



Cloud-to-Ground Lightning in Cities: Seasonal Variability and Influential Factors

Ashraf Dewan¹ · K. M. Ashraful Islam^{2,3} · Muhammad Esmat Enan⁴ · Tanzim Rahman Fariha⁵ · M. Rafiuddin⁶ · Mohammed Sarfaraz Gani Adnan⁷

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Abstract

Urban-induced land use changes have a significant impact on local weather patterns, leading to increased hydro-meteorological hazards in cities. Despite substantial threats posed to humans, understanding atmospheric hazards related to urbanisation, such as thunderstorms, lightning, and convective precipitation, remains unclear. This study aims to analyse seasonal variability of cloud-to-ground (CG) lightning in the five large metropolitans in Bangladesh utilising six years (2015–2020) of Global Lightning Detection Network (popularly known as GLD360) data. It also investigates factors influencing CG strokes. The analysis revealed substantial seasonal fluctuations in CG strokes, with a noticeable increase in lightning activity during the pre-monsoon months from upwind to metropolitan areas across the five cities. Both season and location appear to impact the diurnal variability of CG strokes in these urban centres. Bivariate regression analysis indicated that precipitation and particulate matter (PM) significantly influence lightning generation, whilst population density, urban size, and mean surface temperature have negligible effects. A sensitivity test employing a random forest (RF) model underscored the pivotal role of PM in CG strokes in four of the five cities assessed, highlighting the enduring impact of extreme pollution on lightning activity. Despite low causalities from CG lightning, the risk of property damage remains high in urban environments. This study provides valuable insights for shaping public policies in Bangladesh, a globally recognised climate hotspot.

Keywords Cloud-to-ground lightning · Seasonality · Particulate matter · Rainfall · Land surface temperature · Bangladesh cities

✉ Ashraf Dewan
a.dewan@curtin.edu.au

K. M. Ashraful Islam
ashraful.urp@cuet.ac.bd

Muhammad Esmat Enan
enan.bd95@gmail.com

Tanzim Rahman Fariha
farihatanzim91@gmail.com

M. Rafiuddin
rafiuddin@phy.buet.ac.bd

Mohammed Sarfaraz Gani Adnan
mohammed.adnan@strath.ac.uk

² College of Earth, Ocean and Atmospheric Sciences, Oregon State University, Corvallis, USA

³ Department of Urban and Regional Planning, Chittagong University of Engineering and Technology (CUET), Chattogram 4349, Bangladesh

⁴ Oxfam in Bangladesh, Dhaka 1213, Bangladesh

⁵ Global Change Geography Programme, Humboldt University, Berlin, Germany

⁶ Department of Physics, Bangladesh University of Engineering & Technology, Dhaka 1000, Bangladesh

⁷ Department of Civil and Environmental Engineering, University of Strathclyde, Glasgow G1 1XJ, UK

¹ Spatial Sciences Discipline, School of Earth and Planetary Sciences, Curtin University, Kent Street, Bentley, Perth, WA 6012, Australia

1 Introduction

The expansion of urban landscapes globally has given rise to various environmental challenges (Grimm et al. 2008), affecting local and regional climates (Pimonsree et al. 2022; Weaver and Avissar 2001). One notable consequence of intense urban growth is the Urban Heat Island (UHI) (Oke 1982), which is extensively studied. However, our understanding of atmospheric hazards related to urbanisation, such as thunderstorms, lightning, and convective precipitation, remains less clear (Shepherd et al. 2010). The persistent alteration of landscapes through increased anthropogenic activities, such as urbanisation, has the potential to disrupt local weather patterns, leading to cascading effects on the global population through convection-related hazards (Pathirana et al. 2014; Shepherd 2005).

Westcott (1995) was among the first to explore the impact of urbanisation on the frequency of cloud-to-ground (CG) lightning flashes in a few US cities. Subsequent studies investigated this phenomenon in diverse regions, including the US (Rose et al. 2008; Stallins and Bentley 2006; Steiger and Orville 2003; Steiger et al. 2002; Orville et al. 2001), China (Shi et al. 2023; Wang et al. 2021a; Hu et al. 2018, 2014; Tan et al. 2016), India (Chowdhuri et al. 2020; Chaudhuri and Middey 2013; Lal and Pawar 2011), Thailand (Bentley et al. 2021), South Korea (Kar et al. 2009), Taiwan (Kar and Liou 2014, 2019), Brazil (Neto et al. 2020; Bourscheidt et al. 2016; Farias et al. 2014; Pinto et al. 2004; Naccarato et al. 2003), France (Boussaton et al. 2007) and Spain (Soriano and de Pablo 2002; Areitio et al. 2001). These studies reveal a significant increase in lightning, particularly over and downwind of urban areas, accompanied by a decrease in positive CG flashes. For instance, Wang et al. (2021b) reported a 50% increase in CG strokes in downtown Beijing, whilst Steiger et al. (2002) observed a 45% enhancement in CG flash density in Houston, Texas. However, variations exist, with Naccarato et al. (2003) report a 60–100% increase in lightning over urban areas in south-eastern Brazil.

Recent studies have identified various factors associated with CG strokes, including high pollution load (e.g. particulate matter), UHI-induced differential heating, increased surface roughness, and local topographic factor like sea breezes. However, the influence of these factors varies across different urban locations. For example, Wang et al. (2021a) observed increased CG strokes under conditions of high total aerosol optical depth (AOD) in three urban areas of China, whilst Shi et al. (2023) indicated that UHI fosters thunderstorm development in Beijing. In Sao Paulo, Brazil, Bourscheidt et al. (2016) noted a positive relationship between UHI and lightning, with a synergic effect

involving pollution and thermal factors in three populated regions. Bentley et al. (2021) similarly found that factors influencing CG lightning vary within the same country. However, a Spanish study involving nine towns indicated that urban size and particulate matter did not correlate with enhanced lightning (Soriano and de Pablo 2002). Conversely, an Indian study revealed a negative correlation between AOD and lightning but a positive influence of UHI (Lal and Pawar 2011). A Louisiana study showed that pollution and local topography (e.g. sea breeze) jointly contributed to enhanced CG lightning activity, whereas UHI had no influence (Steiger and Orville 2003). Kar and Liou (2014) suggested that the concentration of sulphur dioxide and particulate matter in the atmosphere contributed to enhanced lightning in urban areas in Taipei. However, after a certain pollution threshold defined by aerosol, lightning activity tends to decrease (Farias et al. 2014). These studies collectively highlight a non-uniform nature of lightning enhancement in cities, indicating connections to geography, local characteristics, and background climate (Wang et al. 2021a; Shepherd et al. 2010). While these studies have enhanced our understanding of the spatiotemporal distribution and causal factors of CG lightning, their findings remain inconclusive. Applying these findings universally is challenging due to the differences in population density, economic activities, and industrial structure (Wang et al. 2021c). As lightning is projected to increase in a warmer world, coupled with the continued growth of urban populations, particularly in the global south, a baseline study of CG lightning climatology becomes crucial for informing public policy decisions. It is also difficult to generalise whether factors contributing to lightning remain the same in densely populated Asian large cities.

Bangladesh, situated in South Asia and characterised by high population density, faces a significant challenge of increased fatalities from lightning, as highlighted by observations from NASA's Earth Observatory (<https://earthobservatory.nasa.gov/images/149447/assessing-lightning-risk-in-south-asia>). This issue has become more pronounced in recent years, despite a discernible upward trend of lightning deaths observed in the country (Dewan et al. 2018). The rise in reported deaths is likely attributed to factors such as the densely populated environment (Dewan et al. 2017), inadequate lightning safety education (Islam and Schmidlin 2020) and widespread outdoor agricultural practices (Holle et al. 2019). Therefore, a thorough examination of the characteristics of cloud-to-ground (CG) lightning is essential to formulate strategies aimed at safeguarding both individuals and property from this perilous atmospheric threat.

Cities of Bangladesh are experiencing rapid expansion to accommodate a growing number of populations, primarily driven by rural-to-urban migration (BBS 2017). This surge

in urbanisation has led to widespread land use changes (Xu et al. 2020), significantly reducing natural covers such as forest, waterbodies and cultivated lands. Simultaneously, uncontrolled urban expansion remains a prominent aspect of land conversion. Major urban centres in the country grapple with various environmental challenges, including rapid warming (Pathirana et al. 2014; Dewan and Corner 2012) and severe pollution (Islam et al. 2022; Qio et al. 2021). Consequently, an increasing number of people and infrastructure are exposed to urban-induced hydro-meteorological hazards, given the variable degree of linkage between urbanisation and atmospheric disturbances like thunderstorms and lightning (e.g., Stallins and Rose 2008). While lightning-related human fatalities are rare in cities, such hazard pose a significant risk to property in urban locations (Hu et al. 2014). Thus, climatic modifications induced by urbanisation have the potential to directly impact civil infrastructures and indirectly affect the livelihoods of millions. This study aims to address a gap in characterising urban lightning patterns for major cities in Bangladesh. Drawing from existing literature,

we pose a broad research question: Do the spatiotemporal patterns and properties of CG lightning in rapidly growing urban centres in Bangladesh resemble those observed in other studies, and if so, are governing factors identical across these urban centres?

The primary objectives of this study are twofold: (a) to develop a climatology detailing the characteristics and spatiotemporal patterning of CG lightning across major cities in Bangladesh; and (b) to evaluate relative significance of factors influencing CG lightning variability. This investigation focuses on the five major cities (Fig. 1)—Dhaka, Chittagong, Khulna, Rajshahi, and Sylhet—chosen due to their rapid population and urban growth (Rahman et al. 2019). Diverging from the predominant approach of using annual data or concentrating on a single city in existing studies, this study adopts a seasonality approach to analyse CG lightning in the context of sub-tropical climate. Hence, the outcomes of this study hold the potential to contribute significantly to the current knowledgebase. The findings may aid in the development of location-specific mitigation strategies, enhancing

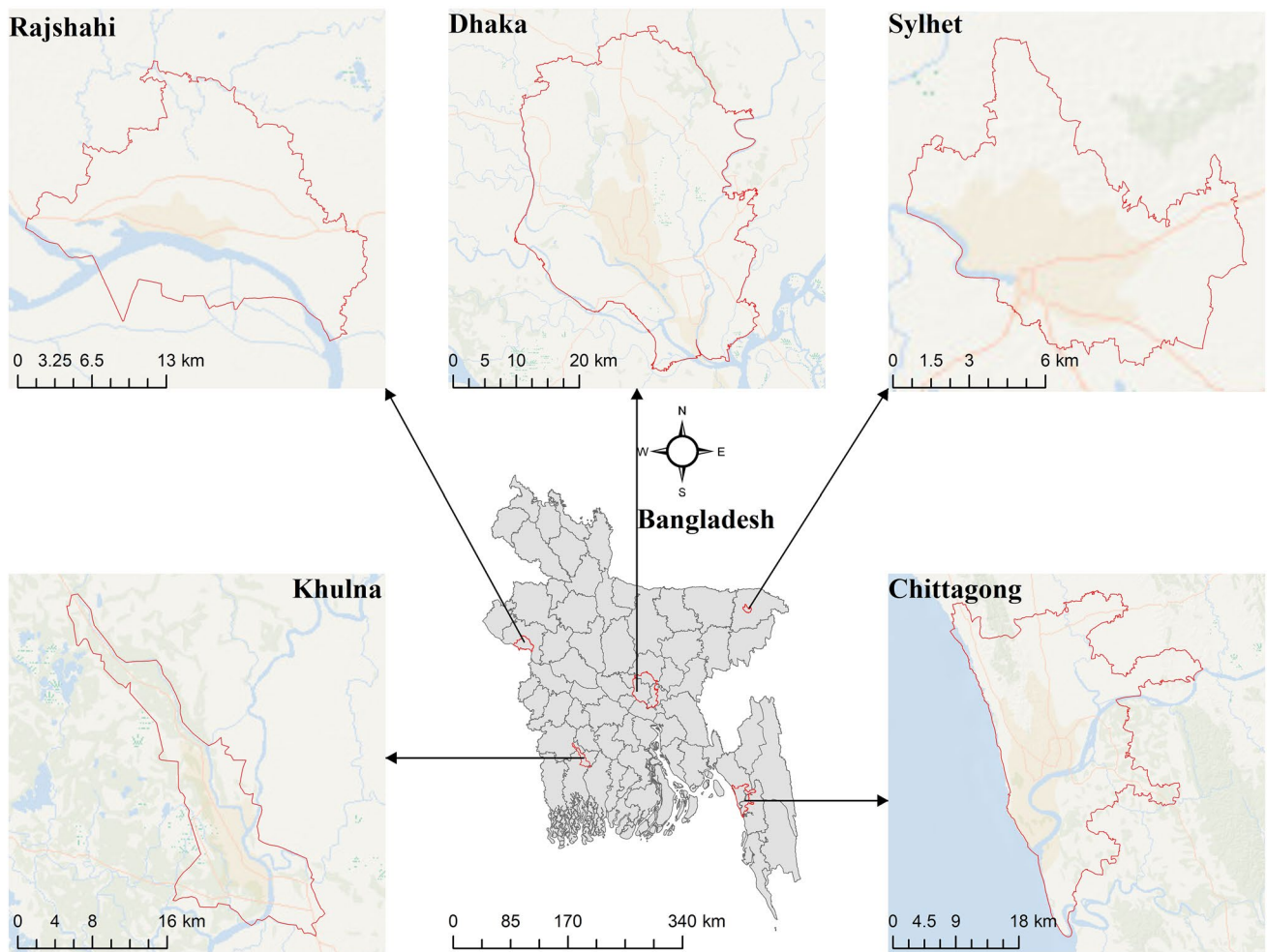


Fig. 1 Map showing the locations of the five major cities in Bangladesh

resilience against atmospheric hazards, particularly lightning, in Bangladesh—a recognised global climate hotspot.

2 Materials and Methods

2.1 Data Preparation

This study employed a Global Lightning Detection Network dataset, commonly known as GLD360, covering a six-year period (2015–2020). The dataset is generated by Vaisala's long-range Lightning Location Systems (LLS) network (<https://www.vaisala.com/en>), offering precise lightning stroke incidence (Said et al. 2010). According to Pohjola and Mäkelä (2013), GLD360 exhibits a median locational accuracy of 2–5 km and a 70% effectiveness in recognising CG strokes. The sensors record the instantaneous charge intensity of individual strokes using low-frequency atmospheric radio waves (~500 Hz to ~50 Hz) along with locational information (Rudlosky et al. 2017). Detailed information regarding GLD360 data can be found in Said and Murphy (2016). The network utilises both time-of-arrival and magnetic direction-finding technologies to detect lightning strokes (Said and Murphy 2016) and employs propagation correction and waveform identification techniques to ensure consistent arrival times across different distances and propagation circumstances. The amplitude of the waveform is additionally attenuated to estimate peak current.

Each GLD360 stroke contains several attributes including date/time, latitudes/longitudes, peak current and polarity. Due to the lack of categorisation between CG and non-CG strokes in GLD360 data before September 11, 2018, a method proposed by Nag et al. (2017) was adopted. This involves filtering out potential CG pulses using peak current values below –10 kA (kilo Amperes) and above +15 kA. Individual strokes were aggregated into a 5 × 5 km grid to ensure a robust sample size (Bourscheidt et al. 2016).

To comprehend factors influencing CG strokes, this study considered six indicators based on literature review. They were PM_{2.5}, total precipitation, land surface temperature (LST), convective precipitation, urban size, and population density. Gridded layers for these indicators were derived from various sources. For instance, cloud-free 8-day MODIS (Moderate Resolution Imaging Spectroradiometer) Terra day and night-time LST and emissivity products (MOD11A2.006) were obtained from <https://lpdaac.usgs.gov/products/mod11a2v006>. Monthly fine particulate matter (PM_{2.5}) data (v5.GL.02) was sourced from <https://wustl.app.box.com/v/ACAG-V5GL02-GWRPM25>. The PM_{2.5} data were produced by van Donkelaar et al. (2021) using a combination of Aerosol Optical Depth (AOD) retrievals from MODIS, MISR (Multi-angle Imaging Spectroradiometer), and SeaWiFS (Sea-viewing Wide Field-of-View

Sensor) satellites, and GEOS-Chem chemical transport model. A geographically weighted regression (GWR) was used to calibrate PM_{2.5} data (van Donkelaar et al. 2021). The current study also acquired monthly precipitation data from TerraClimate (Abatzoglou et al. 2018) and annual land use/land cover (LULC) data from Copernicus Global Land Cover Layers (<https://lcviewer.vito.be/2015>), focussing only on built-up cover. The same grid size (5 km × 5 km) was applied for consistency across datasets. Wind direction data, retrieved from European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis products (<https://cds.climate.copernicus.eu/cdsapp#!/dataset/10.24381/cds.68d2bb30?tab=form>), were used to generate seasonal wind direction maps at 925 hPa (hectopascal) for the period 2015–2020. Metropolitan boundary shapefiles for the five cities were obtained from relevant city authorities.

Convective precipitation was computed from TerraClimate product following an approach by Petersen and Rutledge (1998). Monthly strokes for each grid were derived, and grids with zero strokes were masked out. Subsequently, the rainfall lightning ratio (RLR) was calculated, modifying the method of Kar and Ha (2003) to accommodate the gridded nature of total precipitation in this study. The Queen case contiguity rule (first order) was employed to define neighbourhood weights with a 3 × 3 template. The following equation determined whether RLR represents a convective system or not:

$$\begin{aligned} & \text{IF } RLR_{ij} \geq 3 \times RLR_{i'j} \\ & \text{AND} \\ & RLR_{ij} \geq 3 \times RLR_{ij-1} \end{aligned} \quad (1)$$

THEN non – convective; *ELSE* convective

where i is the grid under consideration; i' represents any of the 8 neighbouring grids, j represents the month under consideration; $j-1$ represents the previous month. If this condition is satisfied for at least one neighbouring grid, the RLR of the original grid is considered non-convective. A grid in a particular month is deemed non-convective if RLR value is three times higher (or more) than the surrounding grids or the previous month.

2.2 Analytical Techniques

To evaluate the spatiotemporal distribution of lightning in the five cities throughout the pre-monsoon (MAM), monsoon (JJAG), post-monsoon (ON), and winter (DJF) seasons, assessments were made for three geographic elements: metropolitan boundary, upwind, and downwind directions. Using the metropolitan boundaries of cities, a 75-km buffer was defined (Westcott 1995), assuming that lightning enhancement typically occurs within a 100 km radius of the city centre (Stallins and Rose 2008). Based on prevailing

wind directions from ECMWF's data, upwind and downwind regions within the 75-km buffer zone were delineated for each of the four seasons.

To compute total and average strokes in upwind, downwind, and metropolitan regions, total number of CG strokes within a grid was aggregated monthly over the study period (2015–2020). Subsequently, the average CG strokes observed in a grid was computed for each season. This process yielded strokes per grid per month for a specific season, and based on this output, the mean over an area was calculated for each region (e.g. upwind, downwind, and metro). The highest value of average strokes in a grid was also recorded. To assess whether seasonal CG strokes were enhanced or suppressed, a two-sided Mann–Whitney *U* test was employed (Mann and Whitney 1947).

To investigate factors influencing CG lightning activity, bivariate relationships were examined between CG strokes and six causative factors (particulate matter or PM_{2.5}, LST, total rainfall, convective precipitation, urban extent, and population density). Monthly data were utilised, and due to the unavailability of urban size and population density at a monthly scale, annual values were used. A log transformation was applied to all data owing to their non-normal distribution.

2.3 Sensitivity Analysis

While bivariate regression is useful for illustrating overall relationship between dependent and independent variables, determining the relative importance of the variable(s) contributing most to CG strokes in each city poses challenges. Given substantial variations in pollution levels, local warming, and the extent of urban growth across cities in Bangladesh, a Random Forest (RF) model (Breiman 2001) was employed for sensitivity analysis to assess the relative importance of factors over others. The RF algorithm offers several advantages over other methods, as it does not rely on the assumptions about the distribution of predictors, can handle mixed variables, and can account for non-linear relationships between factors (Aertsen et al. 2010). Although commonly used for classifying and predicting geographic phenomena such as land use/cover, RF can also be applied to identify important factors associated with a geographic phenomenon (Breiman 2017).

This study conducted a sensitivity analysis of all factors influencing CG strokes by determining the importance rank (%IncMSE and IncNodePurity) of components using RF algorithm (Breiman 2001). The %IncMSE indicates the mean decrease in accuracy or an increase in the mean squared error of the model's prediction when the variable changes, providing insights into the contribution of each variable. The IncNodePurity metric is linked to the loss function, measuring total reduction in node impurities expected

by the Gini Index, averaged over each decision tree. Node impurities are predicted by the Gini Index through variable splits. Higher values of %IncMSE and %IncNodePurity indicators signify greater variable importance (Strobl et al. 2007).

The RF models were established using monthly data to identify important factors influencing lightning in cities. Initially, the dependent variable (CG strokes) was transformed using the z-score normalisation technique. The values of %IncMSE and IncNodePurity indices were estimated using the 'randomForest' function in R package, with the number of decision trees (*ntree*) set to 500. City-specific models were developed, assuming that the effects of various factors on lightning vary spatially. The dependent variable comprised monthly CG strokes, and predictors included PM_{2.5}, total precipitation, LST, convective precipitation, urban size and population density. The 'importance' extractor function under R package was used to extract values for six indicators of %IncMSE and %IncNodePurity for each city.

3 Results

Figure 2 illustrates lightning occurrences across the five cities, exhibiting significant variations in the distribution of CG strokes. Lightning activity notably higher in the pre-monsoon season compared to other seasons. For example, in the downwind region of Sylhet, the maximum strokes reached 336 (Table 1). As the monsoon sets in, these cities experienced varying levels of CG strokes, with the downwind regions showing comparatively reduced lightning activity in the monsoon relative to the pre-monsoon season. During the post-monsoon season, Chittagong exhibited a higher distribution of CG strokes compared to other cities. In winter, CG strokes tended to increase in the downwind region of Khulna, although overall intensity of lightning activity during this season remained low due to calm weather.

Table 1 presents seasonal mean and maximum CG strokes in metropolitan, upwind, and downwind regions, indicating significant variations in the enhancement and suppression of CG strokes. Throughout the study period (2015–2020), pre-monsoonal strokes exhibited enhancement from upwind to metropolitan areas in all cities. However, in comparison to metro areas, the downwind regions experienced a suppression in mean CG strokes in Chittagong and Sylhet (– 0.7% and – 15.3%, respectively). Except for Dhaka, other four cities showed an enhancement in mean strokes in both regions (compared to downwind) during the monsoon season. In the post-monsoon months, average CG strokes decreased in all metropolitan regions, except in Khulna city. Conversely, the number of downwind strokes decreased in Dhaka and Khulna but increased in other cities. The notable enhancement of winter CG strokes in Khulna (131.8%) is worth

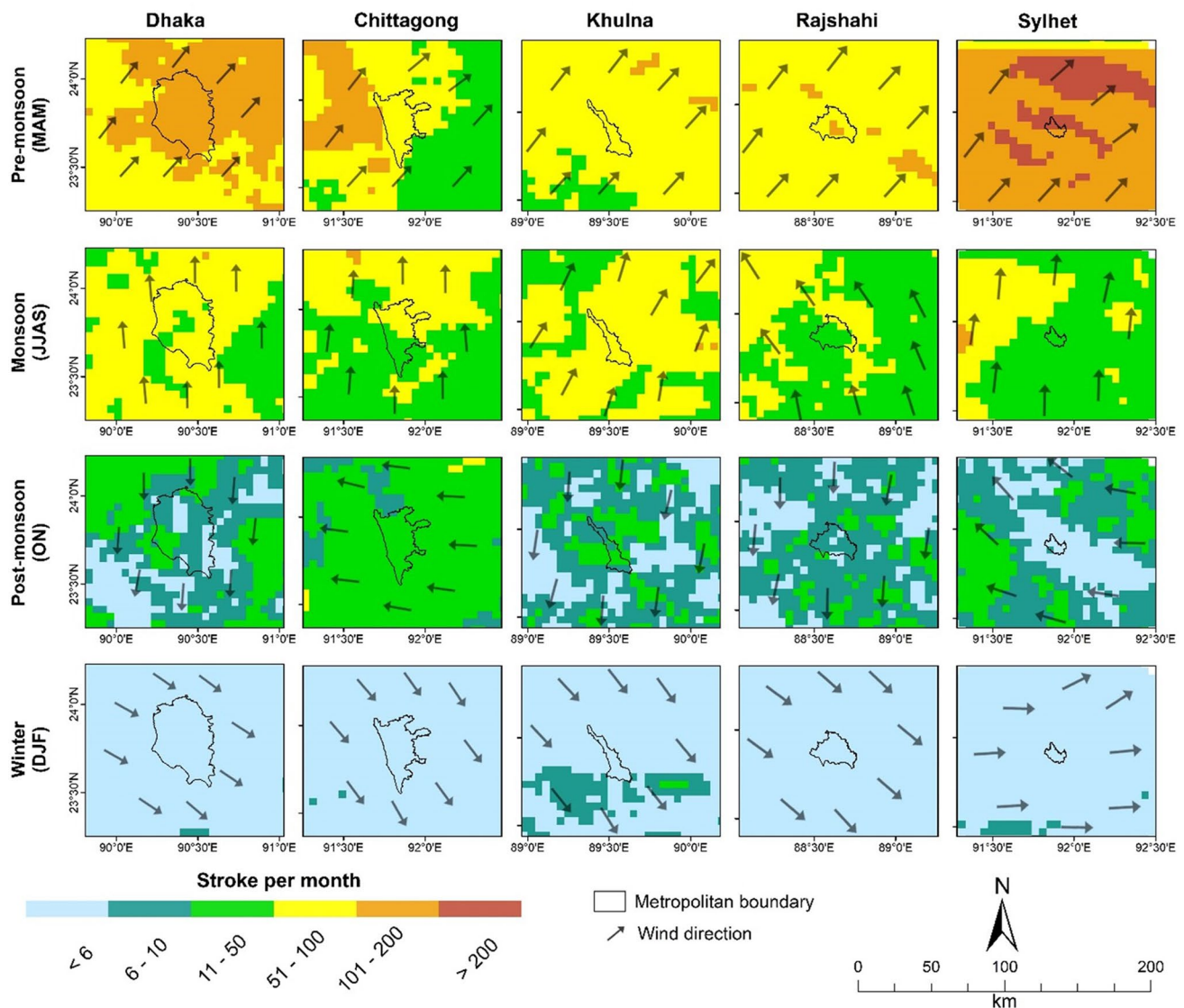


Fig. 2 Spatial distribution of seasonal CG strokes in the five cities of Bangladesh, 2015–2020

mentioning. Furthermore, except for upwind region of Khulna, the mean stroke was highest during the pre-monsoon season in each city. Sylhet's downwind experienced the highest mean of 336 strokes within a single grid in the pre-monsoon season. However, apart from that, no grid showed more than 182 mean CG strokes in the four seasons assessed.

Figure 3 illustrates monthly and diurnal variability of CG strokes in the five cities. In Dhaka, 71% of total strokes occurred during April–June, with a peak in May (29%). Chittagong, the second largest city, also experienced a peak in May, contributing to a total of 38,601 (22%) CG strokes. Notably, Chittagong exhibited a secondary peak of CG strokes in September, with a slight surge observed in Dhaka. Contrasting these patterns, Khulna and Sylhet demonstrated variations in peak months, with Sylhet peaking in

April (44%) and Khulna in June (33%). Rajshahi followed Dhaka and Chittagong with primary (May) and secondary (September) peaks (Fig. 3).

Temporal patterns (Fig. 3) of CG strikes reveal that Dhaka recorded the highest strokes of 29,230 in the afternoon, specifically at 16:00 Local Standard Time (LT), accounting for 8% of all strokes in this city. Furthermore, two other peaks were observed in Dhaka at LT 13:00 and LT 8:00, corresponding ~7% of the total strokes. Chittagong experienced a peak at 2:00 LT, constituting 10% of total strokes (16,743 strokes). In Khulna, two peaks occurred at 5:00 LT and 15:00 LT, averaging 6000 strokes. At 22:00 LT, Rajshahi saw a spike at 22:00 LT, representing 9% of all strokes (7879 strokes). Sylhet, similar to Chittagong, recorded the highest strokes at 2:00 LT, constituting 10% of total strokes.

Table 1 Seasonal CG strokes and their percent changes in upwind, metropolitan and downwind regions of the five cities

City	Season	Mean			% Change (upwind— metro)*	% Change (upwind—down- wind)*	Maximum		
		Upwind	Metropolitan	Downwind			Upwind	Metropolitan	Downwind
Dhaka	Pre-mon	84.15	119.19	122.50	41.6	45.6	137.50	172.94	182.44
	Monsoon	68.99	62.37	51.40	-9.6	-25.5	166.67	99.38	102.63
	Post-mon	14.31	7.54	11.95	-47.3	-16.5	34.17	20.50	39.58
	Winter	1.05	1.18	1.72	13.1	64.1	3.28	2.56	6.78
Chittagong	Pre-mon	61.10	74.12	60.65	21.3	-0.7	119.11	106.61	115.28
	Monsoon	34.91	53.25	49.74	52.5	42.5	63.42	76.08	109.67
	Post-mon	20.11	19.67	20.71	-2.2	3.0	46.67	44.33	82.92
	Winter	1.13	0.81	0.62	-28.1	-44.8	5.06	2.17	2.94
Khulna	Pre-mon	53.91	67.44	75.17	25.1	39.4	90.11	84.11	124.33
	Monsoon	57.13	66.15	60.15	15.8	5.3	95.96	80.33	95.75
	Post-mon	8.51	9.53	8.28	12.0	-2.7	26.50	16.25	47.58
	Winter	1.87	3.34	4.33	78.6	131.8	5.06	5.56	11.22
Rajshahi	Pre-mon	62.40	88.85	66.35	42.4	6.3	87.06	103.72	95.28
	Monsoon	37.26	45.62	56.65	22.4	52.0	68.79	67.17	84.88
	Post-mon	7.23	6.49	7.85	-10.2	8.6	18.33	12.08	25.83
	Winter	1.01	0.89	1.24	-11.4	22.4	3.39	1.50	5.39
Sylhet	Pre-mon	177.03	202.52	150.00	14.4	-15.3	217.22	220.44	336.28
	Monsoon	34.14	34.77	35.81	1.8	4.9	55.79	37.92	82.96
	Post-mon	7.55	3.81	7.93	-49.6	5.0	20.25	4.92	25.42
	Winter	1.68	2.50	1.97	49.1	17.8	4.50	3.28	4.39

*% Change = {(metropolitan OR downwind strokes—upwind strokes)/upwind strokes} × 100%

To assess statistical significance of changes in total lightning activity between upwind-metropolitan and upwind-downwind regions, a Mann–Whitney U test was performed. The results, shown in Table 2, indicated a significant enhancement of CG lightning from upwind to metropolitan areas in the four cities, except Sylhet, during the pre-monsoon. Similarly, the monsoon season exhibited a statistically significant enhancement in all metropolitan areas. The analysis further revealed that Dhaka, Chittagong, and Khulna experienced enhanced lightning from upwind to downwind regions, whilst Sylhet experienced a reduction in lightning activity during the pre-monsoon and monsoon. Rajshahi exhibited enhanced lightning during the monsoon and post-monsoon seasons from upwind to downwind regions.

To analyse monthly CG strokes within metropolitan regions, bivariate regression models were developed for three seasons (pre-monsoon, monsoon, and post-monsoon), excluding winter due to low CG strokes (Table 3). Four out of six causal factors—PM_{2.5}, total precipitation, LST, and convective precipitation—demonstrated strong associations with CG strokes across metropolitans and seasons. Population density and urban size, except for a small correlation in post-monsoon for Sylhet, exhibited no significant association with CG lightning. With the exception of post-monsoon for Sylhet, where a small degree of correlation is noted,

population density and urban size are not associated with CG strokes. The relationships, however, vary by city and season.

The pre-monsoon season generally showed the highest correlation between CG strokes and causal factors, followed by the post-monsoon and monsoon seasons. PM_{2.5} was negatively associated with CG strokes in Sylhet, with the highest coefficient of -4.19 during pre-monsoon, indicating a potential 4.19% reduction in strokes for a 1% increase in PM_{2.5} concentration. Total precipitation and CG strokes exhibited positive correlations in the pre- and post-monsoon seasons, but a negative association during the monsoon (except for Dhaka). Pre-monsoon rainfall could lead to an increase of 1.10% in Dhaka, 0.67% in Chittagong, 1.19% in Khulna, 0.96% in Rajshahi, and 1.45% in Sylhet CG strokes, for every 1% increase in rainfall.

LST and CG strokes demonstrated the highest correlation, though the association varied by cities. Except for post-monsoon in Rajshahi, LST and CG strokes exhibited a positive relationship. In the pre-monsoon season, a 1% increase in LST could lead to an increase in CG strokes of 1.46% in Dhaka, 3.58% in Chittagong, 7.85% in Khulna, 13.01% in Rajshahi, and 3.69% in Sylhet. However, during the post-monsoon season, Rajshahi could experience a 24.8% decrease in CG strokes with a 1% rise in LST. Pre-monsoon convective precipitation showed a positive relationship with

Fig. 3 Diurnal and monthly variations of CG lightning in the five cities

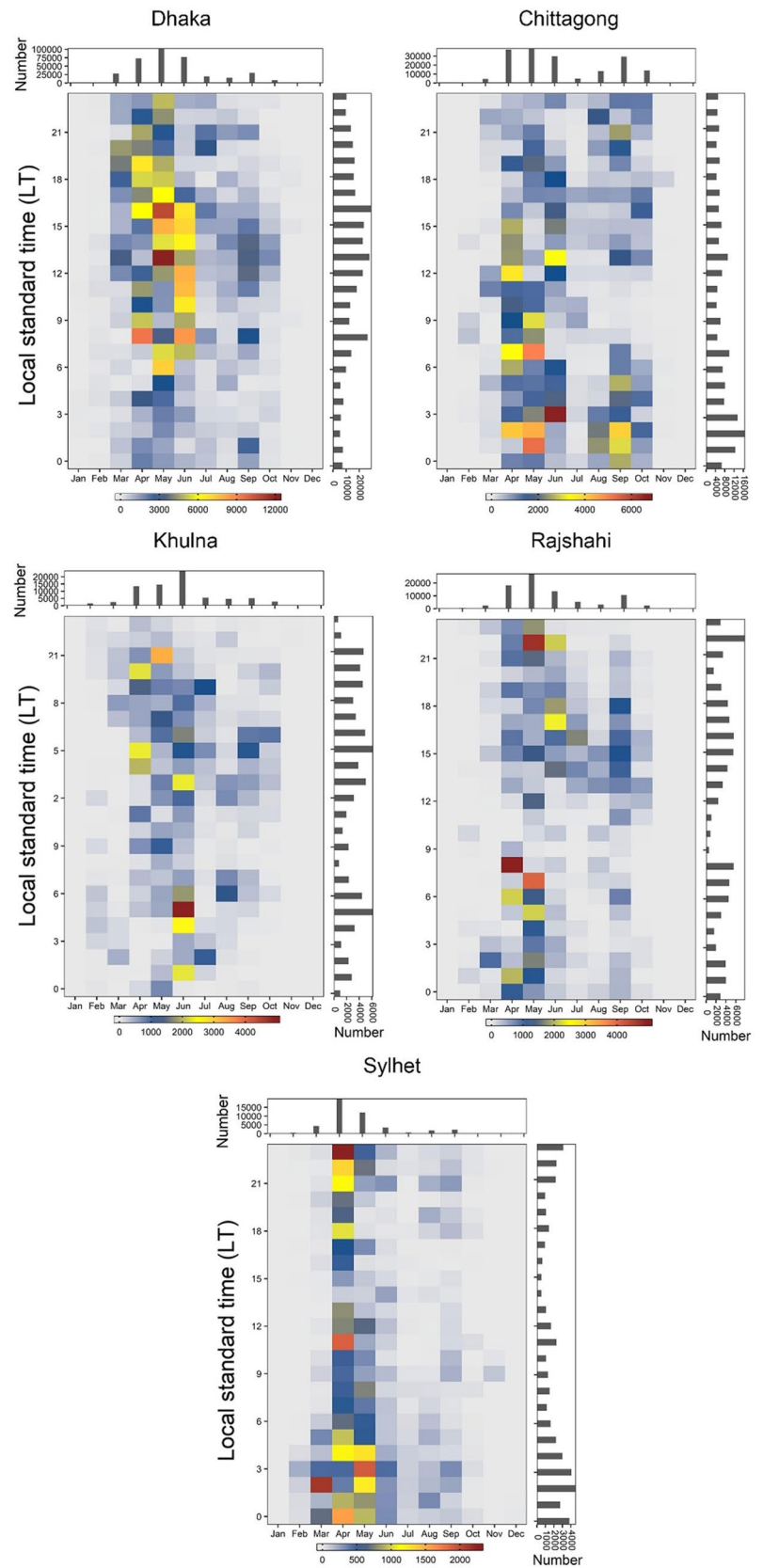


Table 2 Result of Mann–Whitney *U* test of significance

City	Season	Upwind-metro-politan	Upwind-down-wind
Dhaka	Pre-monsoon	(+)	(+)
	Monsoon	(+)	(+)
	Post-monsoon	O	(-)
	Winter	O	(-)
Chittagong	Pre-monsoon	(+)	(+)
	Monsoon	(+)	(+)
	Post-monsoon	O	(-)
	Winter	O	(-)
Khulna	Pre-monsoon	(+)	(+)
	Monsoon	(+)	(+)
	Post-monsoon	O	O
	Winter	O	O
Rajshahi	Pre-monsoon	(+)	O
	Monsoon	(+)	(+)
	Post-monsoon	O	(+)
	Winter	O	O
Sylhet	Pre-monsoon	O	(-)
	Monsoon	(+)	(-)
	Post-monsoon	O	(-)
	Winter	O	(+)

(+) statistically significant enhancement, (-) statistically significant reduction in lightning at the 95% confidence interval, O denotes statistically insignificant

CG strokes, whilst both positive and negative correlations were observed in the monsoon and post-monsoon seasons.

Figure 4 shows the relative importance of factors to explain CG strokes in relation to %IncMSE and %IncNodePurity. In the four cities—Chittagong, Dhaka, Khulna, and Sylhet—PM_{2.5} emerged as the most important variable in relation to %IncMSE. In Rajshahi, total precipitation was the most significant variable. Notably, convective precipitation and LST exerted substantial influence on CG strokes, whilst population and urban size had the least impact. Examining IncNodePurity, it was evident that CG strokes in all cities were extremely sensitive to convective precipitation. Besides, total precipitation and PM_{2.5} also stood out as contributors to CG strokes. Population and urban size registered the lowest degree of importance, potentially due to the absence of monthly data for these variables.

4 Discussion

In the pursuit of social and economic development, cities have become hubs of increased anthropogenic activities and surface conversion, contributing to alterations in local weather patterns (Qian et al. 2022). This shift is anticipated

to escalate hydro-meteorological hazards with rising temperatures, pointing towards profound sociodemographic implications.

This study underscored significant seasonal variations of CG lightning across the five cities of Bangladesh (Fig. 2). This aligns with previous findings, demonstrating pronounced lightning activities during the pre-monsoon season in Bangladesh (Holle et al. 2019). The spatial distribution of lightning activities highlighted that Sylhet city experienced maximum CG strokes in the pre-monsoon, consistent with its recognition as a lightning hotspot in the country (Dewan et al. 2022). The intricate interplay of thermodynamic (e.g. convective available potential energy, CAPE) and dynamic (e.g. surface roughness) factors is likely responsible for the increased lightning activity in Bangladesh (Glazer et al. 2021; Bikos et al. 2016), particularly during the pre-monsoon months. As the monsoon arrives, the magnitude of CG lightning diminishes, albeit with higher strokes observed in the downwind regions of Dhaka and Khulna compared to the other three cities (Fig. 2). This phenomenon could be attributed to substantial monsoonal downpour (Li et al. 2022) and precipitation systems associated with monsoonal troughs and depressions (Rafiuddin et al. 2010).

This study also noted enhanced pre-monsoonal lightning in all cities, extending from upwind to metropolitan regions. However, Chittagong and Sylhet exhibited subtle suppression in CG strokes from upwind to downwind during the same season (Table 1). In contrast, during the monsoon, Dhaka experienced statistically significant suppression, whilst other cities observed enhanced CG strokes between upwind and metro/downwind regions, except for Sylhet, which experienced a suppression in lightning strokes from upwind to downwind areas (Table 2). Discrepancies in enhancement/suppression values between this study and global research stem from variations in data, methodologies, and the extent of anthropogenic activities, as well as the configuration (e.g. urban morphology) of the study area (Stallins and Rose 2008). For example, the use of seasonal data contrasts with the annual scale data employed in most global urban lightning studies, making direct comparison challenging. Nevertheless, our results aligned with existing literature, indicating that CG strokes are enhanced over urban and downwind regions of a city (Kar and Liou 2014; Steiger and Orville 2003; Pinto et al. 2004; Orville et al. 2001; Westcott 1995). The profound impact of intense human activities (Wang et al. 2021b) and the extent of land use change related to urbanisation (Kar and Liou 2019) on lightning enhancement or reduction is particularly evident in Bangladesh cities, where such activities are notably concentrated in Dhaka and Chittagong relative to other three cities considered.

Suppression of CG strokes was also observed in all five cities, especially in Dhaka during the monsoon and

Table 3 Bivariate relationships between CG strokes and predictors

City	Independent variable	Model component	Pre-monsoon	Monsoon	Post-monsoon
Dhaka	PM _{2.5}	Coefficient	- 2.20***	0.94***	- 2.52***
		R ²	0.29	0.03	0.28
	Total precipitation	Coefficient	1.10***	0.26*	0.47***
		R ²	0.48	0.004	0.21
	Mean LST	Coefficient	1.46**	1.23**	8.76***
		R ²	0.004	0.005	0.14
	Convective precipitation	Coefficient	0.95***	0.42***	0.62***
		R ²	0.459	0.0142	0.404
	Urban size	Coefficient	- 0.006	0.0006	0.004
		R ²	0.001	0.00001	0.0006
	Population density	Coefficient	- 0.03	0.007	0.01
		R ²	0.0007	0.00004	0.00008
Chittagong	PM _{2.5}	Coefficient	- 2.48***	- 0.03	- 2.93***
		R ²	0.16	0.00001	0.18
	Total precipitation	Coefficient	0.67***	- 0.33***	1.21***
		R ²	0.19	0.017	0.25
	Mean LST	Coefficient	3.58***	1.74***	14.36***
		R ²	0.02	0.01	0.30
	Convective precipitation	Coefficient	0.73***	- 0.12	1.09***
		R ²	0.393	0.00270	0.294
	Urban size	Coefficient	0.002	- 0.008	0.017
		R ²	0.00007	0.001	0.004
	Population density	Coefficient	- 0.02	- 0.001	0.01
		R ²	0.002	0.00001	0.001
Khulna	PM _{2.5}	Coefficient	- 1.41***	- 0.38	- 0.80
		R ²	0.11	0.003	0.02
	Total precipitation	Coefficient	1.19***	- 0.53*	0.50*
		R ²	0.30	0.015	0.04
	Mean LST	Coefficient	7.85***	5.39***	18.63***
		R ²	0.07	0.05	0.24
	Convective precipitation	Coefficient	0.99***	- 0.56**	- 0.50
		R ²	0.435	0.0256	0.0702
	Urban size	Coefficient	0.002	0.01	0.007
		R ²	0.0001	0.002	0.0006
	Population density	Coefficient	0.02	0.06	0.05
		R ²	0.0001	0.001	0.0009
Rajshahi	PM _{2.5}	Coefficient	- 3.32***	0.54**	0.32
		R ²	0.43	0.01	0.001
	Total precipitation	Coefficient	0.96***	- 0.46**	0.81***
		R ²	0.28	0.014	0.29
	Mean LST	Coefficient	13.01***	1.48	- 24.88***
		R ²	0.16	0.004	0.31
	Convective precipitation	Coefficient	0.70***	- 0.53***	0.90***
		R ²	0.26	0.03	0.43
	Urban size	Coefficient	0.004	- 0.005	- 0.02
		R ²	0.0001	0.0003	0.006
	Population density	Coefficient	0.005	0.04	- 0.05
		R ²	0.00001	0.002	0.003

Table 3 (continued)

City	Independent variable	Model component	Pre-monsoon	Monsoon	Post-monsoon
Sylhet	PM _{2.5}	Coefficient	-4.19***	-0.57	-1.63*
		R ²	0.31	0.003	0.11
	Total precipitation	Coefficient	1.45***	-0.67*	0.24*
		R ²	0.81	0.03	0.08
	Mean LST	Coefficient	3.69*	-2.53*	-0.2
		R ²	0.02	0.03	0.0001
	Convective precipitation	Coefficient	1.27***	-1.24***	0.005
		R ²	0.70	0.19	0.00004
	Urban size	Coefficient	-0.004	0.007	0.04*
		R ²	0.0003	0.002	0.07
	Population density	Coefficient	0.0006	0.06	0.33*
		R ²	7.5 ⁻⁰⁸	0.002	0.05

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

post-monsoon seasons (Table 1). Various factors may contribute to this, including the presence of distinct topographic features in and around cities (Weaver and Avissar 2001; Westcott 1995), the spatial organisation of urban settings (Haberlie et al. 2015), and location such as inland versus coastal (Lal and Pawar 2011). For instance, in a radar-derived study, Haberlie et al. (2016) demonstrated that the presence of relatively small water features can influence regional convective patterns. Given the pervasive distribution of large and small waterbodies in and around the five cities analysed, it is reasonable to infer that these waterbodies, combined with other attributes (e.g. urban morphology), may influence the spatiotemporal patterns of CG lightning observed in this study.

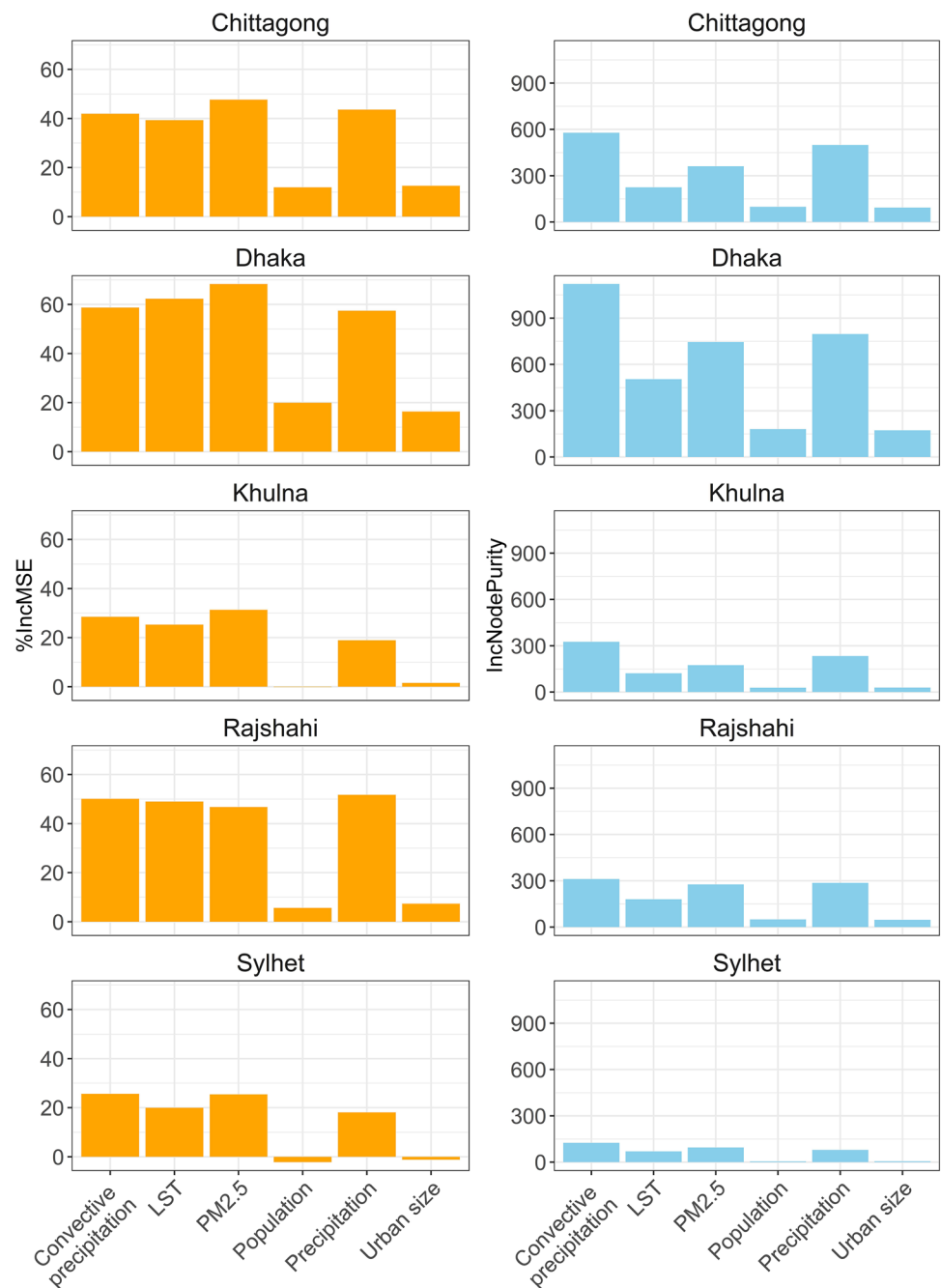
The diurnal variability of CG strokes in the five cities demonstrated a seasonal dependence. While Dhaka and Khulna displayed bimodal peaks in lightning activity, the other cities exhibited a single peak (Fig. 3). Specifically, Dhaka experienced CG peaks in the afternoon and early evening, which may be attributed to the solar heating cycle (Areitio et al. 2001) and the urban effect. Supporting this, Westcott (1995) observed increased lightning activity during the afternoon and early evening in eight of 16 large US cities. Similarly, Soriano and de Pablo (2002) reported enhanced lightning over urban areas in five out of nine cities in Spain. Thus, the peaking of CG strokes may be associated with city size, consistent with our findings and observations in other global cities.

To elucidate the causal factors associated with urban lightning, various hypotheses have been proposed. One such hypothesis concerns city size, and literature shows divergent findings on this matter. In this study, both city size and population density demonstrated a weak

association with seasonal CG strokes (Table 3, Fig. 4), aligning with findings from studies conducted in Brazil, the United States, and Spain (Pinto et al. 2004; Steiger and Orville 2003; Soriano and de Pablo 2002). This stands in contrast to research by del Río et al. (2015), and Areitio et al. (2001), who reported a positive influence. It is worth noting that the use of annual data for these two variables in examining the relationship may have influenced our analysis. Further, the impact of city size on thunderstorm occurrence in four U.S. cities was investigated by Kingfield et al. (2018), revealing that larger cities promote thunderstorms in the downwind region of the prevailing flow, whereas small cities do not. Stallins and Bentley (2006) observed that high-density urban areas did not generate a high number of lightning flashes.

Urban heat island (UHI), or the temperature differential between urban and rural areas associated with intense urban growth, is reported to amplify lightning activity in cities. Lightning, being sensitive to temperature fluctuations (Williams 2005), tends to increase with higher surface temperatures (Pinto 2013). Hot urban areas destabilise the air flowing over the city, leading to the development of a local convergence zone. This, in turn, creates a favourable environment for lightning (Stallins and Rose 2008; Westcott 1995). While a few studies have demonstrated an increase in convection and lightning with the UHI effect (Shi et al. 2023; Bourscheidt et al. 2016; Naccarato et al. 2003; Orville et al. 2001), both bivariate regression and RF model in our study showed a weak relationship between mean LST and CG lightning (Table 3, Fig. 4). This finding aligns with a study by Steiger and Orville (2003). It is important to note that urban land use plays a pivotal role in determining whether convection occurs over and downwind of an urban

Fig. 4 Relative importance of factors associated with CG strokes, based on %IncMSE and IncNodePurity



area (van Den Heever and Cotton 2007). Further investigation is, therefore, warranted.

The extensively tested hypothesis of urban pollution suggests that a higher concentration of aerosol in urban regions, resulting from intense anthropogenic activities, can contribute to enhanced convection and lightning through microphysical effects (Givati and Rosenfeld 2004). Various parameters such as sulphur dioxide (SO_x), particulate matter (PM), and nitrogen oxides (NO_2) have been tested in different cities (Yair et al. 2022; Wang et al. 2021c; Li et al. 2022; Neto et al. 2020; Tan et al. 2016; del Río et al. 2015; Kar and

Liou 2014; Farias et al. 2014; Middey and Chaudhuri 2013; Lal and Pawar 2011; Kar et al. 2009; Naccarato et al. 2003; Orville et al. 2001) to comprehend the association between pollution and lightning. These studies have consistently demonstrated that lightning in cities is sensitive to air pollution, aligning with findings of this study (Fig. 4). Cities in Bangladesh, particularly Dhaka is among the most polluted cities in the world (Islam et al. 2022; Rahman et al. 2020). It is noteworthy that the pollution hypothesis gained further support and offered new insights, especially during the COVID-19 lockdown when many cities experienced reduced

lightning activity (Chowdhuri et al. 2020; Neto et al. 2020). Despite the widely reported positive association, Tan et al. (2016) observed a decrease in lightning flashes in response to air pollution in China. Li et al. (2022) demonstrated that aerosols enhance lightning production under weak wind shear conditions. Moreover, combined effect of convective available potential energy (CAPE) with elevated total aerosol optical depth can enhance urban lightning (Wang et al. 2021a). Given the high CAPE over Bangladesh (Bikos et al. 2016) and significant aerosol loading in the country's cities, our findings provided additional evidence that urban lightning is positively associated with air pollution. However, Farias et al. (2014) noted that the positive relationship between pollution and lightning is threshold dependent, suggesting that lightning intensification tends to reduce after a certain saturation level (Tan et al. 2016). In addition, aerosol–lightning interaction is challenging to tease out over land (Liu et al. 2021). The impact of aerosol was conspicuous over inland locations, whilst coastal cities in India did not exhibit any effect on lightning enhancement (Lal and Pawar 2011). As our study encompassed both inland and coastal cities, the degree of this relationship may have varied accordingly.

5 Conclusion

Using 6 years of data on cloud-to-ground (CG) lightning strokes from the GLD360, this study investigated seasonal variations in lightning activity within the five densely populated urban centres in Bangladesh. In addition, various anthropogenic factors were analysed for their potential influence on lightning patterns in these cities. The results revealed significant spatial disparities in CG lightning occurrences across the five cities during the four seasons. Notably, pre-monsoon exhibited increased lightning activity over both upwind and downwind regions of Sylhet and Dhaka than other three cities. A marked enhancement of CG strokes during the pre-monsoon months was observed from upwind to metropolitan areas in all the five cities. However, only three cities—Dhaka, Khulna, and Rajshahi—experienced a similar enhancement from upwind to downwind regions during this season, whilst Chittagong and Sylhet showed subtle suppression. Other seasons demonstrated a mix of both suppression and enhancement in CG strokes, with the most significant enhancement occurring from upwind to downwind areas in Khulna during the winter season. Temporally, lightning activity exhibited variations both diurnally and monthly. While Dhaka and Chittagong experienced two peaks in May and September, CG strokes peaked in June, April and May in Khulna, Sylhet, and Rajshahi, respectively. Diurnally, CG strokes showed variations in their

activity across the five cities. Bivariate regression analysis revealed that both total and convective precipitation played important roles in lightning activity in the five cities across seasons. In comparison with mean surface temperature, urban size, and population density, particulate matter or $PM_{2.5}$ showed positive correlations with CG strokes in all cities. The relative importance of explanatory variables was assessed using a random forest model, indicating that particulate matter played a key role in lightning occurrence in the four cities, except Rajshahi.

To the best of our knowledge, this is the first study of its kind to assess seasonal variability of CG lightning and its influencing factors in major cities of Bangladesh. However, there are certain limitations to this work. The study employed $PM_{2.5}$ data, which is finer than PM_{10} . Future studies could explore the role of other pollutants such as SO_x , NO_2 and PM_{10} . In addition, the impact of locational factors, such as inland versus coastal positioning, could be examined to determine their influence on CG strokes. Discrepancies in the number of grids between upwind and downwind regions may arise based on city size, presenting a potential limitation in the approach adopted here. A future study could integrate dynamic, thermodynamic, and anthropogenic factors to comprehensively examine their roles in CG lightning enhancement. Lastly, urban barriers such as building density is shown to alter CG lightning patterns in Beijing (Shi et al. 2022). Due to unavailability of such data in the five cities, we could not examine the effect of urban barriers. Despite these limitations, the findings of this study hold significance for informing public policies aimed at safeguarding lives and livelihoods in a globally recognised climate hotspot.

Author Contributions AD: conceptualisation, data curation, methodology, writing—original draft, writing—review and editing, validation, supervision, project administration. KMAI: data preparation, software, methodology, formal analysis, visualisation, writing—review and editing. MEE: data preparation, resources, investigation, review. TRF: investigation, data curation, visualisation. MR: conceptualisation, data curation, writing—review and editing. MSGA: formal analysis, software, writing—review and editing, validation. All the authors have read, reviewed and approved the submitted manuscript.

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Data availability The raw data essential for reproducing the findings presented in this article are derived from proprietary commercial sources, and, unfortunately, the authors are not permitted to share this data due to contractual and authorization constraints. The restrictions imposed by the data providers prohibit the authors from making the raw data publicly available. However, the authors are committed to providing any necessary information or details about the data and methodology upon reasonable request to facilitate reproducibility and further scientific inquiry. Interested parties may contact the corresponding author for additional clarification or specific inquiries regarding the data used in this study.

Declarations

Conflict of Interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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