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Assessing the immediate impact of COVID-19 lockdown on the air quality of Kolkata and Howrah, West Bengal, India

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Abstract

The worldwide spread of COVID-19 caused a nationwide lockdown in India from 24 March 2020 and was further extended up to 3 May 2020 to break off the transmission of novel Coronavirus. The study is designed to assess the changes in air quality from the pre-lockdown period to the during lockdown period in Kolkata and Howrah municipal corporation, West Bengal, India. GIS-based techniques include the spatial and temporal distribution of pollutants using interpolation method, and on the other hand, statistical methods like analysis of variance (ANOVA) was applied to determine the mean differences two phases and correlation matrix helps to understand the changing association of the pollutants in pre- and during lockdown phases. Significant correlations have been found among the pollutants, ANOVA (Two-Way) has shown the significant mean difference of NAQI between the two phases, $F(1,611) = 465.723$, $p < 0.0001$; pairwise comparison for Ballygunge has shown the highest mean difference 108.194 at $p < 0.0001$ significant level between lockdown and pre-lockdown phase. Significant positive correlation has been found between $PM_{2.5}$, PM_{10} (0.99*); $PM_{2.5,}$ NO_2 (0.81*); PM_{10}, NO_2 (0.81*); CO, NO_2 (0.77*) and some negative correlations have also been found between O_3, NO (− 0.15); O_3 and NH_3 (− 0.36) in the pre-lockdown phase. The reduction amount of mean concentration from the pre-lockdown phase to during lockdown of the main pollutants like $PM_{2.5}$, PM_{10} and NO_2 are ~ 58.71%, ~ 57.92% and ~ 55.23%. Near Rabindra Bharati University constant emission of $PM_{2.5}$, 10 and NO_2 have been recorded due to the nearby Cossipore thermal power station.

Keywords COVID-19 · India · Lockdown · Pollutants · Air quality · ANOVA

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1 Introduction

In December 2019, a disease, later named COVID-19, was identified in Wuhan of China and within 3 months more than 100 countries have been affected by devastating consequences (Wang and Su 2020). On 11 March 2020, it was found that the spread of COVID-19 is caused by the new Coronavirus SARS-CoV-2 and it was announced as a pandemic (Figueiredo et al. 2020). The first confirmed case of COVID-19 in India was identified on 30 January 2020 in Kerala and hiked to three by 3 February when three students returned from Wuhan, China, and the first death was recorded on 12 March. Till 3 May 2020, the cumulative number of total infection by COVID-19 was more than forty thousand across India (GOI 2020). West Bengal the fourth-most densely inhabited state in the country recorded the first positive case of COVID-19 on 17 March 2020 after a UK-returned student was tested positive. To avert the infection, countries have strictly restricted the movement of people and transportation, reducing human interactions, enforcing strict quarantine, prohibiting large-scale private and public gatherings, encouraging social-distancing, and restricting private and public transportations and economic behaviour (Fernandes 2020; He et al. 2020; Wang and Su 2020).

India has been following a nationwide lockdown since 24 March 2020, which was initiated with a voluntary public curfew on 22 March, followed by a 21-day lockdown starting from 24 March. Lockdown of the production sectors, restriction on human mobility, and controlled public transportation system have resulted in the lowering of emission of pollutants. Studies by various scholars have shown how the lockdown has improved the ambient air quality, like in India (Gautam 2020; Mahato et al. 2020; Sikarwar and Rani 2020; Srivastava et al. 2020), the USA (Berman and Ebisu 2020), Mexico (Méndez-Arriaga 2020), Kazakhstan (Kerimray et al. 2020), Iran (Abdul Halim et al. 2018), China (Fan et al. 2020; Zambrano-monserrate et al. 2020) especially in Wuhan (Cole et al. 2020; Lu et al. 2020; Sicard et al. 2020; Song et al. 2016; Wang and Su 2020), Barcelona in Spain (Tobías et al. 2020), Sao-Paulo in Brazil (Nakada and Urban 2020), Milan in Italy (Collivignarelli et al. 2020), and Salé City in Morocco (Otmani et al. 2020).

In India, air pollution has become a topic of intense debate at all levels mainly because of the enhanced anthropogenic activities, e.g. rapid urbanization, higher population growth, increased energy consumption, vehicular emission, and industrial emission (Dadhich et al. 2018; Ghose et al. 2005; Gupta et al. 2008). Kolkata is the most polluted metropolis in India and suffers from the highest pollution levels among eight tropical Asian countries; on the other hand, Howrah is considered as one of the highly industrialized districts in the West Bengal (Mukherjee et al. 1998; Upadhyay et al. 2014; Financial Express 2020). The contribution of urban areas in the nation's GDP is gradually increasing in India (Ghose et al. 2005). Hence, the pollution due to vehicular emission (Chowdhury 2015), thermal power plant (Ghose et al. 2004), small-scale industries, industrial clusters, residential areas (Gupta et al. 2008), and street shops (NGT) are increasing in Kolkata and Howrah. Kolkata shares minimum areas for road connectivity only 6%, lesser than Mumbai and Delhi, and the encroachment of roads, on-road illegal parking adds fuel to this problem (Chakrabartty and Gupta 2014). Improving economic conditions and more women's participation in outside jobs has increased the demand for private cars (Chakrabartty and Gupta 2014). The hiking demand for private transportation and other vehicles in Kolkata city without proper traffic management is responsible for the day-by-day increasing pollution (Bhattacharjee 2008). In Kolkata vehicular emission, industrial centres and domestic sources contribute 50%, 48%, and 2% of the total pollution and heavy industries shares 56 percent and 44 percent is shared by the small-scale industries of the total industrial emission (Government of West Bengal 2019). This study aims to evaluate the changes in air quality in terms of pollutant concentration during the implementation of the lockdown measures considering the COVID-19 pandemic in Kolkata and Howrah, the 'twin cities' of West Bengal.

2 Materials and methods

2.1 Study area

Kolkata at the eastern bank and Howrah at the western bank of Hooghly River are 'the twin city' of West Bengal (Fig. 1). The 'city of joy' Kolkata was also the capital of India during the British empire and Howrah is the adjacent main city (Debnath et al. 2018; Haque and Singh 2017). According to the 2001 census, Kolkata is the second most populous city in India with a population of 14.4 million, after Mumbai while the population of Howrah is 10 million. Kolkata and Howrah rank 9th and 30th in world population ranking with a population density of 24,252 persons/km^2 and 20,817 persons/km^2, respectively (Census of India 2011). The population of Kolkata and Howrah is ever increasing due to population growth and labour influx (Debnath et al. 2018).

The pollution level of Kolkata is close to Delhi and higher than that of Mumbai and Chennai in India (Roy et al. 2015). It has also been known as 'the dusty city' (Haque and Singh 2017). In 2018, World Health Organization (WHO) confirmed that Kolkata is the second most polluted metropolis in the country, next only to Delhi. The study revealed another alarming trend that Kolkata's air quality is declining faster than that of Delhi. Kolkata and Howrah industrial belt are considered to be one of the highly industrialized

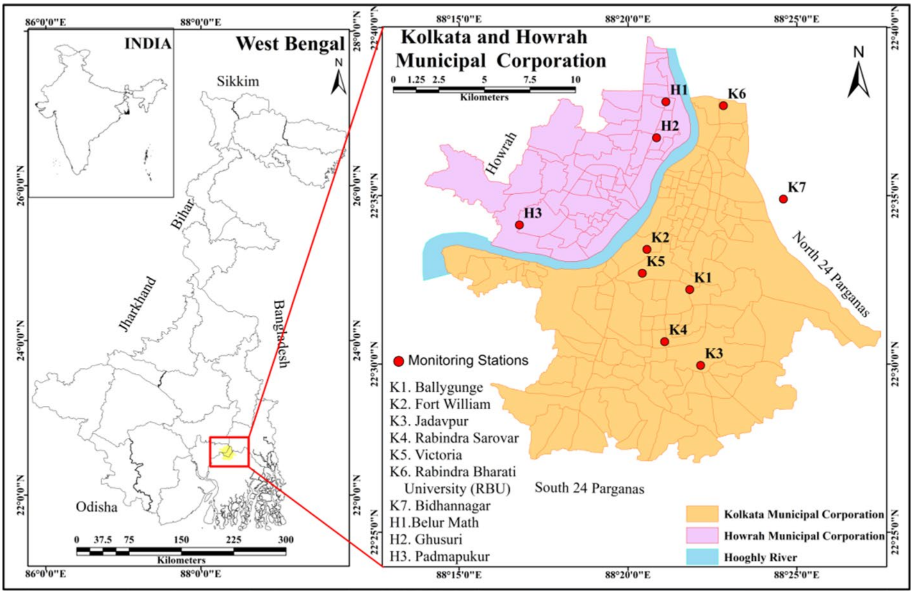

Fig. 1 Location of the study area

districts in West Bengal where industries like engineering, casting, steel fabrication, shipbuilding, consumer goods industries, construction pressure die casting, forging, electric installations, manufacturing of industrial electrical goods accessories, etc. are highly concentrated (Upadhyay et al. 2014). Vehicular emissions from continuously increasing vehicles contribute a large in polluting air, and the number has increased 8 times from 1951 to 2001 (Chowdhury 2015). After the implementation of various measures still, vehicular emission is very high and threatening at traffic intersections in Kolkata (Ghose et al. 2004, 2005). $PM_{2.5}$ and PM_{10} are considered to be the main pollutants and have a constant concentration above the permissible level in Kolkata (Das et al. 2015). The northern part of Kolkata is mainly characterized by the residential areas, small-scale industries, and Cossipore thermal power station and is surrounded by Hooghly River. The location of Dhapa dumping ground and east Kolkata wetland impacts the ambient air quality in the eastern part as well as the small-scale industries, and high traffic junctions in the central Kolkata pollute the air (Gupta et al. 2008). Due to densely distributed small-scale industries without any pollution controlling measures, unplanned traffic flow, and congestion, Howrah city is to endure higher pollution of ambient air (Upadhyay et al. 2014).

Urban morphology differs from north Kolkata to south. North Kolkata is condensed with old buildings and the roads which are very narrow and traffic congestion is another problem but high-rise buildings, highways with more space, and traffic congestion can only be noticed during office hours in the southern Kolkata (Mondal et al. 2000). Small-scale industries (Datta et al. 2016), burning ghats, thermal power stations (Chowdhury 2015) contribute a lot to the level of pollution in both Kolkata and Howrah municipal corporation. Major clusters of polluting sites in Kolkata are Pyrabagan, Maniktala (Battery Patti), Topsia, Picnic Garden, Tangra-Tijalia-Topsia (Charma Patti), Tangra-Kill Khana-Pangladanga, Hazra-Ritchie Road, Raja Bazar, Khiddapore-Garden Reach-Metiabruz, Cossipore-Chitpur, Bowbazar, Mullick Bazar, Jadubabur Bazar, Maniktala-PhoolBagan, Taratola Industrial Estate, Dhapa Landfills, MollarBheri, etc. (Datta et al. 2016). Based on health effects and level of pollution, Central Pollution Control Board categorized the industrial activities in red, orange, green, and white aiming to control the level of pollution and understand the pattern of industries under section 18(1) (b) of water (Prevention and control of pollution) (West Bengal Pollution Control Board 1981). Air quality is monitored automatically at six points in Kolkata Municipal Corporation, one at Bidhannagar and three locations in Howrah Municipal Corporation.

Ballygunge Ballygunge is situated at the central part of KMC, and this area is known for condensed small-scale industries. It has recorded a high pollution level due to major road intersections near like Park Circus Seven Point Crossing, Gariahat, Rashbehari, and Hazara More (Chowdhury 2015). Tannery processing industries of Park circus and Kustia are adjoined to the station as an important industrial cluster.

Fort William and Victoria This part is situated in the western part of Kolkata near Hooghly River, and the main source of pollution is vehicular emission. The major roads those have connected this area with the other part of Kolkata are Khidirpur Road, Acharya Jagadish Chandra Bose Road, and Jawaharlal Nehru Road also Esplanade is another important traffic intersection.

Jadavpur Jadavpur where vehicular emission is very important is another automated station which is located in the southern part of the study area. Jadavpur is highly connected by roads and highly congested, and the major traffic intersections are the intersection of King Anwar Shah and Gariahat road and the flyovers near the K8 bus stand. The queue of the vehicles is seen from South City Mall to Jadavpur PS in the morning from 8.00 am to 11 am and in the afternoon as well as night from 7.30 to 8.30 and 9.00 pm (Nandi 2017).

Rabindra Sarovar Rabindra Sarovar Station is located at the central Kolkata and is affected by high vehicular emission due to the high traffic intersections and roads like Tallygaunge Phari (Chowdhury 2015). Goal Park is the intersection of Gariahat Road and Dr. MeghnathSaha Road, the intersection of Debika Kumar road and Baroj Road, Rashbihari, and Hazra intersection are major traffic intersection.

Rabindra Bharati University (*RBU*) This station is the northernmost among the other stations in KMC. An important entry point in Kolkata is Vivekananda Setu, and the road is always congested with loaded trucks (Ghose et al. 2005) and also it is influenced by the nearby Cossipore thermal power station, high traffic congestion, electro-plating industry, and dyeing industry (Karar et al. 2006), Gold smelting stations (red category industry), and burning ghats are important sources of pollution near RBU (Ghose et al. 2005).

Bidhannagar Bidhannagar is one of the busiest areas. The location of the administrative centres of West Bengal near Salt Lake is connected through Biddhannagar Road Railway Station which is a reason for higher traffic as well as human mobility in this part. Uncontrolled traffic movement, a higher number of auto-rickshaw, bus, and taxi are very important for traffic congestion.

In Howrah Municipal Corporation, only three automated stations among which Belur Math is located in the northern part of HMC, Ghusuri near Liluah Station, and Padmapukur at the southern part of HMC are set to record pollutants' data. Howrah is an industrial centre in West Bengal, and unplanned growth of the city and squatter settlement are responsible for relatively higher pollution in Howrah, West Bengal.

Belur Math The station is located at the northernmost part of HMC and affected by the nearby manufacturing industries like aluminium production, plastic production, chemical industries, and electronics. Within 200 m of radius, the Belur Bazar traffic intersection and Belur Bus terminus are the important traffic intersection and the two main roads that have crossed from the eastern and the western part of the station are Al Banerjee Road and Girish Ghosh Road and another important road is Ramlochan Street.

Ghusuri Ghusuri has its name in history as an industrial centre in West Bengal. This part is now famous for plastic and aluminium industries which are categorized as the 'red' by WBPCB, 2018. Highly condensed settlement patterns are mainly characterized by squatter settlement.

Padmapukur Padmapukur is the southernmost station in HMC. The level of pollution is relatively higher in this part, an intersection of Andul Road, NH 117, Botanical Garden road.

2.2 Data sources

To study the changes in air quality during the lockdown period, the data from ten monitoring sites in Kolkata Municipal Corporation (KMC), as well as in Howrah Municipal Corporation (HMC) (Table 1), are taken into consideration. Monitoring station Bidhannagar is considered for spatial mapping purposes only for better understanding and excluded from all the statistical analysis because the eastern part is only covered by this station but does not come under KMC. The location of all these ten monitoring stations is shown in Fig. 1. Data from 22 February 2020 to 23 March 2020 (4 weeks before the lockdown) and from 24 March 2020 to 3 May 2020 (tenure of complete lockdown) were used to calculate variations in concentrations and appraise the relative change from the pre-lockdown period to the complete lockdown period.

Table 1 Location of the monitoring stations

Municipal corporation	Station ID	Name of the station	Location
Kolkata	K1	Ballygunge	22° 32′ 12.3", 88° 21′ 49.69"
	K2	Fort William	22° 33′ 23.9", 88° 20′ 33.63"
	K3	Jadavpur	22° 29′ 57.44", 88° 22′ 9.01"
	K4	Rabindra Sarovar	22° 30′ 39.82", 88° 21′ 5.11"
	K5	Victoria	22° 32′ 41.31", 88° 20′ 25.33"
	K6	Rabindra Bharati University (RBU)	22° 37′ 40.35", 88° 22′ 49.44"
Bidhannagar	K7	Bidhannagar	22° 34′ 53.65", 88° 24′ 36.09"
Howrah	H1	Belur Math	22° 37′ 47.28", 88° 21′ 7.26"
	H2	Ghusuri	22° 36′ 43.08", 88° 20′ 50.72"
	H3	Padmapukur	22° 34′ 7.43", 88° 16′ 47.02"

The West Bengal Pollution Control Board (WBPCB), under the guidance of the National Air Quality Monitoring Program (NAMP), regularly monitors the ambient air quality of major urban towns and industrial areas of the state. The daily concentration of seven pollutants including particulate matter ($PM_{2.5}$ and PM_{10}), nitrogen dioxides (NO_2), sulphur dioxide (SO_2), ammonia (NH_3) on 24 h interval on the other hand ozone (O_3), and carbon monoxide (CO) have been taken into consideration on an 8-h interval for air quality assessment from the Central Pollution Control Board online portal for air quality data dissemination (https://app.cpcbccr.com/ccr/#/caaqm-dashboard-all/caaqm-landing) to give an inclusive analysis of the air quality data under the national ambient air quality standards. In the AQI system $PM_{2.5}$, PM_{10}, NO_2, SO_2, NH_3, CO, O_3, and Pb but here Pb is excluded because the concentration of this pollutant is not available in real time and cannot be taken into consideration for real-time AQI calculation (CPCB 2014). These data are also verified from different sources like AQI-India (https://app.cpcbccr.com/AQI_India/) under the Central Pollution Control Board, WBPCB (https://emis.wbpcb.gov.in/airquality/JSP/aq/districtwiseReport.jsp) under West Bengal Pollution Control Board and OpenAqportal (https://openaq.org/#/location/Arya%20Nagar,%20Bahadurgarh%20-%20HSPCB?_k=cpmf34).

Concentrations of NO_2 (0.25° level-3 (L3) daily OMI tropospheric) for the period of 22 February to 3 May of 2019 and 2020 were acquired from Giovanni interface (https://giovanni.gsfc.nasa.gov/giovanni/), derived from the NASA Goddard EarthSciences Data Active Archive Center (GES DISC; https://disc.sci.gsfc.nasa.gov).

2.3 Data analysis

The air quality index (AQI) is a measure of the cumulative effect of individual pollutants concentration on the quality of air in different places, but the modification of the method which is termed as National Air Quality Index (NAQI) is based on the maximum operator approach to avoid the uncertainty (CPCB 2014; Dadhich et al. 2018; Joshi and Mahadev 2011; Mahato et al. 2020). Central pollution control board (CPCB), India, monitors the ambient air continuously and has been using the EPA-US method to calculate the air quality indices (AQI) (Chaurasia et al. 2013; Kumar and Dash 2018). Here we only briefly summarized it. Calculation of Sub-indices for each and individual pollutant and then the aggregation of breakpoint values (sub-indices), which depend upon the Indian National

Ambient Air Quality Standards (NAAQS), are the two steps involved in AQI calculation. The maximum value of the sub-indices is taken as the AQI. The AQI standards are displayed in the number form that describes the quality rating (potential health effects) as shown in Table 2.

As the study is carried out in KMC and HMC, the municipal ward boundary map is designed in a GIS environment. ArcGIS 10.3, distributed by the Environmental Systems Research Institute (ESRI), has been employed for spatial analysis to identify air pollution levels. Based on the ten monitoring sites, the interpolated maps of each pollutant and AQI have been generated from pre-lockdown tenure to during lockdown tenure. In this study, inverse distance weighting (IDW) interpolator by linear combination model has been used because it is easy to operate than others without any pre-program assumptions to opt for a semi-variogram model (Jumaah et al. 2019; Poshtmasari et al. 2012).

ANOVA (Two-way), cluster analysis (single linkage) based on the Euclidean distance and Ward's methods, and Pearson moment correlation coefficient (*r*) were computed using the IBM SPSS version23. STATA 12 was used for the Box plots of AQI. The ANOVA helps to understand the variation in air quality index in each location as well as in pre-lockdown and during lockdown tenure, while correlation analysis denotes the degree of association among the different pollutants is done using JMP 15. Box plots are especially valid for comparing two or more distribution and also present a graphical display based on the order-statistic summaries of median and quartiles. Tables and charts have been used to report descriptive statistics by calculating the simple percentage, tabulation, and cross-tabulation. Using MS Excel line graphs for each pollutant is graphically represented.

3 Results and discussion

3.1 Observed concentration of the air pollutants

The concentration of the pollutants in the study area is summarized (Table 3) to understand the changes in maximum–minimum concentration and mean concentration of the pollutants, for all the concerned recording stations of the 'twin city' for the pre-lockdown (PL) period from 22 February to 21 March and the during lockdown (DL) period from 24 March to 3 May 2020. The effect of $PM_{2.5}$ and PM_{10} is severe on the health of people as it results in severe breathing problems as well as lung problems (Ashhar et al. 2007). Particulate matter is the most important pollutant in Kolkata, caused almost 10,000 premature deaths in Kolkata in 1995 (Kazimuddin and Banerjee 2015). For all the stations, a sharp reduction has been noted in the concentration of $PM_{2.5}$ and PM_{10} from the pre-lockdown to during lockdown. The highest concentration with an amount of 149.68 μg/m^3 has been monitored at Ballygunge because the station is nearest to the Garden reach and other small-scale industrial centres in the area for $PM_{2.5}$ in Kolkata, whereas Gusuri is one of the most industrial centres in Howrah and has recorded an amount of 333.52 μg/m^3 for PM_{10} in Howrah at 24 h interval as well. In the pre-lockdown tenure, the monitored amount of $PM_{2.5}$ is above the level of the AQI standards because of intensive industrial belts such as paper pulp, chemical industries, textile, rubber, and iron as well as high traffic congestion and emission from the thermal power plants which are associated with the corresponding stations (Spiroska et al. 2013). The reduction of 2.75 times of PM_{10} at Ghusuri along with the mean difference between the pre-lockdown and during lockdown is 125.4 μg/m^3. On the other hand, minimum concentration has been recorded at Belur Math with a mean

Table 2 Proposed breakpoints for AQI scale 0–500. (*Source*: CPCB 2014)

AQI category (Range)	PM_{10} 24-h (µg/m^3)	$PM_{2.5}$ 24-h (µg/m^3)	NO_2 24-h (µg/m^3)	O_3 8-h (µg/m^3)	CO 8-h (mg/m^3)	SO_2 24-h (µg/m^3)	NH_3 24-h (µg/m^3)
Good (0–50)	0–50	0–30	0–40	0–50	0–1.0	0–40	0–200
Satisfactory (51–100)	51–100	31–60	41–80	51–100	1.1–2.0	41–80	201–400
Moderately polluted (101–200)	101–250	61–90	81–180	101–168	2.1–10	81–380	801–1200
Poor (201–300)	251–350	91–120	181–280	169–208	11–17	381–800	801–1200
Very poor (301–400)	351–430	121–250	281–400	209–748	17–34	801–1600	1200–1800
Severe (401–500)	430+	250+	400+	748+	34+	1600+	1800+

Table 3 Summary statistics of atmospheric pollutants concentration in Kolkata and Howrah Municipal Corporation, 2020. (*Source*: Computed by authors)

	$PM_{2.5}$ (μg/m³)		PM_{10}(μg/m³)		NO_2 (μg/m³)		NH_3(μg/m³)		SO_2 (μg/m³)		CO (mg/m³)		O_3 (μg/m³)	
	PL	DL	PL	DL	PL	DL	PL	DL	PL	DL	PL	DL	PL	DL
Rabindra Bharati, *Kolkata*														
Max	140.38	68.87	313.5	114.97	71.16	28.56	66.96	39.06	23.97	16.17	1.05	0.35	46.25	62.56
Min	23.58	7.96	52.52	16.19	31.21	13.22	35.76	22.52	11.85	7.44	0.29	0.15	22.34	19.32
Mean	73.7 ± 27.7	29.7 ± 17.3	136.6 ± 52.8	51.6 ± 28.8	52.0 ± 9.1	20.2 ± 4.3	46.9 ± 6.9	29.8 ± 4.0	17.5 ± 3.0	11.8 ± 2.6	0.5 ± 0.1	0.2 ± 0.1	34.0 ± 6.1	43.4 ± 9.8
Fort William, Kolkata														
Max	104.81	71.78	187.13	99.48	79.93	23.50	32.61	16.68	16.69	11.21	1.26	0.49	56.49	81.22
Min	26.39	8.99	54.51	16.70	31.50	5.99	16.35	5.57	3.23	3.72	0.44	0.28	8.82	15.99
Mean	58.5 ± 20.1	32.3 ± 17.8	104.6 ± 34.4	50.1 ± 20.4	53.3 ± 13.2	12.5 ± 4.2	22.5 ± 3.8	9.1 ± 3.3	8.8 ± 2.9	6.6 ± 1.9	0.7 ± 0.2	0.4 ± 0.1	38.6 ± 12.7	46.9 ± 12.9
Victoria, Kolkata														
Max	107.03	49.46	216.61	82.93	84.08	27.57	33.20	29.25	23.73	16.50	2.28	1.77	92.60	108.53
Min	23.13	9.19	55.20	27.15	28.00	5.65	19.65	16.78	6.34	6.15	0.44	0.44	10.01	24.02
Mean	57.4 ± 22.1	25.3 ± 10.7	117.5 ± 45.3	46.1 ± 17.3	60.0 ± 15.2	13.4 ± 4.9	25.3 ± 3.2	22.1 ± 3.2	12.1 ± 4.0	10.2 ± 2.7	1.5 ± 0.4	0.8 ± 0.4	57.3 ± 20.7	54.7 ± 27.8
Ballygunge, Kolkata														
Max	149.68	62.07	241.35	27.83	46.29	9.89	25.77	10.28	14.58	8.75	1.17	0.44	79.07	82.58
Min	31.61	4.4	82.15	20.12	12.76	2.34	11.56	3.27	4.09	1.38	0.33	0.21	18.7	28.76
Mean	78.8 ± 32.1	25.4 ± 15.1	144.5 ± 46.5	60.9 ± 40.8	28.0 ± 8.6	5.63 ± 1.97	15.99 ± 4.58	6.61 ± 2.12	8.20 ± 2.57	4.49 ± 2.00	0.68 ± 0.21	0.29 ± 0.05	50.6 ± 15.0	51.8 ± 16.2
Rabindra Sarovar, Kolkata														
Max	91.44	68.11	187.77	92.42	74.35	11.36	22.65	18.29	20.09	14.31	1.03	0.41	68.51	76.44
Min	26.75	2.09	47.24	14.36	8.27	5.24	4.32	7.27	6.87	3.94	0.23	0.15	14.43	24.63
Mean	50.6 ± 17.8	16.8 ± 13.3	102.7 ± 36.2	46.8 ± 20.6	26.2 ± 20.6	8.1 ± 1.9	14.0 ± 5.2	13.0 ± 4.5	13.2 ± 3.8	7.1 ± 2.7	0.6 ± 0.2	0.3 ± 0.05	42.5 ± 13.0	48.9 ± 13.9
Jadavpur, Kolkata														
Max	93.61	60.96	172.4	100.01	52.38	17.62	79.76	15.83	11.96	12.35	1.69	0.58	37.48	61.22
Min	20	6.46	54.66	19.0	20.24	7.31	15.04	5.81	4.75	4.84	0.54	0.39	7.45	17.75
Mean	55.0 ± 20	26.7 ± 16.1	107.0 ± 35.6	52.2 ± 22.2	32.1 ± 9.6	10.2 ± 2.6	26.6 ± 14.8	9.1 ± 3.0	7.8 ± 1.7	7.5 ± 1.7	0.8 ± 0.2	0.4 ± 0.1	21.8 ± 8.3	38.6 ± 10.8
Belur Math, Howrah														
Max	67.34	38.00	159.53	86.02	97.42	29.11	41.47	17.89	31.60	18.64	1.01	0.44	NA	NA
Min	15.42	4.48	43.77	14.58	32.04	11.19	20.02	8.39	10.76	7.67	0.28	0.20	NA	NA
Mean	41.57 ± 13.7	18.97 ± 9.0	99.37 ± 29.6	41.57 ± 18.2	61.73 ± 13.5	18.99 ± 4.5	29.26 ± 5.5	11.89 ± 2.4	21.76 ± 3.8	12.63 ± 3.1	0.61 ± 0.2	0.31 ± 0.1	NA	NA

Table 3 (continued)

	$PM_{2.5}$ (μg/m^3)		PM_{10}(μg/m^3)		NO_2 (μg/m^3)		NH_3(μg/m^3)		SO_2 (μg/m^3)		CO (mg/m^3)		O_3 (μg/m^3)	
	PL	DL	PL	DL	PL	DL	PL	DL	PL	DL	PL	DL	PL	DL
Ghusuri, Howrah														
Max	145.7	64.99	333.52	134.95	73.42	24.04	21.36	15.35	67.39	17.78	1.16	0.65	28.69	62.26
Min	36.13	12.20	105.69	29.44	26.30	10.50	12.04	9.28	16.02	5.73	0.36	0.22	8.53	18.39
Mean	83.2 ± 29.5	30.2 ± 12.3	198.4 ± 63.0	73.1 ± 29.8	53.2 ± 12.7	15.9 ± 3.3	17.2 ± 2.8	11.7 ± 1.7	36.4 ± 13.8	8.8 ± 2.6	0.81 ± 0.2	0.35 ± 0.1	19.2 ± 4.9	36.5 ± 10.0
Padmapukur, Howrah														
Max	136.36	52.13	214.64	91.64	71.99	17.18	40.05	7.20	33.92	21.41	0.97	0.53	62.73	81.69
Min	25.74	10.29	47.81	17.56	6.92	2.05	8.83	3.25	2.30	4.76	0.38	0.34	9.54	8.72
Mean	71.2 ± 27.0	29.6 ± 11.5	118.5 ± 42.8	52.8 ± 22.1	33.5 ± 11.9	10.4 ± 4.5	23.3 ± 10.8	4.7 ± 0.9	10.9 ± 7.7	10.7 ± 3.4	0.63 ± 0.2	0.44 ± 0.1	37.8 ± 15.2	48.5 ± 16.6

PL pre-lockdown, *DL* during lockdown, *NA* data not available at regular interval concentration of 41.57 (μg/m^3) after the imposition of lockdown. The complete lockdown has reduced the power consumption, traffic congestion, and emission from the production units to a very minimal level. The 'Red' category industries like chemical industries, plastic industries, electronic industries, etc. and jute, paper pulp industries are responsible for high emission.

Severe degradation of air quality is also caused by NO_2 and affects health severely such as breathing problems, headache, and corrosion of teeth (Ashhar et al. 2007). It is emitted from both the natural sources of the nitrogen cycle by the process of biological processes, lighting effect, and the anthropogenic sources as vehicular emission from the highly congested traffic flow (Ibe et al. 2020). During weekends, average traffic flow is 2.3×10^4 and it is raised to 2.8×10^4 during weekdays near industrial centres in Kolkata (Gupta et al. 2008). From studies, it has been found that the NO_2 concentration is double than of the CPCB standard of 60 in the residential areas (Bhattacharjee 2008). The highest concentration of NO_2 has been recorded at Belur Math in HMC and a reduction of 3.24 times during lockdown from the pre-lockdown phase. The minimum value is recorded during the lockdown period at Padmapukur, HMC. During the complete lockdown period, Belur Math has recorded the highest concentration and followed by Victoria, Fort William, Ghusuri, Rabindra Bharati, Padmapukur, Jadavpur, Ballygunge, and Rabindra Sarovar. SO_2 with a higher amount may cause death only if anyone is already suffering from previous respiratory problems like emphysema and the effect is more on the older people than young people (Ashhar et al. 2007).

SO_2 as an atmospheric gas is released when coal is burnt, decaying of grassland or vegetation, volcanoes, and ocean. It is a precursor of acid rain in the form of sulphuric acid (H_2SO_4), deposits in the surface and sub-surface, and also in oxidized form as sulphate having a dominating role in 'radiative forcing' of climate (Cox 2003; Wang et al. 2006). From the study, it has been found that 60%, 36%, and 7.8% are released from transport, industrial, transport, and other activities share very little in India (Garg et al. 2001). The concentration of SO2 tends to be higher during the high traffic hours in urban areas (Gaur et al. 2014). A four-time reduction in mean concentration is noted from pre-lockdown to during the lockdown period at Ghusuri in HMC.

Ozone is produced and directly emitted because of reactions among nitrogen oxide (primary pollutant), certain organic compounds, and precursor of methane (CH_4) mixed in the air under the influence of ultraviolet rays (Arbilla et al. 2002). The lifespan of ozone varies from an hour to a day in the normal situation but in the polluted urban atmosphere, it may vary from day to week. Temperature affects the formation of ozone and also the magnitudes of concentration in the atmosphere because the decreasing temperature results in the decomposition of the precursors as well as the high solar radiation amplifies the production of ozone in the atmosphere (Pulikesi et al. 2006). Due to the unavailability of the data at Belur Math, the station is not considered for discussion. Victoria and its adjoining areas are prominent for the concentration of O_3, which varies from 10.1 to 92.60 μg/m^3 in the pre-lockdown period but the concentration has hiked to 24.02–108.53 μg/m^3 in the during lockdown period.

NO, as a harmless gas is directly emitted from the vehicle (85–87.5) and then transformed into NO_2 in reaction with the O_3 and the other nitrogen compounds by other chemical processes, the combination of NO_2 and NO is known as NOx (Palmgren et al. 1996). The ratio between NO and NOx is very important and known as the 'Leighton ratio' in the atmosphere and controls the magnitude of O_3 (Leighton 1962).

Ozone concentration has been hiked because ozone can be degraded and regenerated by NO_x and more degradation is associated with urban areas where local scale ozone depletion is found near high NO_x emitting zone (Arbilla et al. 2002). During the lockdown period, the emission of NO_2 is reduced and has limited the degeneration process of ozone, results in continuous hiking of ozone in the atmosphere.

CO is a trace gas, emitted due to incomplete combustion of fossil fuel and reaction among oxidation of hydrocarbons, volatile organic compounds, and methane, also from the vehicle, industrial hubs, open burning as well as aircraft emission (Jaffe 2012) and wood fires (Aneja et al. 2001; Gaur et al. 2014; Njoku et al. 2016). The diurnal pattern varies highly based on human activities in urban centres (Jaffe 2012). National Green Tribunal (2019) reported that street food stalls on footpaths use charcoal, dump cake, and other materials as fuel are the sources of severe pollution in Kolkata. Victoria has recorded the highest concentration of CO that ranges from 0.44 to 2.28 mg/m^3 in the pre-lockdown phase and is reduced to 0.44–1.77 mg/m^3. During the pre-lockdown phase, the highest concentration is found in Victoria because the vehicle is very important source of CO, and the traffic intersections near Victoria contribute a lot to the atmosphere. Hence, the minimum concentrated zone of CO is Rabindra Bharati.

NH_3 is an alkynes gas, emitted from both the anthropogenic processes (animal waste, fertilizer, waste management, vehicular emission, incomplete burning of home-cooking fuel, and dumping stations) and atmospheric processes (Fenn et al. 2018). In Kolkata, a high concentration of NH_3 can be traced out where the land use pattern is dominated by industrial, commercial, and residential areas associated with dumping stations (Gupta et al. 2008). During the pre-lockdown phase, NH_3 has taken the highest concentration at Jadavpur. The engrossment ranges from 15.07–79.76 to 5.81–15.04 μg/m^3 the during lockdown phase. The mean concentration has dropped from 26.6 to 9.1 μg/m^3, almost a three times reduction from the pre-lockdown to during lockdown.

Line graphs (Fig. 2) have been drawn based on pollutant concentration data for all the stations in KMC and HMC are averaged and then plotted. It represents the trend of the concentration of the pollutants. NO_2, SO_2, CO, O_3, NH_3 have been recorded at a satisfactory level but it has been noted that $PM_{2.5}$ and PM_{10} are above the satisfactory level in the pre-lockdown phase and can be considered as the main pollutants in both KMC and HMC. But during the lockdown phase, the concentration has been reduced to a satisfactory level for all the pollutants except O_3. The main scaling down can be noted for $PM_{2.5}$ and PM_{10} from the pre-lockdown to the complete lockdown period. AQI is the combined form of all the pollutants is also showing that during the lockdown period the air quality has improved to the ‘good’ category.

The box plots (Fig. 3) of all stations are depicting the change in AQI from pre-lockdown to during lockdown. In pre-lockdown tenure, the station Ballygunge in Kolkata Municipal Corporation has been noted for ‘poor’ air quality as prescribed by CPCB (2014) (Table 2) because of the nearby polluting sites like Topsia, Kosba, and Mullickbazar industrial sites (Gupta et al. 2008).

Most of the stations have recorded ‘good’ to ‘satisfactory’ air quality during the lockdown period in both the municipal corporations. Among all the stations Ballygunge has recorded highest AQI during the pre-lockdown phase and the median value is 163.67 but during lockdown phase the median of AQI has reduced to 58.29. From the diagram (Fig. 3), the major polluted stations are Ballygunge, Rabindra Bharati University, and Ghususri. The lowest AQI has been recorded during the lockdown period at Belur Math in Howrah Municipal Corporation.

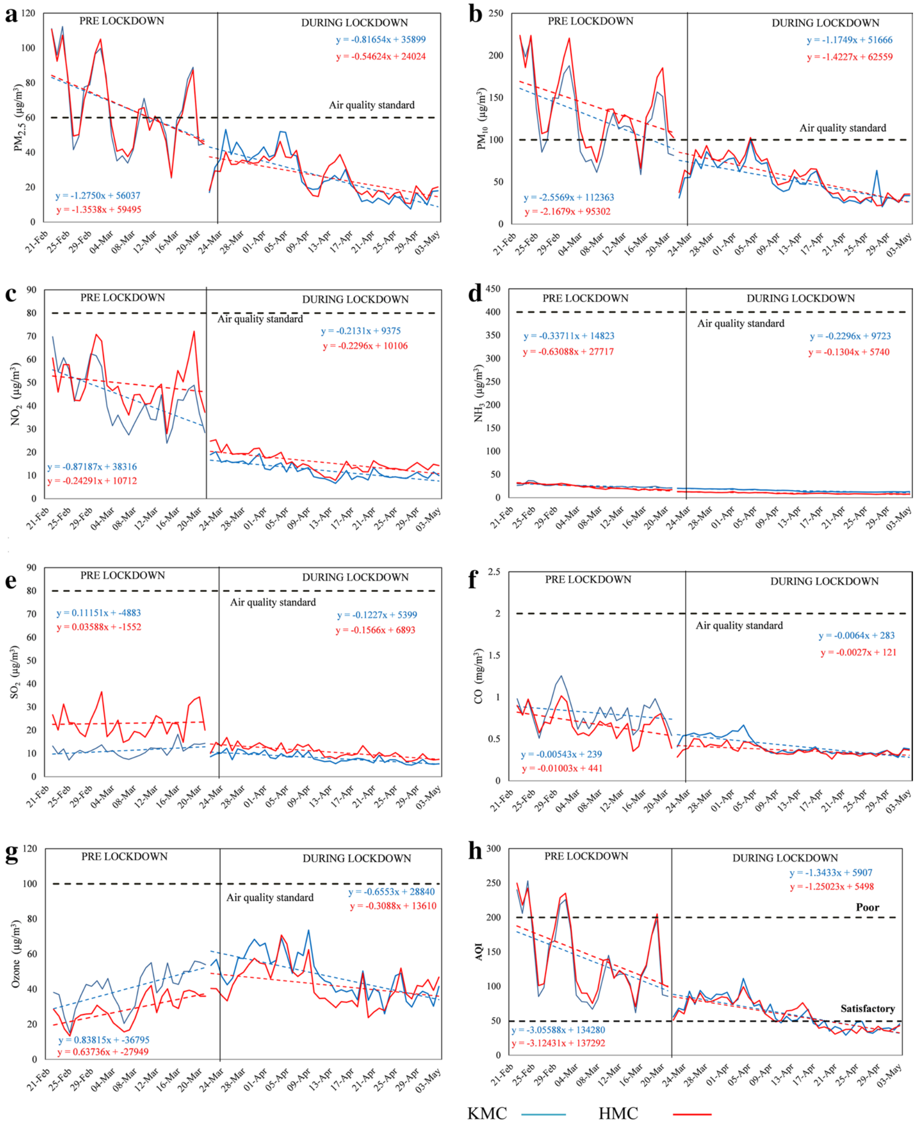

Fig. 2 24-h mean concentrations of **a** $PM_{2.5}$, **b** PM_{10}, **c** NO_2, **d** NH_3, **e** SO_2, **h** AQI and 8-h mean concentrations of **e** CO and **f** O_3 between 22 February and 3 May 2020 in Kolkata and Howrah

3.2 Cluster analysis

Cluster analysis is a multivariate analysis that has been used to determine the grouping pattern of the monitoring stations in the pre-lockdown and during the lockdown phase based on AQI (Fig. 4). Euclidean distance and Ward's methods were employed to measure the distance among stations (David et al. 2019).

In the pre-lockdown phase, the stations Jadavpur, Rabindra Sarovar, Fort William, and Victoria located in the central part of the study area are in the first cluster notifying the

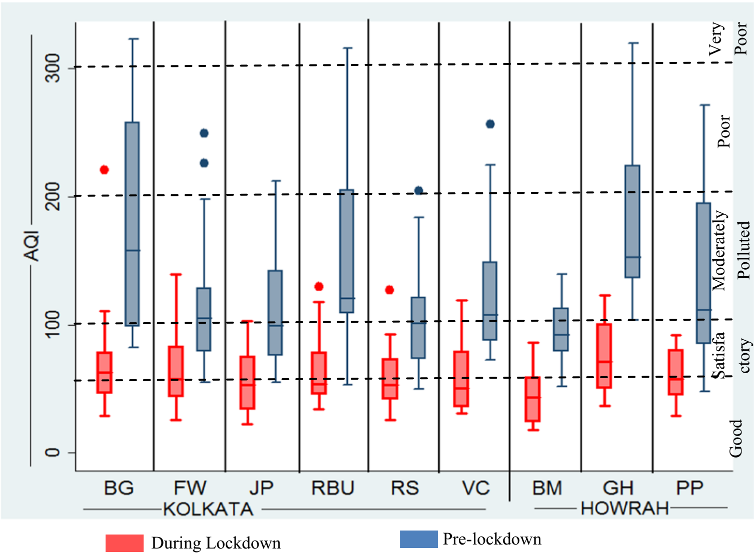

Fig. 3 Box plot comparing AQI distribution for nine monitoring stations between pre-lockdown and during lockdown phase (*BG* Ballygunge, *FW* Fort William, *JP* Jadavpur, *RBU* RabindraBhararti University, *RS* Rabindra Sarovar, *VC* Victoria, *BM* Melur Math, *GH* Ghusuri, *PP* Padmapukur)

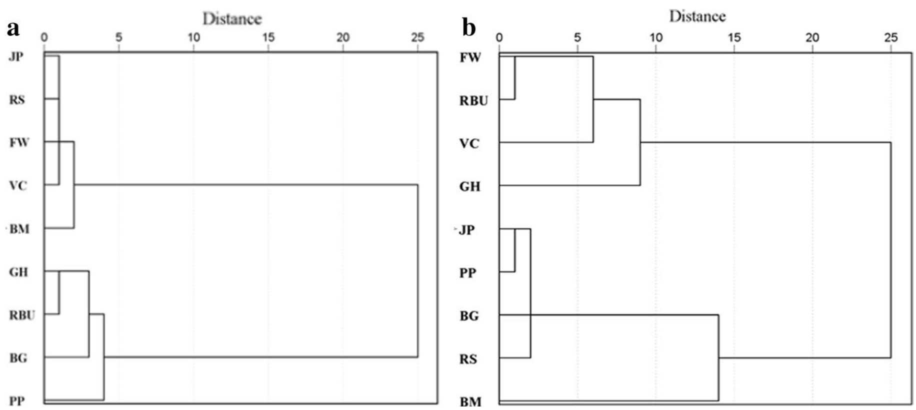

Fig. 4 Cluster analysis of the stations in the **a** pre-lockdown and **b** during lockdown period (*BG* Ballygunge, *FW* Fort William, *JP* Jadavpur, *RBU* RabindraBhararti University, *RS* Rabindra Sarovar, *VC* Victoria, *BM* Melur Math, *GH* Ghusuri, *PP* Padmapukur)

same level of pollution (Fig. 4a). The AQI is similar for these stations RBU, Ghusuri, Ballygunge, and Padmapukur and has made a cluster because Ghusuri and RBU are affected by the nearby Cossipore thermal power station whereas Ballygunge is located among the local small-scale industries in KMC, and Padmapukur is also affected by pollution from small-scale industries in HMC. During the lockdown period, the clustering patterns (Fig. 4b) have changed. Fort William, Rabindra Bharati University, Victoria, and Ghusuri have made a cluster, and the rest of the stations have made the other clusters.

3.3 Spatial distribution of pollutants

The cluster analysis has shown the pattern of clusters of the stations based on the AQI. Spatial variability has been represented in the form of a spatio-temporal map for the pollutants and the AQI from the pre-lockdown phase to during the lockdown phase for few selected days. The variability is represented based on the pollutants for each of the stations. Different factors like vehicular emission are a most important factor for Kolkata and the decennial growth of vehicle is like two wheelers almost 70% followed by four wheelers (20%), three wheeler (10–14%), and bus (8–13%) and the high traffic flow junctions are Park Circus even point junction, B.B.D Bag, Gariahat, Rashbehari, Ballygunge, M.G Road (Chowdhury 2015). Kolkata–Howrah industrial belt is another important source of pollution. Howrah is known for its intense small-scale industries (Upadhyay et al. 2014). The main sites of industrial pollution are Pyarabagan, Garden Reach, Taratala, Mallickbazar, Dhapa, and Cossipore thermal power station (Datta et al. 2016).

$PM_{2.5}$, $PM_{10,}$ and NO_2 are the major pollutants in Kolkata and its adjoining areas (Datta et al. 2016). To avoid the climatic variables in the present study, the maps are used to show how the difference in level of pollution between two consecutive years. In 2019 due to the activity of industries, thermal power stations, vehicular and street shops, etc. the concentration of both $PM_{2.5}$ and PM_{10} which are shown in red colour on the map was very high as in Fig. 5a while in 2020 on the same period the concentration of particulate matters in the atmosphere is considerably much lesser than the previous year (Fig. 5b), due to restricted emission from vehicles, construction sites, and factories during complete lockdown tenure.

24-hour timely averaged map of NO_2 (1/cm^2) from 24 March to 3 May 2019 (Fig. 6a) from the NASA Giovanni and concentration from 24 March to 3 May 2020 (Fig. 6b), the tenure of the complete of lockdown in India is compared. Here a significant reduction has been seen in the NO_2 concentration over Kolkata and Howrah as well as West Bengal as compared to the same phase of the previous year.

To show the spatial variability of pollutants in the pre-lockdown and during the lockdown phase in particularly Kolkata and Howrah Municipal Corporation, 1 March and 13 March during the pre-lockdown span, 24 March, the day when lockdown started, 7 April and 3 May during lockdown, are chosen. The day of Janta Curfew played an important role in bringing down the pollution level in Kolkata and Howrah Municipal Corporation.

$PM_{2.5}$ (Fig. 7) and PM_{10} (Fig. 8) are the two most important pollutants in Kolkata and Howrah (Das et al. 2015). A high concentration of $PM_{2.5}$ is recorded especially near Ghusuri, Howrah (Fig. 7). Another two most important concentration zones can be found near

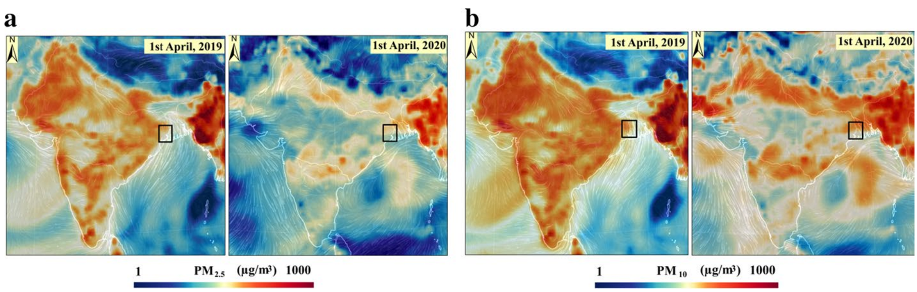

Fig. 5 Change in concentration from 1 April 2019 to 2020 of $PM_{2.5}$ (**a**) and PM_{10} (**b**). (*Source*: https://earth.nullschool.net)

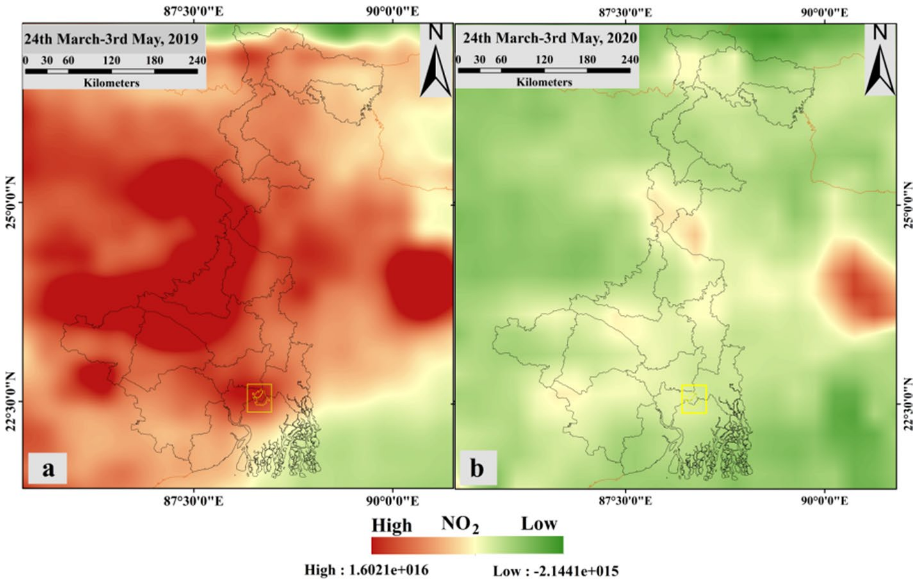

Fig. 6 24-h timely averaged map of NO_2 ($1/cm^2$) from **a** 24 March to 3 May 2019, **b** 24 March to 3 May 2020. (*Source*: NASA Giovanni)

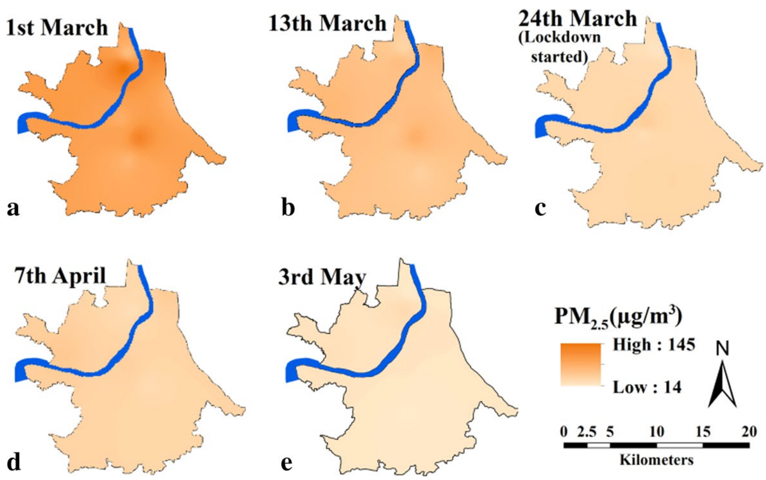

Fig. 7 Spatio-temporal change of $PM_{2.5}$ (2020)

RBU due to its stone-throwing distance to Cossipore power station as the main source of $PM_{2.5}$ and PM_{10} and another is near Ballygunge as this part is surrounded by nearby industrial centres like Mullick Bazar, Picnic Garden, Topsia and Kasba (Das et al. 2015). On 13 March, the reduction in concentration can be noticed only at Ghusuri. On 24 March, the concentration has flattened due to the Janta Curfew on 22 March, shutting down of the industries, reduction in traffic flow, shutting down of street cooking shops, and reduction in power consumption (The Economics Times 2020). On 7 April, a slight increase can be

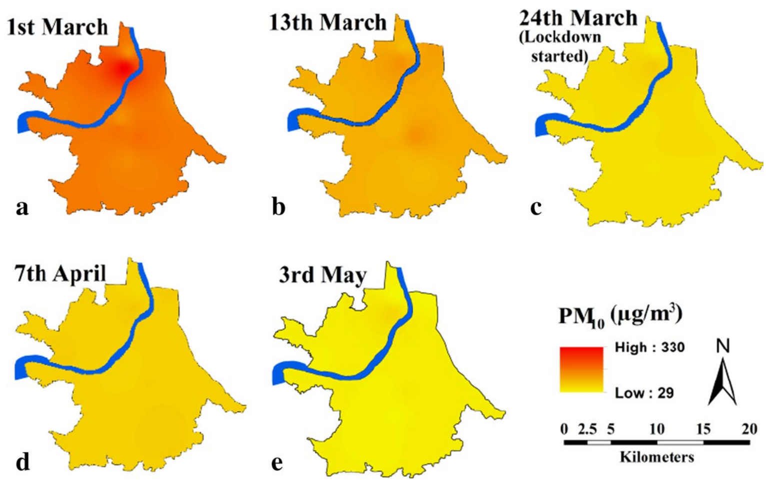

Fig. 8 Spatio-temporal change of PM_{10} (2020)

noted and then again a fall in concentration is reported. Ghusuri recorded medium concentration also during the lockdown period. So this part has a constant emission of $PM_{2.5}$. The pattern of concentration of PM_{10} is the same as $PM_{2.5}$, it may be because of almost the same sources of emission (Ibe et al. 2020).

Major NO_2emitting zones (Fig. 9) are found at Belur Math (97.42 µg/m^3), Rabindra Bharati (59.33 µg/m^3), in the northern part and Fort William (73.25 µg/m^3) and Victoria (79.36 µg/m^3) in the central part on 1 March. The location of Belur Math station in the 'Belur Induatrial Belt' and the association of manufacturing industries are responsible for high NO_2 emission as well as the Belur bus terminus and the Belur Bazar traffic intersection are very important for vehicular emission. Rabindra Bharati University is influenced by Cossipore thermal power station, burning ghats, and important traffic intersections (Karar et al. 2006). Victoria has recorded higher NO_2 concentrations because of the nearby

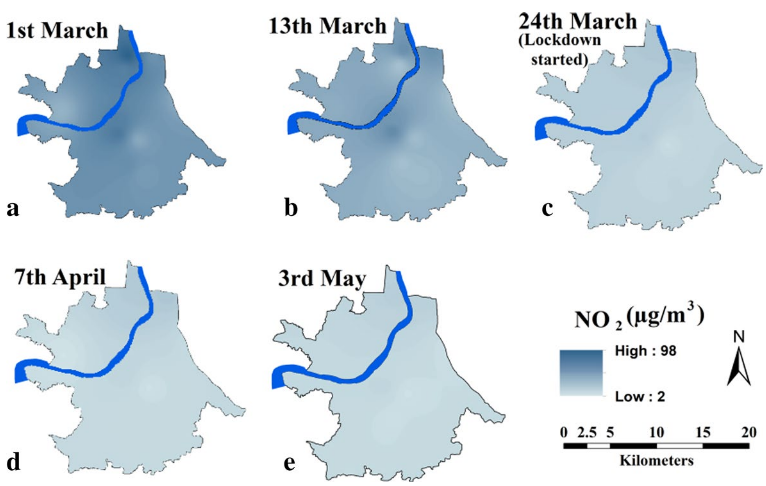

Fig. 9 Spatio-temporal change of NO_2 (2020)

traffic intersections like Khidirpur Road, Acharya Jagadish Chandra Bose Road, Jawaharlal Nehru Road, and Esplanade. Zones of medium concentration are found in the extreme western Kolkata, limited areas of central Kolkata, and the eastern part of Kolkata due to high traffic flow (Gupta et al. 2008). From 13 march before lockdown a slight reduction can be seen (Fig. 9) due to less traffic flow in Kolkata, a moderate concentration is reported. On the day of 24 March when the most important stations like Blur Math and Victoria have recorded very minimum concentration of NO_2 with an amount of 22.85 μg/m^3 and 19.01 μg/m^3, respectively, the concentration was scaled down due to Janta Curfew on 22 March that can be a probable factor, and after 24 March concentration pattern is almost the same for all the stations.

The major concentration of NH_3 (Fig. 10) is identified near RBU (54.01 μg/m^3) and Belur Math (41.47 μg/m^3) on 1 March. The NH_3 concentration at Kosba is high because of animal wastes, livestock, and fertilizer (Carmichael et al. 2003) as a result the concentration at this station is highest during the pre-lockdown period. The concentration has reduced at this part to 8.83 on 3 May, and on the other hand, Rabindra Bharati University (22.52) has recorded a relatively higher amount on that particular day. Dhapa solid waste dumping station in the east margin of Kolkata is responsible for higher NH_3 emission. All the probable sources were active during the pre-lockdown phase but emission started reducing after the Janta Curfew and during the countrywide lockdown.

Small-scale industries in Howrah accelerate pollution level and are responsible for high SO_2 concentration (Fig. 11). The southern part has very minimum emission, but the northern, central, and north-western parts have recorded higher SO_2 emission on 1 March. Concentration is moderately distributed in the northern part near Belur Math, RBU, and Ghusuri but all the parts have a sharp reduction in SO_2 emission on 13 March (Fig. 11). Among the stations, Ghusuri has recorded high SO_2 concentration on 1 March during the pre-lockdown phase with an amount of 67.39 μg/m^3 as this part is highly industrialized, and industries like electronics, plastics, etc. which are considered under the 'red' category by WBPCB, 2018. The second highest concentration has been recorded at Belur Math with an amount of 24.45 μg/m^3 as this particular area is considered as Belur Industrial Belt where manufacturing industries are very important. On 24 March and 7 April, only areas

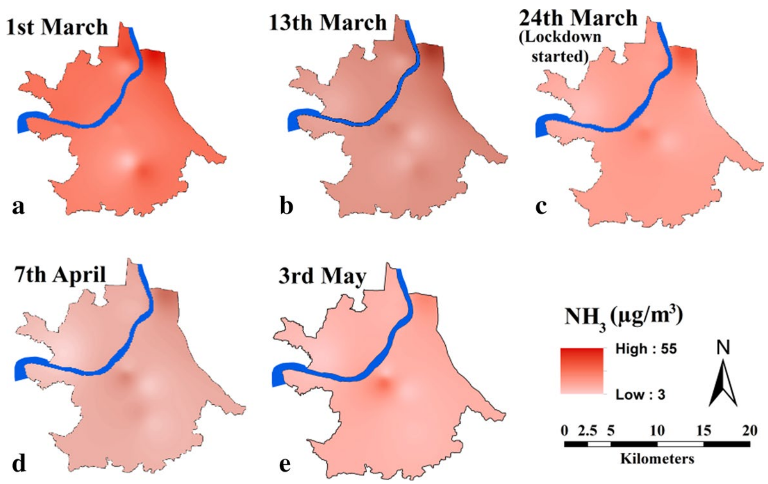

Fig. 10 Spatio-temporal change of NH_3 (2020)

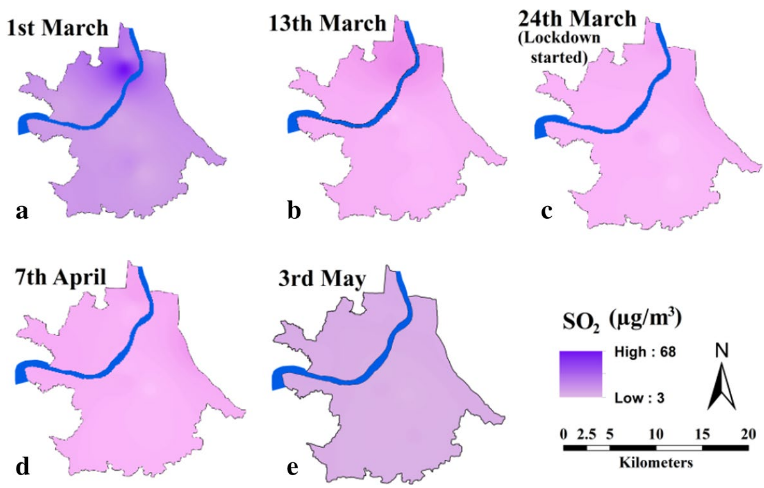

Fig. 11 Spatio-temporal change of SO_2 (2020)

near Belur Math and marginal eastern parts are recorded moderate SO_2 emission and on 3 May, the SO_2 emission has been flattened all over the study area as the most polluted sites noted the very minimum amount of SO_2 concentration with an amount of 6.73 µg/m^3 and 8.36 µg/m^3 at Ghusuri and Belur Math, respectively, due shut down of all the industrial industries.

The concentration of CO is monitored on 8-hrs interval. Medium to high CO concentrations have been observed in KMC and HMC (Fig. 12). Vehicular emission contributes almost 90% of the total CO in the urban atmosphere (Jaffe 2012), and it has been found that the concentration of CO is 1.3–6.8 times higher near the highly intensified vehicle zones than the urban periphery (Brice and Roesler 1966). It has a key role in controlling the oxidation processes of the atmosphere by performing as a sink for a larger fraction of the reactive hydroxyl radicals existing in the lower troposphere. The concentration of the gas

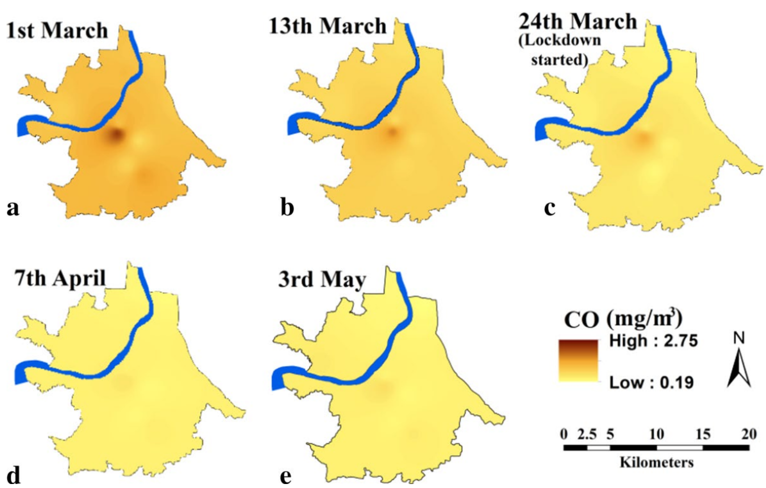

Fig. 12 Spatio-temporal change of CO (2020)

in the urban atmosphere is highly controlled by the pattern of emission and spread of the gasoline by the motor vehicle (Jaffe 2012) and due to high vehicular emission and burning of woods and fossil fuel for cooking in residential areas and street-side shops. During the pre-lockdown period, Victoria with high traffic flow during the office hours, important traffic intersections which are Khidirpur Road, Acharya Jagadish Chandra Bose Road, Jawaharlal Nehru Road and Esplanade traffic intersection result in the highest CO concentration (2.28 mg/m^3) and the lowest concentration has been recorded at Ballygunge (0.72 mg/m^3) on 1 March. CO is released mainly from Kasba, Picnic Garden, Mullick Bazar, and Topsiais which is known for industrial activities that affect the neighbouring stations which are Victoria, FortWilliam, and Ballygunge (Datta et al. 2016). From 24 March, the day of lockdown, a mark reduction in CO concentration is noticed but a centre with relatively higher concentration is found near Victoria where the concentration reduced from 2.28 on 1 March to 0.64 on 3 May and this is the highest concentration among the other stations on that very particular day and later no such considerable changes have been observed.

The spatial pattern of ozone concentration is different from the other pollutants (Fig. 13). Ozone concentration is inversely related to NH_3 (− 0.63) and NO_2 (− 0.15), which is the reason for relatively higher concentration during the pre-lockdown phase and it can also be found from the correlation matrix (Fig. 15). The lowest concentration of O_3 has been recorded at Jadavpur on 1 March (20.15 $\mu g/m^3$), in contrast the NO_2 and NH_3 concentrations are 52.09 $\mu g/m^3$ and 36.33 $\mu g/m^3$, respectively. Here NH_3 concentration is the second highest after Belur Math at Jadavpur supporting the significant inverse relationship between NH_3 and O_3 (− 0.64). Another important station is Ghusuri where the second lowest O_3 concentration has been recorded with 73.19 $\mu g/m^3$ and 18.82 $\mu g/m^3$ amount of NO_2 and NH_3 being recorded. The nearby Cossipore thermal power station near RBU is responsible for higher pollution and is also characterized by a high concentration of $PM_{2.5}$, $PM_{10,}$ and NO_2 as well on 1 March. Only the central Kolkata has recorded a higher O_3 concentration near Victoria (65.76 $\mu g/m^3$) and Rabindra Sarovar (45.00 $\mu g/m^3$). The concentration of O_3 is substantially reduced on 13 March 2020, the day of Janta Curfew because of the partial lockdown of 14 h. On 24 March, the concentration has hiked all over the study area except two centres near RBU and Ballygunge. On 7 April, high concentration is recorded

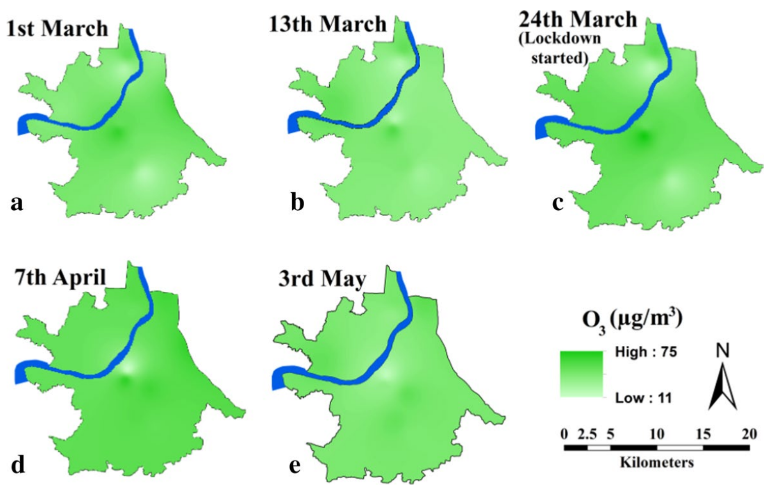

Fig. 13 Spatio-temporal change of O_3 (2020)

again and the areal extent is more than 24 march most importantly the hiking in the concentration in the northern part and Ballygunge adjoined areas because till 24 march, these parts have recorded minimum concentration continuously. After 24 march, the concentration has reduced remarkably and a relatively higher concentration has been recorded on 3 May, the relaxation in the lockdown in KMC and HMC results in this. The role of atmospheric chemistry is important here. The minimum concentration of other pollutants may result in the increase O_3 concentration because hiking of O_3 is caused by lower titration of O_3 by NO due to the minimum emission of NOx from the vehicle (Sicard et al. 2020) and with a decreasing carbonaceous concentration increase the atmospheric visibility that promotes penetration of solar radiation favouring ozone formation (Zhang et al. 2019) that can be understood from the concentration pattern of O_3. The highest concentration of O_3 has been recorded at Rabindra Bharati (53.66 μg/m^3), and very minimum concentration of NO_2 (15.61 μg/m^3) and NH_3 (22.52 μg/m^3) has been noted on 3 May. Particularly, this part of the study area suffers from severe vehicular emission (Chakrabartty and Gupta 2014) but during the lockdown period, the concentration of NO_2 has been remarkably reduced.

AQI has fallen to 25 on 3 May from 325 on 1 march. In the map (Fig. 14), the higher concentration of the pollutants in the atmosphere is responsible for higher AQI and the opposite scenario can be observed during the lockdown period. Ballygunge followed by Ghusuri and Rabindra Bharati has recorded the highest AQI, and it can be noted as 304.31, 302.12, and 300.97 on 1 March during the pre-lockdown time which is considered as the 'poor' air quality and other stations have recoded moderate air quality. On 13 March, the pollution level has reduced half as the news of the COVID-19 spread and awareness started growing and major changes can be noticed on 24 March the day lockdown started just after the 14-h 'Janta Curfew' on 22 March. The levels of pollution have reduced almost six times for Ballygunge from 304.31 to only 50.29, from 302.12 to 78.87 in Ghusuri, and from 300.97 to 65.33 on 24 march as the restriction on human, and vehicular mobility was imposed as well as the effects of the Janta Curfew. Then after, this very little fluctuations can be noted for all the stations. A slight reduction in AQI and can be categorized under 'moderately polluted' on 13 March. On 24 March, air quality is improved to 'good' but a slight degradation can be observed on 7 April and then again the air quality has remarkably

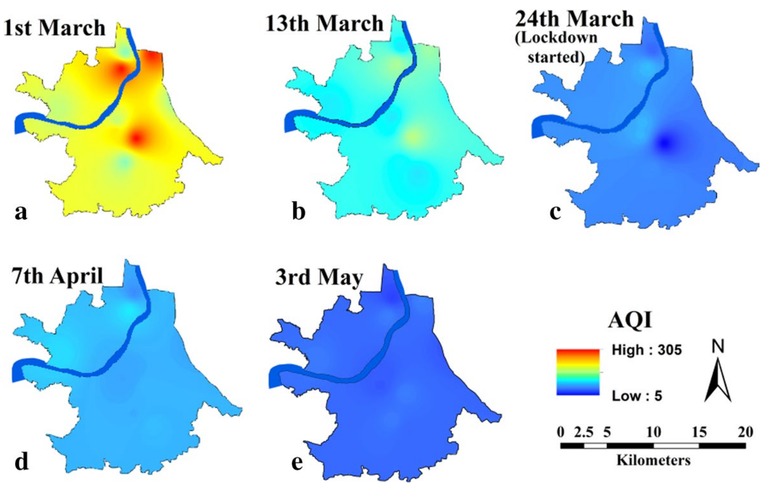

Fig. 14 Spatio-temporal change of AQI (2020)

improved as the highest polluting sites started improving along with the moderately polluted stations like Jadavpur, Rabindra Sarovar, Victoria. On 3 may, the AQIs have been calculated for Ballygunge (51.67), Rabindra Bharati University (53.63), and Ghusri (52.01) and the results are the indication of 'good' air quality in KMC and HMC.

3.4 Co-relationship between the ambient air pollutants

To analyse the association among the pollutants, multiple correlation matrixes are conducted for pre-lockdown and during the lockdown phases (Fig. 15). In the diagram, the monochromatic red colour is showing positive correlations and the blue colour is representing the negative correlations. Different shades are used to show the intensity of relation. On the other hand, scatter plots are also showing the distributional pattern.

$PM_{2.5}$ has a strong significant relationship with PM_{10} ($r=0.99*$), this may be the result of almost the same sources of emission as previously discussed in the pre-lockdown phase, but later during the lockdown phase the correlation is also significant ($r=0.92*$) (Ibe et al. 2020). Due to the reduction in traffic congestion, the lockdown of industrial areas, the emission of these particulates also has reduced. $PM_{2.5}$ is highly associated with CO and NO_2 because the high concentration of both the pollutants is recorded near highly intensified traffic junction and industrial belts. During the lockdown period, the relations among the parameters have drastically changed which can be seen as correlations have taken a new dimension when there is a mark reduction in the concentration of pollutants. Almost the same phenomena can be observed for PM_{10} and these two particulate matters are the major sources of pollution in Kolkata (Das et al. 2015). Significantly moderate correlations have been traced out between NH_3 and NO_2, $PM_{2.5}$, PM_{10}, except these all the relations are insignificant during the pre-lockdown phase. But the correlations have become significant during the lockdown phase. NH_3 has positive significant correlations with $PM_{2.5}$ ($r=0.87*$), PM_{10} ($r=0.80*$), SO_2 ($r=0.79*$), CO ($r=0.85*$) and O_3 ($r=0.73*$).

Sulphur dioxide is the precursor of acid rain as sulphuric acid in reaction with H_2O. Any significant correlation has not been established with SO_2 with other pollutants except a

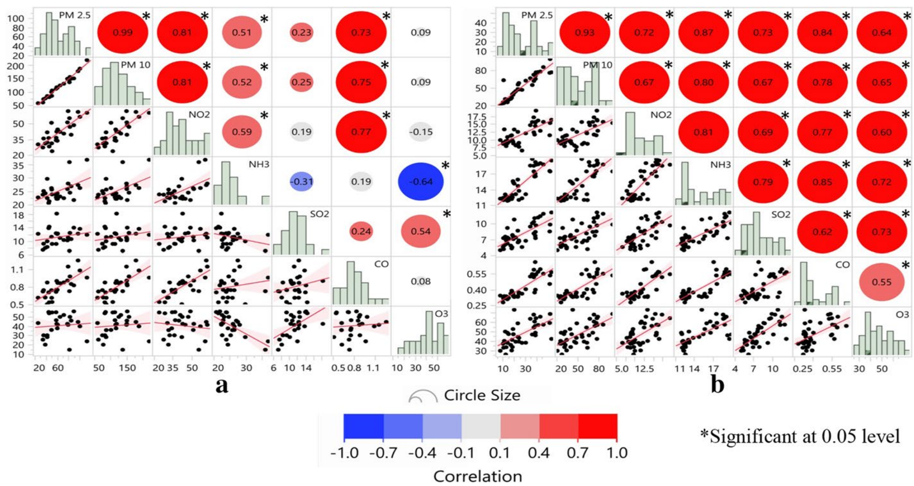

Fig. 15 Correlation among the pollutants during the **a** pre-lockdown and **b** during the lockdown period

significant negative correlation ($r = -0.31$) with NH_3. According to chemists, any chemical reaction is not possible between these two pollutants except water (Guo et al. 2005). But the total scenario of SO_2 has been changed during the lockdown period when there is a dropping down of pollutants concentration that results in the establishment of a significant correlation with $PM_{2.5}$ ($r = 0.73^*$), PM_{10} ($r = 0.67^*$), NH_3 ($r = 0.79^*$), CO ($r = 0.61^*$), and O_3 ($r = 0.73^*$). A moderately significant correlation ($r = 0.54^*$) has been found between SO_2 and ozone. The PL phase is characterized by higher SO2 concentration and relatively less concentration of ozone. Higher SO_2concentration accelerates ozone formation because of its role in the photochemical reaction that produces ozone in combination with NOx, VOC when insolation is higher. During the lockdown phase, a highly significant positive correlation ($r = 0.73^*$) has been found between these two components.

CO is only strongly correlated with $PM_{2.5}$ ($r = 0.73^*$), PM_{10} ($r = 0.75^*$), and NO_2 ($r = 0.77^*$) in the pre-lockdown phase but during the lockdown phase, the relations have also established with other pollutants. The OH radicals which are formed due to chemical reactions in the upper atmosphere are very important in oxidizing (Harteck et al. 1998). CO also reacts with O_3 (Jaffe 2012). The breakdown of ozone produces oxygen and the oxygen reacts with CO in the atmosphere through the reaction is not direct (Zhang et al. 2019).

In the pre-lockdown phase, NH_3 and O_3have a significantly negative correlation ($r = -0.64^*$) where the concentration of both the pollutants was high. Olszyna and Heicklen (1972) showed in an experiment that O_3 is consumed and solid aerosol is formed very rapidly in reaction with NH_3 but it is not reproducible. A high concentration of NH_3 in the pre-lockdown phase and chemical reaction in the atmosphere reduces the amount of Ozone. On the other hand, during the lockdown period the correlation has a significant positive correlation ($r = 0.72^*$) because the reaction is not possible when the amount is not significant (Olszyna and Heicklen 1972).

The processes which are related to the ozone formation are still not revealed so well and are still a challenge and need more studies (Monks et al. 2015). Ozone is also negatively correlated with NO_2 in the urban atmosphere (Palmgren et al. 1996; Pires 2012; Wilby 2008). The photochemical production of ozone in the lower atmosphere (troposphere) is the result of the hydroxyl radical oxidation of carbon monoxide, methane, and non-methane hydrocarbons in the occurrence of nitrogen dioxide (Monks et al. 2015). In brief, ozone is produced depends mainly on the photolysis of nitrogen dioxide and the association of the photoproduct with O_2 via a reaction (Monks et al. 2015; Pires 2012).

The reactions between these two components result in the degeneration and regeneration of ozone (Pires 2012). The high incursion of NO_2 from the vehicle and industrial areas degrade ozone in the atmosphere by chemical reactions (Cox 2003). NO_2 is broken down into NO that reacts with O_3 in the presence of UV, then again NO reacts with O_3 and NO_2 and O_2 are the outcomes (Ebi and McGregor 2008). Colbeck and Harrison (1982) explained the relationship "If formaldehyde is photolysed, then

$$CH_2O + hv \rightarrow CHO_4 + H \quad (\lambda < 370\,\text{nm})$$

$$CHO + O_2 \rightarrow HO_2 + CO$$

$$HO_2 + NO \rightarrow NO_2 + OH$$

$$NO_2 + hv^- \rightarrow NO + O(3P) \quad (\lambda < 420\,\text{nm})$$

$$NO + O_3 = NO_2 + O_2$$

The whole process continues all the time. This phenomenon is normal during the weekdays but during weekends NO_2 concentration is reduced and O_3 is increased in the urban atmosphere (Atkinson-Palombo et al. 2006); the lockdown has affected the emission in the same manner and to some extent more than that. A study by Cox (2003) showed that the area of ozone depletion is highly associated with NO_2 emitting areas. From Fig. 15, it can be noticed that the NO_2 and the O_3 had a negative correlation in the pre-lockdown phase but later the relation has turned into a positive correlation because of the amount if NO_2 is not considered for the reaction in the lower atmosphere, less amount of NO_2 does not affect too much to the concentration of O_3 (Pires 2012). In the lower atmosphere, particulate matters also act like sink so $PM_{2.5}$ and PM_{10} concentration result in reducing the sink of hydroperoxy radicals and boosting the ozone concentration (Li et al. 2019).

3.5 Analysis of variance (ANOVA)

ANOVA two-way has been used to understand the variance of means of air quality index AQI for all the stations (9) of both Kolkata and Howrah (Table 4). AQI is considered as the dependent variable and the period of pre-lockdown and during lockdown as the independent variables. After performing ANOVA two-way, it has been found that period (from pre-lockdown to during lockdown phase) has a very important role in reducing AQI, $F(1,611) = 465.723$, $p < 0.0001$ is a highly significant factor for the changing AQI. In changing AQI, the time has a 43.9% impact along with the stations having a 16.3% impact. If the time is constant, then the station is also significant and the interaction effect is significant at 0.0001 level with $F(8,611) = 14.440$, $p < 0.0001$. The effect of interaction on the AQI is also found significant $F(8,611) = 6.045$, $p < 0.0001$. Table 4 shows the pairwise comparisons within the station of AQI from the pre-lockdown phase to during the lockdown phase, and the mean difference within the station is highly significant with $p < 0.0001$ of all the stations. Station Ballygunge, Kolkata, recorded the highest mean of 108.194 at $p < 0.0001$ significant level between before lockdown and during the lockdown period, and on the other hand, Rabindra Sarovar, Kolkata, recorded a minimum mean difference of 45.735 with a significant level $p < 0.0001$. The estimated mean differences of AQI between the lockdown period and the pre-lockdown period are considered for all the stations (Fig. 16). The air quality was 'poor' at Ballygunge, Rabindra Bharati University, and Ghusuri, but the air quality has remarkably improved in the lockdown period.

Table 4 Two-way ANOVA test for AQI based on stations and time. (*Source*: Computed by author)

Source	Sum of squares	Degree of freedom	Mean squares	*F* values
Time	779,793.621	1	779,793.621	465.723**
Station	193,417.517	8	24,177.190	14.440**
Time * Station	80,973.525	8	10,121.691	6.045**
Error	994,577.145	594	1674.372	
Total	6,860,202.710	612		

**'*F*' significant at $p < 0.01$

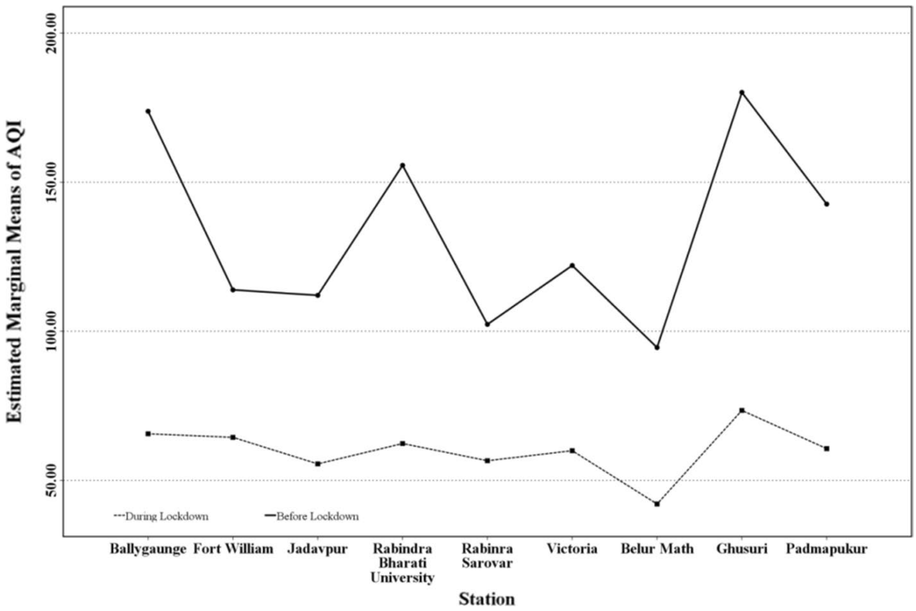

Fig. 16 Mean difference of each station between the pre-lockdown and during lockdown

4 Conclusion

The study has been yielded with a significant outcome that the lockdown has remarkably reduced the pollution level and air quality has improved from the 'poor' category to the 'good' category from the pre-lockdown period to during the lockdown period in KMC and HMC. $PM_{2.5}$ and PM_{10} are responsible for pollution in KMC and HMC though the below-permissible-level concentration of NO_2 has been recorded in both the municipal corporations, it is a very important pollutant and has reduced specifically during the lockdown. In the northern part of KMC near RBU due to the continuation of thermal power production, the pollution level is relatively higher and the other two important centres, Ghusuri and Ballygunge, are worst affected by small-scale industries and after the lockdown, the pollution level has flattened. The relationships among the pollutants have also transformed with the changing magnitude of the pollutants as during the pre-lockdown phase, the some significant and some insignificant relationships have been found but during the lockdown phase, all the relationships have become very significant. Most interestingly, the concentration of O_3 increased after the imposition lockdown as it is related inversely with NH_3 and NO_2.

The major pollutants are $PM_{2.5}$, $PM_{10,}$ and NO_2 and have markedly condensed from pre-lockdown to during the lockdown period. The Cossipore thermal power station, small-scale industrial hubs, and traffic are the main sources of pollution, but the imposition of lockdown all over the country has resulted in a quick fall in the concentration of pollutants. Implementations of lockdown at this temporal and regional scale are not possible, but the situation has proved that the recovery of the environment is very rapid when human interventions are very less.

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Author contributions Mohan Sarkar contributed to conceptualization, methodology, software, formal analysis, visualization, and writing-original draft. Anupam Das contributed to conceptualization, methodology, investigation, validation, data curation, visualization, writing-review, and editing. Sutapa Mukhopadhyay contributed to visualization, writing-review and editing, and supervision.

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Availability of data Data are collected from CPCB online portal for pollutants (https://app.cpcbccr.com/ccr/#/caaqm-dashboard-all/caaqm-landing) and images of NO_2 are downloaded from NASA GIOVANNI (https://giovanni.gsfc.nasa.gov/giovanni/) to compare the change and also from Earth nullschool (https://earth.nullschool.net/)to compare the yearly variability in the concentration of $PM_{2.5}$ and $PM_{10.}$

Code availability MS office 2007, STATA 12, JMP 15, IBM SPSS version 23, ArcGIS 10.3.

Compliance with ethical standards

Conflict of interest Authors have no conflict of interest.

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