Synoptic Climatology of Pre-Monsoon Severe Lightning Events in Bangladesh

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Research Article

Keywords: Pre-monsoon lightning, Bay of Bengal, Convective activity, SLP ridge, Synoptic climatology

Posted Date: April 7th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1502364/v1

Abstract

In Bangladesh, 1073 lightning deaths are reported only in May from 2010 to 2021 that accounts 34% of the total lightning death. The mean thunderstorm days are the maximum in Sylhet that accounts 9.46, 19.27, and 21.67 from March through May with the mean lightning frequency of 29.11, 70.50, and 82.55. Seasonal average temperature difference between winter and pre-monsoon in the country is quite high (7.8ºC) with a sharp jump from February to March (4.5ºC), whilst the maximum temperature peak in April (36.49ºC) indicates pre-monsoon instability. The 700hPa temperature shows a moderate correlation of 0.62 and 0.66 with lightning frequency and thunderstorm days, respectively. A strong SLP ridge from the northwest and 500hPa G_pH ridge over northwest to south-eastern Bangladesh favors thunderstorm mediated severe pre-monsoon lightning. The low pressure trough over the Gangetic plains of India towards Bangladesh is a very unique characteristics for convective activities in May. The pre-monsoon lightning activity is also attributed by very strong temperature anomaly whilst the associated convective precipitation system is triggered by topographic forcing of the Shillong Plateau and Chittagong hill tracts. Southerly to south-westerly low level jet assist moisture transport from Bay of Bengal (BoB) in pre-monsoon. North to north-westerly subtropical jet stream provides conditions conducive to the development of pre-monsoon thunderstorms and resultant lightning activity. Moreover, CAPE all over the country in May destabilizes the country’s atmosphere with lots of thunderstorms. The precise information of pre-monsoon climatological anomaly can be beneficial for the management of direct-death related lightning disaster in Bangladesh.

1. Introduction

Bangladesh is one of the countries at particular risk of devastating lightning mortality and morbidity. A lightning fatality database in Bangladesh developed by Dewan et al. (2017a) from 1990 to mid-2016 reported a total of 5468 casualties, composed of 3086 fatalities and 2382 injuries. They also reported more fatalities during the pre-monsoon season of March through May than during the monsoon of June through September through the year. Kumar and Kamra (2012a) and Siingh et al. (2014) mentioned Bangladesh as one of the most lightning-prone regions in Indian subcontinent mostly due to orography and local meteorological factors. The annual lightning death toll for Bangladesh was estimated 500 to 1000 by Ono and Schmidlin (2011). As the lightning contributed more than 25% of the total electricity-related casualties in Bangladesh (Mashreky et al., 2012), a precise synoptic anomaly based lightning climatology is of utmost important to reliable weather forecasts (Kandalgaonkar et al., 2010) and safety education (Roeder et al., 2015).

Lightning casualties are however, the highest during the months from April to June with its peak on May (Farukh et al., 2017; Karmakar, 2001). Thunderstorm formation and frequency distribution with their physical characteristics were documented for India and Bangladesh by Rao and Raman (1961), Gupta and Chorghade (1962), Guha (1986), Chowdhury and Karmakar (1986) and Chowdhury et al. (1991). In Bangladesh, the lightning activity increases considerably since the past few years with the annual fatality rates of 0.9 (Gomes et al., 2006), but they appear to be lower than expected in terms of the reported deaths (Holle and Lopez, 2003). The neighboring countries like India got a total of 1,755 deaths per year (Illiyas et al., 2014) and 49 annual fatalities were reported for SriLanka (Gomes et al., 2006). The topic of multiple lightning fatalities within a short period drew a great deal of attention during the last several years in Bangladesh. The month of May has both the most lightning deaths and the most lightning strokes with frequent alarmist news reports every year when multiple lightning fatalities occur (Holle and Islam, 2017). Eight of the top ten lightning fatality days since 1990 were in May and the other two were in early June (Dewan et al., 2017a). They also concluded that, the very frequent strokes in April, May, and June indicate the most vulnerable time of year for lightning in Bangladesh. The country's maximum fatality during the pre-monsoon season occurs due to frequent lightning coincident with labor-intensive agricultural practices. In Bangladesh, lightning remained an underestimated natural hazard (Dlamini, 2009) whereas, the majority of the population continues to be engaged in subsistence agriculture (Holle, 2016b), live and work in lightning-unsafe environments (Holle, 2009). For April and May, the lightning fatalities are frequent during both morning and afternoon. An average of 1.73 deaths per day in the pre-monsoon, 0.71 in the monsoon, and very small averages in other seasons is reported from 2013 to 2017 in Bangladesh (Holle et al., 2019). This study also found that all of the top ten fatality days in recent years, comprised of 19 to 51 deaths on each day, occurred during May and early June. Dewan et al. (2017b) pointed out that the lightning injury locations in subtropical and equatorial regions have sharply defined maxima related to the local timing of the arrival of the monsoon. The Global Lightning Dataset (GLD360) network detected 23.9 million strokes in the pre-monsoon, 11.4 million in the monsoon, 1.6 million in the post-monsoon, and 0.4 million in the winter season over Bangladesh with an average of 434,043; 2,049,779; 2,294,359; and 1,085,439 for March, April, May, and June, respectively (Holle et al., 2019). The pre-monsoon season daily lightning strokes detected by is around 300,000 (Holle and Cooper, 2019).

The tropical regions are estimated to account for 78% of global lightning (Christian et al., 2003) where there are marked elevation changes and land–water boundaries (Albrecht et al., 2016; Holle and Murphy, 2016). Murugavel et al. (2014) identified convective available potential energy (CAPE), orography and prevailing local meteorological conditions are the causes of thunderstorm formation and lightning is northeast India. The highest lightning frequencies are related to the regions of greatest instability (Kandalgaonkar et al., 2003; Williams, 2005) over a country's atmosphere. Therefore, the lightning discharges in thunderstorms are due to atmospheric convection (Petersen et al., 1996) occurs as a result of heating of the boundary layer by solar radiation during the day or by the mixing of air masses of different densities. The resultant lightning activity is thus an indication of convective rainfall (Petersen and Rutledge, 1998) and distribution of thunderstorms (Chaudhuri and Middey, 2013) for a particular area. The increased frequency and intensity of lightning could rise more lightning fatalities (Zhang et al., 2011). Several studies reported that the northeast parts of Indian subcontinent are a lightning hotspot with unique spatial and temporal attributes (Lal and Pawar, 2009; Ranalkar and Chaudhari, 2009; Kandalgaonkar et al., 2003, 2005, 2010; Dewan et al., 2017a; 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). Denoting Bangladesh as a lightning hotspot only a few studies have been reported like Karmakar (2001), Chowdhury and De (1995), Mashreky et al. (2012), Siingh et al. (2014), Saha and Quadir (2016), SMRC (2010), Karmakar and Alam (2005), Tinmaker and Chate (2013), Nath et al. (2009), Holle et al. (2019), Dewan et al. (2017a,b).

Since past decade a growing number of studies around the world has started to quantify lightning hazard with a goal of developing initiatives to mitigate the impacts of lightning. As the lightning casualty has been identified as one the main causes of weather-related deaths in Bangladesh, research on lightning activity in regard to synoptic climatology is worth to go through. A couple of studies have been conducted on synoptic climatology context but particularly on Indian territory to characterize spatial and temporal variations, model relationships, satellite based lightning activity etc. (Holle et al., 2019; 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., 2001; Cardoso et al., 2014). Lightning characteristics along with worldwide lightning activity over land have also been documented by numerous studies (Turman and Edgar, 1982; Orville and Henderson, 1986; Christian et al., 1999).

Farukh et al. (2011a, b) characterized lightning occurrence in Alaska using various instability indices. The CAPE, a conditional instability parameter of the tropical atmosphere (Williams and Renno, 1993), appears to play a vital role in the occurrence of lightning in Bangladesh. The Lifted Index (LI) is a measure of upper level instability considering elevated convection which tends to occur when upper level disturbances move across unstable equilibrium environment aloft (Tinmaker et al., 2017) whilst, negative LI indicates the possibility of convection (Basu and Mondal, 2002; Chaudhari et al., 2010; Litta et al., 2012). The K Index (KI) has been proved useful in indicating the probability of air mass thunderstorms (Anderson, 1991, Holle et al., 1992, Reap, 1994, and Reap and Foster, 1979). KI values higher than 35ºC indicate high probability for the development of numerous and/ or severe thunderstorms (Tinmaker et al., 2017). Nag et al. (2017) indicated that the annual, seasonal, and diurnal cycles of lightning occurrence are unique to Bangladesh and this combination does not occur elsewhere in the Indian subcontinent. Apart from 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 (Siingh et al., 2014; Pathak and Bhuyan, 2014; Kar et al., 2009; Bell et al., 2008). The typical pre-monsoon seasonal maximum in lightning fatalities in Bangladesh can now be placed into the context of knowing its synoptic climatology thoroughly. Therefore, the present piece of work explores the synoptic climatology behind severe lightning occurrence during the pre-monsoon season over Bangladesh that neither of the study includes. Three connected research questions are addressed: (i) what is the scenario of pre-monsoon severe lightning events over Bangladesh in terms of death, (ii) what are the synoptic climatological features behind this severe weather phenomena, and (iii) what are conditions of atmospheric stability indices related to pre-monsoon severe lightning events? The issues are essentially relevant for Bangladesh where near real-time weather forecasting for lightning activities is unavailable due to limitations in resources and technical expertise. The order of presentation on these issues are: section 2 will be a description of data and methodology used to conduct the study; section 3 will be focusing on results and discussions on pre-monsoon death pattern, pre-monsoon surface and upper temperature conditions, anomaly in pre-monsoon synoptic features based on 1981–2010 climatology, results of instability indices using radiosonde parameters; and finally the study summarizes by linking the above results in section 4.

2. Data And Methodology

2.1. Study area

The riverine country Bangladesh is one of the most densely populated countries in the world, located in the delta of the Padma (Ganges) and Jamuna (Brahmaputra) rivers in the northeastern part of the Indian subcontinent. The country's geographical position in South Asia lies between 20°34' to 26°38' north latitude and 88°01' to 92°41' east longitude (Fig. 1) with the maximum extension is about 440 km in E-W direction and 760 km in NNW-SSE direction having the total area of 147,570 km^2. The country's current population is 166.5 million with a density of 1265 persons per km^2 (BBS, 2020) and is impacted frequently by various natural hazards including lightning. Mostly as an impact of huge urbanization since last 1.5 decade, the rural population has decreased from 80% in 1990 to 70% in 2015 (Biswas et al., 2016). Straddling the Tropic of Cancer, the country's climate is tropical with a mild winter (December to February) and a hot, humid summer with warm and humid monsoon (June to September). The southwest and northeast monsoons have major influence on the country's climate, resulting in marked seasonality in rainfall and temperature (Salahuddin et al., 2006). The pre-monsoon (March to May) is characterized by strong, incoming solar radiation, such that thunderstorms are very frequent in this time period (Chowdhury and De, 1995) and a distinct post-monsoon appears from October through November. The country's average temperature ranges from 27.8º to 29 ºC in summer and from 18.5º to 21ºC in winter (Dewan et al., 2017c). The pre-monsoon climate of Bangladesh that potentially provide necessary ingredients for increased severe storms and lightning activity are: presence of moisture gradient or dry line (Weston, 1972), vertical wind shear (Yamane and Hayashi, 2006), land surface properties (Medina et al., 2010), subsidence of Hadley circulation (Qie et al., 2014), and low-level convergence (Saha and Quadir, 2016).

2.2. Lightning fatality data

The daily lighting death tolls were the compilations of primarily disaster reports and newsletters from national and different agencies of Bangladesh. Unfortunately, none of the relevant government agencies in Bangladesh possess precise information related to lightning casualty. In this study, the archives of two reputed most popular daily Bengali national newspapers namely The Daily Ittefaq and The Daily Prothom Alo were the dominant sources of information, which involved physically scanning of each newspapers from 2010 to 2021. Additionally, the reports from non-government agencies named Disaster Forum and Network for Information Response & Preparedness Activities on Disaster were taken into consideration to reduce the data inhomogeneity. To avoid duplication, data were cross checked against the corresponding day, year, and location of other entries. Data from these reports were compared with National Disaster Response Coordination Center (NDRCC) of the Ministry of Disaster and Relief from 2016 to 2021, as

NDRCC started recording the death tolls after declaring lightning as a national disaster in 2016. Holle and Cooper (2019) noted that the growth of internet-based reports of lightning events that had been occurring but not disseminated beyond a local region in less developed countries including Bangladesh. The statement led to the realization that many more lightning injuries are occurring than had previously been considered. For much of Africa and Southeast Asia, lightning fatality and injury data are notably missing whilst existing data indicates that the current number of people killed per year is about 4,000 to 5,000 (Holle and Cooper, 2019). Fortunately for Bangladesh, a well-documented database of lightning fatalities has been revealed by Dewan et al. (2017a), where 93% of the lightning deaths were reported in rural areas and associated with work times. A similar rural percentage of 91% was found by Biswas et al. (2016). Nevertheless, improved information about the impacts of lightning by encouraging more complete press coverage and news reports of events when they occur in more remote areas possess enormous importance for Bangladesh.

2.3. Thunderstorm days and lightning frequency data

The ‘number of thunderstorm days’ and ‘lightning frequency’ data for the period of 2010 to 2021 were obtained from the Climate Division of Bangladesh Meteorological Department (BMD) for 35 stations only, though the frequency seems too undermined compared to Vaisala or NASA’s TRMM Lightning Imaging Sensor (LIS, Christian et al., 1999; Bond et al., 2002) based satellite observations. For example, the Global Lightning Dataset (GLD360) network detected a total of 37,222,493 lightning strokes from 2013 to 2017 over Bangladesh (Holle et al, 2019). LIS based distribution of lightning flash by season over Bangladesh landmass counts: pre-monsoon (69.2%), monsoon (24.1%), post-monsoon (4.6%) and winter (2.1%) (Dewan et al, 2017a). LIS records both cloud-to-ground (CG) and intra-cloud (IC) lightning and shows them as a total flash count (Tinmaker et al., 2009). BMD however, records the ‘number of thunderstorm days’ and ‘lightning frequency’ using the National Coding practices in the codes those have been formulated in accordance with the recommendations of the WMO Region II. Here, the ‘lightning frequency’ include surface code 13 (lightning visible, no thunder heard), and the thunderstorm days are the ‘days of thunderstorms’ which include surface codes of 17 (thunderstorm but no precipitation), 29 (thunderstorm with or without precipitation, hail, small hail, snow pellets), 95 (thunderstorm, slight or moderate, without hail but with rain and/or snow), 96 (same as 95 with hail), 97 (heavy thunderstorm without hail but with rain and/or snow), 98 (thunderstorm combined with dust or sandstorm), 99 (heavy thunderstorm with hail) (BMD, 1996; Karmakar, 2001). These Codes have been amended and modified according to WMO Manual on Codes, Volume 1.1, WMO No. 306, 1995 edition and replaced the 1988 edition. The new modified Code Form FM 12-X-SYNOP has been adopted by the BMD for use of the land stations.

2.4. Temperature data

The long term monthly maximum (T_{max}) and minimum (T_{min}) temperature data for Dhaka station from 2010 to 2021 were obtained from Climate Information Management System (CIMS) database of Bangladesh Agricultural Research Council (BARC) of the Government of the People’s Republic of Bangladesh. The data source is more reliable without having any missing values. The T_{max} and T_{min} values are widely used to characterize extreme meteorological phenomena as measures of dispersion and frequency of occurrence (Bednorz, 2011). Changes in surface temperature may affect the seasonal and spatiotemporal distribution of lightning activity. Relatively rapid seasonal temperature changes from the minimum in winter to the maximum during pre-monsoon may have a role in increased lightning activity in Bangladesh (Kumar and Kamra, 2012a, b). Moreover, surface air temperature (Williams et al., 1992; Reeve and Toumi, 1999) and air pollution (Kar et al., 2009; Coquillat et al., 2013) have been found to influence lightning at both global and local scales. To assess upper atmospheric temperature conditions, 700 hPa temperature data from March to May for the Dhaka radiosonde station (VGTJ; 41923) measured at 0600 LST were derived from the web portal of the Department of Atmospheric Science, University of Wyoming, and analyzed for the period of 2010 to 2021.

2.5. Synoptic climatology data

To reveal the synoptic climatology, individual synoptic composite anomaly maps for March, April, May and three months composite mean for March to May were constructed for 2m & 850 hPa air temperature (in ºK), sea level pressure (SLP, in Pa) & 500 hPa geopotential height (G_pH, in gpm), 1000 & 850 hPa relative humidity (in %), 850 & 300 hPa vector wind (in m s^{-1}), convective available potential energy (CAPE, in J kg^{-1}), precipitable water (in kg m^{-2}), and precipitation rate (in mm day^{-1}) based on 1981–2010 climatology. To derive the synoptic circulation patterns, all data were used from the National Centers for Environmental Prediction/National Center for Atmosphere Research (NCEP/NCAR) reanalysis (Kalnay et al., 1996) encompassing the synoptic region 9° to 39°N and 75° to 105°E of the southeast Asia which ensured quality atmospheric data at a 2.5° grid resolution. Thunderstorms and the attendant lightning activity can vary dramatically in response to large-scale synoptic forcing. Reap (1994) mentioned that, lightning is a manifestation of cumulonimbus cloud dynamics and microphysics and poses the scope to have further insight into the synoptic systems. VanWagtendonk and Cayan (2008) have reported high lightning occurrences to be associated with increased G_pH patterns in California.

2.6. Radiosonde data

To assess the upper atmospheric stability indices, radiosonde data from March to May for the Dhaka radiosonde station (Station identifier: VGTJ; Station number: 41923) measured at 0600 LST (GMT + 6) were derived from the web portal of the Department of Atmospheric Science, University of Wyoming (http://weather.uwyo.edu/upperair/). Stability indices namely Showalter index (SHOW; Showalter, 1953), lifted index (LI; Galway, 1956), severe weather threat index (SWEAT; Miller et al., 1971, 1972), K index (KI; George, 1960), Convective available potential energy (CAPE; Alves et al., 2020), Convective inhibition (CIN; Alves et al., 2020), lifted condensation level temperature (LCL_T) & pressure (LCL_P), and precipitable water (P_{WAT}; Huschke, 1959) were derived and analyzed for the period of 2010 to 2021. The calculations were done using following equations:

$$SHOW = Te_{500} - Tp_{850} \text{ ………………………………}(i)$$

$$LI = Te_{500} - Tp_{500} \text{ ………………………………}(ii)$$

$$SWEAT = 12\ Td_{850} + 20\ (TT - 49) + 2\ (f8) + f5 + 125\ (S + 0.2) \ldots\ldots\ldots\ldots (iii)$$

$$KI = \Delta Te_{850-500} + Td_{850} - DD_{700} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (iv)$$

$$CAPE = \int_{Zf}^{Zn} g\left\{\frac{Tp - Te}{Te}\right\} dz \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (v)$$

$$CINS = \int_{\approx bottom}^{\approx top} g\left\{\frac{Tp - Te}{Te}\right\} dz \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (vi)$$

where, Te_{500} & Te_{850} is the environmental temperature at 500 & 850 hPa in *ºC*, Tp_{850}& Tp_{500} is the temperature of air parcel lifted adiabatically to 850 & 500 hPa in *ºC*,Td_{850} is the dew point temperature at 850 hPa in *ºC*, *TT* represents the total totals index value, *f8* and *f5* represent the 850 & 500 hPa wind speed in *knots*, *S* is the *sine* of the angle between the 500 & 850 hPa wind directions (i.e., the shear), $\Delta Te_{850-500}$ is the temperature difference between 850 to 500 hPa in *ºC*, DD_{700} is the dew point depression at 700 hPa in *ºC*, Z_n is the height of the equilibrium level (EL) in *m*, Z_f is the height of the level of free convection (LFC) in *m*, *g* is the acceleration due to gravity in ms^{-2}, $\approx_{top}$ is the top altitude of a CIN layer in *m*, and $\approx_{bottom}$ is the bottom altitude of a CIN layer in *m*. The values for LCL_T, LCL_P and P_{WAT} were directly taken from the daily radiosonde data records. These stability indices are a measure of the atmospheric static stability, and the values are used to quickly assess the potential of the atmosphere to produce convection and consequently severe weather (Tinmaker et al., 2017).

3. Results And Discussion

3.1. Pre-monsoon lightning pattern

Figure 2(a) shows the reported annual total of lightning death and injury along with the total death in May from 2010 to 2021 for whole of Bangladesh. The highest annual death toll was 361 reported in 2016 while the maximum annual injury was 275 in 2014. The total lightning tempted death and injury count in last one decade (2010–2021) reaches 3154 and 2075, respectively. According to Hoque et al. (2019), Bangladesh is one of the world's leading lightning-prone countries. Cooper and Holle (2018), and Dewan et al. (2107a) reported that lightning related deaths and injuries are increasing in Bangladesh from 1990 through 2017. The annual fatality rate per million is 1.6 with 251 fatalities per year for the period from 1990 to 2016 (Dewan et al., 2017a). They also indicated the unusually large number of morning fatalities during the pre-monsoon and monsoon seasons. A large number of deaths are reported in May compared to the whole year. According to news reports, some mentionable lightning death events are the death of 31 people on 31 May 1993, 17 & 24 people on 21 & 23 May 2011, 33 people on 5–6 May 2013, 19 killed on 2–3 May 2015, 51 & 38 on 12 & 13 May (Dewan et al., 2017a), 22 killed on 19 May 2021 in 10 districts. However, following the deaths of 89 people on 12 and 13 May 2016 (Holle and Islam, 2017), the Ministry of Relief and Disaster Management of the Bangladesh government declared lightning as a natural disaster on 17th May 2016. Holle et al. (2016a) also mentioned the death of 64 people on 12–13 May 2016 in another study. A review of medical records found 10 injuries per death in the United States (Cherington et al., 1999) and four injuries per death in Malawi (Salerno et al., 2012). Some earlier findings reported that the majority of fatalities in developing countries are located in rural areas (Cardoso et al., 2014; Gomes and Ab Kadir, 2011; Holle, 2016a; Zhang et al., 2011). The database of Dewan et al. (2017a) for Bangladesh has yearly 30 deaths and 22 injuries from 1900 to 1999, 106 deaths and 72 injuries from 2000 to 2009, and 251 deaths and 220 injuries from 2010 to 2015.

Moreover, annual casualties had increased by a significant amount due to improved news coverage. The daily reliable newspapers, news from electronic and print media, and NDRCC reports were the main source of lightning induced death tolls. In Bangladesh, improved news reporting in the last decade has had a major effect on documenting more lightning injuries that had probably been occurring but not documented nor reported to a national data collection center where, underreporting is a major issue due to various reasons (Holle et al., 2005; Dlamini, 2009; Trengove and Jandrell, 2015). Though there have discrepancies regarding the death toll data, a comparison among news reports and NDRCC has been drawn in Fig. 2(b) along with percentages of monthly average reported deaths. Death in May however, is one of the important lightning induced death pattern in Bangladesh. In last 12 years, 1073 deaths were reported in May only (Fig. 2(b)) that accounts 34% of total death. The per cent of death in May varied from 13% in 2019 to 53% in 2018 with the maximum death count of 145 in 2018. April, May, and June accounted for 69% of all lightning fatalities for the year 2013 to 2017 where, the farming-related deaths were the maximum in May and was more than three times as higher as either April or June (Holle et al., 2019). Most of these victims were male specifically in rural Bangladesh because of their outdoor work commitments (Dlamini, 2009; Raga et al., 2014; Singh and Singh, 2015).

Figure 3(a) and 3(b) shows the month wise lightning frequency and thunderstorm days, respectively averaged for the period of 2010 to 2021 for the top five lightning affected districts. Sylhet and Srimangal are the extreme northeast districts of Bangladesh (Fig. 1) having the larger number of lightning occurrences along with higher thunderstorm days. The mean thunderstorm days are 9.46 in March, 19.27 in April and 21.67 in May for Sylhet with the mean lightning frequency of 29.11, 70.50 and 82.55 for the respective months. The 2nd most deadly spot Srimangal poses the mean thunderstorm days and mean lightning frequency values as 6.82, 14.45, 17.73 and 18.0, 42.86, 56.91, respectively for the months of March, April and May. In contrast, the capital city Dhaka experiences 41% of thunderstorm days and 44% of lightning frequencies in monsoon season (June–September) compared to pre-monsoon with 36% and 42%, respectively. Figure 3(a) and 3(b) also indicates that during the annual course, both of the lightning frequency and thunderstorm days show bimodality for most of the districts. The lightning frequency shows a consistent increase from February that attains a maximum in May and, thereafter, starts decreasing consistently till August (except for Sylhet) and again increases to a second lower peak in September (Fig. 3a). The thunderstorm days also exhibit the same pattern but with a second lower peak in October (Fig. 3b). Tinmaker et al. (2017) found the similar trend for flash rate density in Indo-Gangetic plains. Karmakar (2001) observed that, the mean frequency of thunderstorm days increases considerably as the season progresses from March to May showing a significant linear relationship. He also noted that, the mean thunderstorm days varies from 1 to 10 in March, 2 to 21 in April, and 4 to 23 in May. According to LIS observation from 1998 to 2014, 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 (BoB) (Dewan et al, 2017b). They also computed the total flash counts for pre-monsoon, monsoon, post-monsoon and winter over land as 49,526 (69.2%), 17,245 (24.1%), 3284 (4.6%) and 1480 (2.1%), respectively whereas, during pre-monsoon the flash rate density ranges from 0.26 to 57 flash per km^2 per season with a mean of 17.

3.2. Pre-monsoon air temperature and lightning activity

Figure 4(a) shows the variations in monthly mean air temperature (T_{avg}) averaged over maximum (T_{max}) and minimum (T_{min}) monthly temperature, and standard deviation (SD, boxes), as well as the T_{max} and T_{min} (upper & lower circles) during the period of 2010–2021 for Dhaka station. The figure indicates that the T_{avg} difference between winter (December–February) and pre-monsoon (March–May) season is quite high (7.8ºC) with a sharp jump in temperature from February to March (4.5ºC). The T_{avg} increases by 2.4ºC from March to April and reach the maximum of 29.07ºC in June. Surprisingly, the T_{avg} shows a steady trend from May to September with the values ranges from 28.85ºC (July) to 29.07ºC. Though the T_{avg} in monsoon (June–September) is higher by 0.83ºC compared to the pre-monsoon but it drops by 3.11ºC as the post-monsoon (October–November) arrives. Figure 4(a) suggests that the bimodality of lightning activity as shown in Fig. 3(a) is related to the variation in air temperatures whilst, variations in the incoming shortwave radiation from the Sun are attributed mostly (Williams, 1994). The months of April, May and June are the warmest in Bangladesh and the moist air quickly rises upward to meet with dry north-westerly winds to cool and form large storm clouds (Bandara et al., 2004), which may lead to severe pre-monsoon lightning activity. Price and Rind (1994) found that surface air temperature is a parameter leading to more instability in the lower atmosphere and could increase the amount of lightning. Almost the similar findings can be drawn from the Fig. 4(a), where the mean T_{max} increases by 6.63ºC in pre-monsoon than winter. Notably the T_{min} difference in between winter and pre-monsoon is the maximum (9.84ºC) compared to all other seasons. The peak of T_{max} (36.49ºC) clearly indicates the possible reasons behind more instability in April and the resultant lightning activity. Williams (1992; 1994; 2005) pointed out that in response to projected increase in global temperature the worldwide lightning activity is expected to enhance by up to 40% (Nath et al., 2009; Reeve and Toumi, 1999) by the rise of average global temperature of 1°C. Wang (2006) urged that the trigger for release of convective latent instability is provided by the day time heating, orographic features and sea breeze penetration. Figure 4(b) shows a moderate correlation ($R^2 = 0.51$, $p \leq 0.0001$) between T_{avg} and lightning frequency while, 4(c) denotes interrelations between T_{avg} and thunderstorm days ($R^2 = 0.46$, $p \leq 0.0001$).

To assess the response of upper air temperature to pre-monsoon lightning activity, air temperature data for 700 hPa level has been analyzed and shown in Fig. 4(d) and 4(e). Figure 4(d) and 4(e) imply correlation values of 0.62 and 0.66 for the interrelations in between 700 hPa temperature and lightning frequency, and 700 hPa temperature and thunderstorm days, respectively. Tinmaker et al. (2017) found the similar results of 700 hPa air temperature with lightning flash rate density during pre-monsoon over Indo-Gangetic plains with a higher correlation ($R^2 = 0.70$, $p \leq 0.0001$). Rorig et al. (2003), and Rorig and Ferguson (1999, 2002) also studied the 700 hPa and 500 hPa temperature difference and dewpoint depression for the western US and found significant differences on ‘dry’ and ‘wet’ days.

3.3. Synoptic climatology and severe lighting activity

3.3.1. Sea level pressure (SLP) & Geopotential height (G_pH)

Figure 5(a), (b), and (c) shows composite geographical distributions of March, April, and May SLP (in Pa, shaded) and 500 hPa G_pH (in gpm, solid line) anomalies compared with the climatology from 1981 to 2010 encompassing the synoptic region 9° to 39°N and 75° to 105°E. In March, a depression zone (-120 Pa) exists over the far northeast of Bangladesh particularly with its center on south of Arunachal Pradesh of India (Fig. 5a). Notably, the edge of this anomaly zone covers the extreme northeast of Bangladesh. Romatschke et al. (2010) and Romatschke and Houze (2011a) reported northeast part of Bangladesh and its neighborhood as a favorable area for convective activities during pre-monsoon. In April, a ridge with strong positive SLP anomaly (> 120 Pa) enters into Bangladesh from the northwest (Fig. 5b) whilst, most of the country’s area are covered by moderate positive (15 to < 120 Pa) SLP anomaly zone. The transition zone between the positive and negative anomaly partly covered the extreme northeast and southeast of the country. Conversely, a ridge with positive 500 hPa G_pH anomaly (8 gpm) extended over northwest to southeastern Bangladesh, suggestive of a predominantly northern airflow in the mid-troposphere. Under these circumstances, the orographic lifting with respect to complex terrain in the north and north-eastern Bangladesh could initiate instability of the atmosphere that favors thunderstorm mediated severe lightning during pre-monsoon (Chaudhuri and Middey, 2013; Lefort, 2013; Tinmaker and Ali, 2012; Yamane et al., 2012). Wang (2006) reported that thunderstorms and lightning activity are mostly isolated, but sometimes widespread if the upper level features such as the penetration of deep westerly trough up to 15ºN over India are favorable.

In May, a trough with moderate negative SLP anomaly (-75 Pa) exists over Bangladesh and West Bengal-Bihar-Jharkhand of India with its center on west, keeping the extreme east of the country free from it (Fig. 5c). This elongated trough of low pressure over the Gangetic plains of India which intrude Bangladesh through the middle of the country is a very unique characteristics for the development of convective activities over the country. Holle and Cooper (2016b) found a good relation of frequent lightning with equatorial trough in tropical regions. Furthermore, 500 hPa G_pH shows the strongest positive anomaly (12 gpm) dominated over southeastern Bangladesh. In addition to strong insolation and orographic lifting, presence of low to the north of 25°N and large-scale flow at 500 hPa lead to the genesis of numerous thunderstorms in northeast India and Bangladesh during pre-monsoon (Bhattacharaya et al., 2013). The seasonal GLD360 maps for the larger Indian subcontinent (Nag et al., 2017) and LIS maps (Dewan et al., 2017b) show the pre-monsoon to have the most lightning in the northeast, but displaced somewhat to near and north of Bangladesh border (Holle et al., 2019). On the onset of monsoon, lightning activity move in a south-westerly direction from north-eastern Bangladesh towards West Bengal in India, while the south and south-eastern parts of Bangladesh experience high lightning activity during post-monsoon due to regional orographic lifting and low-pressure systems in the BoB (Dewan et al., 2017b). The swing of the strongest 500 hPa G_PH anomaly center from May to June seems to be related with the shifting of lightning activity from northeast (in pre-monsoon) to southwest (in monsoon) of Bangladesh *(figure not shown here, supplied as a supplement figure-1)*.

Figure 5(d) represents the composite geographical distributions of three months mean SLP and 500 hPa G_pH from March to May. In respect to pre-monsoon, the whole of Bangladesh was dominated by low SLP system with the strongest elongated trough (1008 hPa) from the west. In contrast, the mean 500 hPa G_pH shows 5810 to 5840 gpm zone from north to south of Bangladesh. Kamble and Kanoujia (1990) reported that the occurrence of multiple squalls started in April and got the maximum in May influences severe lightning events over central India. Moreover, landmass and orography act as passive components whilst large-scale circulation acts as active component in the distribution of lightning over Bangladesh (Kandalgaonkar et al., 2005).

3.3.2. Surface and upper air temperature

Figure 6(a), (b), and (c) show composite geographical distributions of March, April, and May air temperatures of '2m height' (in ºK, shaded) and '850 hPa' (in ºK, solid line) anomalies compared with the climatology from 1981 to 2010. Figure 6(d) represents the same but for March to May composite mean air temperature in ºK. The strongest positive anomaly zone (2 ºK) of 2m air temperature is noticed in March (Fig. 6a) over the far northeast of Bangladesh particularly on the south of Arunachal Pradesh of India that coincide with the position of depression as shown in Fig. 5(a). On the other hand, the strongest positive 850 hPa temperature (2.1 ºK) anomaly in March also is also seen over the same location. In April, a moderate (1.5 ºK) positive temperature anomaly zone at 2m height covers all over Bangladesh with a relatively stronger anomaly (2 ºK) in the far north, specifically on the south (29ºN) of Tibetan Plateau (Fig. 6b). Though confined within a very small area, another positive anomaly zone (1.75 ºK) is also noticed on the extreme middle-eastern edge of the country. Conversely, the strongest positive 850 hPa temperature (2.5 ºK) with very steep anomaly gradient is seen over the extreme northeast of Bangladesh over the Shillong Plateau and over the Chittagong hill tracts.

Figure 6(c) shows a very strong positive 2m temperature anomaly zone (2 ºK) from southeast to northwest of Bangladesh and extends over the central Myanmar for May. The north-eastern districts of Bangladesh is extremely influenced by this anomaly formation where the annual stroke densities are very large and decrease gradually to the south and west as described by Dewan et al. (2017a). The strokes have a peak occurrence between mid-April and end-May, and many morning strokes occur in the afternoon during the pre-monsoon and monsoon seasons which is unique within the Indian subcontinent (Nag et al., 2017). Daytime occurrence of cloud to ground lightning is more evident in these regions as the ground is heated by daytime incoming solar radiation (Dewan et al., 2017a). Temperature at 850 hPa however, also shows the existence of deep positive anomaly core (1.05 ºK) over northern Bangladesh. The lightning activity in these regions broadly attributed by solar heating leading to destabilization of the atmosphere and development of convection, particularly during pre-monsoon and monsoon seasons (Williams, 1994; Kumar and Kamra, 2012a; Patra et al., 1998; Tinmaker and Chate, 2013; Nath et al., 2009; Manohar and Kesarkar, 2003). Romatschke et al. (2010) demonstrated that deep convective cores over land in South Asia is clearly associated with solar heating and topography, whilst terrain and land surface characteristics triggers intense convection in the Meghalaya Plateau region (Choudhury et al., 2016; Romatschke and Houze, 2011a, b). The mean composite of March to May in Fig. 6(d) represents two distinct maximum (310 ºK) and minimum (270 ºK) temperature zones particularly over the Indo-Gangetic Plains (24 ~ 27ºN) and over the north of Himachal Pradesh (32 ~ 36ºN). The influence Indo-Gangetic temperature zone is also evident for 850 hPa level that intruded from the west toward Bangladesh.

3.3.3. Relative humidity & Vector wind

The distribution of low level (1000 hPa; shaded) relative humidity in Fig. 7(a) represents a strong positive anomaly (15%) over the southern parts of Bangladesh in March. The southern positive anomaly zone is the extension from Peninsular India with its center on BoB. The circulation of southerly to southwesterly (Fig. 8a) low level jet (LLJ) transports required moisture from the BoB to the plains of Bangladesh and the adjoining states of India in March. Figure 7(b) represents a stronger negative anomaly (-10%) over most of the eastern and northern parts of Bangladesh for April. The circulation of southerly to south-westerly (Fig. 8b) LLJ supplies huge moisture from the BoB toward Bangladesh in April, and seriously impacted on severe lightning events followed by genesis of severe thunderclouds. One of the characteristics of Asian monsoon affecting Bangladesh is the tropical moisture that brought from the south into the Indian subcontinent. It is reported that the sufficient moisture in the atmosphere leads to an increase in the number of thunderstorm clouds (Chaudhari et al., 2010; Litta et al., 2012; Galway, 1956; Schulz, 1989). Petersen et al. (1996), and de Pablo and Soriano (2002) also concluded that lightning activity is mostly affected by the moisture content, where during pre-monsoon, the land areas receive large moisture content from the BoB up to a height of about 2 km but confined only below latitude around 15ºN (Tinmaker et al., 2009). The solid dashed lines in Fig. 7(b) denotes relative humidity at 850 hPa which shows a deep negative anomaly zone (-8%) over northeast of Bangladesh. The LLJ near 850 hPa is the main artery through which moisture is fed into the flow over southern parts of South Asia and is then carried across the BoB to adjoining Southeast Asia (Tinmaker et al., 2009). However, Saha et al. (2017) reported that the 300 hPa water vapor strongly influenced lightning activity of Indian region.

In May, almost different moisture pattern (Fig. 7c) has been seen for both of 1000 and 850 hPa level. The strongest negative anomaly zone (-20%) is evident at 1000 hPa over the southeast of Bangladesh (southeast Myanmar) that extends toward northwest. Simultaneously, two negative anomaly zones (-12.5%) are seen at 850 hPa over southeast (southeast Myanmar) and north (in between Bhutan & Nepal) of Bangladesh. The circulation of north to north-westerly jet stream toward Bangladesh (Fig. 8c) is another characteristics of severe lightning events in May. A westerly jet stream lies south of the Tibetan Plateau at upper levels while there is ascent over the India and Bangladesh land mass, and descent over the surrounding seas (Weston, 1972), has profound influence on pre-monsoon lightning activities. The mean 1000 hPa humidity for March to May (Fig. 7d) denotes a strong negative zone (-10%) over far east of Bangladesh that stretched from the north of Laos toward the south of Tibetan Plateau. Two anomaly zones (-10%) with very steep gradients are also noticed at 850 hPa over the same regions. The situation impacted on large-scale circulation, which takes place across the eastern coast of India and Bangladesh at about 80 km from BoB (Lohar et al., 1994; Sadhukhan and De, 1998).

The strong southerly to south-westerly (Fig. 8a, b, c) LLJ converged over the narrow belt of Bangladesh and could vigorously assist in moisture transport from BoB, and finally to develop severe convective activity within the country. Williams et al. (2000) argue that the sustained lightning incidence may be related to nonlinear effects of cold outflow boundaries which destabilizes the atmosphere over a large area. The overrunning of a warm moist southerly or south-easterly wind by a westerly or north-westerly cold air with a high lapse rate is believed to be an important mechanism behind the genesis of many nor'westers in pre-monsoon in Indian subcontinent (Ranalkar and Chaudhari, 2009; Mukhopadhyay et al., 2005; Peterson and Mehta, 1981; Weston, 1972).

The anomaly distribution of 300 hPa wind flow represents the subtropical jet stream (Fig. 9a, b, c) over Bangladesh that provides favorable mechanism of strong vertical wind shear and development of severe convection, and contribute to the severity of the thunderstorms as well. The transition between cold dry air from the north (Fig. 9a, b, c) and warm moist air from the south (Fig. 8a, b, c) over the country could contribute for the development of thunderstorms and severe lightning activity. However, the intense thunderstorms associated with pre-monsoon severe lightning activity over northeast of Bangladesh implies that the mesoscale convection is higher in the mountainous region (Qie et al., 2003; Pathan, 1994). The mechanisms 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 abundant moisture in the lower troposphere (Siingh et al., 2014; Ranalkar and Chaudhari, 2009). The three months composite mean in Fig. 8d however, shows southwest to north-easterly flow as a usual pattern for lower tropospheric wind circulation. In contrast, west to easterly wind motion with very steep gradients from 25ºN to 17ºN are noticed for 300 hPa level (Fig. 9d).

3.3.4. Precipitation rate, Precipitable water (P_{WAT}), & Convective available potential energy (CAPE)

Figure 10(a), (b), and (c) shows composite geographical distributions of March, April, and May precipitation rate (in mm day^{-1}) anomalies with three months (March–May) composite mean in Fig. 10(d). On the beginning of pre-monsoon (i.e., in March), only the extreme northeast of Bangladesh was covered by very low positive zone (1 mm day^{-1}) of precipitation. But in April, the maximum positive anomaly (4 mm day^{-1}) exists over northeast of Bangladesh with its center on Shillong Plateau of Meghalaya (Fig. 10b). The strong positive trough also extends over the hill tracts of Chittagong district. The largest pre-monsoon lightning activity over the north, extreme northeast, and southeast of Bangladesh is attributed by severe thunderstorm development associated with convective precipitation system by topographic forcing of the Shillong Plateau and Chittagong hill tracts. It is reported that lightning frequency within Bangladesh is largest a short distance to the south of the Shillong Plateau (1900 m) whereas, lightning strokes detected by GLD360 are most frequent in the south of the Shillong Plateau and decrease to the south and west (Holle et al., 2019). Cherrapunji on the southern edge of the Shillong Plateau possess very large annual rainfalls of 11.4m (Jennings, 1950), 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) whilst arc shaped mesoscale convective precipitation system also exists (Lal and Pawar, 2009; Rafiuddin et al., 2013). In the northeast and south-eastern Bangladesh, topographic forcing of the Shillong Plateau and Chittagong hills allow convection and associated lightning to develop (Romatschke et al., 2010; Medina et al., 2010). Thus, topography in conjunction with favorable 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) particularly in the northeast and southeast of Bangladesh in April. Almost the same situation prevails in May also (Fig. 10c), whilst the thunderstorm mediated precipitation and lightning activities were dominated by orographic effects particularly in northeast and southeast of Bangladesh. The composite geographical distributions of March, April, and May P_{WAT} (in kg m^{-2}) anomalies are shown in Fig. 11(a), (b), and (c), with March to May composite mean in Fig. 11(d). In the months of March and April, extending from the south-eastern (Peninsular) India a robust positive P_{WAT} anomaly zone occupies all over the country. In April, the anomaly extends up to 4.5 kg m^{-2} with a negative anomaly zone (-3 kg m^{-2}) far southeast of Bangladesh (Fig. 11b) particularly over southern Myanmar. Almost opposite condition is seen in May whilst extending from the southwest, a robust negative anomaly zone (-4.5 kg m^{-2}) occupies all over Bangladesh (Fig. 11c) with its center on southwest. This further provides conditions conducive to the development of thunderstorms and hence more lightning activity over Bangladesh is noticed during the pre-monsoon season. Three months composite mean in Fig. 11(d) shows intrusion of huge (35 kg m^{-2}) southern P_{WAT} zone stretching from the BoB toward the narrow belt of Bangladesh.

Figure 12(a), (b), and (c) shows composite geographical distributions of CAPE (in J kg^{-1}) anomalies from March through May, with three months (March–May) composite mean in Fig. 12(d). The strongest negative CAPE anomaly center (-500 J kg^{-1}) is noticed over southwest of Bangladesh (Fig. 12a) in March that extends toward northeast covering almost whole of the country except the extreme north. In April, a negative anomaly zone (-200 J kg^{-1}) extending from the southwest to northeast is also seen (Fig. 12b) that covers up to 25º15'N. These anomaly zones suggest the origin of instability that mainly started from western BoB (alongside of Peninsular India) and gradually moved inside Bangladesh in March, and persists over Bangladesh with a relatively lower degree of instability (-150 J kg^{-1}) in April. But in May, a very strong CAPE anomaly zone exists all over the country with its center (-500 J kg^{-1}) in the middle (Fig. 12c). The situation may destabilizes the country’s atmosphere with lots of thunderstorms and the resultant lightning occurrence. Dewan et al. (2017b) noticed the maximum mean monthly CAPE from 1998 to 2014 over Bangladesh occurred in April while the mean maximum lightning flashes occurred in May. They also concluded that the correlation between CAPE and lightning over Bangladesh landmass have significant relationship at the 95% confidence level, for example, the correlation coefficient was found 0.90 (monthly), 0.70 (pre-monsoon), 0.55 (monsoon) and 0.70 (annual) (Dewan et al., 2017c). Figure 12(d) shows the existence of very strong CAPE zone (2000 J kg^{-1}) on the southwest of BoB extended over southern Bangladesh. The seasonal distribution of 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 in the month of April and May (Yamane et al., 2010a, b).

3.4. Stability indices and severe lightning activity

In regard to a thunderstorm prone country like Bangladesh, factors influencing lightning activity are important for understanding the mechanism of its generation and improving forecasting of the phenomenon (Saha et al., 2017). In this study, an attempt was taken to assess nine upper air stability indices (Fig. 13a ~ i) for the pre-monsoon season over Dhaka station in Bangladesh. Lifted index (LI; equation *ii*) is proved as an indicators of thunderstorm conditions whilst Fig. 13(a) clearly shows the upper atmospheric destabilization from mid-March to May. This is because the rising air parcel is much warmer than its surroundings and can accelerate rapidly and create severe thunderstorms (Tinmaker et al., 2017). The monthly mean LI are 0.58, -2.76, and − 2.97 ºC for March, April, and May, respectively. The gradual decreasing trend from March through May suggests huge possibility of pre-monsoon thunderstorm and lightning activity. K index (KI; equation *iv*) is a measure of thunderstorm potential based on the vertical temperature lapse rate, and the amount and vertical extent of low-level moisture in the atmosphere. The monthly mean KI are 18.69, 27.06, and 31.77 ºC for March through May. The gradual increasing trend of KI (Fig. 13b) from mid-March suggests initiation of convective activities with possibilities of thunderstorm occurrence. In case of monthly lightning distribution, 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 BoB and local sources (Tinmaker et al., 2014; Kodama et al., 2005; Tinmaker and Ali, 2012; Tyagi et al., 2011; Lohar et al., 1994). Tinmaker et al. (2009) noted that the lightning discharges are an indication of atmospheric convection occurs under unstable atmospheric conditions where the extreme lightning frequencies are related to the regions of greatest instability. Showalter index (SHOW; equation *i*) is a popular severe weather index especially useful when a shallow, cool layer of air below 850 hPa conceals greater convective potential above. The monthly mean SHOW are 4.26, 1.13, and 0.18 ºC from March through May, whilst the gradual decreasing trend suggests the possibility of thunderstorm. Figure 13(c) shows a sharp decline of SHOW from March to April and the minimum in May implies the possible reasons of huge pre-monsoon thunderstorms. This maximum lightning activity occurs when the heating of the land surface results in vertical instability leading to lightning producing convection as described by Yamane et al. (2010a, b) and Holle and Cooper (2016b).

Severe weather threat index (SWEAT; equation *iii*) evaluates the potential for severe weather by combining low-level moisture, instability (total totals index), lower and mid-level wind speeds, and warm air advection into one index. The SWEAT from March through May are 158.17, 211.56, and 242.81, respectively. Figure 13(d) suggests slight severe thunderstorms due to atmospheric instability from

March to May and that has been gradually increasing in respect of months. In fact, the thunderstorm and associated lightning activity is the manifestation of mesoscale instability of the atmosphere (Goodman and MacGorman, 1986; Kandalgaonkar et al., 2003; Williams, 2005). Moreover, the convergence flow in the planetary boundary layer is driven by the sea surface temperature gradient in tropical zones, is strongly related to atmospheric instability (Numaguti, 1995; Barrows et al., 2007; Kandalgaonkar et al., 2002). CAPE (equation *v*) is considered as an important variable for predicting lightning occurrence whereas, an increase of lightning activity with increasing CAPE is evident from several studies (Williams and Renno, 1993; Romps et al., 2014; Galanaki et al., 2015). Analysis showed that CAPE increases from March to May with the peak in mid-May (Fig. 13e) and begins decreasing with the onset of monsoon in June. The monthly mean CAPE are 575.17, 1095.57, and 1140.05 J kg^{-1} from March through May. Yamane and Hayashi (2006) found the maximum median CAPE over Bangladesh in April while the frequency of squall-type systems is highest in May (Rafiuddin et al., 2010). Similar findings are also noted from the studies of Pawar et al. (2012), Romatschke and Houze (2011), Qie et al. (2014) and Choudhury et al. (2016). The convective inhibition (CIN) in Fig. 13(f) depicts the maximum declination from mid-March to mid-May suggests the possibility of pre-monsoon lightning activities. The monthly mean CIN are − 112.06, -163.32, and − 129.30 J kg^{-1}, respectively from March through May.

P_{WAT} indicates the amount of water vapor in the atmosphere. The monthly mean P_{WAT} are 30.67, 39.68, and 49.98 mm from March through May, respectively. The anticyclones in the northern BoB and presence of large inland water bodies within Bangladesh are huge sources of moisture, leading to higher P_{WAT} content in the lower troposphere during pre-monsoon (Ranalkar and Chaudhari, 2009; Chowdhury and De, 1995). As seen from Fig. 13(g), the increasing trend of P_{WAT} in pre-monsoon indicates supply of huge moisture as a fuel for thunderstorm and the resultant lightning activities. Lifted condensation level temperature (LCL_T) and pressure (LCL_P) in Figs. 13(h) and (i), respectively show gradual increase from winter to pre-monsoon that may also impacted to the atmospheric destabilization and eventually to the process of pre-monsoon thunderstorm mediated lightning activities. The monthly mean of TCL_T and LCL_P are 288, 292, 294 ºK and 887, 920, 930 hPa from March through May, respectively. Using data from a ground-based detection network over the Indian subcontinent, Nag et al. (2017) concluded that the pre-monsoon months of March, April, and May dominates the annual cycle of lightning distribution over Bangladesh.

4. Conclusions

This study examines the synoptic climatology of severe pre-monsoon lightning activity over Bangladesh emphasized on death pattern, temperature conditions, anomalies in pre-monsoon synoptic features, and on atmospheric stability indices. A better understanding on pre-monsoon synoptic climatology relating to lightning deaths and injuries is required to develop more targeted public awareness and safety measures. The precise information of pre-monsoon climatological anomaly can be beneficial for the management of this direct-death related disaster in Bangladesh. In spite of underreporting, annual casualties had increased by a significant amount due to improved news coverage in Bangladesh. Death in May however, is one of the important lightning induced weather related death pattern in Bangladesh whilst a total of 1073 deaths were reported only in May from 2010 to 2021 that accounts 34% of the total death. Sylhet, the extreme northeast district of Bangladesh possess the largest number of lightning frequencies along with the highest thunderstorm days. The mean thunderstorm days are 9.46, 19.27, and 21.67 from March through May with the mean lightning frequency of 29.11, 70.50, and 82.55 for the respective months. Dhaka, the capital city of Bangladesh experiences 41% of thunderstorm days and 44% of lightning frequencies in monsoon season (June–September) compared to pre-monsoon (March–May) with 36% and 42%, respectively. In Bangladesh, T_{avg} difference between winter and pre-monsoon is quite high (7.8ºC) with a sharp jump in temperature from February to March (4.5ºC). Though T_{avg} increases by 2.4ºC from March to April but shows a steady trend from May to September with the maximum of 29ºC in June. T_{avg} in monsoon is higher by 0.83ºC compared to the pre-monsoon but it drops by 3.11ºC as the post-monsoon arrives. In contrast, the mean T_{max} increases by 6.63ºC in pre-monsoon than winter with the maximum T_{min} difference of 9.84ºC compared to all other seasons. The peak of T_{max} (36.49ºC) in April clearly indicates the possible reasons behind more instability in pre-monsoon and the resultant lightning activity. T_{avg} show correlation values of 0.51 and 0.46 with lightning frequency and thunderstorm days whereas, 700 hPa air temperature shows a moderate correlation of 0.57 and 0.62, respectively. Therefore, the bimodality of lightning activity in Bangladesh is strongly related to the variations in air temperatures in surface and above.

A strong SLP ridge from the northwest and 500 hPa G_pH ridge over northwest to south-eastern Bangladesh favors thunderstorm mediated severe lightning in April. The intruded elongated low pressure trough over the Gangetic plains of India towards Bangladesh is a very unique characteristics for the development of convective activities over the country in May. The swing of the strongest 500 hPa G_PH center from May to June seems to be related with the shifting of lightning activity from northeast during pre-monsoon to southwest during monsoon of Bangladesh. The largest pre-monsoon lightning activity over the north, extreme northeast, and southeast of Bangladesh is attributed by very strong 2m temperature anomaly whilst the associated convective precipitation system is triggered by topographic forcing of the Shillong Plateau and Chittagong hill tracts. The lightning occurrence with a peak in May is extremely influenced by solar heating leading to destabilization of the atmosphere and development of convection by the existence of deep positive temperature anomaly core at 850 hPa over northern Bangladesh. Strong southerly to south-westerly LLJ converged over the narrow belt of Bangladesh and could vigorously assist in moisture transport from BoB, and finally to develop severe convective activity within the country in April. In May, 850 hPa strong anomaly zones impacted on large-scale circulation due to strong solar heating at the lower levels with inflow of warm moist air from the BoB. The circulation of north to north-westerly subtropical jet stream toward Bangladesh is another characteristics of severe pre-monsoon lightning events, which provides favorable mechanism of strong vertical wind shear and development of severe convection, and contribute to the severity of the thunderstorms as well. The CAPE anomaly zone from the south-western BoB towards Bangladesh suggests starting of potential instability in March and April, whilst very strong CAPE all over the country in May destabilizes the country’s atmosphere with lots of thunderstorms. The southwest robust P_{WAT} anomaly zone over Bangladesh provides conditions conducive to the development of thunderstorms and the resultant pre-monsoon lightning activity over Bangladesh. The LI, SHOW, and CAPE as the upper atmospheric stability indices could be used efficiently formulating lightning forecasting techniques. It is, therefore, necessary to formulate forecasting methods to anticipate the arrival of thunderstorms (Holle and Islam, 2017), and on those days farm workers should be alerted to this possibility and a safe location should be sought from lightning (Cooper and Holle, 2018). The results of synoptic scale climatology along with atmospheric stability indices would be invaluable in efficient management of lightning-related disasters in Bangladesh.

Declarations

Acknowledgements: The authors were the recipients of generous support for the work reported here and wish to thank: 1. The Physical Science Division: Data Management of NOAA, Boulder, Colorado, USA; 2. Department of Atmospheric Science, University of Wyoming; 3. Climate Division of Bangladesh Meteorological Department (BMD); 4. Archives of daily Bengali newspapers namely The Daily Ittefaq (https://www.ittefaq.com.bd/archive) and The Daily Prothom Alo (https://www.prothomalo.com/) as the dominant sources of lightning death information; and 5. Climate Information Management System (CIMS; http://lri.barcapps.gov.bd/) of Bangladesh Agricultural Research Council (BARC) of the GoB, for providing various reliable datasets and resultant stimulating findings which encourages the authors being enabled research on this issue. We acknowledge the critical comments from anonymous reviewers and editor.

Conflict of Interest*:* The authors declare that they have no conflict of interest.

Funding

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions

Murad Ahmed Farukh designed the research, conducted the analysis and wrote the majority of the manuscript content. Md Azharul Islam, and Md Nasir Uddin contributed to the writing and analysis. All of the authors discussed the results and reviewed the manuscript.

Author statement

Murad Ahmed Farukh: Conceptualization; Data curation; Methodology; Investigation; Formal analysis; Writing- Original draft.

Md. Azharul Islam: Writing- Reviewing and Editing.

Md. Nasir Uddin: Writing- Reviewing and Editing.

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Figures

Figure 1

Geographical position of Bangladesh with its elevation (in m) from sea level (red circle denotes top five lightning affected districts, pink circle denotes location of CIMS, BARC weather station, yellow cross denotes location of radiosonde station).

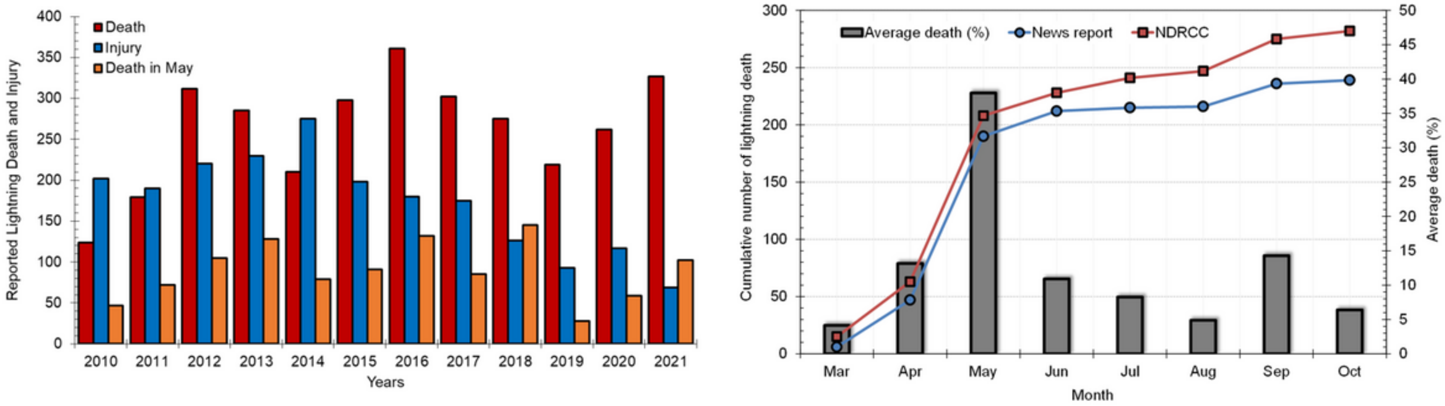

Figure 2

(a). Reported annual total of lightning death and injury along with the total death in May from 2010 to 2021 for whole of Bangladesh.

Fig. 2(b). Comparison among news reports and NDRCC records along with percentages of monthly average reported deaths from 2010 to 2021 for whole of Bangladesh.

Figure 3

(a). Month wise lightning frequency averaged for the period of 2010 to 2021 for the top five lightning affected districts.

(b). Month wise thunderstorm days averaged for the period of 2010 to 2021 for the top five lightning affected districts.

Figure 4

(a). Monthly mean air temperature (T_{avg}) averaged over maximum (T_{max}) and minimum (T_{min}) monthly temperature, and standard deviation (SD, boxes), T_{max} and T_{min} (upper red & lower blue circles) during the period of 2010–2021 for Dhaka station.

(b). Scatter plot of pre-monsoon lightning frequency and air temperature (T_{avg}) for the period of 2010–2021 for Dhaka station.

(c). Scatter plot of pre-monsoon thunderstorm days and air temperature (T_{avg}) for the period of 2010–2021 for Dhaka station.

(d). Scatter plot of pre-monsoon lightning frequency and air temperature at 700 hPa for the period of 2010–2021 for Dhaka radiosonde station.

(e). Scatter plot of pre-monsoon thunderstorm days and air temperature at 700 hPa for the period of 2010–2021 for Dhaka radiosonde station.

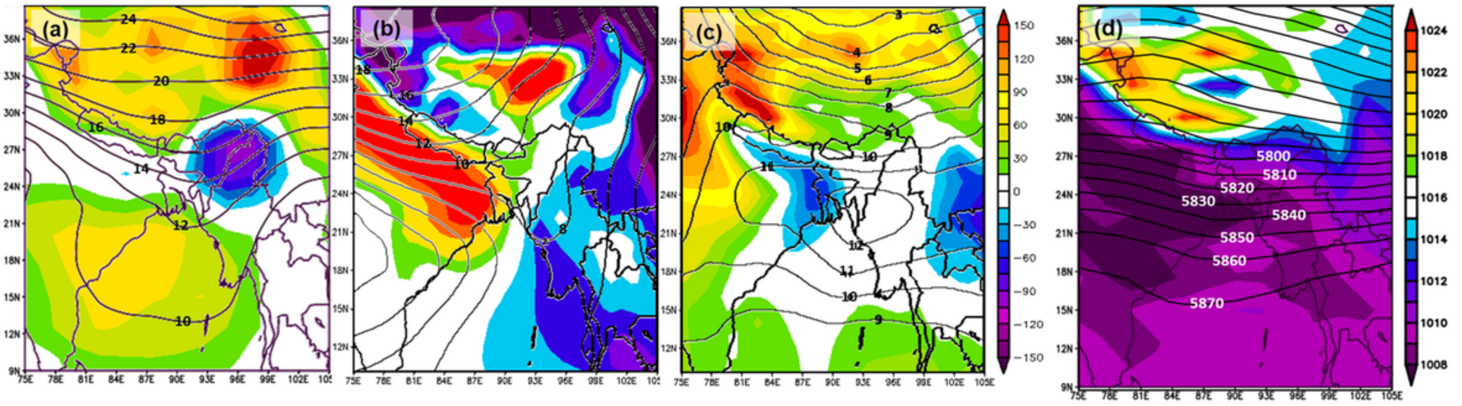

Figure 5

(a),(b),(c). Composite geographical distributions of March, April, and May SLP (in Pa, shaded) and 500 hPa GpH (in gpm, solid line) anomalies compared with the climatology from 1981 to 2010.

(d). Composite geographical distributions of three months mean SLP and 500 hPa GpH from March to May.

Figure 6

(a),(b),(c). Composite geographical distributions of March, April, and May air temperature anomalies at 2m (in ºK, shaded) and 850 hPa (in ºK, solid line) compared with the climatology from 1981 to 2010.

(d). Composite geographical distributions of three months mean air temperatures at 2m and 850 hPa from March to May.

Figure 7

(a),(b),(c). Composite geographical distributions of March, April, and May relative humidity anomalies at 1000 hPa (in %, shaded) and 850 hPa (in %, solid line) compared with the climatology from 1981 to 2010.

(d). Composite geographical distributions of three months mean relative humidity at 1000 hPa and 850 hPa from March to May.

Figure 8

(a),(b),(c). Composite geographical distributions of March, April, and May vector wind anomalies at 850 hPa (in m s^{-1}) compared with the climatology from 1981 to 2010.

(d). Composite geographical distributions of three months mean vector wind at 850 hPa from March to May.

Figure 9

(a),(b),(c). Composite geographical distributions of March, April, and May vector wind anomalies at 300 hPa (in m s^{-1}) compared with the climatology from 1981 to 2010.

(d). Composite geographical distributions of three months mean vector wind at 300 hPa from March to May.

Figure 10

(a),(b),(c). Composite geographical distributions of March, April, and May precipitation rate anomalies (in mm day^{-1}) compared with the climatology from 1981 to 2010.

(d). Composite geographical distributions of three months mean precipitation rate from March to May.

Figure 11

(a),(b),(c). Composite geographical distributions of March, April, and May P_{WAT} anomalies (in kg m^{-2}) compared with the climatology from 1981 to 2010.

(d). Composite geographical distributions of three months mean P_{WAT} from March to May.

Figure 12

(a),(b),(c). Composite geographical distributions of March, April, and May CAPE anomalies (in J kg^{-1}) compared with the climatology from 1981 to 2010.

(d). Composite geographical distributions of three months mean CAPE from March to May.

Figure 13

Upper air stability indices from March through May averaged over the period from 2010–2021 **(a)** Lifted index, **(b)** K index, **(c)** Showalter index, **(d)** SWEAT index, **(e)** CAPE, **(f)** CIN, **(g)** P_{WAT}, **(h)** LCL_T, and **(i)** LCL_P.

Supplementary Files

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