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Effects of COVID-19 pandemic on the air quality of three megacities in India

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ABSTRACT

COVID-19 pandemic compelled many countries in the world to go for a nationwide lockdown to prevent the spread of the coronavirus. India started the lockdown on 24 March 2020. We analyzed the air quality of three megacities of India, namely Mumbai, Delhi, and Kolkata, during the lockdown phase and compared it with the pre-lockdown and post-lockdown scenarios. We considered seven major air pollutants: $PM_{2.5}$, PM_{10}, NO_2, NH_3, SO_2, CO, and O_3. We analyzed the data acquired from 56 automatic air-monitoring stations (AAMS) under the Central Pollution Control Board (CPCB) spread across the megacities. The air pollution level in the eastern part of Mumbai and the western part of Delhi and Kolkata usually remains high. Delhi was the worst polluted megacity, followed by Kolkata and Mumbai. The stop of vehicular movements and industrial lockdown across the nation has substantial effects on the environment, especially in the atmosphere near the Earth's surface. Our analysis showed significant improvements in air quality during the period of lockdown (25 March to 14 April 2020) compared to the pre-lockdown phase (3 March to 23 March 2020) and the same time window of the previous year (25 March to 14 April 2019). The post-lockdown (15 April to 5 May) phase exhibited mixed results. We mapped the spatial pattern of these pollutants and the air quality index (AQI). According to CPCB, $PM_{2.5}$, PM_{10}, and CO are the major air pollutants in India that reduced by 47%, 41%, and 27% in Mumbai; 52%, 39%, and 13% in Delhi; and 49%, 37%, and 21% in Kolkata, respectively, in the lockdown phase. $PM_{2.5}$, PM_{10}, and NO_2 exhibited significant correlations across the three megacities. This study shows that occasional short-term lockdowns can effectively refresh the air in these megacities.

1. Introduction

The pandemic caused by a coronavirus (COVID-19) poses a significant threat to the human population throughout the world. Coronaviruses are single-stranded ribonucleic acid (RNA) viruses that can infect not only humans but also a variety of animals as well (Kooraki et al., 2020). The mode of spread of this coronavirus requires exhaustive studies; however, maintaining social distance is recognized as one of the most fruitful solutions to prevent its rampant spread (Lipsitch et al., 2020). The World Health Organization (WHO) declared in March 2020 that the COVID-19 has turned out into a global pandemic and called for a forceful worldwide reaction. The most affected countries like United States, Brazil, United Kingdom, Mexico, Italy, India, France, Spain, Peru, Iran, and Russia recorded millions of infected and thousands of deaths (Docherty et al., 2020). The COVID-19 pandemic severely affected the world economy, especially in developing countries. Gita Gopinath from the International Monetary Fund (IMF) pointed out that due to the impact of the COVID-19, the global economy would experience a recession in 2020, and the economic growth rate would drop to −3% (Gopinath, 2020). Researchers found an undeniable link between the effectiveness of COVID-19 and polluted air. A higher level of air pollution led to a higher rate of COVID-19 infection in many polluted cities of Asia, Europe, and North America. A recent study by Xie and Zhu (2020) covering 120 cities in China showed a critical relationship between air contamination and COVID-19 disease. Moreover, studies from the United States show that an increase in long-term exposure to particulate matter ($PM_{2.5}$) results in a significant rise in the death rate from COVID-19 (Wu et al., 2020a, 2020b).

Each year the emission of anthropogenic pollutants contributes to undesirable air quality levels in India (Balakrishnan et al., 2019). The

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major cities in India like Chennai, Delhi, Hyderabad, Kolkata, and Mumbai are among the most populated, where ambient concentrations of $PM_{2.5}$ remain above WHO annual guideline values of 10 μg m^{-3} (WHO, 2016). Several studies indicated that air quality in India has deteriorated beyond measures in recent times (Chauhan and Singh, 2020; Sarkar et al., 2018, 2019). New Delhi, the capital of India, suffers from stable air quality with much higher levels of pollution than Beijing (Zheng et al., 2017). India is one of the largest populated countries in the world, and due to its high population density in urban areas, the air pollution level remains significantly high. The principal sources of pollutants are vehicular emission, industrial activities, and domestic fuel burning (Mor et al., 2021). Except for ozone (O_3), the others, such as $PM_{2.5}$, PM_{10}, nitrogen dioxide (NO_2), ammonia (NH_3), sulfur dioxide (SO_2), and carbon monoxide (CO), are the primary air pollutants (see Table S1 in supporting information). It is pertinent to note that air pollution is associated with respiratory and cardiovascular diseases (Zheng et al., 2020). A higher degree of air pollution has more impact than COVID-19 (Giani et al., 2020). The government of India imposed a complete lockdown all over the country initially for 21 days to combat the critical pandemic on 24 March 2020. All the social gathering places such as restaurants, cinemas, schools, shopping complexes, and educational institutions were closed. Staff and students worked from home to maintain a strategic distance from swarms. Suspension of all transportation services including rail, road, and air took place, except for the emergency services. Besides, almost all production and industrial activities came to a halt (Kumari and Toshniwal, 2020). The total lockdown has adversely influenced the economy of the nation. However, limited transportation and economic activity led to a drastic decrease in air pollution (Gautam, 2020). Globally, it has been proven by satellite images and ground data that air pollution in the form of NO_2 emissions in many parts has dropped in a way that the stratosphere ozone layer is recovering (NASA, 2020). This reduction of pollutants brought a blessing to human health and the environment. The high concentration of different air pollutants has varied effects on human health and the environment (see Table S2 for supporting information).

In India, studies of the impact of COVID-19 on Air Quality are limited (Mahato et al., 2020; Sharma et al., 2020; Mitra et al., 2020). A reduction in $PM_{2.5}$ levels have been observed in major cities, such as 35–39% in Delhi (Chauhan and Singh, 2020; Mahato et al., 2020), 30–40% in Kolkata (Mitra et al., 2020), and 14–43% in Mumbai (Chauhan and Singh, 2020; Sharma et al., 2020) due to the lockdown. It is evident from several pieces of research that the nationwide lockdown in India improved the air quality (Singh and Chakraborty, 2020). However, most of the papers concentrated on few selected parameters or only one specific location. Moreover, most of these studies did not take into account the pollutant concentrations during the same time of the year under no lockdown condition, which led to incomplete inferences. The meteorological conditions were also overlooked in many of these papers. This paper aims to show the changes in the air quality of three megacities (Mumbai, Delhi, and Kolkata) in India during the lockdown and compared the observations with the scenario in the previous year (under no lockdown restrictions), and characterized the role of the meteorological variables. For the present study, we took into account seven air pollutants like $PM_{2.5}$, PM_{10}, NO_2, NH_3, SO_2, CO, and O_3. We also analyzed four meteorological parameters like ambient air temperature, relative humidity, wind velocity, and precipitation. We implemented statistical and model-based approaches for this study to examine the changes in the Air Quality Index (AQI) during the lockdown through a comparative analysis. We believe that this type of study can help the policymakers to cope up with the increasing air pollutants in urban areas and seek some path through action plans to reduce the level of pollution.

2. Material and methods

2.1. Study area

The present study focused on three megacities of India, namely Mumbai, Delhi, and Kolkata. Mumbai, the financial capital and the largest megacity of the country, located on the west coast (Arabian Sea), shelters 18.2 million people (Table 1). The second-largest megacity of the nation is Delhi (16.3 million), the national capital of India situated in the northern part. Kolkata, in the north-eastern part of India, has a population of over 14.1 million (Census of India, 2011). Due to the rapid growth rate (27%) observed in the last decade, now, Delhi is the second leading megacity in the World, with a population of 30.29 million. Mumbai (20.41 million) and Kolkata (14.85 million) hold the 9th and 16th position in the World, respectively (World Economic Forum, 2016; United Nations, Department of Economic and Social Affairs, Population Division, 2019).

Mumbai experiences a tropical climate with hot summers and humidity throughout the year and heavy monsoon rainfall. Delhi has a semi-arid climate with extreme dryness, hot summer (March to May), cold and foggy winters (December to February), and moderate rainfall during monsoon (June to September) (Gurjar et al., 2016; Mahato et al., 2020; Singh and Chauhan, 2020). Kolkata experiences a typically tropical climate with hot and humid summers and moderate winters (Singh and Chauhan, 2020). The average elevations of the megacities are 14 m for Mumbai, 216 m for Delhi, and only 9 m for Kolkata. The geographical parameter such as climate, elevation, and wind direction plays a crucial role in regulating the air quality of these megacities.

We considered the entire Mumbai megacity, the Kolkata megacity, including the twin cities of Kolkata and Howrah, and the total geographical area of Delhi in this study. The wind circulation of western marine air and the eastern industrial area largely controls the air pollution load in Mumbai (Gurjar et al., 2016). There are ten automatic air monitoring stations (AAMS) situated in Mumbai city under the control of the Mumbai Pollution Control Board (Fig. 1a). A large number of industries, power plants, and increasing vehicular density are leading to extraordinary air pollution in megacity Delhi. 36 AAMS monitors the air quality in and around Delhi. Five stations are under the Indian Meteorological Department. Another five stations are under Central Pollution Control Board (CPCB). The remaining 26 stations are under Delhi Pollution Control Board (Fig. 1b).

The megacity of Kolkata encompasses the entire Kolkata district and portions of the other areas like Haora, Hugli, Nadia, North 24 Paraganas, and South 24 Paraganas. Kolkata Municipal Corporation (KMC) is the heart around which this megacity has grown (Dasgupta et al., 2013). Kolkata and Howrah are the twin cities situated on the east and west bank of the River Hooghly, and these are also the first and second most populous (KMC population: 44,96,694 and Haora Municipal Corporation (HMC) population: 13,70,448) towns within the megacity Kolkata. The geographical area of Kolkata and Howrah were 185 km^2 and 51.7 km^2 (Census of India, 2011), respectively, but after the amalgamation of Joka with KMC and Bally municipality with HMC, the area has increased to 205 km^2 and 63.5 km^2, respectively. Currently, 10 AAMS are in operation in the Kolkata megacity under West Bengal Pollution Control Board (WBPCB). Seven stations are within Kolkata city, and the remaining three are in Howrah city (Fig. 1c). Rapid unplanned urbanization, the emerging density of vehicles, and the industrial belt of Howrah are the main reasons behind the rising pollution level in this megacity.

2.2. Data used

We extracted the ground monitored air pollutants data of $PM_{2.5}$, PM_{10}, NO_2, NH_3, SO_2, CO, and O_3 from the CPCB web portal (https://app.cpcbccr.com/AQI_India/). We collected data from 10 AAMS of Mumbai, 36 AAMS of Delhi, and 10 AAMS of Kolkata. Nationwide

Table 1
Description of megacities in India.

Megacities	Geographical position		Average elevation (m)	No. of air monitoring stations[a]	Population (million) 2011	Growth rate (%) 2001–11
Mumbai	19°04′33.54″N	72°52′39.56″E	14	10	18.4	12.05
Delhi	28°42′14.61″N	77°06′08.96″E	216	36	16.3	26.69
Kolkata	22°34′21.53″N	88°21′50.02″E	9	10	14.1	6.87

[a] Automatic air monitoring stations data applied in this study.

lockdown started in India on 24 March 2020. We extracted the data for three weeks before the lockdown (3 March to 23 March 2020), three weeks during the lockdown phase (25 March to 14 April 2020), and three weeks for post-lockdown (15 April to 5 May 2020). We also extracted the data of one station from Mumbai, 36 stations of Delhi, and four stations of Kolkata from the CPCB web portal during the same time window period (25 March to 14 April) of the previous year, 2019, to compare the air quality between two years. The data from the rest of the stations for the year 2019 is unavailable. We extracted and analyzed the air pollutants data for twelve dates having weekly intervals for the year 2020: 3 March, 10 March, 17 March, 23 March, 25 March, 31 March, 7 April, 14 April, 15 April, 21 April, 28 April, and 5 May. For the year 2019, we extracted the data for the dates 25 March, 31 March, 7 April, and 14 April. Daily meteorological data of four parameters, namely ambient air temperature, relative humidity, wind velocity, and precipitation for March, April, and May (of the years 2019 and 2020) were retrieved from the weather stations deployed at the airports of these three megacities (See Text S1 in supporting information for more details). Shapiro-Wilk test was conducted to examine the normality of the meteorological data. Based on the outcomes, independent samples Student's *t*-test (for normal data sets) and Mann-Whitney *U* test (for non-normal datasets) were performed to test the significance of the difference in meteorological parameters between the years 2019 and 2020.

2.3. Methodology

We analyzed the spatial distribution of the daily average air pollutants data using a GIS platform. To produce a spatial-temporal variation map of all the seven air pollutant parameters, we implemented the interpolation technique based on Inverse Distance Weighting (IDW) interpolator by linear combination model using ESRI ArcGIS 10.5 platform. The pollutant data for three selected dates, viz., 17 March, 31 March, and 21 April 2020 were mapped to show the spatial distribution for pre-lockdown, lockdown, and post-lockdown scenarios of those pollutants using the same GIS platforms. On the other hand, the point plots, box plots, and sparklines diagram for changing trend change in average concentration and correlation matrixes of pollutants have been prepared by MS Excel 10.

We also computed the AQI to characterize the overall status of air quality in the three megacities. An AQI is an inclusive system that changes the weighted values of the individual air pollution-connected parameters into one variety or set of numbers (CPCB, 2014). To calculate the AQI, CPCB, India continually monitors the ambient air using the EPA-US method. The CPCB report (CPCB, 2014) has elaborated on all the steps required for processing the data. The Ministry of Environment and Forest (MoEF) had revised the national ambient AQI in November 2009 by amending the Environment Protection Rule 1986. They listed a threshold for the air pollutants in the (i) Industrial, Residential, and Rural areas and the (ii) Ecologically Sensitive areas (see Table S3 in supporting information). AQI formulation mainly includes two steps: (i) Formation of sub-indices (for each pollutant) and (ii) Aggregation of sub-indices to get an overall AQI. We computed the sub-indices of seven pollutants at each station based on the 24 h average data (only CO and O_3 were 8-h average) and health break-point range. AQI computation needs $PM_{2.5}$, PM_{10}, NO_2, NH_3, SO_2, CO, O_3, and Pb as input parameters, of which at least three pollutant concentrations should be available and must include either $PM_{2.5}$ or PM_{10}. The AQI has six categories: good,

satisfactory, moderate, poor, very poor, and severe, based on a scale of 0–500 (see Table S4 in supporting information).

3. Results and discussion

3.1. Changes in the concentration of Particulate matter ($PM_{2.5}$ and PM_{10})

Particulate matter is one of the major pollutants, particularly in urban and industrial areas (Santra, 2015). $PM_{2.5}$ and PM_{10} levels declined significantly across the megacities of India after imposing the lockdown (Fig. 2a and 2b). The pre-lockdown concentration was substantially higher compared to the permissible limit of 60 μg/m³ for $PM_{2.5}$ and 100 μg/m³ for PM_{10} across all the megacities. The concentrations of $PM_{2.5}$ during lockdown dropped below the permissible limit in Mumbai, but on the other two megacities, it remained above the limit. However, the PM_{10} levels went below the said permissible limit across all the megacities of India during the lockdown. The post-lockdown concentration of $PM_{2.5}$ for Mumbai and Kolkata remained below the said permissible limit following a decreasing trend over time whereas, Delhi exhibited the opposite. Here, $PM_{2.5}$ concentrations exhibited an increase in the post-lockdown phase (Fig. 2b). Similarly, PM_{10} levels declined significantly in Mumbai and Kolkata whereas in Delhi it exhibited a rising trend (Fig. 2a). The post-lockdown amounts of PM_{10} were always below the permissible limit.

In the pre-lockdown phase, the concentration of $PM_{2.5}$ in Mumbai, Delhi, and Kolkata varied from 35.63 to 168.13 μg/m³, 108.69 to 195.28 μg/m³, and 74.90 to 190.30 μg/m³, respectively, whereas during the lockdown these ranges were 36.25 to 57.22 μg/m³, 60.93 to 108.00 μg/m³, and 47.00 to 85.60 μg/m³, respectively (Table 2). The post-lockdown concentrations ranged from 14.57 to 33.33 μg/m³ for Mumbai; 56.11 to 96.37 μg/m³ for Delhi; and for Kolkata, it was 13.78 to 52.50 μg/m³. The pre-lockdown and lockdown ranges of PM_{10} in Mumbai were 63.38 to 187.25 μg/m³ and 95.66 to 168.75 μg/m³, respectively. In Delhi, the pre-lockdown PM_{10} ranged from 77.90 to 148.50 μg/m³, and lockdown PM_{10} varied from 65.25 to 82.89 μg/m³. In Kolkata, the pre-lockdown and lockdown ranges of PM_{10} were 63.21 to 120.66 μg/m³ and 54.00 to 80.00 μg/m³, respectively. The post-lockdown PM_{10} ranges were 39.00 to 62.67 μg/m³ for Mumbai; 61.89 to 97.44 μg/m³ for Delhi; and for Kolkata, it was 20.00 to 61.00 μg/m³. To break the chain of the spread of COVID-19, maintaining the social distancing among people, the complete closure of all sectorial activities was the only way for the Government. Therefore, the movement of vehicles, closing of industries, administrative centers, shopping malls, and all other allied services except emergency services remained closed during those days. Such widespread closure has caused a drastic improvement in the ground-level air quality (NASA, 2020; Muhammad et al., 2020; Bera et al., 2020; Sharma et al., 2020; Mahato et al., 2020; Singh and Chauhan, 2020; Srivastava et al., 2020; Lancet, 2020). After completion of the lockdown phase (24 March-14 April), the regular flow of bus services and industry in a systematic manner as the earlier scenario did not begin. The railway service was under a complete shutdown. The post-lockdown new-normal included mostly work from home activities except for any emergency and online services.

$PM_{2.5}$ during the lockdown reduced by about 46.61% (41.87 μg/m³), 51.84% (80.06 μg/m³) and 48.81% (63.68 μg/m³) for Mumbai, Delhi, and Kolkata, respectively, compared to the pre-lockdown concentrations
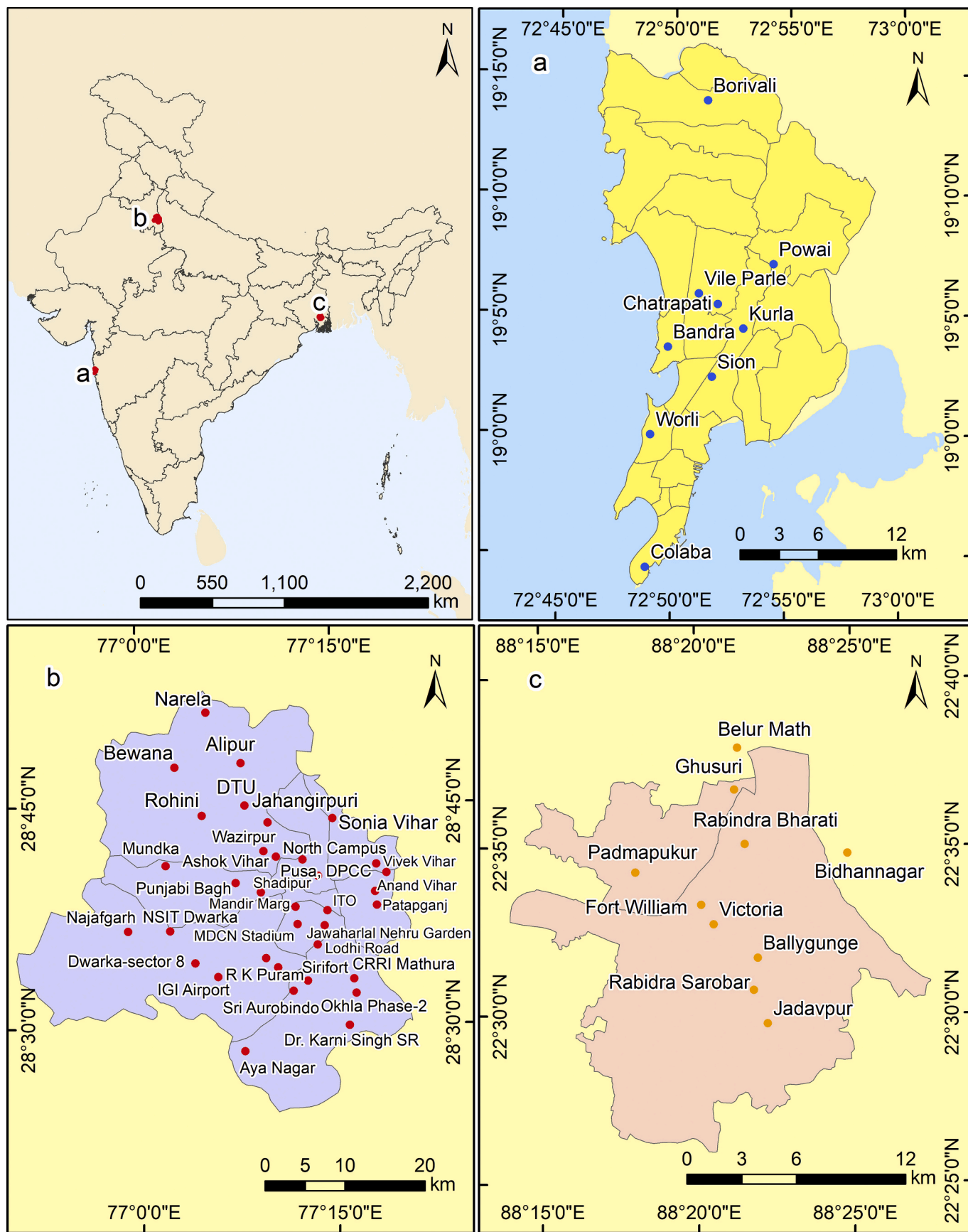
Fig. 1. The study area map of (a) Mumbai, (b) Delhi, and (c) Kolkata-Howrah showing the locations of the automatic air monitoring stations (AAMS).

Pre-lockdown   **During-lockdown**   **During-lockdown**   **Post-lockdown**
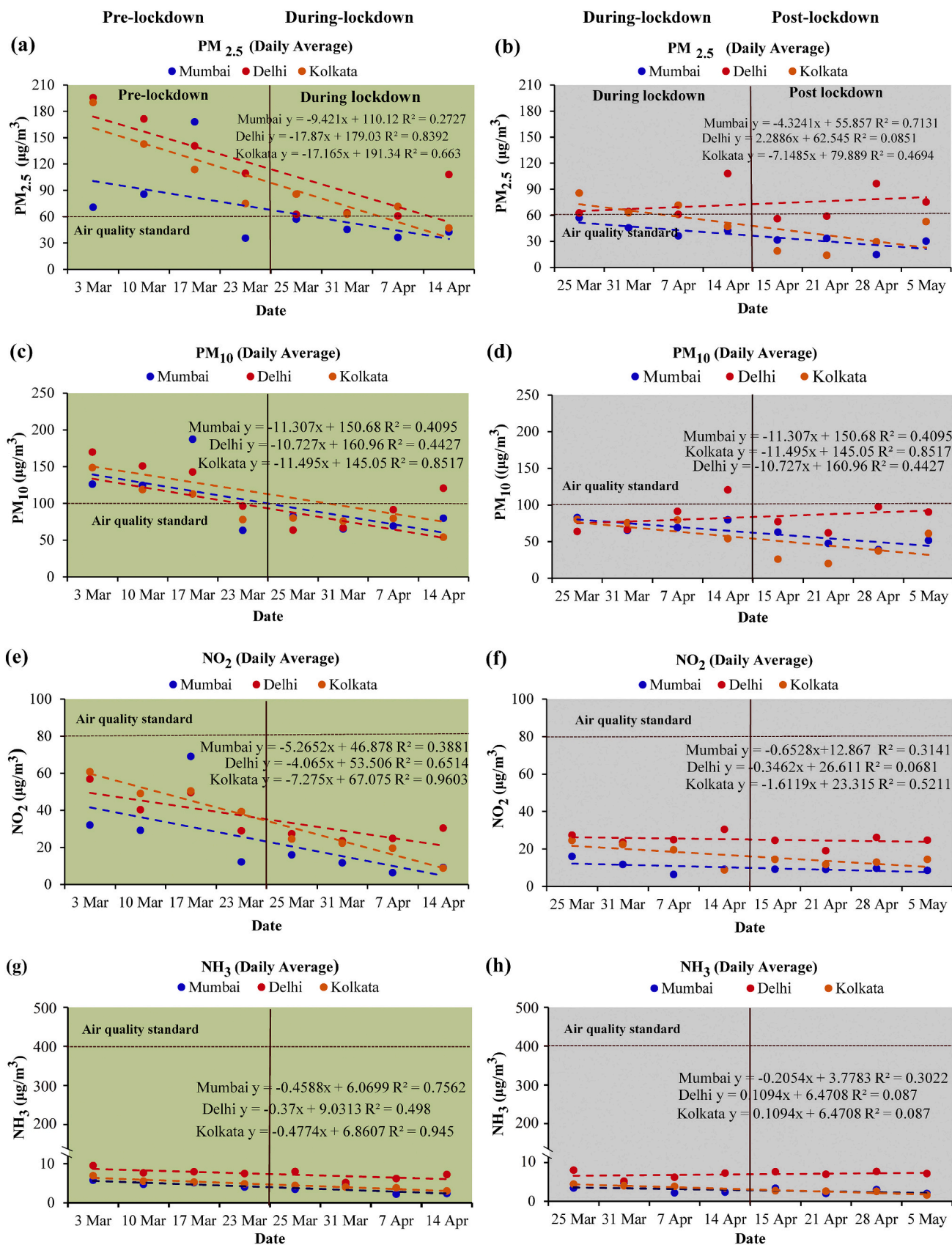
Fig. 2a. The trend of average concentrations of (a; b) $PM_{2.5}$, (c; d) PM_{10}, (e; f) NO_2, (g; h) NH_3 between 3 March to 14 April 2020 and 15 April to 5 May 2020 in all three megacities of India.
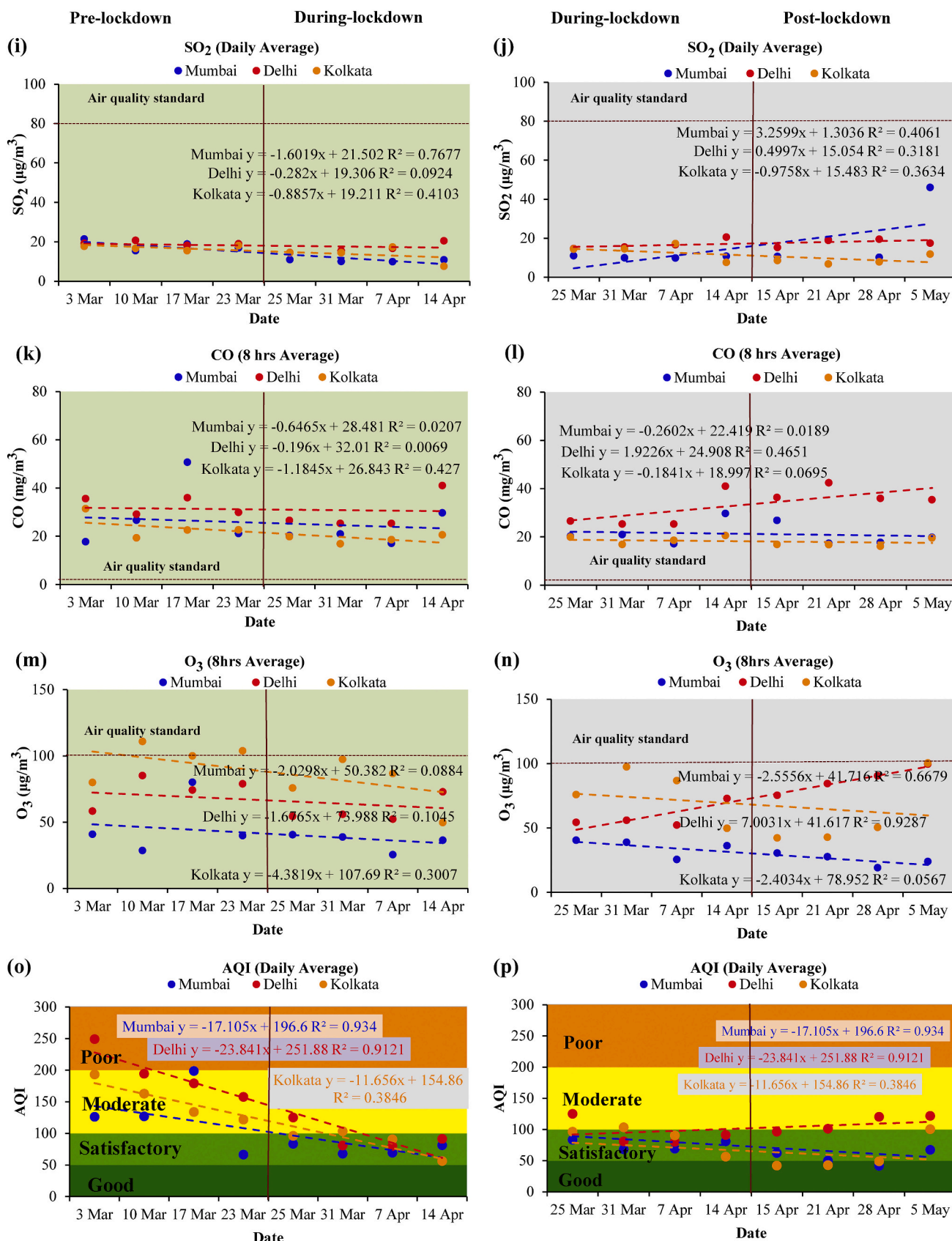
Fig. 2b. The trend of average concentrations of (i; j) SO$_2$, (k; l) CO (m; n) O$_3$, and (o; p) AQI between 3 March to 14 April 2020 and 15 April to 5 May 2020 in all three megacities of India.

Table 2
Weekly data of air pollutants in pre-lockdown, during-lockdown, and post-lockdown across all three megacities of India.

Pollutants	Megacities	Pre-lockdown				During-lockdown				Post-lockdown			
		3 March	10 March	17 March	23 March	25 March	31 March	7 April	14 April	15 April	21 April	28 April	5 May
PM$_{2.5}$ (µg/m^3)	Mumbai	70.88	85.70	168.13	35.63	57.22	45.38	36.25	42.67	31.60	33.33	14.57	30.17
	Delhi	195.28	171.80	141.36	108.69	62.06	64.28	60.93	108.00	56.11	59.06	96.37	75.38
	Kolkata	190.30	142.70	113.90	74.90	85.60	63.00	71.50	47.00	18.89	13.78	29.50	52.50
PM$_{10}$ (µg/m^3)	Mumbai	126.13	124.70	187.25	63.38	82.89	65.25	69.17	79.60	62.67	47.63	39.00	51.50
	Delhi	168.75	150.53	143.88	95.66	63.21	66.55	91.35	120.66	77.22	61.89	97.44	90.25
	Kolkata	148.50	118.50	112.60	77.90	80.00	75.70	79.40	54.00	25.90	20.00	37.10	61.00
NO$_2$ (µg/m^3)	Mumbai	32.00	29.20	69.00	12.11	16.00	11.67	6.33	9.17	9.17	9.00	9.60	8.50
	Delhi	57.58	41.03	50.88	28.97	27.64	23.53	24.90	30.42	24.50	19.04	26.13	24.63
	Kolkata	60.80	49.10	50.40	39.30	24.50	22.30	19.50	8.80	14.40	11.67	12.90	14.43
NH$_3$ (µg/m^3)	Mumbai	5.75	4.67	5.13	4.00	3.38	4.63	2.17	2.33	3.33	2.00	3.00	2.00
	Delhi	9.62	7.62	7.92	7.54	8.15	5.17	6.14	7.20	7.55	6.91	7.65	7.13
	Kolkata	6.90	5.50	5.30	4.80	4.4	4.00	3.80	3.00	2.70	2.56	2.50	1.57
SO$_2$ (µg/m^3)	Mumbai	21.38	15.50	18.89	16.89	11.00	10.00	9.86	10.83	10.67	19.29	10.14	46.00
	Delhi	19.43	21.17	18.19	19.11	14.48	15.44	16.64	20.52	15.30	18.96	19.47	17.48
	Kolkata	17.70	16.70	15.50	18.10	14.40	15.44	17.30	7.60	8.50	6.78	7.80	11.86
CO (mg/m^3)	Mumbai	17.78	26.70	50.70	21.22	20.33	21	17.13	29.71	26.86	17.38	17.75	19.83
	Delhi	37.53	30.69	36.51	30.78	24.85	26.36	27.10	41.43	36.37	42.40	35.96	35.44
	Kolkata	31.40	19.40	22.60	22.70	19.90	16.90	18.60	20.60	16.90	16.78	16.10	19.57
O$_3$ (µg/m^3)	Mumbai	40.75	28.50	80.10	39.78	40.44	38.78	25.43	36.20	30.50	27.57	19.00	23.80
	Delhi	57.31	84.94	71.94	78.06	54.77	54.63	50.89	74.57	75.36	84.45	90.46	99.50
	Kolkata	79.90	110.78	100.00	103.67	75.78	97.33	86.67	49.67	42.22	42.67	50.33	100.43

Table 3
Variation of air pollutants in pre-lockdown and during-lockdown periods across all three megacities of India.

Pollutants	Megacities	Pre-lockdown (3 March to 23 March)	Lockdown (25 March to 14 April)	Total variation Avg.	% of variation
PM$_{2.5}$ (µg/m^3)	Mumbai	89.82	47.96	−41.87	−46.61
	Delhi	154.44	74.38	−80.06	−51.84
	Kolkata	130.45	66.78	−63.68	−48.81
PM$_{10}$ (µg/m^3)	Mumbai	125.32	74.32	−51.00	−40.70
	Delhi	139.70	85.28	−54.42	−38.95
	Kolkata	114.38	72.28	−42.10	−36.81
NO$_2$ (µg/m^3)	Mumbai	35.50	11.24	−24.26	−68.33
	Delhi	44.66	26.64	−18.02	−40.36
	Kolkata	49.90	18.78	−31.13	−62.37
NH$_3$ (µg/m^3)	Mumbai	4.88	3.25	−1.63	−33.39
	Delhi	8.16	6.74	−1.42	−17.39
	Kolkata	5.63	3.80	−1.83	−32.44
SO$_2$ (µg/m^3)	Mumbai	18.00	10.42	−7.58	−42.11
	Delhi	19.52	16.80	−2.72	−13.91
	Kolkata	17.00	13.45	−3.55	−20.88
CO (mg/m^3)	Mumbai	29.61	21.73	−7.88	−26.61
	Delhi	33.88	29.73	−4.15	−12.25
	Kolkata	24.03	19.00	−5.03	−20.92
O$_3$ (µg/m^3)	Mumbai	47.84	35.73	−12.10	−25.30
	Delhi	72.99	58.85	−14.14	−19.37
	Kolkata	98.08	77.36	−20.72	−21.13
AQI	Mumbai	129.29	75.50	−53.79	−41.61
	Delhi	164.53	96.42	−68.11	−41.39
	Kolkata	152.78	86.48	−66.30	−43.40

Table 4
Variation of air pollutants in during-lockdown and post-lockdown periods across all three megacities of India.

Pollutants	Megacities	During-lockdown (25 March to 14 April)	Post-lockdown (15 April to 5 May)	Total variation Avg.	% of variation
PM$_{2.5}$ (µg/m^3)	Mumbai	47.96	27.42	−20.54	−42.83
	Delhi	74.38	71.73	−2.65	−3.56
	Kolkata	66.78	28.67	−38.11	−57.07
PM$_{10}$ (µg/m^3)	Mumbai	74.32	50.20	−24.12	−32.46
	Delhi	85.28	81.70	−3.58	−4.20
	Kolkata	72.28	36.00	−36.28	−50.19
NO$_2$ (µg/m^3)	Mumbai	11.24	9.07	−2.17	−19.35
	Delhi	26.64	23.57	−3.07	−11.51
	Kolkata	18.78	13.35	−5.43	−28.90
NH$_3$ (µg/m^3)	Mumbai	3.25	2.58	−0.67	−20.51
	Delhi	6.74	7.31	0.57	8.40
	Kolkata	3.80	2.33	−1.47	−38.64
SO$_2$ (µg/m^3)	Mumbai	10.42	21.52	11.10	106.57
	Delhi	16.80	17.80	1.00	5.96
	Kolkata	13.45	8.73	−4.72	−35.07
CO (mg/m^3)	Mumbai	21.73	20.45	−1.27	−5.86
	Delhi	29.73	37.54	7.81	26.28
	Kolkata	19.00	17.34	−1.66	−8.75
O$_3$ (µg/m^3)	Mumbai	35.73	25.22	−10.52	−29.43
	Delhi	58.85	87.44	28.59	48.59
	Kolkata	77.36	58.91	−18.45	−23.85
AQI	Mumbai	75.5	55.2	−20.3	−41.61
	Delhi	96.42	109.89	13.47	−41.39
	Kolkata	86.48	58.47	−28.01	−43.4

(Table 3). Similarly, PM$_{10}$ reduced by about 40.70% (51.00 µg/m^3), 38.95% (54.42 µg/m^3) and 36.81% (42.10 µg/m^3) in Mumbai, Delhi, and Kolkata, respectively. The post-lockdown average concentrations of PM$_{2.5}$ reduced by about 42.83% (20.54 µg/m^3), 3.56% (2.65 µg/m^3) and 57.07% (38.11 µg/m^3) compared to the lockdown concentrations in Mumbai, Delhi, and Kolkata, respectively (Table 4). PM$_{10}$ reduced by about 32.46% (24.12 µg/m^3), 4.20% (3.58 µg/m^3) and 50.19% (36.28 µg/m^3) in Mumbai, Delhi, and Kolkata, respectively. Delhi had the highest average concentrations of PM$_{2.5}$ and PM$_{10}$ compared to the other two megacities of India. According to WHO, Delhi was the most polluted city among 4300 cities of the World based on the concentration of PM$_{2.5}$ (World Economic Forum, 2018).

Mumbai had moderately polluted (89.82 µg/m^3) to satisfactory (47.96 µg/m^3) air quality while Delhi and Kolkata were very poor to moderately polluted by PM$_{2.5}$ in lockdown (See Table S4 in supporting information). On the other hand, the megacity of Mumbai (125.32 to 74.32 µg/m^3), Delhi (139.70 to 85.28 µg/m^3), and Kolkata (114.38 to 72.28 µg/m^3) have noted a very healthy air, due to fall of PM$_{10}$. The post-lockdown PM$_{2.5}$ and PM$_{10}$ were well in Mumbai and Kolkata, whereas in Delhi it was above the permissible limit. Hence, breathing discomfort to the people of a sensitive group and the people of lung diseases has taken place instead of prolonged suffering with lung diseases in lockdown. The post-lockdown impacts were minimal for Mumbai and Kolkata. Besides that horizontal visibility in surface air was also improved to the effect of the COVID-19 pandemic.

The spatial distributions of $PM_{2.5}$ and PM_{10} across all three megacities of India have been shown in Figs. 3, 4, 5. The significant improvements in air quality have been detected in the Lockdown phase and it continued to post-lockdown. We have mapped the weekly (3 March to 14 April) change of spatial variability of pollutants (see Fig. S1, S2 in supporting information). The significant improvements in air quality were recorded on the very next day of lockdown, 25 March 2020. The spatial patterns were almost similar on 31 March, after a week.

The eastern part of the megacities of Delhi and Kolkata had better air quality compared to the western part. The industrial activities and vehicular emissions in the western part were more than that observed in the east. The marine wind refreshed the west part of Mumbai. Therefore, the scenario was opposite here; the eastern part was more contaminated compare to the western part. Though, in the later few weeks, deteriorations of air quality were recorded due to partial relaxation on transport service and industry sectors.

Delhi recorded the highest $PM_{2.5}$ and PM_{10} for 2019 and 2020 except the PM_{10} of 2020 during the period of 25 March-14 April (Fig. 6a, b). Mumbai recorded the lowest amount of $PM_{2.5}$ and PM_{10} while Kolkata noted a moderate amount concentration. Compared to the 2019 scenario, the PM_{10} value of Delhi has witnessed the highest reduction (58.60%) during the COVID-19 lockdown. $PM_{2.5}$ also exhibited the highest reduction (34.67%) compared to Mumbai and Kolkata (Table 5).

3.2. Changes in the concentration of Nitrogen Dioxide (NO_2)

NO_2 helps in the ozone formation in the troposphere, and it also leads to aerosol formation. The concentration of NO_2 substantially reduced over India during the lockdown period (NASA, 2020; ESA, 2020; Muhammad et al., 2020; Bera et al., 2020; Ghosh and Ghosh, 2020; Mahato et al., 2020). Fig. 2e shows the significant declining trend of NO_2 in the megacities due to the COVID-19 lockdown. The same decline was also noticed in the post-lockdown phase (Fig. 2f). NO_2 concentration was below the permissible limit of 80 $\mu g/m^3$ in all three phases of pre-lockdown, lockdown, and post-lockdown.

The NO_2 concentration in the pre-lockdown for Mumbai, Delhi, and Kolkata were 12.11–69.00 $\mu g/m^3$; 28.97–57.58 $\mu g/m^3$; and 39.40–60.80 $\mu g/m^3$, whereas during the lockdown those were

6.33–16.00 $\mu g/m^3$; 23.53–30.42 $\mu g/m^3$; and 8.80–24.50 $\mu g/m^3$. During the post-lockdown, the NO2 concentrations varied as 8.50–9.60 $\mu g/m^3$; 19.04–26.13 $\mu g/m^3$; and 11.67–14.43 $\mu g/m^3$, respectively (Table 2). The pre-lockdown concentrations were higher while during-lockdown a significant drop was noted across the megacities. The continuous fall was also noted in post-lockdown. Hence, improvements in air quality (NO_2) were observed across the megacities of India, due to the COVID-19-induced lockdown.

The average concentration of NO_2 reduced in lockdown by about 68.33%, 40.36%, and 62.37% for Mumbai, Delhi, and Kolkata, respectively (Table 3). Their post-lockdown reduction was 19.35%, 11.51%, and 28.90% for those megacities (Table 4). Therefore, the highest reduction was recorded in Kolkata (31.13 & 5.43 $\mu g/m^3$) followed by Mumbai (24.26 & 2.17 $\mu g/m^3$) and Delhi (18.02 & 3.07 $\mu g/m^3$), respectively, in both during-lockdown and post-lockdown phases. Nationwide strict lockdown and new-normal post-lockdown checked the level of NO_2. Hence, the less concentration of this pollutant, the impact on human health was nominal, i.e. good air quality (See Table S4 in supporting information). On the other hand, this may reduce the precursor of ozone formation and aerosol formation in the troposphere.

The sharp improvement of air quality for all three megacities during-lockdown and post-lockdown compared to pre-lockdown has been mapped here (Figs. 3, 4, 5). We found that just after one day of the commencement of nationwide lockdown the remarkable improvement of NO_2 has been noted compared to pre-lockdown in all three megacities. It lasted up to 14 April 2020 (see Fig. S3 in supporting information). The west part of Delhi and Kolkata and the east part of Mumbai have witnessed healthy air.

The box plots (Fig. 6c) have shown that the NO_2 level has dropped in megacities in India during the lockdown year (2020). The high range, 30.75–75.25 $\mu g/m^3$ with maximum average concentrations of Kolkata was on top followed by Mumbai and Delhi during the same time of the previous year (2019). Mumbai, Delhi, and Kolkata witnessed a reduction of about 44.35%, 42.77%, and 39.45% in the lockdown period compared to the 2019 scenario (Table 5).
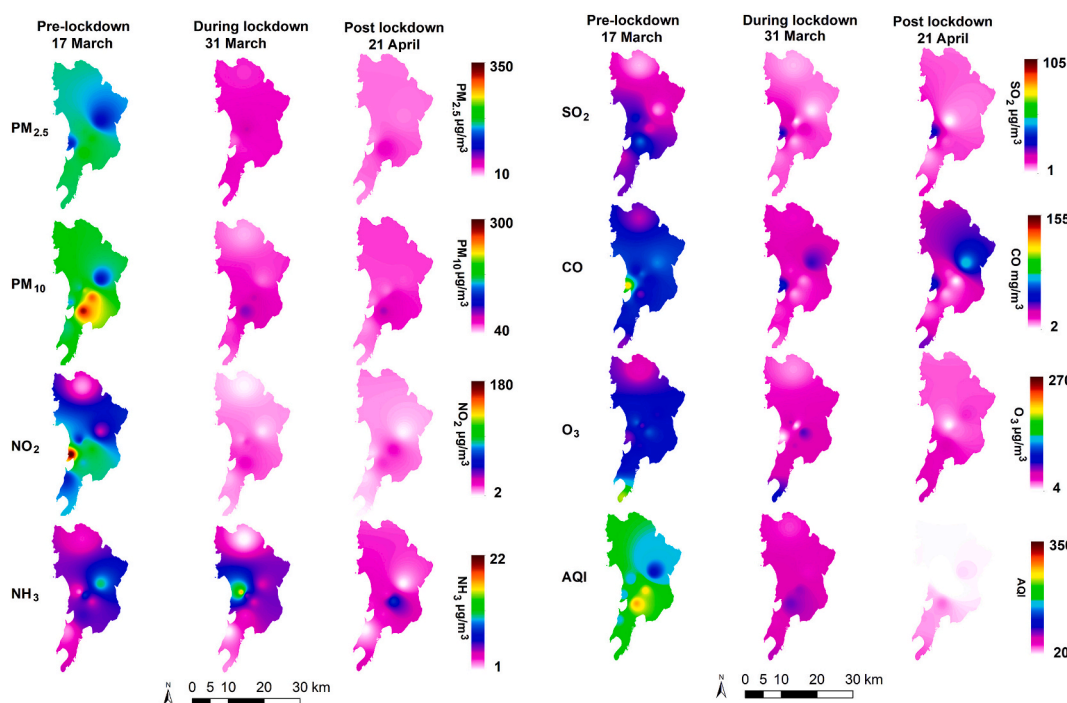

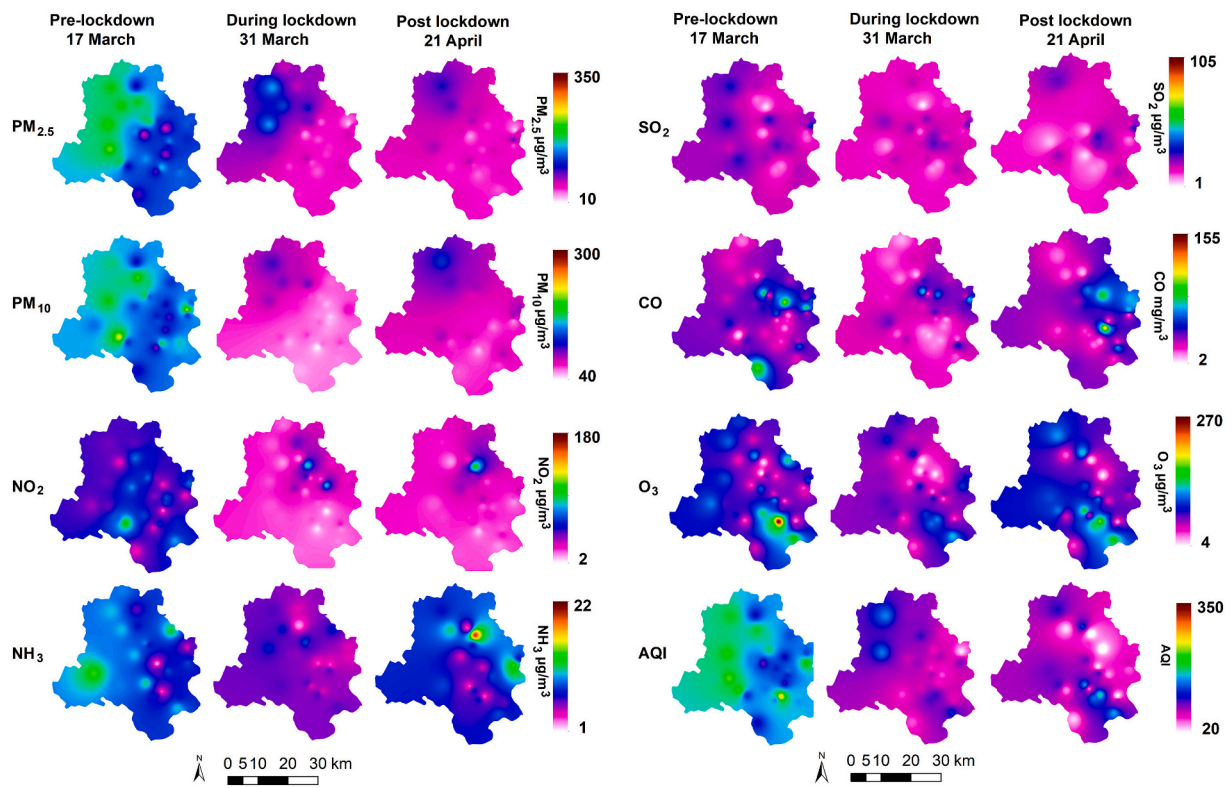**Fig. 3.** The spatiotemporal variability of pollutants over the megacity of Mumbai.

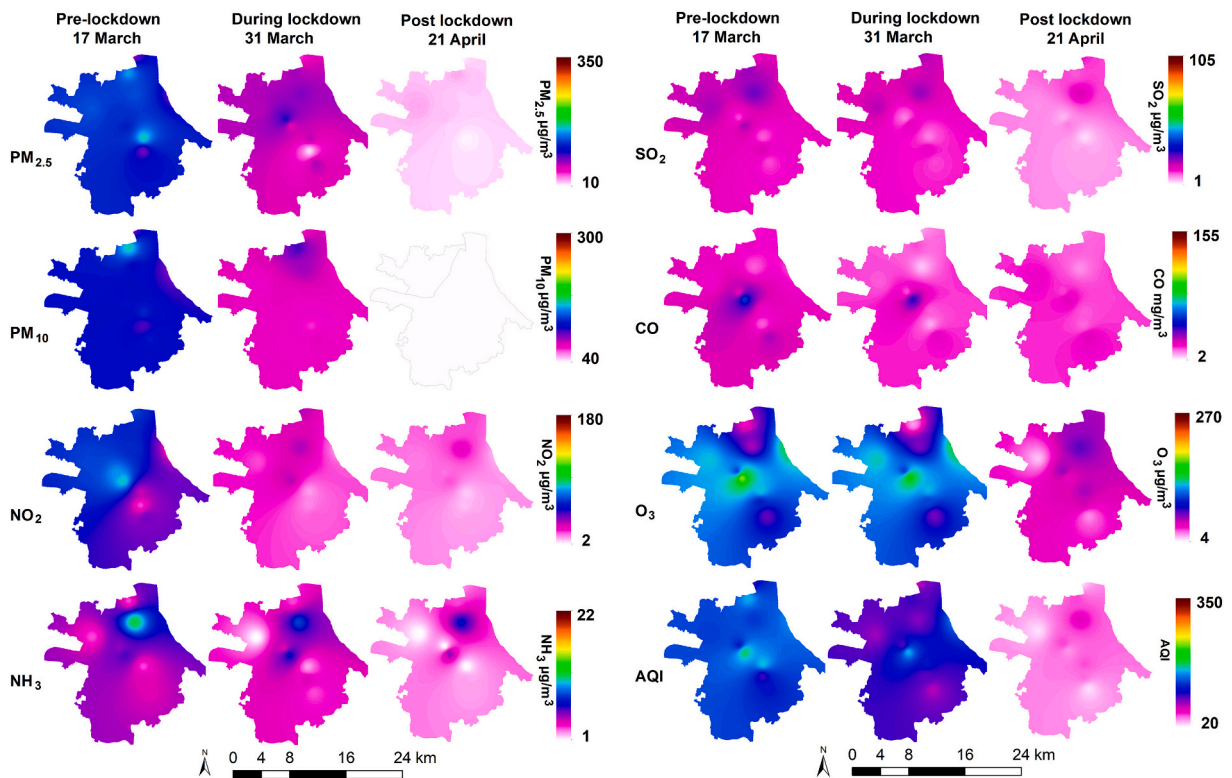**Fig. 4.** The spatiotemporal variability of pollutants over the megacity of Delhi.

Fig. 5. The spatiotemporal variability of pollutants over the megacity of Kolkata.

3.3. Changes in the concentration of Ammonia (NH₃)

Ammonia (NH_3) is a highly reactive and soluble alkaline gas. The agricultural fields, the additional amount added from petrol cars, industry, and sewage are the principal sources of NH_3 (Sutton et al., 2000;

Wilson et al., 2004). The nationwide lockdown played a significant role in regulating its concentration. Its concentration substantially declined in all three megacities during the lockdown period (Fig. 2 g). The same decline was also noticed in post-lockdown for the megacities of Mumbai and Kolkata, except for Delhi (Fig. 2 h). The average NH_3 concentrations
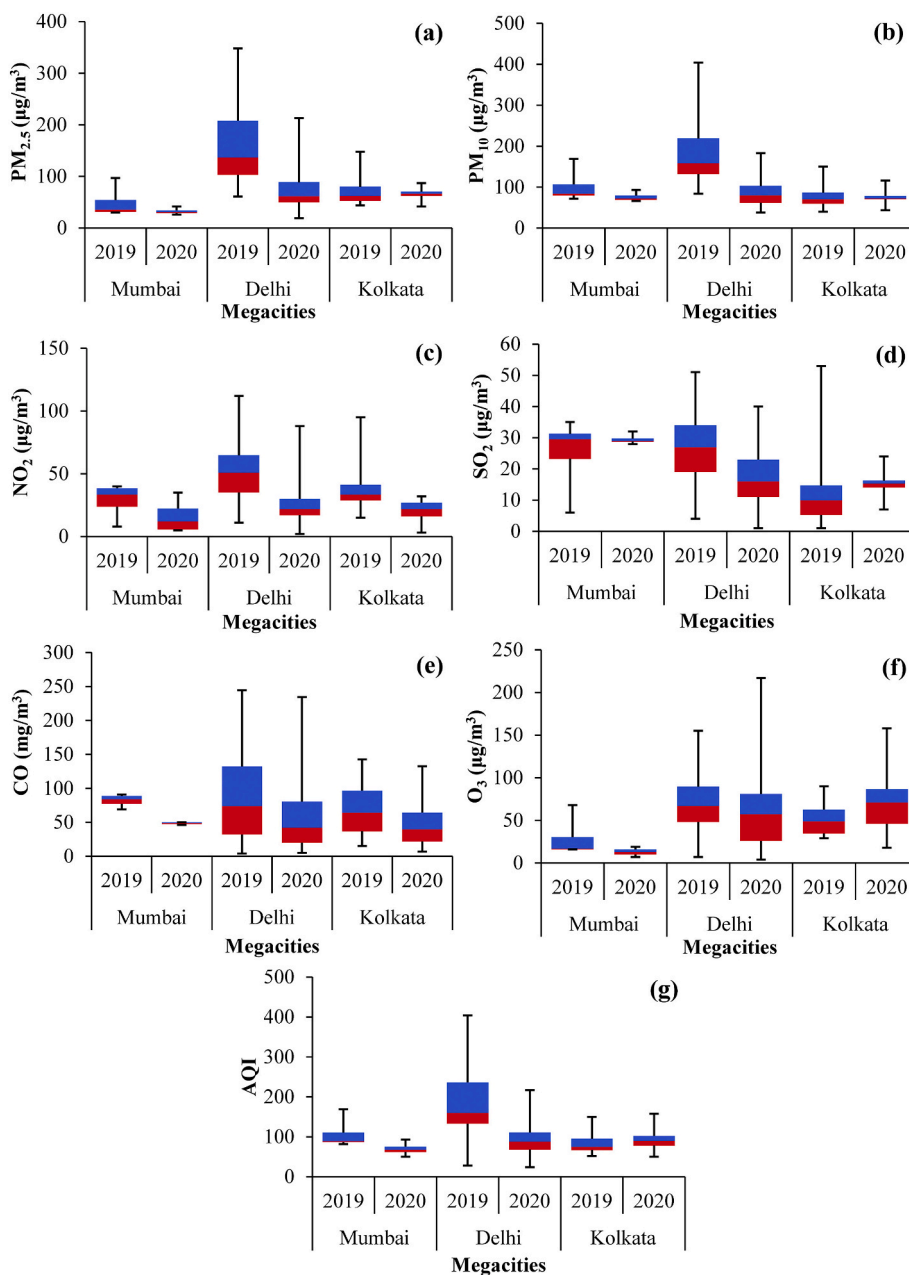
Fig. 6. Changes in average concentrations of (a) $PM_{2.5}$, (b) PM_{10}, (c) NO_2 (d) SO_2, (e) CO (f) O_3, and (g) AQI between 25 March to 14 April 2019 and 25 March to 14 April 2020 observed in all three megacities. The lower and upper end of the box represents the first (Q1) and the third (Q3) quartile. The divider of the box represents the median. The error bars represent the minimum and the maximum values.

were very nominal not only in the lockdown phase; the pre-lockdown and post-lockdown period also, compared to the permissible limit of 400 $\mu g/m^3$ across the megacities of India.

The pre-lockdown concentration of NH_3 in Mumbai, Delhi, and Kolkata were 4.00–5.75 $\mu g/m^3$, 7.62–9.62 $\mu g/m^3$, and 4.80–6.90 $\mu g/m^3$, respectively. During the lockdown, those ranges were 2.17–4.63 $\mu g/m^3$, 5.17–8.15 $\mu g/m^3$, and 3.00–4.40 $\mu g/m^3$, respectively (Table 2). The post-lockdown concentrations were 2.00–3.33 $\mu g/m^3$, 6.91–7.65 $\mu g/m^3$, and 1.57–2.70 $\mu g/m^3$ for those megacities. Hence, NH_3 concentrations in Delhi were slightly higher compared to the other two megacities.

During the lockdown, Mumbai, Delhi, and Kolkata witnessed a reduction of 33.39%, 17.39%, and 32.44% in NH_3 levels, respectively (Table 3). The post-lockdown reductions were 20.51% and 28.64% for Mumbai and Kolkata, while Delhi exhibited an increase of 8.40% (Table 4). Therefore, Kolkata recorded the maximum decline (1.83 &

1.47 $\mu g/m^3$) followed by Mumbai (1.63 & 0.67 $\mu g/m^3$) and Delhi (1.42 & 0.57 $\mu g/m^3$). Such a nominal concentration of NH_3 in all the phases is a healthy sign for the lower tropospheric atmosphere.

The spatial maps showing the gradual decrease in NH3 levels in all three phases (pre-lockdown, lockdown, and post-lockdown) are illustrated in Figs. 3, 4, and 5. However, the scenario was slightly different after two to three weeks due to partial relaxation on necessary transportation and controlled industrial activity outside the COVID-19 infected zone or containment zone declared by the government for Delhi (Mahato et al., 2020; Srivastava et al., 2020; Kumar et al., 2020). The weekly variations are in supporting information (see Fig. S4 in supporting information).

NH_3 records of Mumbai for the year 2019 were not available on the CPCB website due to some technical error. Delhi witnessed a declining trend from 8.95 to 3.75 $\mu g/m^3$ in the lockdown year 2020 compared to

Table 5
Average concentration of air pollutants in Mumbai (Bandra), Delhi (ITO), and Kolkata (RBU) for the period of 25 March to 14 April during 2019 and 2020.

Pollutants	Megacities	25 March to 14 April 2019	25 March to 14 April 2020	Total variation Avg.	% of variation
$PM_{2.5}$ (µg/m^3)	Mumbai	49.75	32.50	−17.25	−34.67
	Delhi	158.62	147.33	−11.29	−7.11
	Kolkata	90.29	87.75	−2.54	−2.81
PM_{10} (µg/m^3)	Mumbai	102.25	76.00	−26.25	−25.67
	Delhi	187.84	77.75	−110.09	−58.60
	Kolkata	88.93	79.75	−9.18	−10.32
NO_2 (µg/m^3)	Mumbai	28.75	16.00	−12.75	−44.35
	Delhi	51.99	29.75	−22.24	−42.77
	Kolkata	50.79	30.75	−20.04	−39.45
NH_3 (µg/m^3)	Mumbai	NM[a]	NM	NM	NM
	Delhi	8.95	3.75	−5.20	−58.10
	Kolkata	5.21	8.50	3.29	63.14
SO_2 (µg/m^3)	Mumbai	25.00	29.50	4.50	18.00
	Delhi	27.03	19.75	−7.28	−26.93
	Kolkata	13.57	17.25	3.68	27.11
CO (mg/m^3)	Mumbai	82.00	48.50	−33.50	−40.85
	Delhi	44.63	46.00	1.37	3.06
	Kolkata	27.43	10.50	−16.93	−61.72
O_3 (µg/m^3)	Mumbai	29.50	13.00	−16.50	−55.93
	Delhi	69.63	60.50	−9.13	−13.11
	Kolkata	53.21	66.50	13.29	24.97

[a] NM = not measured.

the previous year 2019 (Table 5). On the other hand, Kolkata witnessed an increase (5.21 to 8.50 µg/m^3) from 2019 to 2020. Therefore, NH_3 exhibited mixed results in the megacities of India between 2019 and 2020.

3.4. Changes in the concentration of Sulfur Dioxide (SO_2)

SO_2 is a colorless gas that is very harmful to plant, animal, and human health. People with lung diseases, children, older people, and those who are more exposed to SO_2 are at higher risk of skin and lung diseases (Ghorani-Azam et al., 2016). COVID-19 lockdown led to a declining trend of SO_2 in megacities of India (Fig. 2i). Compared to the pre-lockdown concentrations, the lockdown phase concentrations were lower in all three megacities. However, the post-lockdown trend changed except for Kolkata. Mumbai and Delhi exhibited a rising trend during the post-lockdown phase (Fig. 2j). The concentration of SO_2 was very low compared to the permissible limit of 80 µg/m^3 for all three phases, pre-lockdown, during-lockdown, and post-lockdown.

The pre-lockdown concentration of SO_2 in Mumbai, Delhi, and Kolkata varied as 15.50–21.38 µg/m^3; 18.19–21.17 µg/m^3; and 15.50–18.10 µg/m^3, respectively, whereas during the lockdown those were 9.86–11.00 µg/m^3; 14.48–20.52 µg/m^3; and 7.60–17.30 µg/m^3; and during the post-lockdown phase, the ranges were 10.14–46.00 µg/m^3; 15.30–19.47 µg/m^3; and 6.78–11.86 µg/m^3, respectively (Table 2). The pre-lockdown concentrations were higher while during the lockdown period, a significant fall was noted across the megacities. The continuous drop was also noted in post-lockdown only for Kolkata. Overall, significant improvements in air quality in the form of SO_2 reduction were observed across the megacities of India due to the blessing of COVID-19 amid lockdown.

The average concentration of SO_2 reduced during the lockdown by about 42.11%, 13.91%, and 20.88%, for Mumbai, Delhi, and Kolkata, respectively in the lockdown phase (Table 3). The only post-lockdown reduction was 35.07% in the case of Kolkata, while the rise in Mumbai and Delhi were 106.57% and 5.96%, respectively (Table 4). The concentration of SO_2 in Delhi was higher compared to the other two megacities. For that reason, Delhi can occasionally experience acid rain in the main city and the suburbs. However, due to the overall low

concentrations of SO_2 below the threshold, the megacities of India relished good quality air with zero health impact (See Table S4 for supporting information).

The spatial pattern of SO_2 is illustrated in Figs. 3, 4, 5. The weekly variations are in supporting information (see Fig. S5 in supporting information). The box plots (Fig. 6d) have shown that the SO_2 level was fluctuating in megacities of India (2020). The maximum averaged concentration was in Mumbai followed by Delhi and Kolkata. Delhi recorded a decline (26.93%), while Mumbai (18.00%) and Kolkata (27.11%) observed an increase in SO_2 compared to the previous year 2019 (Table 5).

3.5. Changes in the concentration of Carbon Monoxide (CO)

CO is a colorless and odorless gas. Its excessive concentrations can lead to headache, dizziness, weakness, nausea, vomiting, and loss of consciousness on human health (Ghorani-Azam et al., 2016). The concentration of CO has remarkably reduced over India during the lockdown period (Bera et al., 2020). Fig. 2 k has shown the significant declining trend of CO in the megacities due to the pandemic-induced lockdown. The post-lockdown trend has remained the same (decline trend) for Mumbai and Kolkata; however, Delhi remained an exception (Fig. 2 l). All the recorded values were very high compare to the permissible limit (2 mg/m^3) that has a noticeable impact on human health and the environment too.

The CO concentrations during the pre-lockdown phase for Mumbai, Delhi, and Kolkata varied as 17.78–50.70 mg/m^3; 30.69–37.53 mg/m^3; and 19.40–31.40 mg/m^3, respectively, whereas during the lockdown those were 17.13–29.71 mg/m^3; 24.85–41.43 mg/m^3; and 16.90–20.60 mg/m^3, respectively (Table 2). The megacities in the same order exhibited a post-lockdown variation of 17.38–26.86 mg/m^3; 35.44–42.43 mg/m^3; and 16.10–19.57 mg/m^3, respectively.

The average concentration of CO reduced during the lockdown by about 26.61%, 12.25%, and 20.92% for Mumbai, Delhi, and Kolkata, respectively (Table 3). Mumbai (5.86%) and Kolkata (8.75%) maintained a continuous drop in the concentration, whereas Delhi experienced a rise (26.28%) again in the post-lockdown phase. The spatial pattern map for the megacity of Mumbai, Delhi recorded a fall in lockdown (Fig. 2, 3). The megacity Kolkata has noted a gradual fall from 17 March to 31 March and 21 April respectively (Fig. 4). The weekly change map has been shown in supporting information (See Fig. S6 in supporting information). Overall, the CO levels did not improve to a large extent due to the effect of the lockdown. High CO levels can cause Anoxemia, which in turn, can lead to various cardiovascular problems; infants, pregnant women, and old aged people will be at high risk due to its dense concentration in the lower troposphere.

In the similar period of the previous year, 2019, and the lockdown period of 2020, the average concentrations of CO have reduced by about 40.85% and 61.72% for Mumbai and Kolkata, respectively. However, in Delhi, the CO concentrations slightly increased (3.06%) (Table 5). Hence, Kolkata has witnessed the extreme change followed by Mumbai and Delhi in 2019–2020 (Fig. 6e).

3.6. Changes in the concentration of ozone (O_3)

O_3 is a colorless gas and produced by a chemical reaction between oxides of nitrogen and volatile organic compounds emitted from natural sources and domestic activities (Ghorani-Azam et al., 2016). With the increase in ground-level O_3, an increased risk of respiratory diseases, particularly asthma prevails. The declining trend of O_3 is illustrated in Fig. 2 m. The post-lockdown trend has remained the same (decline trend) for Mumbai and Kolkata, and Delhi like the case of many other pollutants exhibited an increase (Fig. 2n). Except for Kolkata, the other two megacities had O_3 levels below the permissible limit (60 µg/m^3) of CPCB, in both pre-lockdown and during the lockdown phase. The post-lockdown concentration was below the limit in Mumbai, whereas in

Delhi and Kolkata the concentrations were not consistent. The high concentrations lead to various health problems like asthma, bronchitis, and harmful effects on plants as it interferes in photosynthesis and results in the death of plant tissues since it assists in the formation of peroxy acyl nitrates.

The O_3 varied as 28.50–80.10 $\mu g/m^3$; 57.31–84.94 $\mu g/m^3$; and 79.90–110.78 $\mu g/m^3$ for Mumbai, Delhi, and Kolkata in pre-lockdown, whereas during the lockdown the ranges were 25.43–40.44 $\mu g/m^3$; 50.89–74.57 $\mu g/m^3$; and 49.67–97.33 $\mu g/m^3$ respectively (Table 2). The post-lockdown variation was 19.00–30.50 $\mu g/m^3$, 75.36–99.50 $\mu g/m^3$, and 42.22–100.43 $\mu g/m^3$ for the megacities in the same order.

The average concentrations of O_3 reduced in the lockdown phase by about 25.30%, 19.37%, and 21.13% for Mumbai, Delhi, and Kolkata, respectively (Table 3). The megacity of Delhi noted a rising (48.39%) concentration and the rest of the two have remained the same, 29.43% & 23.85% respectively in the post-lockdown (Table 4). Therefore, Mumbai and Kolkata experienced a continuous drop in O_3 concentration whereas Delhi experienced an increase during the post-lockdown phase.

We found a regular improvement of O_3 from 17 March to 14 April in the spatial distribution map for Mumbai and Kolkata (Fig. 2, 4). Megacity Delhi has recorded a sequential fall and rise in lockdown and post-lockdown (Fig. 3). The partial relaxation on transport service and industry sectors in Delhi increased the O_3 level. The weekly change of O_3 has shown in supporting information (See Fig. S7 in supporting information).

Compared to the previous year (2019), the average concentration of O_3 during the COVID period (2020) reduced by about 55.93% for Mumbai followed by 13.51% for Delhi (Table 5). Kolkata, on the contrary, exhibited an increase in O_3 level (Fig. 6f).

3.7. Changes in the AQI

The declining trend of AQI is shown for the period of lockdown in Fig. 2o. The post-lockdown trend has remained the same (decline trend) for Mumbai and Kolkata; Delhi being an exception (Fig. 2p). Mumbai air quality levels ranged from moderate to satisfactory; Delhi ranged from poor to satisfactory; and Kolkata moderate to the good category (according to the standards of CPCB). Overall the temporal change in AQI in the year 2020 exhibited a significant improvement in air quality during the lockdown and post-down phase compared to the pre-lockdown phase.

Spatial change in AQI for all three megacities is shown in Figs. 2, 3, 4 on the selected dates of 17 March, 31 March, and 21 April. We found that Mumbai had a better air quality compared to the other two megacities in all three phases (pre-during-post-lockdown). The south-eastern part of the megacities Delhi and Kolkata and the western part of Mumbai had better air quality. Hence, the lockdown seemed to improve the air qualities to a varying extent in all three megacities.

The average magnitude of AQI in all three phases (pre-lockdown, lockdown, and post-lockdown) were very close to each other (Table 3). The AQI range in pre-lockdown and lockdown was highest for Delhi (164.53–96.42) followed by Kolkata (152.78–86.48) and Mumbai (129.29–75.50). The post-lockdown variations were 75.5–55.2; 96.42–109.89; and 86.48–58.47 for Mumbai, Delhi, and Kolkata, respectively (Table 4). Therefore, Delhi was in the worst condition. Kolkata was the second most polluted megacity in India. Mumbai had a comparatively lower pollution level in the air.

The box plots (Fig. 6g) have shown that the AQI level dropped in megacities of India during the lockdown year, 2020 compared to the previous year, 2019. Delhi was the worst megacity as per high range with maximum average concentrations followed by Kolkata and Mumbai. The weekly variations are in supporting information (see Fig. S8 in supporting information).

3.8. Correlation between ambient air pollutants

Pearson correlation coefficient matrixes with scatter plots were derived between the air pollutants for all three megacities of India from 3 March to 5 May 2020. The daily average concentration of $PM_{2.5}$, PM_{10}, and NO_2 had a strong significant positive relationship in Mumbai (r = 0.97**, 0.97**, & 0.95**); Delhi (r = 0.96**, 0.91**, & 0.91**) and Kolkata (0.98**, 0.92**, & 0.91**) (Fig. 7a, b, c) (* denotes $p < 0.05$; ** denotes $p < 0.01$). The combined concentrations of air pollutants affected not only human health also the environment. The correlations between ambient air pollutants were not always strong. A weak positive relationship was also detected often. The daily (24 h) average concentration of $PM_{2.5}$ moderately correlated with daily (24 h) average NH_3 in Mumbai (r = 0.63) and Delhi (r = 66); however, the relationship was not significant. While in Kolkata the same couple exhibited a significant positive correlation (r = 0.91*). The relationship between $PM_{2.5}$ and SO_2 noted a near-zero or no relationship in Mumbai while in Kolkata, a significant positive relationship was observed (r = 0.77*). Likewise, $PM_{2.5}$ and CO were also strongly correlated in Mumbai & Kolkata (r = 0.85*, r = 0.82*) but Delhi exhibited a poor positive relationship. The $PM_{2.5}$ and O_3 were strongly correlated (r = 0.89**) in Mumbai and exhibited no relationship (r = 0.04) in Delhi.

The daily (24 h) average concentration of PM_{10} moderately correlated with daily (24 h) average NH_3 in Mumbai (r = 0.71) and Delhi (r = 0.60) while in Kolkata, it was a strong significant positive (r = 0.90*) relationships. The relationships of PM_{10} and SO_2 were moderately positive (r = 0.67) in Delhi while in Kolkata, it was a strong significant positive (r = 0.85*) but no relationship was noted in Mumbai. Likewise, PM_{10} and CO, strongly (r = 0.77*, r = 0.78*) correlated in Mumbai & Kolkata while Delhi has counted a very poor positive correlation. The PM_{10} and O_3 were strong (r = 0.82*) correlation in Mumbai and Kolkata, it was moderate (r = 0.69) while no relations (r = 0.03) were noted for Delhi.

The relationships between NO_2 with NH_3 were moderately positive in Mumbai and Delhi while it was a very strong positive (0.93**) in Kolkata. The NO_2 with pollutants of SO_2 strongly significantly correlated (r = 0.77*) in Kolkata while moderate and almost no relations taken place in Delhi and Mumbai. The relationships between NO_2 and CO were strong significant (r = 0.81*, r = 0.77*) in Mumbai and Kolkata while Delhi was with a weak relation. The NO_2 and O_3 were strong significantly correlated (r = 0.87*) in Mumbai and moderately correlated (r = 0.61) in Kolkata though it was exceptionally a very weakly negative correlation in Delhi.

On the other hand, a strong significant positive relation (r = 0.84*) between CO and $O_{3\ was}$ observed in Mumbai. Likewise, NH_3 & SO_2; SO2 & O_3 were also noted strong significant positive relationship (r = 0.77*, r = 0.84*) in Kolkata. Hence, except for the daily average concentration of $PM_{2.5}$, PM_{10}, and NO_2, the rest of the four pollutants (NH_3, SO_2, CO, and O_3) had a cent percent positive correlation; they were not always significantly correlated in all three megacities some times.

3.9. Role of meteorological parameters

The mean ± standard deviation of air temperature, relative humidity, wind speed, and total rainfall observed from 3 March to 23 March, 25 March to 14 April, and 15 April to 5 May for the years 2019 and 2020 are illustrated in Fig. 8. Air temperature exhibited an increasing trend from March to May in all three megacities; however, the trend was most prominent in Delhi. The same trend was observed in both the years 2019 and 2020. An increase in air temperature at the ground level destabilizes the atmosphere and facilitates enhanced vertical mixing of pollutants (Cichowicz et al., 2017). Thus, increasing air temperature facilitates the reduction of pollutants concentration at the ground level (Ravindra et al., 2019). From Fig. 8, it is evident that the air temperature increased during the lockdown period compared to that observed in the pre-lockdown phase. Hence a fraction of the reduction in the
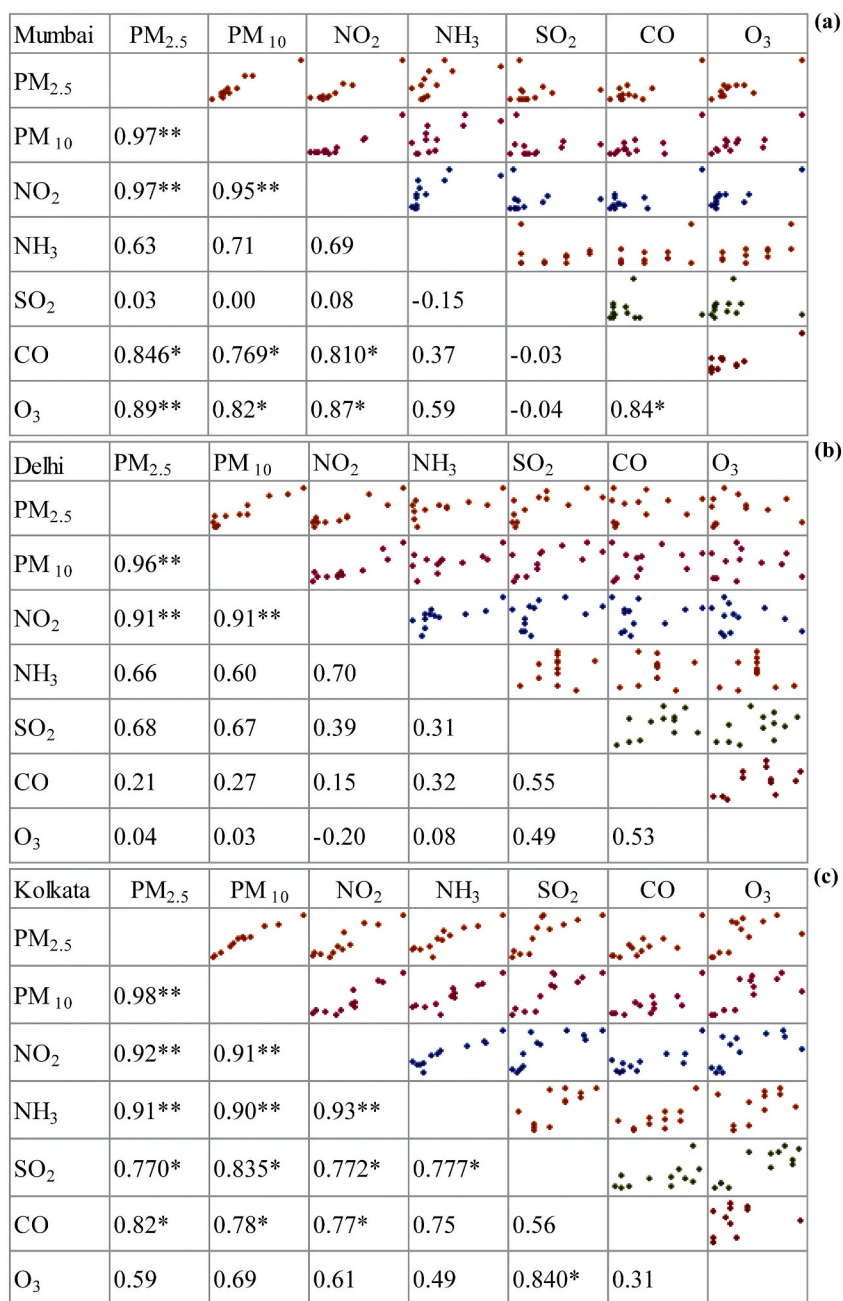
(a)

Mumbai	$PM_{2.5}$	PM_{10}	NO_2	NH_3	SO_2	CO	O_3
$PM_{2.5}$							
PM_{10}	0.97**						
NO_2	0.97**	0.95**					
NH_3	0.63	0.71	0.69				
SO_2	0.03	0.00	0.08	-0.15			
CO	0.846*	0.769*	0.810*	0.37	-0.03		
O_3	0.89**	0.82*	0.87*	0.59	-0.04	0.84*	

(b)

Delhi	$PM_{2.5}$	PM_{10}	NO_2	NH_3	SO_2	CO	O_3
$PM_{2.5}$							
PM_{10}	0.96**						
NO_2	0.91**	0.91**					
NH_3	0.66	0.60	0.70				
SO_2	0.68	0.67	0.39	0.31			
CO	0.21	0.27	0.15	0.32	0.55		
O_3	0.04	0.03	-0.20	0.08	0.49	0.53	

(c)

Kolkata	$PM_{2.5}$	PM_{10}	NO_2	NH_3	SO_2	CO	O_3
$PM_{2.5}$							
PM_{10}	0.98**						
NO_2	0.92**	0.91**					
NH_3	0.91**	0.90**	0.93**				
SO_2	0.770*	0.835*	0.772*	0.777*			
CO	0.82*	0.78*	0.77*	0.75	0.56		
O_3	0.59	0.69	0.61	0.49	0.840*	0.31	

Fig. 7. The Pearson correlation coefficient matrices showing the relationship between the different air pollutants across the megacities of (a) Mumbai, (b) Delhi, and (c) Kolkata. The dots represent the scatter plots between the respective parameters. [*Correlation is significant at the 0.05 level (2-tailed); **Correlation is significant at the 0.01 level (2-tailed)].

concentration of the pollutants can be accounted for due to this increase in temperature. However, the degree of increase in air temperature during the same period was the same in the previous year (2019) ($p >$ 0.05). Despite a similar increase in temperature in the years 2019 and 2020, the concentration of several pollutants was lower in the lockdown phase of 2020. Thus, the effect of lockdown can not be ignored.

Like higher air temperature, higher wind speed also facilitates the dispersal of pollutants (Li et al., 2020), except for some pollutants like PM_{10}, which gets resuspended at the ground level due to higher wind speed (Zhang et al., 2018). Mumbai did not exhibit any significant difference in wind speed between the pre-lockdown and lockdown phase; however, the difference was noticeable in the case of Kolkata and Delhi. Though the overall mean wind speed for the years 2019 and 2020 did not show any statistically significant difference for Delhi and Mumbai (p

> 0.05). The wind speed in Kolkata for the year 2019 was significantly high than that observed in the year 2020. If wind speed would have played a crucial role in governing the pollutant concentrations, an increase in pollutant levels could have been expected in Kolkata. However, except for O_3 and NH_3, all the other pollutants were reduced in the year 2020 compared to that in 2019. Thus, it can be inferred that wind speed played a negligible role in reducing the pollutants level during the lockdown.

Particulate matters, as well as SO_2 and NO_2, populates the ground-level atmosphere at a lower relative humidity ($< 40\%$), and at higher ranges, the pollutant concentration usually decreases (Lou et al., 2017; Munir et al., 2017). However, during the study period in both the years, the mean relative humidity never went below 55% in any of the phases. Except for Mumbai, a marginal decrease in relative humidity was
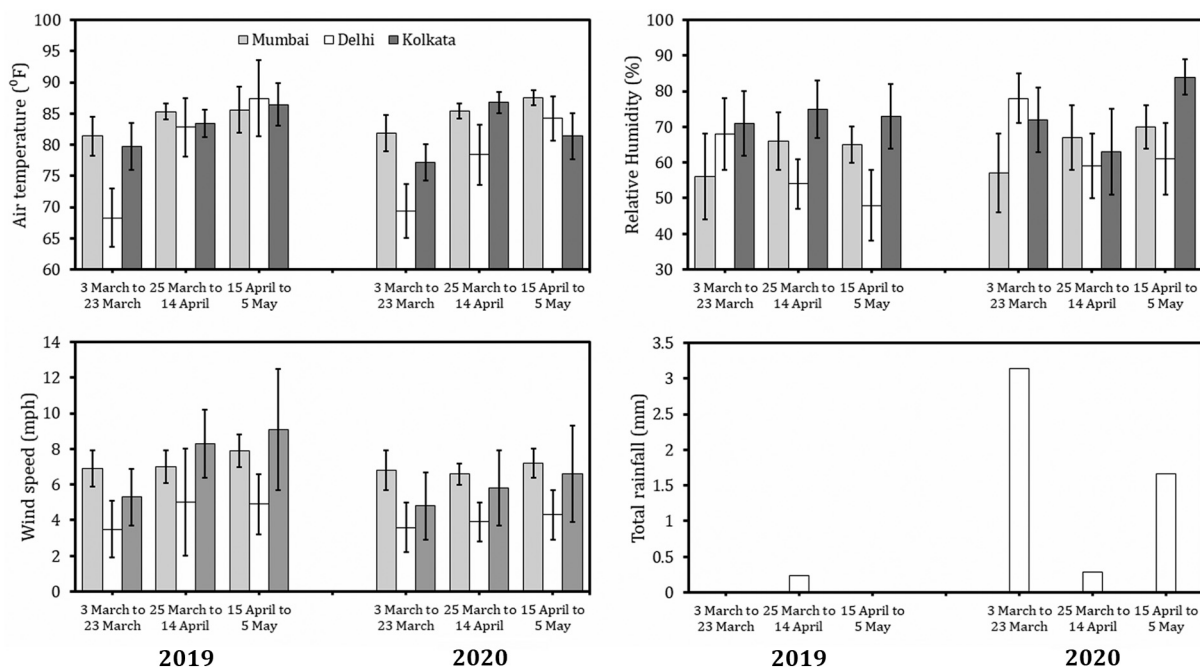
Fig. 8. The column graph showing the monthly mean of the meteorological parameters (air temperature, relative humidity, and wind speed) and total rainfall observed during March, April, and May in the years 2019 and 2020 in Mumbai, Delhi, and Kolkata. The error bars denote the standard deviation from the mean.

observed in Kolkata and Delhi between the pre-lockdown phase and the lockdown phase. The way relative humidity affects pollutant concentrations, this lowering in relative humidity should have increased the pollutants concentrations. However, the present observations indicated otherwise. Thus, it can be deduced that relative humidity also played a negligible role in the reduction in pollutant concentrations during the lockdown phase of 2020. Like relative humidity, rainfall also helps in decreasing air pollutants (Yoo et al., 2014); however, there was no rain in Mumbai and Kolkata in either of the years. In Delhi, there was negligible rainfall in both of the years. Thus, on the whole, we can infer that except for the air temperature, the other meteorological parameters did not play a significant role in reducing the pollutant concentrations during the lockdown of 2020.

4. Conclusion

The nationwide lockdown has had significant impacts on the air quality of the megacities of India. The seven air pollutants were employed in this study to assess the AQI due to the effect of COVID-19 lockdown. $PM_{2.5}$, PM_{10}, and CO are the major pollutants across the megacities while remaining pollutants such as NO_2, NH_3, SO_2, and O_3 concentrations were below the CPCB standards during both the pre-lockdown and the lockdown phases. $PM_{2.5}$, PM_{10} & CO recorded a decline of 47%, 41%, & 27% for Mumbai; 52%, 39%, & 13% for Delhi; and 49%, 37%, & 21% for Kolkata during the lockdown phase. These pollutants exhibited the same decline trend with 43%, 32% & 19% for Mumbai, 4%, 4% & 12% for Delhi; and 57%, 50% & 29% in the post-lockdown phase. The declining trend of AQI was observed during the COVID-19 lockdown period (25 March-14 April 2020) compared to the same window of the previous year, 2019. Delhi was in the worst condition as per average concentrations of pollutants and even when compared to last year's (2019) scenario, followed by Kolkata and Mumbai. The megacity of Delhi and Kolkata had more pollution in the western part compared to the east, whereas Mumbai exhibited an opposite spatial pattern. The meteorological parameters had a negligible role in reducing the pollutant concentrations during the lockdown period, except for the increasing air temperature. Among the seven pollutants only three, $PM_{2.5}$, PM_{10}, and NO_2 were significantly (positive)

correlated across the megacities. The other than three correlated positively although their fluctuations in relationships counted. To stop the spread of this global pandemic, social distancing, i.e., the prevention of mass gathering was the only option. All sectorial lockdowns such as vehicle movement, industry, domestic, and allied services except the emergency services were completely closed, and as a result improvement of air quality was recorded in the megacities, Mumbai, Delhi, and Kolkata. Some data limitations imparted minor constraints in this study; more automatic air monitoring stations need to be established within the boundary of megacities. Only LPG fueled three-wheelers operation, procurement of natural gas-driven buses, up-gradation of auto emission testing centers (Pollution Under Control, PUC), making artificial rain for the dry period, water sprinkling along roads in winter months, roadside eateries switch over from solid fuels to LPG, all constructions sites are to remain covered and awareness program from the school level, are some of the major actions needed throughout the year to improve the air quality of these megacities. Hence, the current study will help the policymakers, planners, decision-makers to architect the proper megacity planning to make a healthy and eco-friendly environment. This study indicates that to clean the megacities' air, short-term (like 3–5 day) lockdowns once a month can serve as an effective tool.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.

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