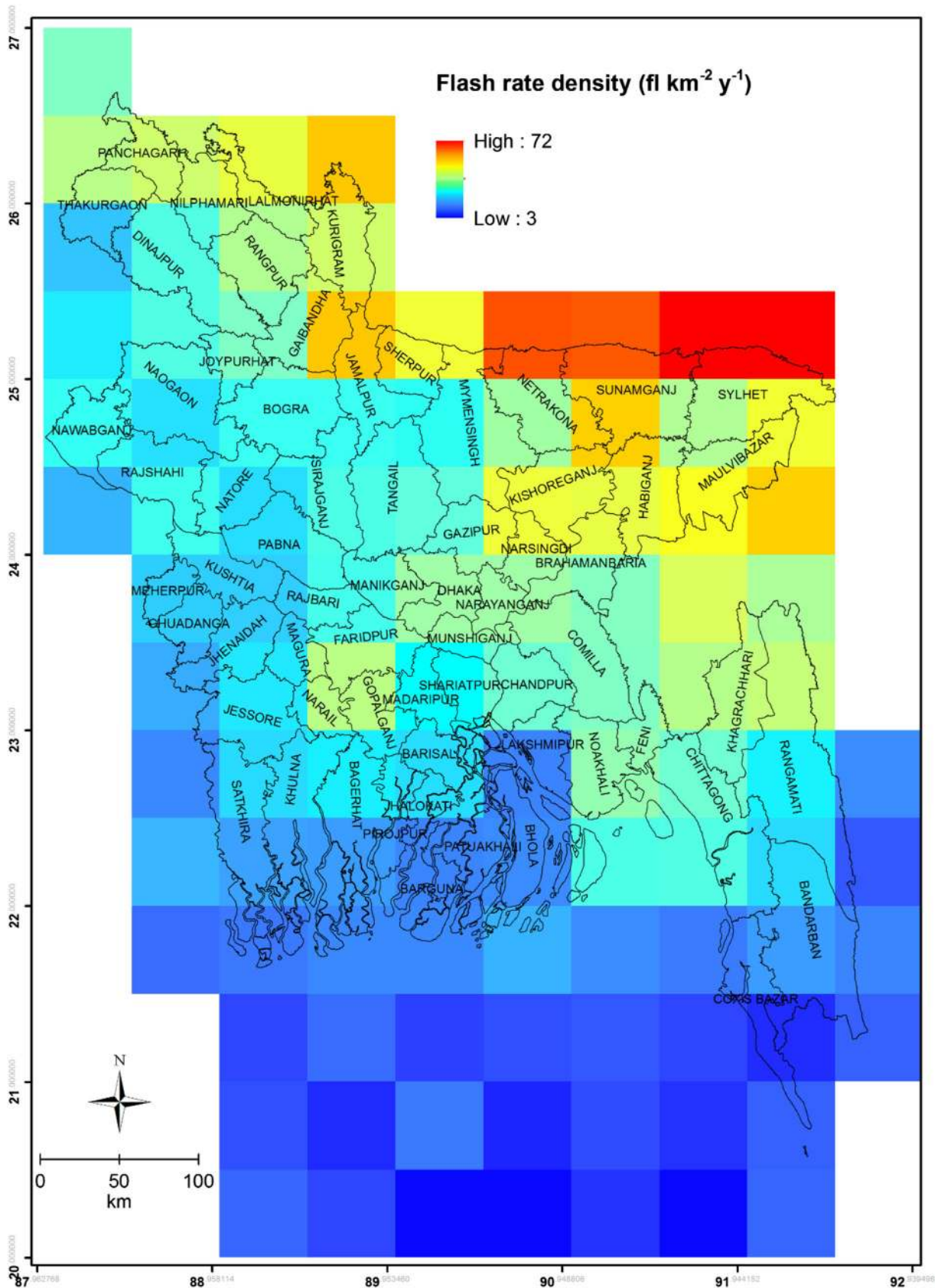


Fig. 6 Spatial variation of lightning flash density over Bangladesh between 1998 and 2014

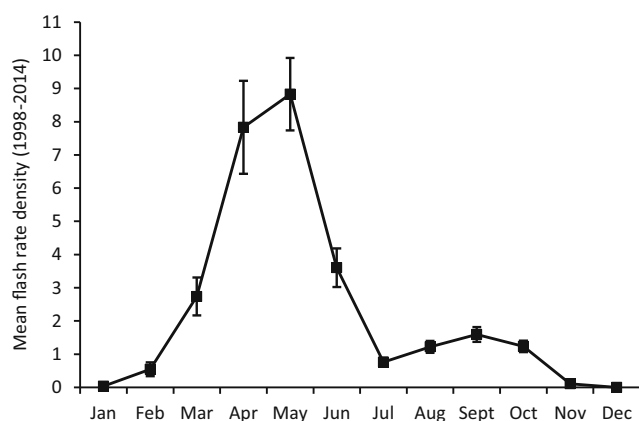


Fig. 7 Mean flash rate density in Bangladesh during 1998–2014. The vertical bars are confidence intervals (CI)

diurnal pattern in Bangladesh, with a tendency to occur during the midnight and early morning hours. Williams et al. (2000) argue that the sustained lightning incidence in the afternoon and evening may be related to nonlinear effects of cold outflow boundaries which destabilises the atmosphere over a large area.

Early morning or nocturnal regime may reflect the effect of land and sea breeze circulation (Kumar and Kamra 2012a; Lohar et al. 1994). In addition, nocturnal valley wind in conjunction with south-easterly monsoonal flow promotes convection during midnight to early morning hours (Terao et al. 2006; Ohsawa et al. 2001). Also, the cooling effect of cloud tops at night promote convective overturning, therefore enhanced nocturnal thunderstorms (Oladipo and Mornu 1985). Furthermore, seasonal distribution in CAPE and vertical wind shear are found to be responsible for strong local convection during pre-monsoon season in Bangladesh (Yamane and Hayashi 2006) which is likely to influence the occurrence of severe storms such as nor'westers and associated lightning activity, particularly during early morning and early to late evening hours in the month of April and May (Yamane et al. 2010a, b). Nocturnal jet-induced midnight to early morning convective system over north-eastern Bangladesh may be another factor that affects diurnal variation in the occurrence of lightning (Terao et al. 2006; Ohsawa et al. 2001).

5.2 Lightning at annual timescale

On the *annual timescale*, northern and northeast districts (Fig. 6) exhibit high lightning activity during 1998–2014. This may be related to a number of previously discussed influencing factors, including insolation, orography, surface elevation, cloud base heights, large moisture content and convection. As noted by Kandalgaonkar et al. (2005), landmass and orography act as passive components whilst large-scale circulation acts as active component in the distribution of lightning over Bangladesh and surrounding regions.

5.3 Lightning at monthly timescale

Comparison of mean monthly FRD of the country (Fig. 7) suggests that our finding is generally consistent with other studies (see Siingh et al. 2014; Tinmaker and Ali 2012). However, compared to these studies, a subtle difference in flashes per km² per year (Fig. 7) is evident in our research which may be attributed to two factors. The first is the differences in time period of this study and other studies; whilst this study used 17 years' worth of data, other studies were based on shorter timespan (of less than 10 years). The second source of discrepancy could be related to substantial downtime during the satellite's power-saving measures in 2014 (Cecil et al. 2015). Monthly FRD between 1998 and 2014 showed that April has the largest margin of error. This may be attributed to large interannual changes of lightning activity and the limitation of the infrequent sampling (Qie et al. 2003). Interestingly, mean FRD and thunderstorm peaks coincides over the same month (e.g. May) in Bangladesh.

Several factors may influence the spatial and temporal distribution of lightning activity. In terms of countrywide monthly distribution of lightning activity, the first peak in April/May is clearly associated with increasing solar heating, topographic forcing, longer day length and advection of low level moisture from the Bay of Bengal and local sources. The second peak in September is largely influenced by monsoonal moisture and orography of the region (Tinmaker et al. 2014; Kodama et al. 2005; Tinmaker and Ali 2012; Tyagi et al. 2011; Lohar et al. 1994). Ohsawa et al. (2000, 2001) and Pathan (1994) notice that the active and break monsoon periods are diametrically opposite, whilst vigorous synoptic scale convective activities exist over the areas north of 18° N and near the equator in active monsoon time; during break period, severe local convection occurs from midnight to early morning due to meso-scale disturbance together with orographic effect. This particular observation may explain the phenomenon of pronounced early morning and nocturnal lightning activity in Bangladesh. Apart from causal factors noted above, enhanced aerosol in the atmosphere caused by increased anthropogenic activities over the country during the last few decades may also influence enhanced lightning activity as Siingh et al. (2014), Pathak and Bhuyan (2014), Kar et al. (2009) and Bell et al. (2008) showed that presence of aerosol in the atmosphere can either invigorate or reduce lightning activity in a given area.

5.4 Lightning at seasonal timescale

5.4.1 Pre-monsoon season lightning activity

On the *seasonal timescale*, the results revealed that pre-monsoon season has the maximum lightning activity in Bangladesh. However, activity is located in north and north-eastern parts of the country (Fig. 8a). This is also consistent

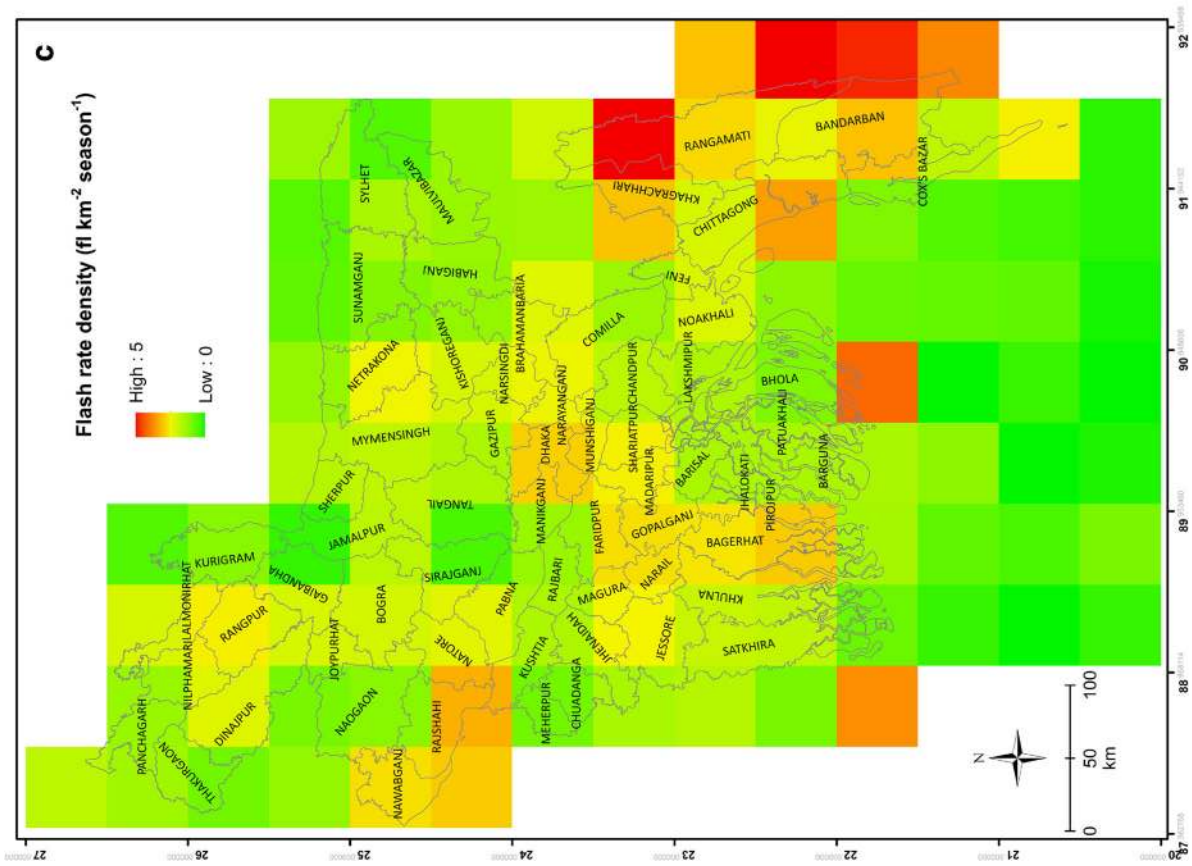
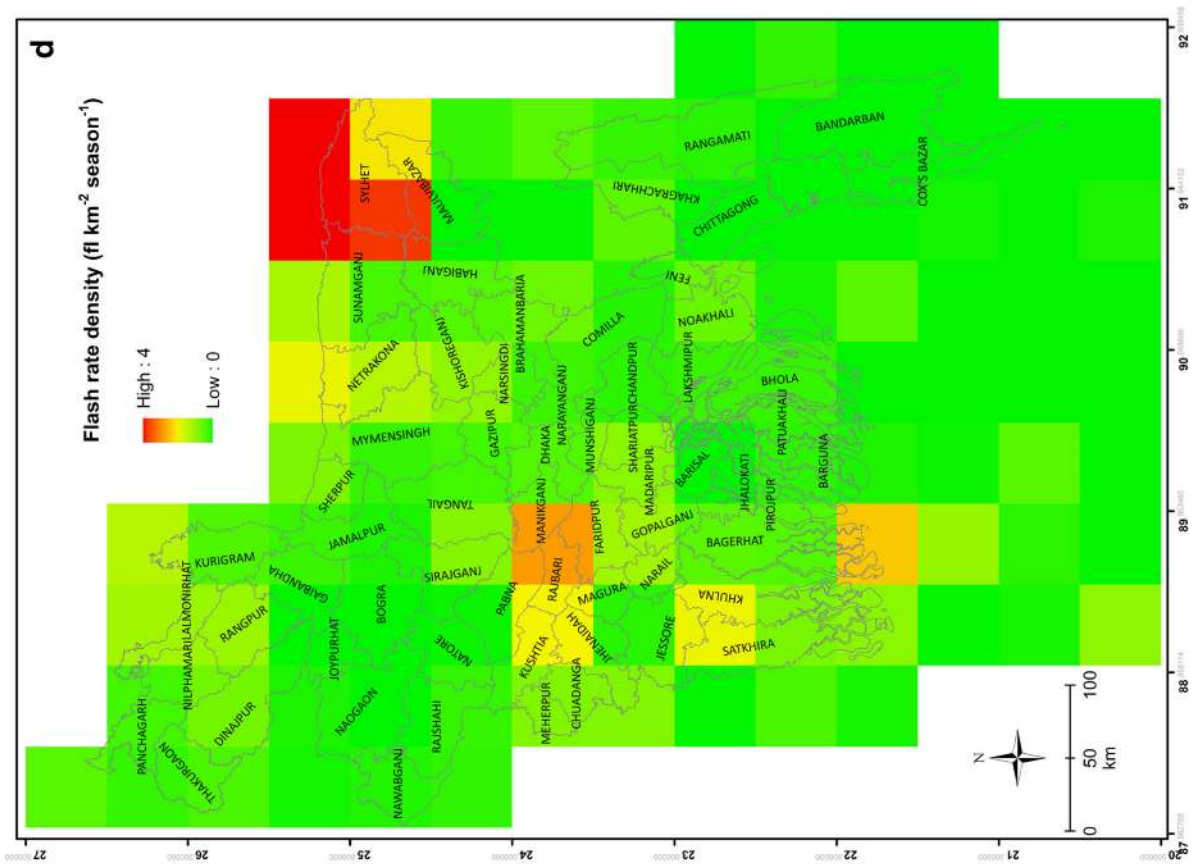


Fig. 8 (continued)

with other studies for the nearby areas (Murugavel et al. 2014; Siingh et al. 2014; Chaudhuri and Middey 2013; Tinmaker and Ali 2012; Ranalkar and Chaudhari 2009; Kandalgaonkar et al. 2005). Note that these areas also experience highest thunderstorms in Bangladesh (Saha and Quadir 2016; Tyagi 2007; Chowdhury and De 1995). Intense thunderstorms associated with higher lightning activity over north-eastern part of Bangladesh supports the observation that mesoscale convection is higher in the mountainous region (Qie et al. 2003; Pathan 1994). Three mechanisms are largely attributed to such lightning distribution during this season. They include orography and terrain effects (Tinmaker et al. 2014; Chaudhuri and Middey 2013; Medina et al. 2010; Romatschke et al. 2010; Nath et al. 2009; Kandalgaonkar et al. 2005; Chowdhury and De 1995), presence of wind discontinuity line (Tinmaker and Ali 2012) or dry line (Weston 1972), and availability of copious moisture in the lower troposphere (Siingh et al. 2014; Ranalkar and Chaudhari 2009).

Because north and north-eastern parts of Bangladesh are dominated by moderate terrain, orographic lifting with respect to complex terrain could initiate conditional instability of the atmosphere which favours development of thunderstorm-mediated lightning during pre-monsoon period (Chaudhuri and Middey 2013; Lefort 2013; Tinmaker and Ali 2012; Yamane et al. 2012). Again, it is reported that northeast part of Bangladesh and its neighbourhood is a favourable area for convective activities during pre-monsoon (Romatschke et al. 2010; Romatschke and Houze 2011a). Note that Cherrapunji, which frequently observes one of the highest rainfall in the world, is just 10 km away from the border of Bangladesh, where orographic effect plays a dominant role in determining convective activities (Choudhury et al. 2016; Bhowmik et al. 2008; Ohsawa et al. 2000; Pathan 1994). Changes in surface temperature may also affect the spatial distribution of lightning activity. It is suggested that relatively rapid seasonal temperature changes from the minimum in winter followed by the maximum during pre-monsoon may have a role in increased lightning activity (Kumar and Kamra 2012a, b).

Furthermore, the nor'wester type of thunderstorms, which are common during pre-monsoon, develop due to overrunning of a warm moist southerly or south-easterly wind by a westerly or north-westerly cold air with a high lapse rate. This is believed to be an important mechanism behind the genesis of many nor'westers in pre-monsoon season (Ranalkar and Chaudhari 2009; Mukhopadhyay et al. 2005; Peterson and Mehta 1981; Weston 1972). Lal and Pawar (2009) reported that convective rainfall is highly correlated with lightning activity in the region during pre-monsoon as a result of arc-shaped mesoscale convective precipitation systems over Bangladesh (Rafiuddin et al. 2013). Romatschke and Houze (2011a) observe that pre-monsoon rainfall is largely convective in nature which frequently drives more lightning activity in the region, particularly in northeast India and neighbouring

areas (Kodama et al. 2005). Although anticyclones in the northern Bay of the Bengal can supply significant amount of moisture, leading to higher precipitable water content, presence of large inland waterbodies within Bangladesh is no less important source for moisture in the lower troposphere during pre-monsoon season (Ranalkar and Chaudhari 2009; Chowdhury and De 1995). As far as the thermodynamics of the atmosphere is concerned, Bhattacharaya et al. (2013) indicated that presence of low to the north of 25° N, high to the south of 20° N and large-scale flow at 500 hPa, in addition to strong insolation and orographic lifting, lead to the genesis of numerous thunderstorms in northeast India and Bangladesh during pre-monsoon season.

5.4.2 Monsoon season lightning activity

A westward longitudinal expansion/shift of lightning activity in monsoon relative to pre-monsoon was observed, with the exception of two northern (88.65° E and 26.30° N; 88.90° E and 26.15° N) and one north-eastern (91.25° E and 25.00° N) districts that showed high lightning activity (Fig. 8b). This shift is most likely due to movement of the convection system (Choudhury et al. 2016; Romatschke and Houze 2011b; Zipser et al. 2006), linked Madden Julian Oscillation (MJO) (Kandalgaonkar et al. 2005). Moreover, instead of solar forcing, low level wind and moisture regimes play an important role in the genesis of thunderstorms during monsoon (Tyagi et al. 2011). Because of orographic influence, the level of free convection (LFC) and equilibrium level (EL) remain low resulting in low CAPE in the monsoon environment (Tinmaker and Ali 2012). Despite its low value, it appears that the incidence of lightning during monsoon is greatly influenced by CAPE (Murugavel et al. 2014). Also, cloud base heights remain low in this season due to its maritime nature and large moisture contents (Lal and Pawar 2009). Since maritime clouds are characterised by moderate updraft and minimum electrification capacity (Takahashi 1990), relatively less lightning activity is expected during monsoon season (Kandalgaonkar et al. 2005; Tinmaker and Ali 2012; Lal and Pawar 2009). Choudhury et al. (2016) in their study also noticed that mesoscale convective systems (MCSs) during monsoon are often not associated with maximum rainfall over northeast India and Bangladesh. A similar observation is made by Romatschke and Houze (2011b). However, lightning activity over Bangladesh during this season may also be related to periodic local-scale clearing of cloud cover when surface temperature increases due to higher insolation and subsequent development of instability that results in thunderstorms in northeast and central parts of Bangladesh (Saha and Quadir 2016; Tyagi et al. 2011; Ohsawa et al. 2000).

5.4.3 Post-monsoon season lightning activity

Lightning activity drops during this season (maximum of 5 fl km⁻² season⁻¹) as compared to monsoon and pre-monsoon seasons. Also, locations of lightning hotspots moved from previous locations to new areas (Fig. 8c) which may be attributed to western disturbances and northeast monsoon activity (Tinmaker et al. 2010, 2014). Kandalgaonkar et al. (2005) observed that the retreat of Inter-tropical Convergence Zone (ITCZ) results in changes in the synoptic scale system, and that lightning activity in southeast corner of Bangladesh is possibly related to this change. Since a number of cyclones and depressions formed in the Bay of Bengal during post-monsoon season, intersection of south-easterly low and strong outflow under the influence of local orography produces a unique convective environment over south-eastern Bangladesh and adjoining areas (Ahsan et al. 2013). As a result, southwest coast, north-eastern and south-eastern hilly areas of Bangladesh experience intense lightning compared to other parts of the country.

5.4.4 Winter season lightning activity

During *winter season* (Fig. 8d), northeast and southwest parts of Bangladesh experience relatively high lightning activity relative to other areas; however, the magnitude is not as intense as in pre-monsoon or monsoon period. Tinmaker and Ali (2012) observed that lightning activity in winter is boosted by frontal-type systems that develop over northeast India due to the interactions between cold and dry air (of higher elevations) and relatively less cold and moist air (of relatively lower altitude) associated with the western disturbances. Due to dry and stable atmosphere throughout the country, thunderstorm occurrence is limited (Saha and Quadir 2016), and likewise lightning. Also, the Tibetan Plateau acts as a heat sink during northeast monsoon which precludes the development of strong local convection in and around the Indian region, resulting in low lightning activity (Kumar and Kamra 2012a).

6 Conclusion

To the best of our knowledge, this is the first study of its kind to make use of TRMM's lightning imaging sensor (LIS) to capture diurnal and spatio-temporal variability of lightning activity over Bangladesh. In this work, we have developed a database, spanning 1998 to 2014, capable of providing important and reliable baseline information on characteristics of lightning activity over Bangladesh. Although global lightning climatology data products are available over the internet, at the time of this work, they were limited to observations made prior to 2014. However, this study uses LIS data to develop an

area-specific lightning climatology from 1998 to 2014 that include seasons relevant to the Indian subregion.

The study found that *diurnal* cycle of lightning activity in Bangladesh is characterised by afternoon and evening peaks. Pre-monsoon diurnal variation suggests that the activity is high during evening. Both early morning and evening have the highest lightning occurrences during monsoon, whilst in post-monsoon season, most lightning activity takes place in the afternoon. The lowest activity was found in winter with a strong peak at 1900 LST. On monthly diurnal time scale, May had overall highest and December had the lowest flash activity. The diurnal cycle is highly influenced by both local and synoptically forced convections linked to strong topographic forcing.

Spatial and temporal variability of flash rate density over Bangladesh demonstrates that north and northeast (Sylhet region) Bangladesh had highest FRD (72 fl km⁻² year⁻¹). The *monthly* FRD over 17 years indicated two prominent peaks over a year. April/May had the first peak which is generally related to intense solar heating, leading to instability in the atmosphere and convective activity. Synoptic scale support for the pre-monsoon convective activities in Bangladesh somewhat resembles convective activities and severe storms of the North American Great Plains. The second peak occurs in September and attributable to periodic monsoon break, orographic forcing and the availability of abundant moisture.

Seasonal FRD pattern revealed that the highest FRD values occur during pre-monsoon months over the northern and north-east regions with a maximum FRD of 57 fl km⁻² season⁻¹. A longitudinal expansion in the occurrence of lightning activity during monsoon season was observed as a result of shifting of convection activity associated with active and break episodes of southwest monsoon. The intensity of lightning significantly declines during post-monsoon season, with hotspots in the south-eastern and southern part of Bangladesh. Further, the activity is greatly influenced by western disturbances and the cyclogenesis in the Bay of Bengal. Due to dry and stable atmosphere, higher lightning occurred in the north-eastern and central parts of Bangladesh during winter.

Since Bangladesh currently lacks detailed and reliable information on diurnal and spatio-temporal characteristics of lightning activity, it is hoped that the database developed in this study will prove invaluable in efficient management of lightning-related disasters. Association of lightning with meteorological parameters for Bangladesh is therefore warranted. We suggest that similar types of research can be undertaken for other regions of the world where data is sparse.

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