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## Significant decrease of lightning activities during COVID-19 lockdown period over Kolkata megacity in India



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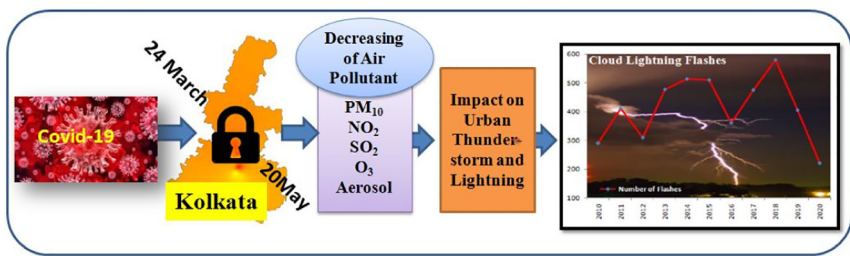
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### HIGHLIGHTS

- Average of PM<sub>10</sub>, NO<sub>2</sub>, SO<sub>2</sub>, O<sub>3</sub>, Aerosol reduced by –40 to –68% during the lockdown.
- Daily reduction of PM<sub>10</sub>, NO<sub>2</sub>, SO<sub>2</sub>, O<sub>3</sub>, and Aerosol is about –0.153 to –1.099 µg/m<sup>3</sup>.
- Air pollutants have significant impact on the climate phenomenon in Kolkata.
- PM<sub>10</sub>, NO<sub>2</sub>, SO<sub>2</sub>, O<sub>3</sub> and aerosol are positively linked with pre-monsoon lightning.
- Average lightning flash decreases by –49.16% in Pre-monsoon, 2020 due to lockdown.

### GRAPHICAL ABSTRACT



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### ABSTRACT

The outbreak of COVID-19 has now created the largest pandemic and the World health organization (WHO) has declared social distancing as the key precaution to confront such type of infections. Most of the countries have taken protective measures by the nationwide lockdown. The purpose of this study is to understand the effect of lockdown on air pollutants and to analyze pre-monsoon (April and May) cloud-to-ground and inter-cloud lightning activity in relation to air pollutants i.e. suspended Particulate matter (PM<sub>10</sub>), Nitrogen dioxides (NO<sub>2</sub>) Sulfur dioxide (SO<sub>2</sub>), Ozone (O<sub>3</sub>) and Aerosol concentration (AC) in a polluted tropical urban megacities like Kolkata. After the strict lockdown the pollutants rate has reduced by more than 40% from the pre-lockdown period in the Kolkata megacity. So, decreases of PM<sub>10</sub>, NO<sub>2</sub>, SO<sub>2</sub>, O<sub>3</sub> and AC have a greater effect on cloud lightning flashes in the pre-monsoon period. In the previous year (2019), the pre-monsoon average result shows a strong positive relation between the lightning and air pollutants; PM<sub>10</sub> ( $R^2 = 0.63$ ), NO<sub>2</sub> ( $R^2 = 0.63$ ), SO<sub>2</sub> ( $R^2 = 0.76$ ), O<sub>3</sub> ( $R^2 = 0.68$ ) and AC ( $R^2 = 0.83$ ). The association was relatively low during the lock-down period (pre-monsoon 2020) and the  $R^2$  values were 0.62, 0.60, 0.71, 0.64 and 0.80 respectively. Another thing is that the pre-monsoon (2020) lightning strikes decreased by 49.16% compared to the average of previous years (2010 to 2019). The overall study shows that the reduction of surface pollution in the thunderstorm environment is strongly related to the reduction of lightning activity where PM<sub>10</sub> and AC are the key pollutants in the Kolkata megacity.

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## 1. Introduction

The World Health Organization (WHO) has announced that COVID-19 was a pandemic in the first week of March, so the Government of India has implemented a nationwide lockdown since the last week of March 2020. India has a transit of 58 days of lockdown and has entered 4.0 phases of lockdown. Most (about 90%) of COVID-19 cases come from highly urban density areas such as Delhi, Mumbai and the megacity of Kolkata. Approximately 2000 people were diagnosed in Kolkata, 1100 were active, 700 were recovered and 200 deaths were reported on May 19 (WB HEALTH Portal, 2020).

COVID-19 pandemic forced India as a whole to lockdown from 24 March 2020 to 14 April 2020 (first phase), extended to 3 May 2020 (second phase). The central and state governments of India and West Bengal have implemented strict measures, such as the closure of shops, supermarkets, malls, all industries, public transport, airports, etc. There is also some relaxation after lockdown 3.0 (after 3 May 2020), with the exception of the red zone of infection with COVID-19. Due to the social distancing prevention, some researchers (Kerimray et al., 2020; Li et al., 2020) reported air quality improvements associated with lockdown measures like consequent decrease of vehicle and industrial transit. The improvement of air quality and the reduction of air pollutants have a broad effect on large urban areas or megacities. The worldwide research has also proved that due to the lockdown, air and water quality has also been improved (Yunus et al., 2020). Sharma et al. (2020) analyzed data on air pollutants and assessed the impact of the lockdown on air quality in different parts of India. During the partial lockdown, the air quality of Sao Paulo in Brazil improved dramatically and the level of pollutants decreased by 77% (Nakada and Urban, 2020). The National Capital Region (Delhi) in India is India's most polluted megacity, but the COVID-19 pandemic lockdown suddenly reduced the concentration of air pollutants and significantly improved air quality after three days of lockdown (Mahato et al., 2020).

As a result, many researchers (Mahato et al., 2020; Mandal and Pal, 2020; Yunus et al., 2020) have carried out the COVID-19 pandemic lockdown on environmental quality, such as air, water and noise quality, in different parts of the world. However, due to the decline in air pollutants, some micro-climatic phenomena have also changed where the levels of air pollutants have changed dramatically, as lightning and thunderstorms are among them. Lightning is an electrostatic discharge of approximately one gigajoule of energy during the electrical charge of the clouds in the atmosphere or in the ground (Maggio et al., 2009). There are three major types of lightning, based on a flash channel's ends. These are inter-cloud, cloud-to-cloud and cloud-to-ground lightning and most lightning occurs within the clouds. The upward movement of air and cloud temperatures from  $-15^{\circ}\text{C}$  to  $-25^{\circ}\text{C}$  results in a positive charge of super-cooled cloud droplets and a negative charge of soft hail or snow pellets. The super-cooled cloud droplets move upward, positioned in the upper part of the cloud, and the soft hail in the middle or lower part of the cloud (Ogawa and Brook, 1964). Thus, the positive charge accumulated in the upper part of the thunderstorm cloud and the middle and lower parts of the cloud are accumulated by negative charges and their electrostatic discharge is generated by a massive lightning (Lhermitte and Williams, 1985). Many scientists have shown that the change in major weather conditions caused the urban effect (Orville et al., 2001; Soriano et al., 2001). A large number of literature (Chaudhuri and Middey, 2013; Kar et al., 2009; Kar and Liou, 2014) has shown that there is a strong relationship between the air pollutant and the lightning in the highly polluted megacity of the tropical region. Different studies have shown that the increase in cloud-to-ground and inter-cloud lightning has an effect on nitrate oxide and  $\text{O}_3$  in urban atmospheres (Pawar et al., 2012). Air pollution, therefore, has a direct and indirect impact on the global climate and atmosphere. Concentration of aerosols in the atmosphere has an effect on rainfall and cloud formation and has worked as a change in weather conditions. Suspended particulate materials ( $\text{PM}_{10}$ ) are the most important air

pollutants and cloud lightning determinants (Naccarato et al., 2003). Possible concentration of  $\text{SO}_2$  in the atmosphere to increase lightning flashes in urban areas (Soriano and de Pablo, 2002). Kar et al. (2009) reported that the major concentration of  $\text{PM}_{10}$  and  $\text{SO}_2$  in the atmosphere is responsible for the hike of lightning strikes. On the other hand, the concentration of  $\text{NO}_2$  on the troposphere has a major effect on the significant increase in lightning. Kar & Liou (2014) analyze the cloud-to-ground lightning in relation to  $\text{PM}_{10}$ ,  $\text{NO}_2$ ,  $\text{SO}_2$ , and  $\text{O}_3$  concentration of Taipei in Taiwan. Chaudhuri & Middey (2013) discussed the pre-monsoon (April–May) lightning, considering the effects of PM,  $\text{NO}_2$  and  $\text{SO}_2$  of Kolkata metropolitan area.

Although different studies have included a lockdown impact on improving air quality in urban areas, changes in air quality and air pollutants and the impact on the climate of micro-regions such as megacities have not yet been discussed. This means that the COVID-19 lockdown imposed has an indirect impact on the micro-climate phenomenon. The present study has been conducted considering the ambient air pollutants, i.e.,  $\text{PM}_{10}$ ,  $\text{NO}_2$ ,  $\text{SO}_2$ ,  $\text{O}_3$  and aerosol on lightning flashes during the pre-monsoon period (April and May). A higher amount of pre-monsoon lightning flash is reported over the Kolkata megacity area than the monsoon period (Chaudhuri and Middey, 2013). Hence, the pre-monsoon season has been selected for this study because this time coincides with the COVID-19 lockdown period. The main objectives of this study are therefore to analyze the trend of ambient air pollutants ( $\text{PM}_{10}$ ,  $\text{NO}_2$ ,  $\text{SO}_2$ ,  $\text{O}_3$  and aerosol) during the lockdown and pre-lockdown periods. And to compare the pre-monsoon cloud-lightning activities affecting these air pollutants during the COVID-19 lockdown period and some pre-lockdown periods in the Kolkata megacity area.

### 1.1. Study area

The location of the study is the Kolkata megacity, the capital city of West Bengal, as well as the largest megacity in Eastern India (Fig. 1). Physiographically, it is situated over the Indo-Gangetic plain specifically the mature part of the Ganges delta. The average altitude of Kolkata and its environs is 6.05 m with salty marshy wetland topography; after the implementation of the wetland restoration project, it is found especially towards the eastern parts of the megacity. The climate is tropical wet and dry ('AW' type of Kopen classification), characterized by wet in summer and dry in winter. The mean annual temperature and rainfall are  $26^{\circ}\text{C}$  and 1582 mm respectively. The megacity faces five seasons, i.e., Pre-monsoon (Apr–May), monsoon (June–Sep), post-monsoon (Oct–Nov), winter (Dec–Jan) and spring (Feb–Mar). During the pre-monsoon period, this area experienced several local storms, characterized by strong winds and afternoon rains with thunderstorms and lightning. The monthly average temperature of pre-monsoon season is  $30^{\circ}\text{C}$  to  $38^{\circ}\text{C}$  and rainfall ranges from 0 to 150 mm. The rainfall mainly occurs due to the Nor-wester and severe tropical cyclone over the Bay of Bengal. The wind blows in the north, north-east, south and south-east direction during the pre-monsoon period. As per records of the census of India and Government of West Bengal, huge urbanization took place around the Kolkata and the population of megacity has touched 14.85 million. Kolkata is the main commercial hub of eastern India, and a number of macro and micro industries are located here. So pollution is the main problem in Kolkata, mainly air pollution, PM and other air pollutants are higher than other major cities in India. It caused respiratory diseases, such as lung cancer.

## 2. Materials and methods

Most of the lightning studies were conducted in Kolkata during the pre-monsoon season (April–May). This study period is therefore 24 March to 20 May, which is the period of lockdown due to the COVID-19 pandemic. Air pollutant data were collected from the West Bengal Central Pollution Control Board (WBPCB) and the Central Pollution Control Board (CPCB) of India (CPCB/Central Pollution Control Board, 2020),

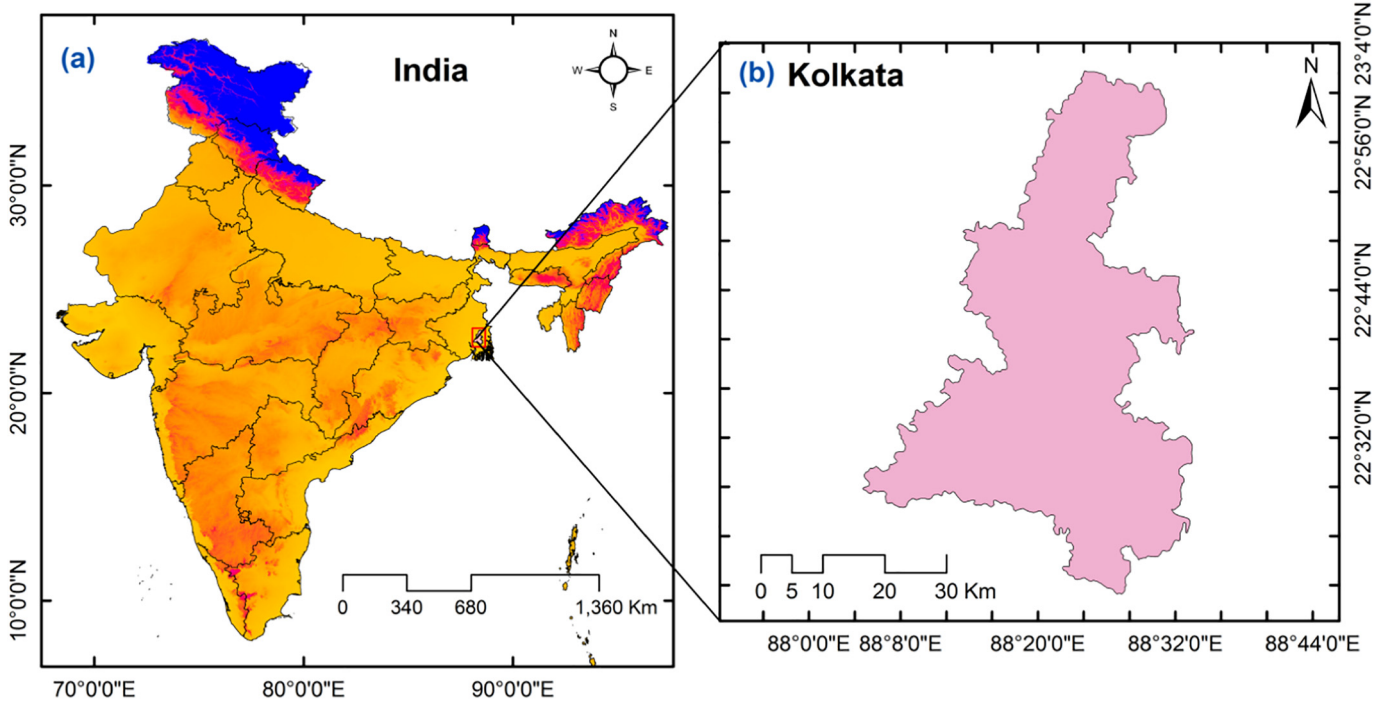


Fig. 1. Location Map of the study area.

which includes particulate matter (PM<sub>10</sub>), NO<sub>2</sub>, SO<sub>2</sub> and O<sub>3</sub> concentrations over the Kolkata megacity of West Bengal. Monthly average PM<sub>10</sub>, NO<sub>2</sub>, SO<sub>2</sub> and O<sub>3</sub> values were collected during the months of March (24<sup>th</sup>) to May (20<sup>th</sup>) from 2010 to 2020 to show the trend of selective air pollutants. The Lightning data is provided by LIS (Lightning Imaging Sensor) database from Tropical Rainfall Measuring Mission (TRMM) for the period of 2010 to 2015. The LIS detects cloud-to-ground and inter-cloud lightning activities together in the troposphere. The TRMM satellite rounded the earth at an altitude of 350 Km and the LIS sensed the 777.4-nm atomic oxygen multiple detecting pulses of illumination (Producing from lightning) from the cloud (Boccippio et al., 2002; Cecil et al., 2005). Daily and monthly sound lightning data were collected from THUNDERSTORM (2020) by the Indian Meteorological Department from 2016 to 2020. Only lightning data from 14H to 20H IST are considered, which corresponds to the time of day with maximum lightning activity in the Kolkata megacity. Aerosol concentration was extracted from Moderate Resolution Imaging Spectroradiometer (MODIS) data (Aqua and Terra) products, level 3 daily data for 1° × 1° grid and it has significant effect on lightning.

Different ground base stations used to assess the levels of mentioned air pollutants which are strongly associated with thunderstorm and lightning. For each station daily data (24H) from before lockdown (Feb 24<sup>th</sup> to March 23<sup>th</sup>) to during lockdown (March 24<sup>th</sup> to 20<sup>th</sup> May) for 2019 and 2020 and pre-monsoon average for 2010 to 2018 were collected. The famous non-parametric method Mann Kendal and Sen's Slope estimation methods (Eq. 1 to 8) used the PM<sub>10</sub>, NO<sub>2</sub>, SO<sub>2</sub> and O<sub>3</sub> trend analysis and aerosol concentration during the lockdown period (March to May) of 2020. Pearson coefficient of correlation method has been applied to know the association between the lightning and air pollutants in the year of 2019 and 2020 (Fig. 4). The Normal trend method used to compare both air pollutants and lightning flash counts for the period 2010 to 2020 (Pre-monsoon period).

The Mann-Kendall statistical S test calculated as following Eq. (1) (Kendall, 1975; Mann, 1945).

$$S = \sum_{i < j} a_{ij} \quad (1)$$

$$a_{ij} = \text{sign}(X_j - X_i) = \text{sign}(R_j - R_i) = \begin{cases} 1 & X_i < X_j \\ 0 & X_i = X_j \\ 1 & X_i > X_j \end{cases} \quad (2)$$

Here, R<sub>i</sub> and R<sub>j</sub> are rank of observation in X<sub>i</sub> and X<sub>j</sub> time series. Mann (1945) and Kendall (1975) have reported that statistics S and the mean and variance are computed as Eq.3.

$$\text{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{j=1}^m t_j(t_j-1)(2t_j+5)}{18} \quad (3)$$

where, n is the number of observations, m is the number of groups of tied ranks and the notation t is extend of any given time. When the n > 10 the standard normal variable (Z) is computed as following Eq. (4).

$$Z = \begin{cases} (S-1)/\sqrt{V_0(S)} & S > 0 \\ 0 & S = 0 \\ (S+1)/\sqrt{V_0(S)} & S < 0 \end{cases} \quad (4)$$

The slope estimates of N datasets were computed by the following equations (Sen, 1968).

$$Q_i = \frac{x_j - x_k}{j - k} \text{ for } i = 1, 2, \dots, N \quad (5)$$

where, x<sub>j</sub> and x<sub>k</sub> are the value of data at the time j and k (j > k), respectively. The median of slope or Sen's slope estimator of odd and even data is computed as Eqs. (6) and (7)

$$Q_m = Q_{\lfloor (N+1)/2 \rfloor} \quad (6)$$

$$Q_m = \frac{1}{2} [Q_{\lfloor N/2 \rfloor} + Q_{\lfloor (N+2)/2 \rfloor}] \quad (7)$$

where, Q<sub>m</sub> is median of data trend. Eq. (6) applied if N is odd data and if N is even Eq. (7) is used. When the median slope is statistically different than zero, then confidence interval of Q<sub>m</sub> at specific probability (Da Silva et al., 2015; Gilbert, 1987) estimated as Eq. (8)

$$C_{\alpha} = Z_{1-\alpha/2} \sqrt{\text{Var}(S)} \quad (8)$$

where,  $\text{Var}(S)$  is calculated from in Eq. (3) and  $Z_{1-\alpha/2}$  is obtained from the standard normal distribution.

### 3. Result

#### 3.1. Air pollutants rate in during the lockdown and before lockdown

Air pollutants and pollution of the major megacity of India have seen a significant decrease following the announcement of a nationwide lockdown on 24 March 2020 (Fig. 2). From the literature survey, several studies (Chaudhuri and Middey, 2013; Kar and Liou, 2014; Soriano and de Pablo, 2002) have shown that high concentrations of  $\text{PM}_{10}$ ,  $\text{NO}_2$ ,  $\text{SO}_2$  and  $\text{O}_3$  have caused inter-cloud and cloud-to-ground lightning flashes.  $\text{PM}_{10}$  decreased by about  $-51.01\%$  from the pre-lockdown to during lockdown period and the trend of daily  $\text{PM}_{10}$  decreases by  $-1.00 \mu\text{g}/\text{m}^3$  during the lockdown period (Tables 1 and 2). The  $\text{PM}_{10}$  sources, such as vehicles and traffic, are very low on the roads and the industries have been tightly closed to maintain the social distance in Kolkata during the lockdown. Other important pollutants, i.e.  $\text{NO}_2$  and  $\text{SO}_2$  have also shown the significant reduction during the COVID-19 pandemic lockdown (Fig. 2). In the study area, average concentrations of  $\text{NO}_2$  and  $\text{SO}_2$  decreased by almost  $-68.38\%$  and  $-40.38\%$  respectively, and the trend of daily reduction is about  $-0.373$  and  $-0.153 \mu\text{g}/\text{m}^3$  from the pre-lockdown to lockdown (Fig. 2, Tables 1 and 2) due to the emission from diesel, in smaller degree from gasoline vehicles, manufacturing industry and power plants have totally stopped.  $\text{O}_3$  in the lower troposphere acts as a pollutant and potential for respiratory hazards. Therefore, the concentration of  $\text{O}_3$  is also much below the permissible limit and also has reducing trend ( $-42.58\%$ ) from pre-lockdown to lockdown, with a daily trend of  $-0.571 \mu\text{g}/\text{m}^3/\text{day}$  (Fig. 2, Tables 1 and 2). The concentrations of aerosol extracted from daily MODIS data during the pre-locking period to the lock-down period also show the same trend as for other pollutants ( $-57.92\%$ ) from the pre- and during the lock-down period and a daily decrease of  $-1.099 \mu\text{g}/$

**Table 1**

Total variation of pollutants in lockdown period.  
Sources: CPCB|Central Pollution Control Board, 2020.

Period	Avg. pollutant concentration ( $\mu\text{g}/\text{m}^3$ )				
	$\text{PM}_{10}$	$\text{NO}_2$	$\text{SO}_2$	$\text{O}_3$	Aerosol
Lockdown (24 Mar to 20 May, 2020)	44.94	12.67	9.15	38.66	40.67
Before lockdown (17 Feb to 23 Mar, 2020)	91.74	40.06	15.35	67.33	96.66
Total variation (avg.)	-46.79	-27.39	-6.20	-28.67	-55.99
% of variation	-51.01	-68.38	-40.38	-42.58	-57.92

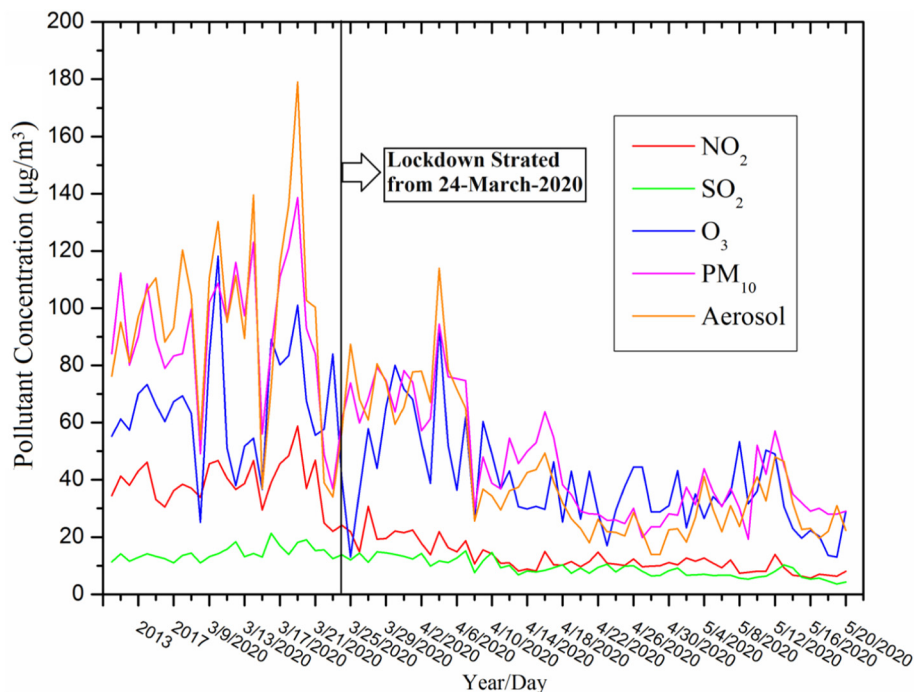
**Table 2**

Trend of  $\text{PM}_{10}$ ,  $\text{NO}_2$ ,  $\text{SO}_2$ ,  $\text{O}_3$  and Aerosol concentration.  
Source: CPCB|Central Pollution Control Board, 2020.

Pollutant ( $\mu\text{g}/\text{m}^3$ )	Mann-Kendal Z	Sen's slope
$\text{PM}_{10}$	-7.11***	-1.000
$\text{NO}_2$	-8.98***	-0.373
$\text{SO}_2$	-8.54***	-0.153
$\text{O}_3$	-5.57***	-0.571
Aerosol concentration	-6.86***	-1.099

\*\*\*, \*\*, and \* are the significant at 1%, 5%, and 10% level of significance respectively.

$\text{m}^3/\text{day}$  (Fig. 2, Tables 1 and 2). The concentration of  $\text{PM}_{10}$ ,  $\text{NO}_2$ ,  $\text{SO}_2$ ,  $\text{O}_3$  and aerosols (biomass burning aerosols, dust minerals, household and industrial smoke, sea salt, etc.) for the pre-monsoon period from 2010 to 2018 is equal to the pre-monsoon period from 2020 (Fig. 3). In India, strict measures such as lock-down are put in place to maintain social distance, avoid community gathering, etc. The lockdown was extended to different phases (Lockdown 1.0, 2.0, 3.0 and 4.0) and now (May 18, 2020) India has entered 4.0 phases of lockdown. After lockdown 3.0 (Ended at 17 May and 55 days after the lockdown), some relaxation has given except red zone (High spreads of COVID-19). Thereafter the above mentioned pollutants and aerosol concentration are minutely increases in the present phase of the lockdown period (Fig. 2).



**Fig. 2.** Trend of  $\text{PM}_{10}$ ,  $\text{NO}_2$ ,  $\text{SO}_2$ ,  $\text{O}_3$  and aerosol concentrations.

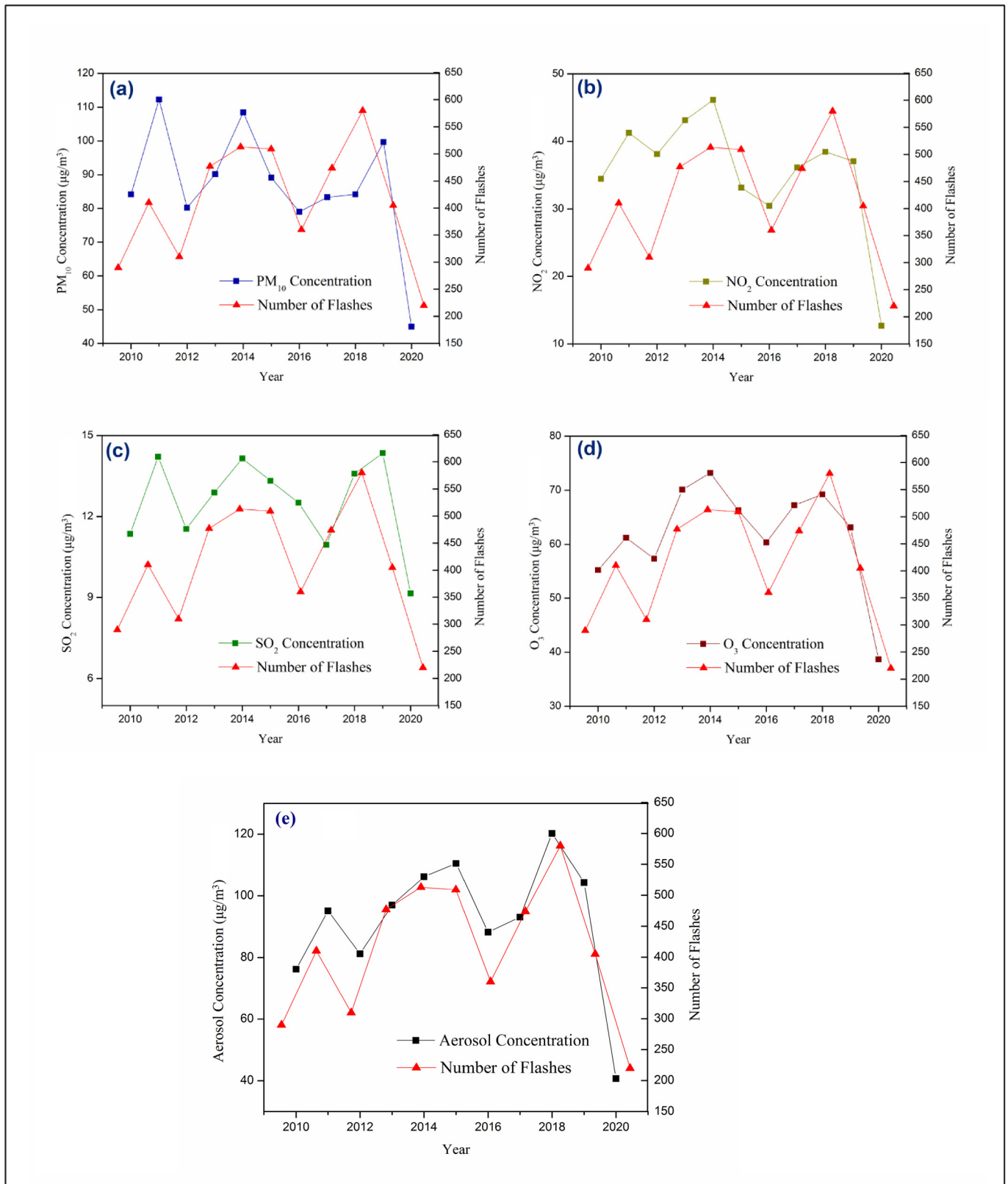


Fig. 3. The variation of the total number of lightning flashes with average (a) PM<sub>10</sub>, (b) NO<sub>2</sub>, (c) SO<sub>2</sub>, (d) O<sub>3</sub> and (e) Aerosol concentrations during pre-monsoon months for period of 2010 to 2020.

### 3.2. Trend of cloud lightning and air pollutants

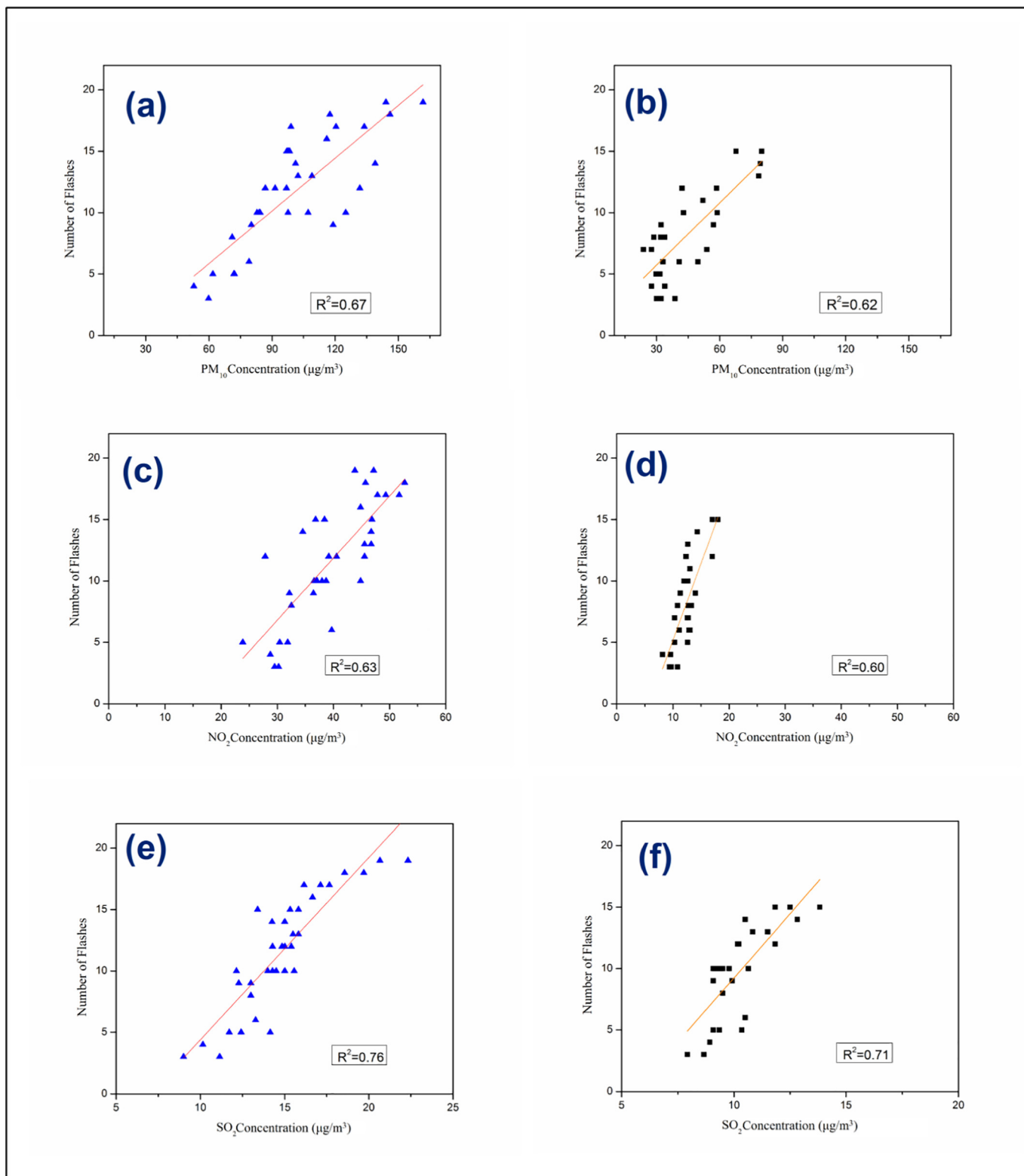
Current research corresponded to pre-monsoon thunderstorm and lightning activity during the period of the COVID-19 Pandemic

Lockdown of April–May in Kolkata Megacity. In this previous section, major lightning related air pollutants were shown to fall sharply from the pre-locking months of 2020 and the previous year (2010 to 2019) in Kolkata. So, for the association analysis, the data for PM<sub>10</sub>, NO<sub>2</sub>, SO<sub>2</sub>,

O<sub>3</sub>, AC and lightning flash counts for the current year as well as for the previous 10 years have been divided into two types. Total average data for the normal association between lightning flash and air pollutants was used during the pre-monsoon period from 2010 to 2020. On the other hand, daily data were also used to analyze the coefficient of

correlation ( $R^2$ ) between the lightning flash and the air pollutants during the pre-monsoon period of 2019 and 2020.

The variation in the total number of lightning flashes during the pre-monsoon season is shown by the pre-monsoon average PM<sub>10</sub>, NO<sub>2</sub>, SO<sub>2</sub>, O<sub>3</sub> and aerosol concentrations for the period 2010 to 2020 in Fig. 3. The



**Fig. 4.** Scatter plot of the daily PM<sub>10</sub>, NO<sub>2</sub>, SO<sub>2</sub>, O<sub>3</sub> and Aerosol concentrations and daily lightning flashes during the pre-monsoon season. The Left column represents the pre-monsoon of 2019 and the right column represents the pre-monsoon of 2020. Where, (a) and (b) is PM<sub>10</sub>, (c) and (d) is NO<sub>2</sub>, (e) and (f) is SO<sub>2</sub>, (g) and (h) is O<sub>3</sub>, (i) and (j) is Aerosol concentration.

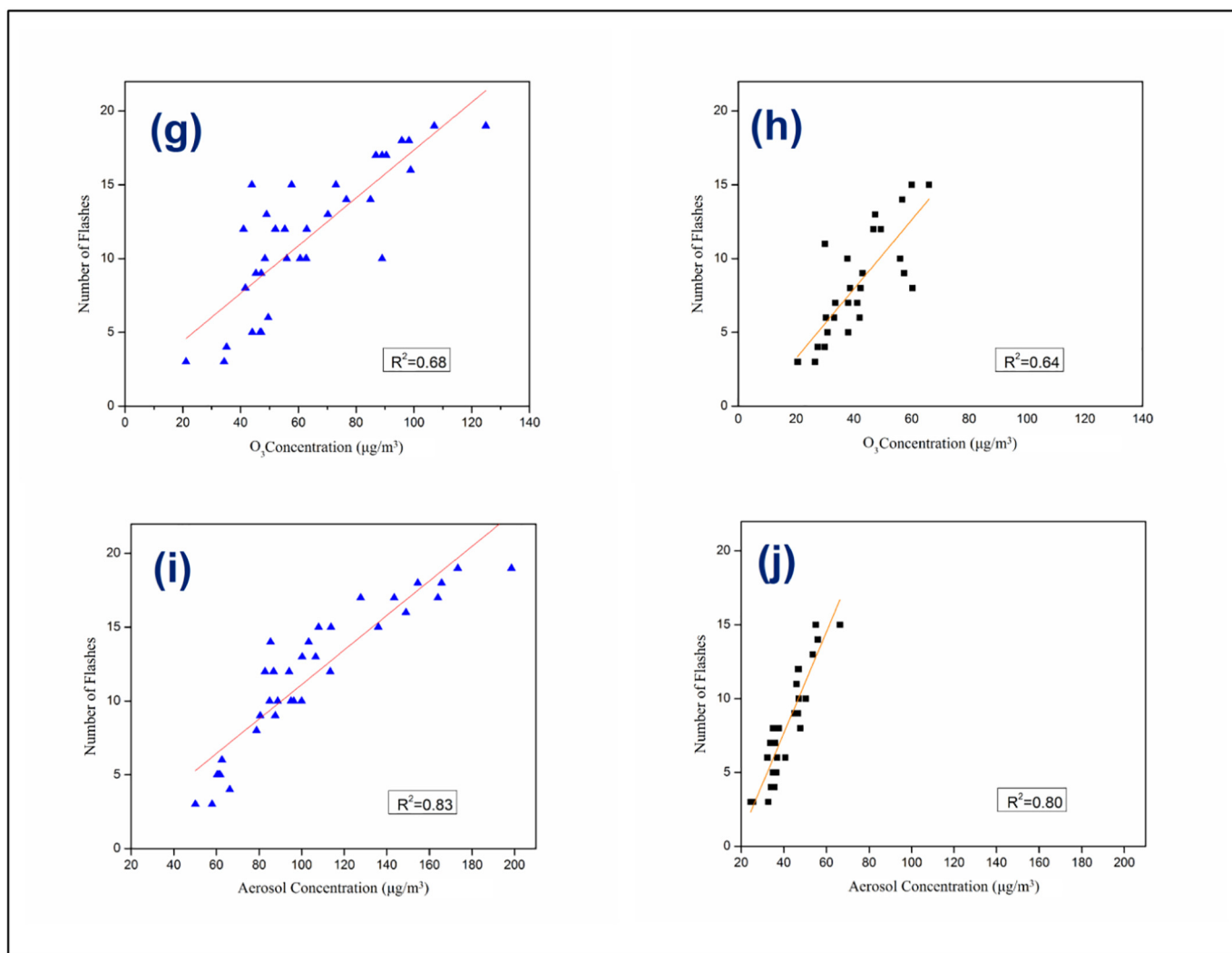


Fig. 4 (continued).

figure shows the year of high concentrations of atmospheric pollutants with the maximum lightning flash count and low concentrations of pollutants with the minimum lightning flash count compared to other years. The lightning flash count ranges from 580 to 220 during the pre-monsoon period (April and May) from 2010 to 2020 and the lowest lightning recorded in 2020.  $PM_{10}$  is a significant air pollutant responsible for cloud formation, precipitation, and electrical atmospheric activity (Feudale and Manzato, 2014). The mean  $PM_{10}$  ranges from  $44.94 \mu\text{g}/\text{m}^3$  to  $112.26 \mu\text{g}/\text{m}^3$  and the lowest  $PM_{10}$  concentration is also recorded in this year as a result of the COVID-19 lockdown (Fig. 3. a). From the scatter plot of average daily concentrations of  $PM_{10}$ ,  $NO_2$ ,  $SO_2$ ,  $O_3$  and aerosol with daily lightning flash counts of 2019 and 2020 the dependence of lightning flashes on concentrations of air pollutants is shown in both years (Fig. 4). We have chosen 2020 pre-monsoon (24<sup>th</sup> March to 20<sup>th</sup> May) for lockdown impact and 2019 is a normal year (Fig. 4.a to j). The scatter plot shows that all these have a more or less positive correlation coefficient with all air pollutants and lightning flashes for both years. But if we consider scatter plotting, there is a huge difference between 2019 and 2020.  $PM_{10}$  has a strong positive association with lightning flash, where there is a correlation coefficient; 0.62 for 2020 and 0.67 for 2019.  $NO_2$  is the major pollutant of the predecessor for lightning in the lower troposphere rather than the high cloud (Schumann et al., 2004). There is a positive relationship with the lightning flash for 2020 and 2019 (Fig. 4.c and d), but it can be seen from the

Fig. 3.b that  $NO_2$  concentrations and lightning activity decreased drastically in 2020 ( $12.66 \mu\text{g}/\text{m}^3$ ) compared to other periods.

Previous studies have shown that Sulfuric acid ( $H_2SO_4$ ) particle is more active in the formation of new cloud condensation nuclei (CCN) as well as thunderstorm and lightning (Perry and Hobbs, 1994; Siingh et al., 2011; Thornton et al., 1997). The reaction of  $SO_2$  with hydroxyl radical (OH) formed  $H_2SO_4$  in the atmosphere. The formation of  $H_2SO_4$  is shown in Eqs. (9), (10) and (11) as follows.



Scatter plot ( $R^2$  value of 2019 is 0.76 and 2020 is 0.71) revealed that higher  $SO_2$  concentration is associated with high lightning and flashing in Kolkata, but the scatter distribution and ten-years trend showed a reduction in  $SO_2$  and lightning both during the 2020 lockdown period (Figs. 3.c, 4.e and f).  $O_3$  is important for the upper troposphere by protecting life from the ultraviolet rays of sun, but with a high concentration in the lower troposphere caused by lightning. There is a medium association ( $R^2 = 0.68$ ) between this pollutant and flash count in 2019, but there is a lower association ( $R^2 = 0.64$ ) between 2020 (Figs. 3.d, 4.g



and h). The science of the aerosol concentration effect on lightning flash is well established in several studies (Tan et al., 2016; Yuan et al., 2011). Higher aerosol concentrations affect the size of the droplets, reduce warm rainfall warm rainfall coalescence process, and increase the amount of cloud water resulting in a change in the microphysical process of ice formation and cloud lightning (Farias et al., 2009). In Kolkata, the lightning flash count is strongly associated with aerosol concentration ( $R^2$  is 0.83 in 2019), but in 2020 ( $R^2 = 0.80$ ) is lower than 2019 (Figs. 3.e, 4.i and j). Scatter plot of aerosol concentration and lightning shows a low concentration of aerosol and lightning flash count of Kolkata megacity in 2020 than 2019 (Fig. 4). Lightning flash count day and per day flash count are relatively low in the pre-monsoon period of 2020 compared to the other years.

More than 20 flash counts were recorded in five different days during the pre-monsoon period of 2019 and, on the other hand, more than 20 flash counts were not recorded in one single day in 2020. Total lightning flashes are reduced by 49.16% from the previous average total flash count.

#### 4. Discussion

The impact of the lock-down and its associated level of pollutants has been estimated in this study to determine the relationship between the level of pollutants and cloud flashes. For this purpose, the pre-monsoon season in the present and previous years has been selected purposively. The atmospheric disturbances have been found in this region and associated surrounding regions, popularly known as "Kalbaisakhi" or "Norwester". Pollution in urban areas has a significant impact on the generation of lightning flashes and their associated frequency and intensity. Although the Kolkata megacity was considered to be one of the major polluted megacity due to rapid commercial, industrial and transport activities, heavy lightning flashes with high vertical air currents are common in any pre-monsoon season. Apart from the various meteorological components, the suspended particulate matter (SPM) has a major impact on surface lightning flashes during the pre-monsoon period. The global pandemic of the COVID-19 lockdown has changed India's air quality. All cities in India are witnessing a downward trend in pollutants. This is primarily due to fewer automobiles and roadside food vendors using coal stoves, which is the significant source of emissions in Indian cities. There is a significant decrease in the tendency of lightning flashes has been observed during the lockdown period of the Kolkata megacity and its associated regions (Fig. 3). However, the COVID-19 lockdown reduces the level of air pollutants by closing down man-made sources of emissions. On the other hand, major air pollutants, nitrate oxides and  $O_3$  can naturally be reduced by reducing the flash of lightning (Beirle et al., 2004; Bond et al., 2002). Because the lightning flash generated heat in the troposphere, which is ten times higher than radiant solar insolation (Maggio et al., 2009; Marshall and Stolzenburg, 2001). And high atmospheric heating produces large amounts of nitrate oxide and  $O_3$  (Bond et al., 2002). In the tropical area, the effect of lightning flashes can increase by 30% to 90% of  $O_3$  and nitrate oxide in the troposphere (NASA, 2003). This study is useful in identifying the impact of major pollutants on changes in weather conditions such as lightning and associated thunderstorms.

#### 5. Conclusion

The present research shows that pollutants are closely connected to lightning activities in the megacity of Kolkata. Not only meteorological factors, but also particulate matter ( $PM_{10}$ ), aerosols,  $NO_2$ ,  $SO_2$  and levels of  $O_3$  have played a major role in the modification of high-frequency atmospheric events, such as lightning. The study reveals that the level of pollutants and aerosol concentrations during the COVID-19 imposed lockdown phase has decreased by more than 40% from the pre-lockdown period in the Kolkata megacity, which decreases the overall lightning flashes by 49.16% from the previous estimated cumulative

lightning flash count. According to the National crime record bureau of India, more than 2300 people were died by lightning strikes in 2018. This is evident from the findings that the strict lockdown form of the measure will not only contribute to a significant reduction in the level of pollutants, aerosol concentrations, but will also control the cumulative lightning flash count of the regional climate, which in turn controls losses such as property and life. So lockdown not only prevents the Corona pandemic but also reduces the causalities of thunderstorms and lightning. Therefore, urban dwellers can rethink about their contribution to air pollution and decision-makers may take some management measures to reduce air pollution.

#### CRedit authorship contribution statement

**Indrajit Chowdhuri:** Visualization, Data curation, Software, Methodology, Writing - original draft, Writing - review & editing. **Subodh Chandra Pal:** Conceptualization, Investigation, Supervision, Formal analysis, Writing - original draft, Writing - review & editing. **Asish Saha:** Data curation, Methodology, Writing - review & editing. **Rabin Chakraborty:** Formal analysis, Data curation, Writing - review & editing. **Manoranjan Ghosh:** Software, Methodology, Writing - review & editing. **Paramita Roy:** Formal analysis, Data curation, Writing - review & editing.

#### Declaration of competing 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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