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Short-term exposure to ambient air quality of the most polluted Indian cities due to lockdown amid SARS-CoV-2

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ABSTRACT

Air pollution has happened to be one of the mounting alarms to be concerned with in many Indian cities. COVID-19 epidemic endow with a unique opportunity to report the degree of air quality improvement due to the nationwide lockdown in 10 most polluted cities across the country. National Air Quality Index (NAQI) based on continuous monitoring records of seven criteria pollutants (i.e. common air pollutants with known health impacts e.g. PM_{10}, $PM_{2.5}$, CO, NO_2, SO_2, NH_3 and O_3) for a total of 59 stations across the cities, satellite image derived Aerosol Optical Depth (AOD) and few statistical tools are employed to derive the outcomes. NAQI results convey that 8 cities out of the 10 air quality restored to good to satisfactory category during the lockdown period. Within week + 1 of the lockdown period, PM_{10} and $PM_{2.5}$ concentrations have suppressed below the permissible limit in all cities. CO and NO_2 have reduced to about −30% and −57% respectively during the lockdown period. Diurnal concentrations of PM_{10} and $PM_{2.5}$ have dropped drastically on the very 4th day of lockdown and become consistent with minor hourly vacillation. In April 2020 the AOD amount was reduced to about 36% and 18% in contrast to April 2018 and April 2019 respectively. This add-on reporting of the possible recovery extent in air quality may help to guide alternative policy intervention in form of short term lockdown so as to testify whether this type of unconventional policy decisions may be put forward to attain a green environment. Because, despite numerous restoration plans, air pollution levels have risen unabated in these cities. However, detailed inventory needs to be focused on identifying the localized pollution hotspots (i.e. source contribution).

1. Introduction

In many Indian cities air quality is one of the intimidating issues to be concerned with and often has been counted within the world's top polluted city (Kota et al., 2018; Mukherjee and Agrawal, 2018; Garaga et al., 2018). Out of the world's top 20 most polluted cities during 2019, 14 are located in India (IQAir, 2019). Greenpeace India (2020) identified 231 Indian cities (> 80%) having concentration of PM_{10} beyond 60 $\mu g/m^3$ (Permissible limit is 50$\mu g/m^3$m as per WHO (2006). The Airpocalypse-Report IV (Greenpeace India, 2020) of the Central Pollution Control Board (CPCB) has included 102 non-attainment cities under the National Clean Air Programme (NCAP) that have exceeded the Indian National (ambient) Air Quality Standards (INAQS). There are however another 116 cities/towns that qualify the non-attainment cities list criteria but excluded in the report submitted by the Ministry of Forest, Environment and Climate Change (MoEF&CC) under NCAP and CPCB to the National Green Tribunal (Greenpeace India, 2020). The NCAP operated under the MoFE&CC has targeted to reduce air pollution level by 20–30% by 2024 from 2017 levels. However, most of the current literature related to pollution focuses primarily on Tier 1 cities (Guttikundaa et al., 2019). Yet there is little attempt to unveil the air pollution scenario for the most polluted urban centers. Therefore in order to remedy this vacuum information thorough appraisal of the level of air pollution in the pollution hotspot cities across the country needs to be evaluated afresh.

The COVID-19 infection caused by Novel Coronavirus SARS-CoV-2 which at the outset was detected in Wuhan (Central China) in late December 2019 (WHO, 2020a) and stated as a global endemic by World Health Organization (WHO) on march 11 (WHO, 2020b). To cope up with the threat of mass transmission in many parts of the world lockdown measures were primed restricting human activities, reducing public transport and closing industries. In India The first lockdown (for 14 h) across the country was imposed on 22nd March which afterward followed by two consecutive lockdowns first from 24th March to 13th

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April and second from 14th April to 3rd May. This extraordinary state of affairs arising out of COVID-19 over the last few months across the globe has led to several unforeseen consequences (Harapan et al., 2020) and restoration of environmental health (Gautam and Trivedi, 2020; Dutheil et al., 2020) due to imposed restriction on human activities is the most obvious one. Consequently the global concerns for air pollution had escorted momentous attention to the scientific community to examine the level of pollution amid this epidemic.

SARS-CoV-2 brought significant health threat particularly for the people having respiratory disorders (Halpin et al., 2020; CDC COVID-19 Response Team, 2020). Study of Coccia (2020) showed that the accelerated diffusion of COVID-19 is to some extent associated with higher air pollution levels in the 55 north Italy province capitals. However, the study of Bontempi (2020) suggests that the role of airborne particulate matter (PM) for the virus diffusion is not evident in the case of Lombardy (Italy). Therefore, it is not possible to demonstrate that PM can be a virus carrier. In third world countries air pollution is the leading cause for premature death and disease load globally (Burnett et al., 2014; Cohen et al., 2017; Landrigan et al., 2018; State of Global Air, 2019). About 3.7 million deaths are ascribed to outdoor air pollution globally of which 88% are in the low-medium income countries during 2012 (WHO, 2014) whereas, the death count is about one million people in 2015 in India (Guo et al., 2017). In this country one out of every 8 deaths is allied to air pollution and is the second major contributor for disease burden after malnutrition (ICMR, PHFI & ICMR, PHFI, IHME, 2017). Despite numerous policy measures taken from time to time air pollution levels have risen unabated in many cities across the county. The joint venture of the Council on Energy, Environment and Water (CEEW) and the International Institute for Applied Systems Analysis (IIASA) revealed that regardless of the pollution control measures, poor air quality will likely to threat as much as 674 million people across the country by 2030 (Purohit et al., 2019). However, the lockdown measures amid the epidemic escort environmental restoration simultaneously and the consequential environmental health benefits may reduce the disease burden in future we presume.

There are several methods for calculating air pollution incorporating major pollutants among which Air Quality Index (AQI) or Air Pollution Index (API) (Shenfeld, 1970; Thom and Ott, 1975; Ott and Thorn, 1976; Murena, 2004) or Pollutant Standards Index (PSI) (Ott and Hunt, 1976; USEPA, 1994) are prevalent. Though, there is no single well established scheme that eventually fit for all conditions (Stieb et al., 2005). In India, to facilitate real-time monitoring of air quality across the country (https://app.cpcbccr.com/AQI_India/) in more scientific and robust way the first ever National Air Quality Index (NAQI) has introduced on April 2015 (CPCB, 2015) with a new scheme of Indian National (Ambient) Air Quality Standards (INAQS) (http://www.cpcb.nic.in). The NAQI with less eclipsing and ambiguity is comparable to other available indices and therefore in the present article we have employed NAQI in order to examine air quality of the pollution hotspot cities. Apart from merely calculating air quality from continuous monitoring of common air pollutants with known health impacts (often called 'criteria pollutants') in the present inventory we have also used Aerosol Optical Depth (AOD) from the NASA Earth Observations (NEO) in order to detect the temporal changes in aerosol concentration based on optical properties of gases and aerosols during the lockdown period for the cities across the country.

In course of the COVID-19 pandemic during lockdown episode ceasing of manufacturing and transportation activity resulted declination of fuel demand worldwide (Muhammad et al., 2020). This has resulted in a drastic drop in the global carbon emission (Wang and Su, 2020; Saadat et al., 2020), Greenhouse Gases release and concentration of pollutants (NASA, 2020). In many parts of the world air quality is reported to improve significantly (Cadotte, 2020; Watts and Kommenda, 2020; Lauri, 2020; Shrestha et al., 2020; Venter et al., 2020; IQAir, 2020 etc.). Up to date there are several other studies all through the world (viz. Dantas et al., 2020; Nakada and Urban, 2020; Isaifan, 2020; He et al., 2020; Zhu et al., 2020; Huang et al., 2020; Wang et al., 2020; Bashir et al., 2020; Tobías et al., 2020; Yousefi et al., 2020 etc.). Most of these studies however have considered only one or in a few cases a few criteria pollutants or in certain cases remote sensing for appraisal of air quality for this rare window episode. Continuously monitored multi-pollutant data coupled with remote sensing may however be able to reveal the situation more precisely. Moreover, India's cities are the leading hubs of air pollution of global concern and worlds' air quality reports (IQAir, 2018; IQAir, 2019) repeatedly ranked Indian cities among the most polluted lists. Hence, re-reading air pollution for millions plus cities, urban agglomerations, industrial clusters across the country amid the current lockdown period must be an issue of interest to the scientific community. Although, attempts to report air quality for India cities during the lockdown in the course of SARS-CoV-2 pandemic is very limited. Until recently there have been a few efforts in this regard (viz. Sharma et al., 2020; Chauhan and Singh, 2020; Shrestha et al., 2020) and have paid more attention to few of the Tier-1 cities (megacities or million plus cities) (Mahato et al., 2020; Kambalagere, 2020; Srivastava et al., 2020). As air pollution has reported to be a growing nationwide problem (Green peace India, 2017) therefore it needs to be addressed with utmost earnestness across the most polluted Indian cities. In view of this dearth of study the present article will therefore systematically report air quality during the lockdown period for 10 most polluted urban centers (Table 1) which are well accredited for their worst air pollution level ($PM_{2.5}$) in the 2019 World Air Quality Report (IQAir, 2019). The ensuing partial operational status of most industries across the country would likely diminish the air pollution level as a result. However, to what extent the improvement of air quality actually holds true needs more in-depth investigation. To achieve this, a combination of measured parameters and geospatial techniques has been employed. The objectives are (i) to reveal the reduction in the level of key pollutants' concentration during the nationwide lockdown period in contrast to the past-lockdown period with the aid of statistical measures, and (iii) to report the rejuvenation of air quality during the consecutive lockdown periods based on geoinformatics. The study primarily intended to present an insight into the likely improvement of air quality when there are noteworthy restrictions on emissions sources. The baseline information presented herein provides insights into the air quality enhancement obtainable by short-term periodic suspension of polluting industrial activities as well as transportation and will hopefully supplement necessary startups to the academicians, policy makers and citizens to chart out healthier policies so as to manage air pollution.

2. Materials and methods

2.1. Sample cities intended for air pollution study

The present article has focused on 10 most polluted urban centers in India out of the 20 most polluted cities globally (IQAir, 2019) (Fig. 1). The list includes the megacity Delhi with 10 million plus population; 2 cities (Ghaziabad and Faridabad) with population more than 1 million; 2 cities (Gurugram and Noida) with population above 6 lakh and 5 cities (Muzaffarnagar; Bulandshahr; Greater Noida; Jind and Bhiwadi) having population 1 lakh and above (Table 1). All of the cities are located in the Indo-Gangetic plain region (northern counterpart) and considered as the most polluted region in India (Fig. 2). However, there are four more urban centers listed within in the in the 2019 World Air Quality Report (IQAir, 2019) namely Bandhwari (Rank 10; one of the major landfills in north India located in an ecologically sensitive Aravalli forest area), Lucknow (Rank 11; Capital city of the Indian state of Uttar Pradesh); Baghpat (Rank 15; part of the national capital region located in Uttar Pradesh) and Coraut (Rank 19; located in Varanasi Tehsil of Varanasi district in Uttar Pradesh). These four are excluded

Table 1
Concise particulars of the 10 most polluted urban centers in India.

Sl. No.	Name of the city	Location appraisal	IQAir ranking 2019 ($PM_{2.5}$ concentration in µg/m^3)	Population as per 2011 census [Rank]	Pollution Index by City (2019) Mid-Year [Rank]	No of Continuous Monitoring Stations
1	**Ghaziabad**	A city in the Indian state of Uttar Pradesh (UP), Part of the National capital region (NCR)	1 (110.2)	1648643 [21]	94.46 [7]	3
2	**Delhi**	A Megacity, Officially the National Capital Territory of Delhi (NCT),	5 (98.6)	11007835 [2]	91.41 [16]	38
3	**Noida**	Planned city in the Indian state of UP, Part of NCR	6 (97.7)	642381 [70]	93.01 [10]	4
4	**Gurugram (Gurgaon)**	A city in the Indian state of Haryana, Part of NCR	7 (93.1)	876824 [55]	90.24 [22]	4
5	**Greater Noida**	A census Town city in the Indian state of UP, part of the NCR	9 (91.3)	102054	93.01 [10]	2
6	**Bulandshahr**	A city in Bulandshahr district in the Indian state of UP, Part of NCR	13 (89.4)	222519 [205]	–	1
7	**Muzaffarnagar**	A city under Muzaffarnagar Urban Metropolitan Region in the Indian state of UP	14 (89.1)	392451 [117]	–	1
8	**Jind**	An oldest city in the Indian state of Haryana.	17 (85.4)	167592	–	1
9	**Faridabad**	A city in the Indian state of Haryana, Part of NCR	18 (85)	1414050 [25]	95.58 [5]	4
10	**Bhiwadi**	A city of Alwar district in the Indian state of Rajasthan	20 (83.4)	104921	–	1

Source: Compiled from Numbeo (2019), IQAir 2019; Census (2011).

from the present analysis because of the fact that, daily continuous air quality monitoring data for all the criteria pollutants, particularly for the study period are not available for those cities.

All the sample cities are located within the National Capital Region (NCR) which is considered as the largest urban agglomeration in India with a decadal growth rate of > 20%. The geographical extension of the NCR within which the cities are located is 27.60°N to 29.30°N latitude and 76.20°E to 78.40°E longitude with a total of twenty three districts (Hazarika et al., 2019). Physiographicaly the NCR region belongs to the Indo-Gangetic alluvial plain and sandwiched between two states-Haryana and Uttar Pradesh. The average density of the cities are > 6000 persons/sq. km in 2011 and a significant portion of population in the region reside in urban areas (about 60%) which is much higher than the national average. All the sample cities experience semi-arid climate having five major seasons: Summer (Mar–May), Monsoon (Jun–Sept), short Post-monsoon (Oct–Nov), Winter (Dec–Feb) and Pre-monsoon (March–May). Temperatures stuck between 4 °C and 10 °C in winter and 42 °C to 48 °C in summer (Kumar et al., 2017). Average air temperature during the month of March, 2020 and April, 2020 counts 294.35 K (SD: 10.44) and 299.06 K (SD: 10.47) respectively (Fig. 1b and c). Whereas there is no significant variation in the average wind speed during the month of March and April (Max: 7.27 m/s, Min: 1.27 m/2, Avg.: 4.08 m/s; SD: 0.9) this year (Fig. 1d & e). More than 80% of the total annual precipitation occurs during the monsoon months (Perrino et al., 2011). Currently there are a total of 59 ambient air quality monitoring stations across the sample cities (Table 1) all having capacity to monitor and record pollutants.

As far as the selection of the urban areas is concerned, the IQAir regularly publishes air quality reports (IQAir, 2018; IQAir, 2019) every year for regions and cities across the globe based on the concentration of $PM_{2.5}$. $PM_{2.5}$ is the prevailing pollutant across the cities of India having its source primarily from traffic, power and automated industry and dust (Guo et al. 2017, 2019). Higher concentration of $PM_{2.5}$ is also the leading cause of human respiratory problem (Xing et al., 2016; Li et al., 2018; Hopke et al., 2019). COVID-19 is more likely to infect people having respiratory diseases (Chen et al., 2020) and also found to have accelerated spread over the region having higher pollution (Coccia, 2020). Therefore selection of urban areas having more concentration of $PM_{2.5}$ pollutants is logical one.

2.2. Data sources

In order to investigate the spatial and temporal scenario of air pollution for 10 most polluted cities across the country during the four week lockdown period (21st March to 20th April) amid COVID-19 daily or hourly concentrations of different criteria pollutants are taken into consideration. Data for a total of eight criteria pollutants namely Particulate Matters ($PM_{2.5}$ and PM_{10}), Sulphur Dioxide (SO_2), Nitrogen Dioxide (NO_2), Carbon Monoxide (CO), Ozone (O_3), Ammonia (NH_3) and Nitrogen monoxide (NO) are obtained from the CPCB online web portal of air quality data (https://app.cpcbccr.com/AQI_India/). The data can be used rigorously as the CPCB strictly maintains data quality assurance through its Quality Assurance/Quality Control (QA/QC) programme. Moreover, MERRA-2 (Modern Era Retrospective-Analysis for Research and Applications, Version 2) Aerosol Optical Depth (AOD) data (https://giovanni.gsfc.nasa.gov/giovanni/) has been utilized in this study to show the variation in aerosol concentration in the month of March and April this year from the previous two year.

2.3. Methods employed and analysis procedure

In order to understand the overall improvement in air quality during the lockdown period in comparison to the pre-lockdown period and proceeding years the National Air Quality Index (NAQI) introduced by CPCB (2015) has been utilized. The CPCB also prescribed the Indian National (Ambient) Air Quality Standards (INAQS) for each of the pollutants and are highlighted in Appendix 1.

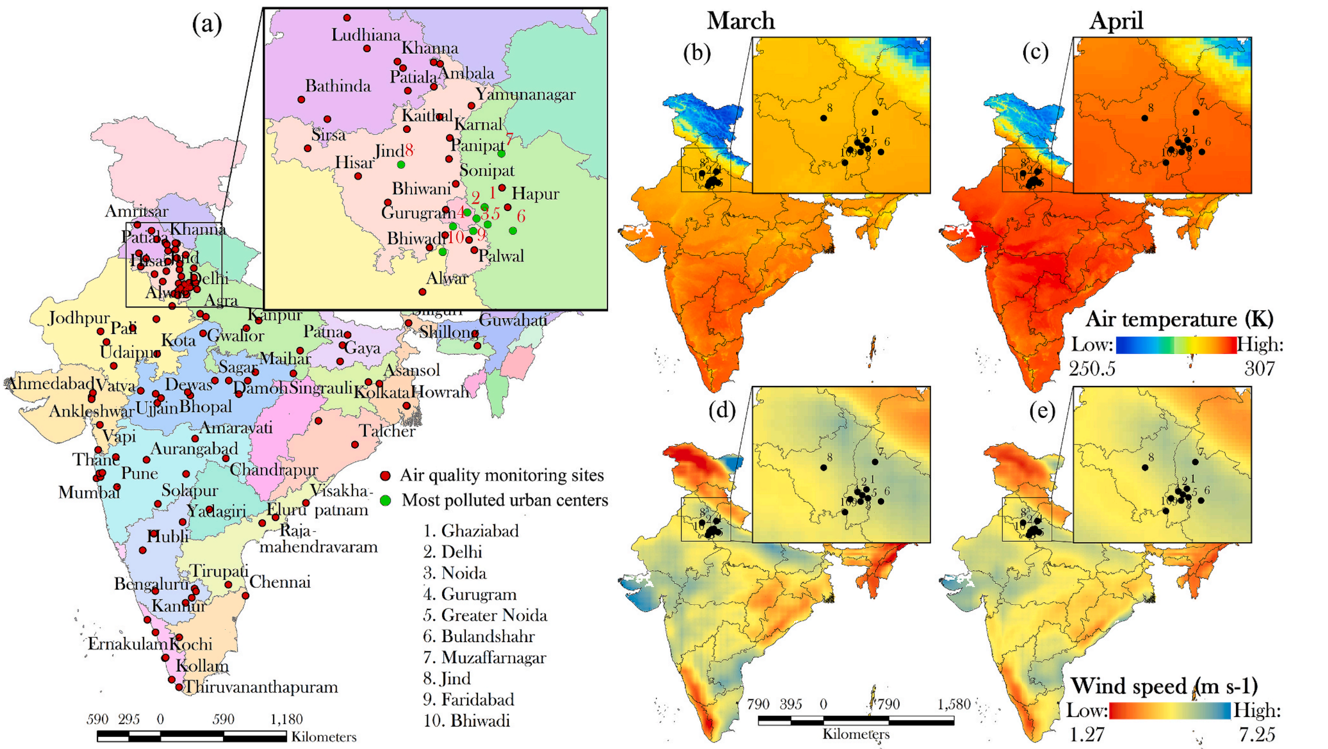

Fig. 1. Reference map of the study area showing (a) the 10 most polluted urban centers selected for the present study (inset) and the air quality monitoring stations across India; average air temperature for the month of (b) March; & (c) April; and Average wind speed for the month of (e) March; & (f) April. ***Note:*** The average air temperature and wind speed shown on the map are derived from FLDAS Noah Land Surface Model L4 Global Monthly 0.1 × 0.1° (MERRA-2 and CHIRPS).

The newly framed, NAQI was launched by CPCB in October 2014 in order to broadcast air quality to the common public in a lucid way. The detailed calculation procedure of NAQI is available at the National Air Quality Index - India Environment Portal (www.indiaenvironmentportal.org.in CPCB, 2015). The CPCB has also developed an excel template for calculation of the same and is available at http://www.arthapedia.in/docs/AQI-Calculator-aug15.xls. In the present article we will highlight the method very briefly.

The calculation of NAQI is based on data of eight criteria pollutants (namely PM_{10}, $PM_{2.5}$, SO_2, NO_2, CO, O_3, Pb and NH_3) of which data for at least three pollutants is desirable including one being either PM_{10} or/and $PM_{2.5}$. In the present article, we have excluded Pb because of the fact that the data for Pb is rarely available for all the sample stations used in the study. Based on different ambient concentrations range of each of the criteria pollutants corresponding health break points are specified (Appendix 2). Predominantly two steps are involved in NAQI calculation- Formulation of sub-indices for each criteria pollutant and aggregation of the sub-indices to obtain the NAQI.

For each pollutant ($_i$) the sub index ($NAQI_i$) is calculated as (Equation (1))-

$$NAQI_i = \frac{IN_{HI} - IN_{LO}}{B_{HI} - B_{LO}} X\ (C_i - B_{LO}) + IN_{LO} \quad (1)$$

where, Ci implies concentration of pollutant 'i'; B_{HI} and B_{LO} are breakpoint concentrations greater and smaller to Ci; IN_{HI} and IN_{LO} are corresponding NAQI values.

The overall NAQI is the maximum NAQIi, and the corresponding pollutant is the predominant pollutant. The NAQI has six classes of air quality where each category is associated with certain health impacts specified in Appendix 2.

The MERRA-2 is a NASA atmospheric reanalysis data released by the NASA Global Modeling and Assimilation Office (GMAO) that was launched in 2017 (Randles et al., 2017) replacing the original MERRA of 1980 (Rienecker et al., 2011). The MEERA-2 uses the data assimilation system of the upgraded version of Goddard Earth-observing System Model, Version-5 (GEOS-5) (Randles et al., 2017). In the present analysis the Aerosol optical depth (AOD) products from MERRA-2 are evaluated using available independent ground-based in situ and remote sensing products. MERRA-2 AOD has 8 instantaneous values a day that the 8 instantaneous values are taken every 3 h (from 00:00 to 21:00 UTC). In the present case MERRA-2 instantaneous AOD at 06:00 (UTC- Coordinated Universal Time) were chosen as it corresponds to 11:30am (Indian Standard Time (IST). The MERRA-2 AOD for the month of March and April from 2018 to 2020 is used to analyze the variation during the 2 months as well as comparison with the preceding two years.

3. Results analysis

3.1. National Air Quality Index (NAQI) at the 10 most polluted cities prior to and during the lockdown

In the present slot we have considered 6 week window period-two weeks before (10th of March to 23rd of March) the commencement of lockdown (i.e. 24th of March); during the three week 1st phase full-fledge lock down (24th of March to 13th of April) as well as 1st week of the 2nd phase partial lockdown (14th of April to 20th of April). Fig. 2 highlights the air quality standard as revealed by the NAQI in different weeks belonging to the pre-lockdown, first phase lockdown and partial lockdown stage. In compassion to the other cities across India (Fig. 2a and b), the 10 selected cities show worse condition of air quality particularly in comparison to the south Indian and coastal cities. In south India strong wind and in coastal cities the land-sea breeze disperses a large amount of the emissions coming out of the industries, vehicles and ports. The sampled cities of the NCR region are landlocked with higher degree of convective activity during pre-monsoon months (Tiwari et al., 2015) and hence higher concentration of ambient air pollutants leading to added NAQI.

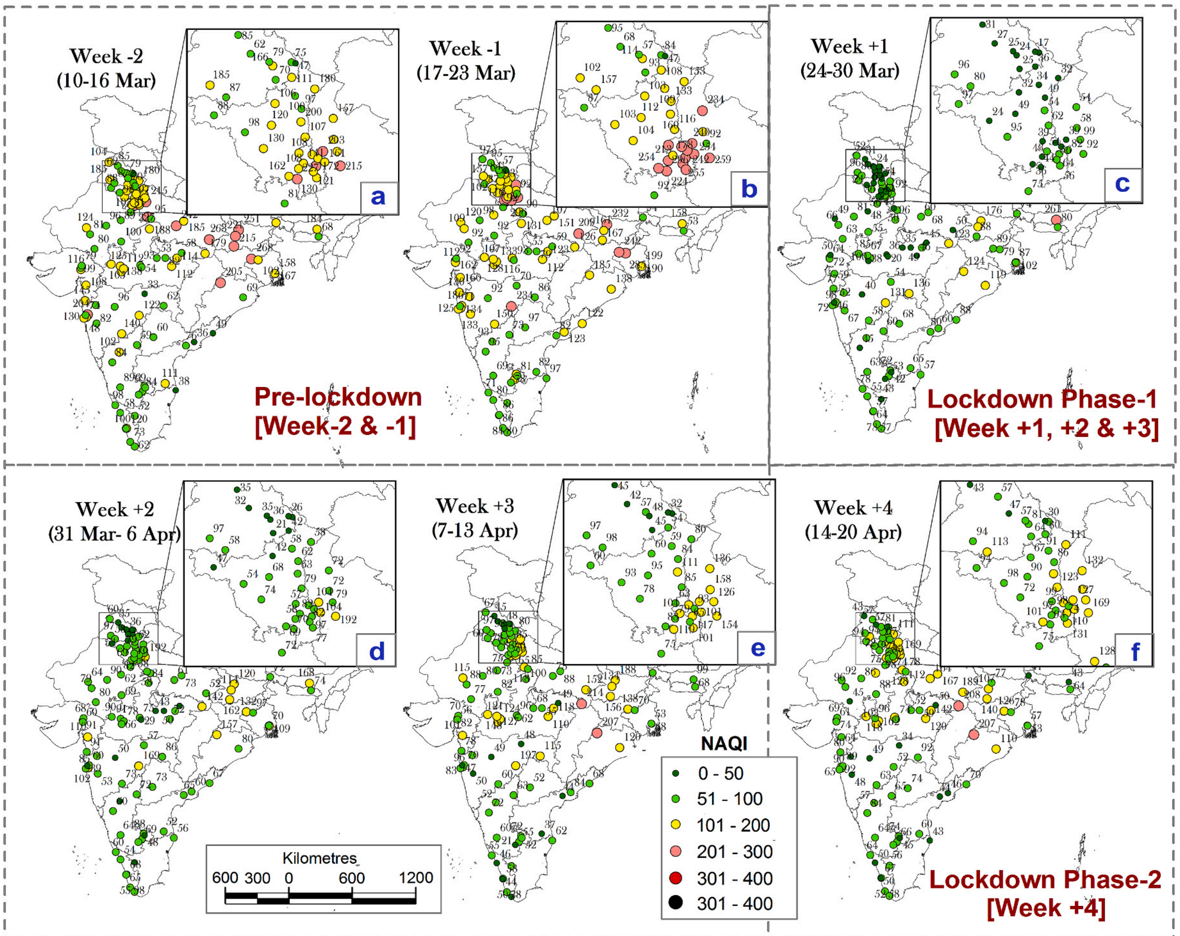

Fig. 2. The state of air quality as revealed by the National Air Quality Index (NAQI) in different cities across India throughout the pre-lockdown and lockdown weeks. ***Note:*** 10 most polluted urban centers are shown in the inset.

Table 2
Deviation in air quality (NAQI) between the pre-lockdown, first phase lockdown and second phase lockdown periods at the 10 most polluted urban centers of India.

Cities/Phase	Pre-lockdown (PLD)		PLD avg.	During 1st phase lockdown (LD1)			LD1 avg.	LD2	Variation PLD & LD1		Variation between PLD & LD2	
	Wk-2 [10–16 Mar]	Wk-1 [17–23 Mar]		Wk + 1 [24–30 Mar]	Wk + 2 [31Mar-6 Apr]	Wk + 3 [6–13 Apr]		Wk +4 [14–20 Apr]	Net	%	Net	%
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Ghaziabad	203	240	221.5	39	104	115	86	127	−135.5	**−61.2**	−94.5	−42.7
Delhi	188	205	196.5	45	79	118	80.7	105	−115.8	**−58.9**	−91.5	−46.6
Noida	172	242	207	38	72	93	67.7	100	−139.3	**−67.3**	−107	**−51.7**
Gurugram	141	178	159.5	54	82	104	80	98	−79.5	−49.8	−61.5	−38.6
Greater Noida	161	254	207.5	82	104	101	95.7	117	−111.8	**−53.9**	−90.5	−43.6
Bulandshahr	215	259	237	92	192	154	146	169	−91	−38.4	−68	−28.7
Muzaffarnagar	157	234	195.5	54	72	136	87.3	132	−108.2	**−55.3**	−63.5	−32.5
Jind	120	112	116	49	68	95	70.7	90	−45.3	−39.1	−26	−22.4
Faridabad	250	244	247	64	97	117	92.7	110	−154.3	**−62.5**	−137	**−55.5**
Bhiwadi	227	296	261.5	44	70	119	77.7	93	−183.8	**−70.3**	−168.5	**−64.4**
All cities avg.	183.4	226.4	204.9	56.1	94	115.2	88.4	114.1	−116.5	**−55.7**	−90.8	−42.7

NAQI categories:

0–50	51–100	101–200	201–300	301–400	401–500
Good	Satisfactory	Moderately polluted	Poor air	Very poor air	Severely polluted

Note: Stations having > 50% variations are indicated by bold text; PLD, LD1 and LD2 represent Pre-lockdown (10th to 23rd March), 1st phase lockdown (24th March to 13th April) and partial lockdown (14th to 20th April) period respectively; 'Wk' and 'avg.' are the abbreviation form of Week and Average respectively. NAQI Classes (Ranges) are taken from CPCB (2015) (see Appendix 2 for details).

In the week-1 (17th - 23rd March) of the pre-lockdown phase (Fig. 2b inset) air quality in the eight cities out of the ten remained in the poor category but in the subsequent week + 1 (24th – 30th March) in the lockdown phase (Fig. 2c inset) air quality all of these cities restored to good or satisfactory level. Over 50% improvement in air quality has noticed for Bhiwadi, Noida, Delhi, Faridabad, Muzaffarnagar and Ghaziabad in the 3 weeks of first phase lockdown in comparison to the two weeks pre-lockdown phase (Table 2, column 11) and at all cities in the first phase of lockdown the improvement is > 38% than its previous. In the partial lockdown phase (Week + 4) air quality standard (Fig. 2f inset) became little inferior in comparison to its preceding weeks (Week + 1 to Week + 3) of the lockdown phase (Fig. 2c, d, 2e inset). As stated earlier, after three weeks of lockdown due to letting off of certain controlled industrial activity and necessary transportation in some cities is the possible cause for the slight increase in NAQI on the partial lockdown week. Nevertheless, in this partial lockdown phase as much as 40% reduction in NAQI has been noticed in Bhiwadi, Faridabad, Noida, Greater Noida, Ghaziabad and Delhi (Table 2, column 13). However, improvement in air quality during the entire 4 week lockdown period is relatively less in Jind and Bulandshahr. There may be some localized cause for such lesser reduction in NAQI in the two cities. The attenuation in NAQI during the subsequent weeks of the lockdown periods is for the most part coupled with the variation of prevailing pollutants, mainly PM_{10} and $PM_{2.5}$ discussed afterward.

3.2. Alterations in the concentrations of PM_{10} and $PM_{2.5}$ in pre and post weeks of lockdown announcement

In comparison to the other pollutants, particulate matter (PM) is the foremost one in most of the Indian cities (Guo et al. 2017, 2019). It has also been observed that a nearly uniform meteorological condition for pollutants dispersion prevails during the month of March to April in Indian subcontinent (Tiwari et al., 2015; Yadav et al., 2014). In order to portray the changes in the concentration of PM_{10} and $PM_{2.5}$ in the most polluted cities 24 h readings for each day of a week are taken and averaged for respective weeks and subsequently plotted as Box-and-Whisker Plots (Fig. 3 and Fig. 4) and the results of the same are shown in the Supplementary Material section (Supplementary 1 and 2).

As a general trend, during the first phase three week lockdown period all of the cities have witnessed substantial reduction of PM_{10} as $PM_{2.5}$ concentration below the permissible limit (Figs. 3 and 4). In particular, the two primary pollutant concentrations have shown substantial decrease in the first and second week (+1 Week and +2 Week) of the lockdown when the medium concentration of the two pollutants are reduced up to about −49% to −57% respectively. However, during the 3rd and 4th week of lockdown (+3 Week and +4 Week) there was partial relaxation on necessary transportation and controlled industrial activity particularly power plants outside the COVID-19 infected area (Red and Orange Zone) which has caused the concentration of pollutants appreciably. Increase in the concentration of both PM_{10} and $PM_{2.5}$ during the 3rd and 4th week of lock down in the entire 10 sample cities may also be associated with the increase of convective activity. This is because in the month of April and May particularly the north India due to convective activities PM_{10}, $MP_{2.5}$ and O_3 are generally remains at its highest level (Yadav et al., 2019). However, for all the cities during the month of April concentrations of the two pollutants however much lower than the previous years and outlined in detail in the subsequent section. This may be due to the fact that in this year, there is no significant variation in the average wind speed (SD 0.9) signifying lesser convective activity during the month of March and April as evident from Fig. 1d and e. When comparing between the cities pertaining to the concentration of primary pollutant PM_{10} the reduction was substantial for the city Gurugram, Jind, Bhiwadi, Ghaziabad and Noida during 24th March to 06th April (+1 week and +2 Week) (Fig. 3). Nearly similar patterns can also be noticed in these cities in case of $PM_{2.5}$ concentration also for the first two weeks of the lockdown period (Fig. 4). Noticeably, the outskirt cities located within the National Capital Region namely Gurugram, Gaziabad, Noida, Faridabad and Greater Noida the concentration of the two primary pollutants have reduced to an average of 39% during the first phase of lockdown period (+1 week to +3 Week).

3.3. Changes in the 24 h concentrations of other pollutants at the selected cities before and during the lockdown

During the pre-lockdown weeks (10–23rd March) all cities (except Jind for PM_{10}) exceed the annual PM_{10} and $PM_{2.5}$ standard of 100 μg/m^3 and 60 μg/m^3 respectively but during the lockdown weeks (24th March to 13th April) pollution level reduced below the INAQS (except Bulandshahr for PM_{10}) (Fig. 5a and b). Combining all cities, the average PM_{10} concentration during the lockdown and partial lockdown period is as much as −49% and −12% respectively (Appendix 3). Whereas the $PM_{2.5}$ averaged concentrations is reduced by about −46.9% and −31.5% during the consecutive lockdown periods. Exceptionally in Bulandshahr, Jind and Muzaffarnagar PM_{10} concentration during the partial lockdown period has increased in comparison to the pre-lockdown period (See Appendix 3, column 9, 10 & 11). However, in the case of $PM_{2.5}$ in these cities the considerable decrease (−9%–25.7%) during the partial lockdown period has increased in comparison to the pre-lockdown period. An increase of only PM_{10} in these cities may be due to the increase in the typical crustal elements (like-Fe, Al, Ti) and dust transport particularly in the urban-traffic sites as evident from several other studies (Chenery et al., 2020; Contini et al., 2014). In Bulandshahr a similar pattern of increase can also be noticed in case of NO and NH_3. NH_3 also found to have increased in Noida, Greater Noida and Gurugram during the partial lockdown period. These cities, located in the NCR Delhi region are counted among the fastest growing Indian cities, usually recognized to be dusty due to lots of construction activities. The regional meteorological factor in association with operation of few coal based industries and biomass burning may be some other factor. Apart from the particulate matter pollution, CO and NO_2 are found to have higher concentration in these cities (Fig. 5g and d) particularly during the pre-lockdown period which has reduced to about −30% and −57% respectively during the three week lockdown period. In the partial lockdown period the trend continues and their concentration has reduced up to −21% and −51% respectively (Appendix 3). In these cities the two pollutants namely CO and NO_2 are largely emanate from traffic, manufacturing industry and power plants and hence their concentrations remained higher. During the partial lockdown period certain relaxation has been given for restricted public transportation, controlled industrial activity and hence their concentration during the partial lockdown period has increased slightly. The 24 h mean concentration of SO_2 and NH_3 for all cities has remained below the permissible limit even during the pre-lockdown period (Fig. 5e and f). This is because all of these cities are landlocked located in northern India, but majority of the SO_2 emission source are from shipping activities and NH_3 emanating from non-agricultural sources is insignificant (Sutton et al., 1995). However, slight reduction (> -18%) in mean concentration of these two pollutants can be noticed during the lockdown periods. Concentration of O_3 has increased during the consecutive lockdown period (Fig. 5g). Generally, the month of April to August is considered as the period of high concentration of O_3 particularly in south-east Asia due to an increase in Insolation (Gorai et al. 2017). Increase in the average air temperature during April, 2020 as evident from Fig. 1b and c supports the fact. The concentration of O_3 has also augmented in these industrial and transport dominated cities possibly due to the decrease in NO (Fig. 5c) which resulted in lesser O_3 consumption (titration, $NO + O_3 = NO_2 + O_2$) and consequent increase of O_3 concentrations.

3.4. Diurnal variation of PM_{10} and $PM_{2.5}$ concentrations in three selected sample day belonging to pre-lockdown, lockdown and partial lockdown period

Real-time hourly concentrations of PM_{10} and $PM_{2.5}$ for all the 10 cities for three sample dates from pre-lockdown (10th March), lockdown (27th March) and partial lockdown (20th April) are considered for detecting the pattern of variation (Fig. 6; Supplementary 3). 24 h

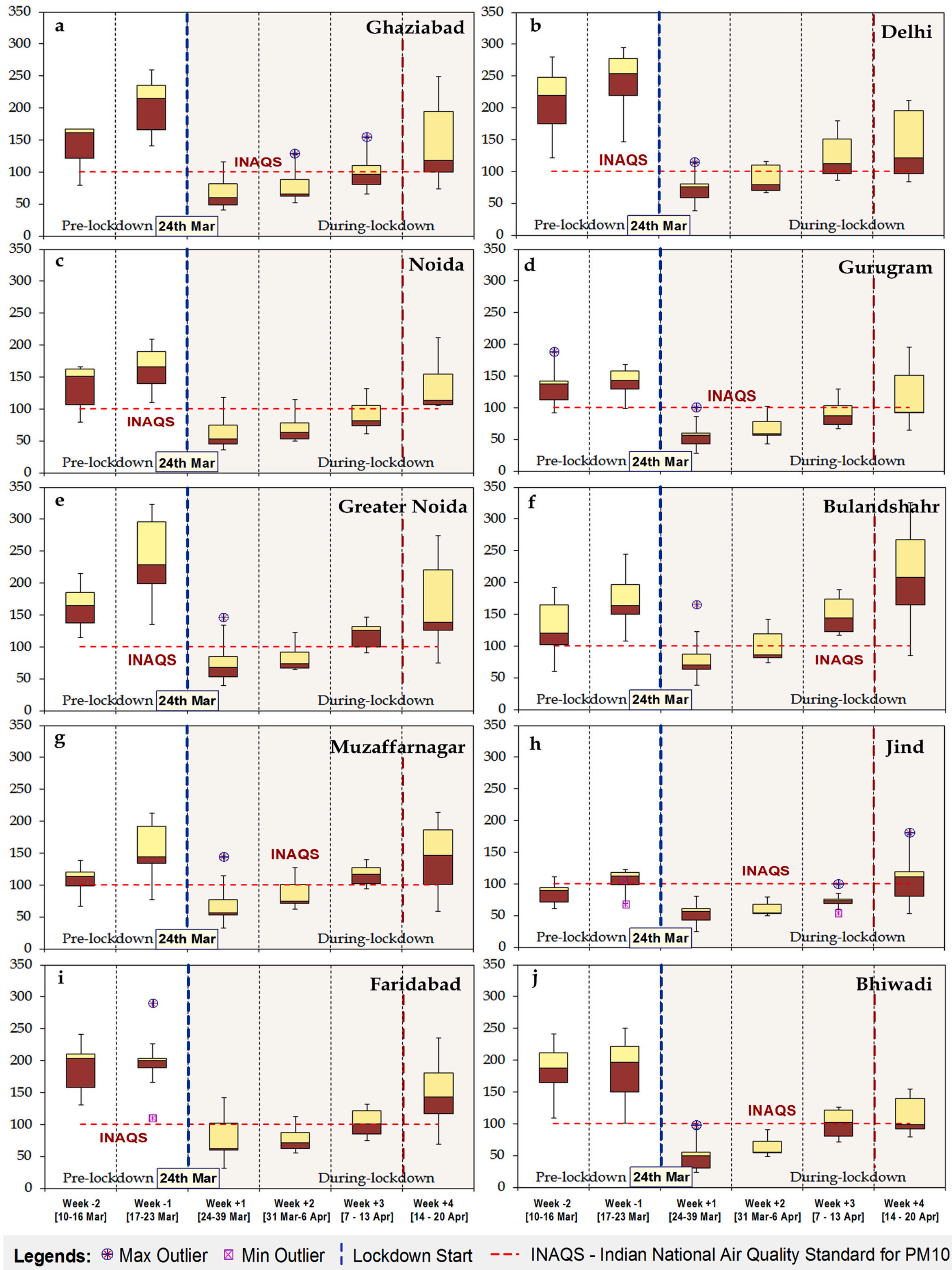

Fig. 3. Weekly average concentrations of PM_{10} (μgm^3) from 10th March to 20th April, 2020 in (a) Ghaziabad, (b) Delhi, (c) Noida, (d) Gurugram (Gurgaon, (e) Greater Noida, (f) Bulandshahr, (g) Muzaffarnagar, (h) Jind, (i) Faridabad and (j) Bhiwadi. ***Note:*** The lockdown began on 24th March 2020; Week −1 & Week −2 represents Pre-lockdown phase and Week +1 to Week +3 represents lockdown phase 1 and partial relaxation in lockdown started from Week +4.

mean concentration and standard deviation (SD) considering all stations are calculated for each sample date to show the pattern of variation between sample dates. The daily mean PM_{10} in 10th March (pre-lockdown) was as high as 165.8 (SD 81.8) (Fig. 6a), this has dropped to nearly 70% (avg. 43.2; SD 27.8) only on 4th day of the lockdown (27th of March) (Fig. 6c) and remained below the permissible limit. This pattern of variation remains almost the same for $PM_{2.5}$ also, however the drop in the mean concentration between 10th of March (pre-lockdown) and 27th of March (lockdown) is almost −72% (Net variation 60.7) (Fig. 6b and d). On 20th of April (partial lockdown) both the PM_{10}

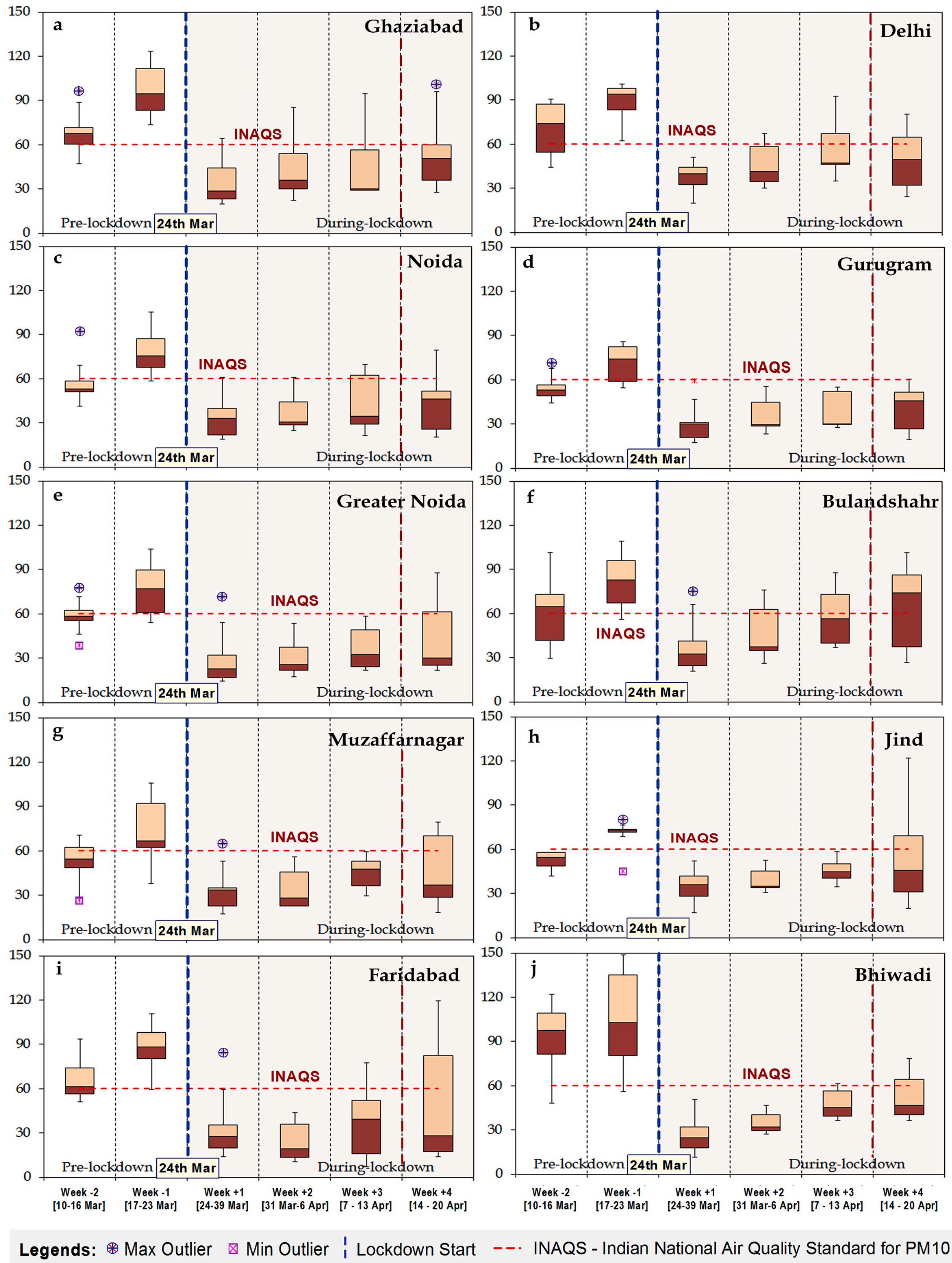

Fig. 4. Weekly average concentrations of PM2.5 (μgm3) from 10th March to 20th April, 2020 in (a) Ghaziabad, (b) Delhi, (c) Noida, (d) Gurugram (Gurgaon, (e) Greater Noida, (f) Bulandshahr, (g) Muzaffarnagar, (h) Jind, (i) Faridabad and (j) Bhiwadi. ***Note:*** The lockdown began on 24th March 2020; Week −1 & Week −2 represents Pre-lockdown phase and Week +1 to Week +3 represents During-lockdown phase 1; partial relaxation in lockdown started from Week +4.

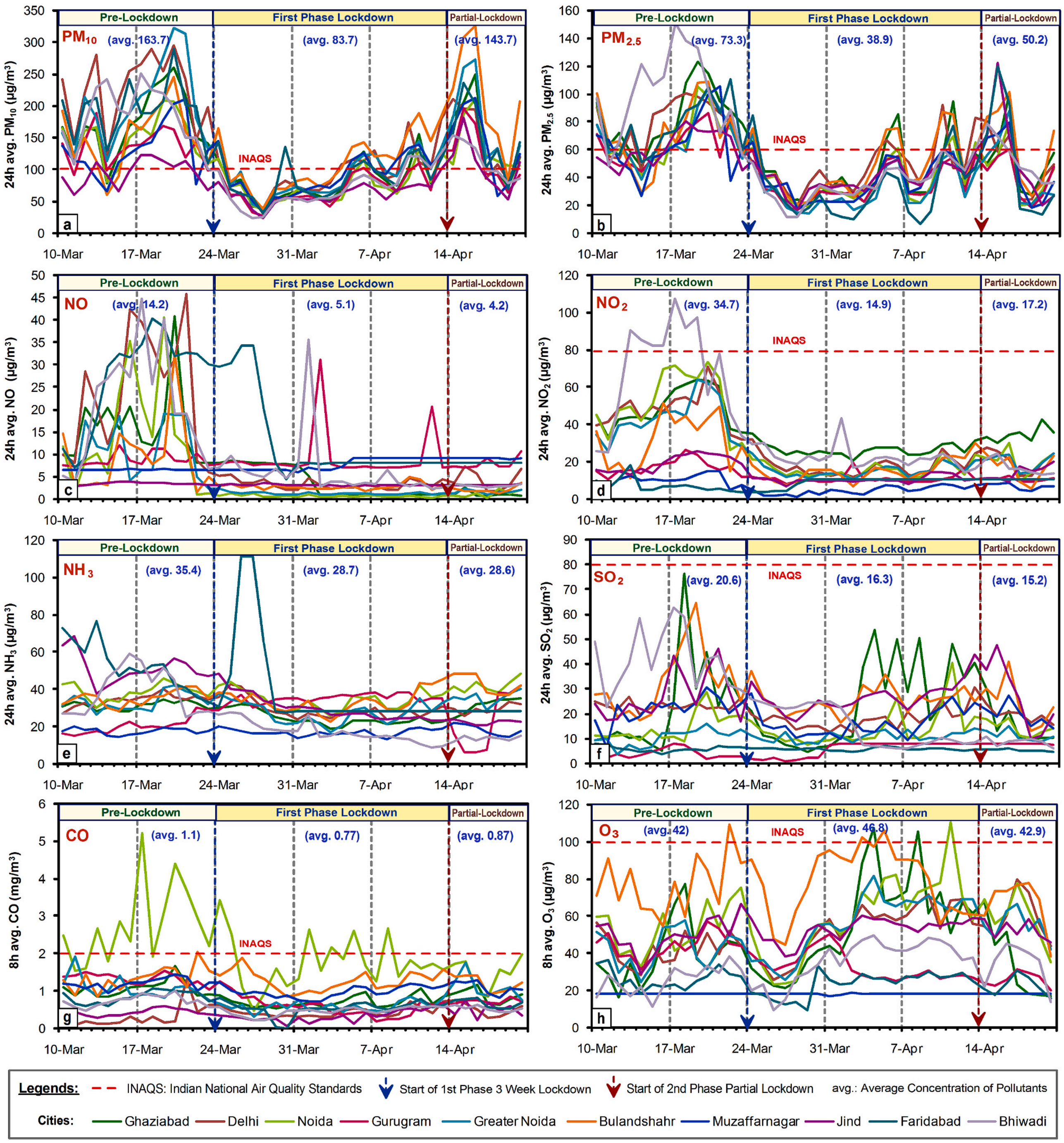

Fig. 5. Variation in the daily (24 h) average concentrations of (a) PM_{10}, (b) $PM_{2.5}$, (c) NO, (d) NO_2, (e) NH_3 (f) SO_2, and 8 h average daily maxima of (g) CO & (h) O_3 between March 10th and April 20th (with lockdown on March 24th) in 10 most polluted urban centers of India.

(Fig. 6e) and $PM_{2.5}$ (Fig. 6f) again attained its pre-disposition when the average concentration has risen to 122.7 (SD 66.4) and 48.4 (SD 34.5) respectively. Interestingly, very good consistency with lesser standard deviation can be observed in both the pollutants on 27th of March (lockdown), which was less consistent during 10th of March (pre-lockdown). The hourly concentration of PM_{10} and $PM_{2.5}$ also shows significant differences among the cities. Particularly, cities like Ghaziabad, Muzaffanagar, Gurugram, Faridabad and Greater Noida are

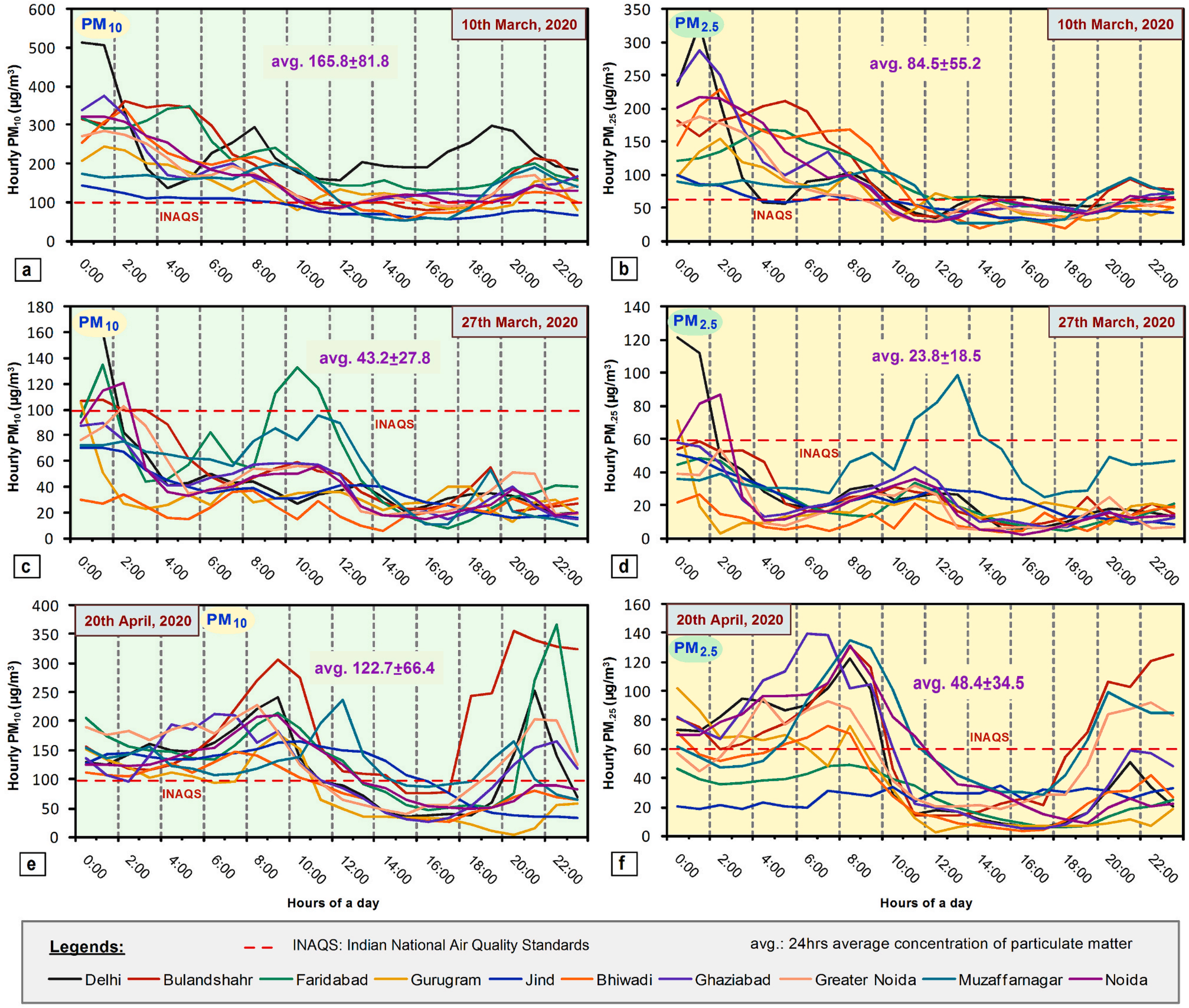

Fig. 6. Hourly concentration of PM_{10} and $PM_{2.5}$ during a pre-lockdown day (10th March), lockdown day (27th March) and a partial lockdown day (20th April)in the selected cities.

closer to intensive emission sources from manufacturing and power plant industries leading to more concentration of pollutants. However, heavy PM pollution typically associated with sluggish weather conditions with gentle wind and hence site specific climatic conditions is one of the key influencing factors for such variation.

3.5. Changes in the aerosol optical depth (AOD) over the last three years

In aim to supplement the particulate matter concentration during the lockdown and non-lockdown period as outlined in the earlier subsections, we have also tried to detect the real-time concentration of particulate air pollution with the aid of aerosol remote sensing for the preceding three years (from 2018 to 2020) for the identical window period (i.e. March and April) (Fig. 7). From the time series AOD maps for month March (Appendix 4) it is quite evident that the AOD for the year 2020 (Fig. 7e) is more than its previous years 2018 (Figs. 7a) and 2019 (Fig. 7c). As lockdown imposed at the last week of March this year, therefore while considering the entire month for AOD, the effect of the lockdown week (24th march to 31st March) suppressed while deriving in the average concentration for the entire month as the first three weeks of March this year have counted quite more AOD. However, during the month of April in the current year the AOD amount reduced to about 35.5% and 17.5% and in comparison to April 2018 and April 2019 respectively (Table 7). The reduction of AOD during the month of April this year in comparison to April 2018 for the cities ranged from −32.81% (Greater Noida) to-40.68% (Bhiwadi). This is a clear indication that the lockdown has lead to up-gradation of air quality as a result of the sizable reduction aerosol optical thickness concentration and also been documented in Gautam (2020); Dutheil et al. (2020) etc.

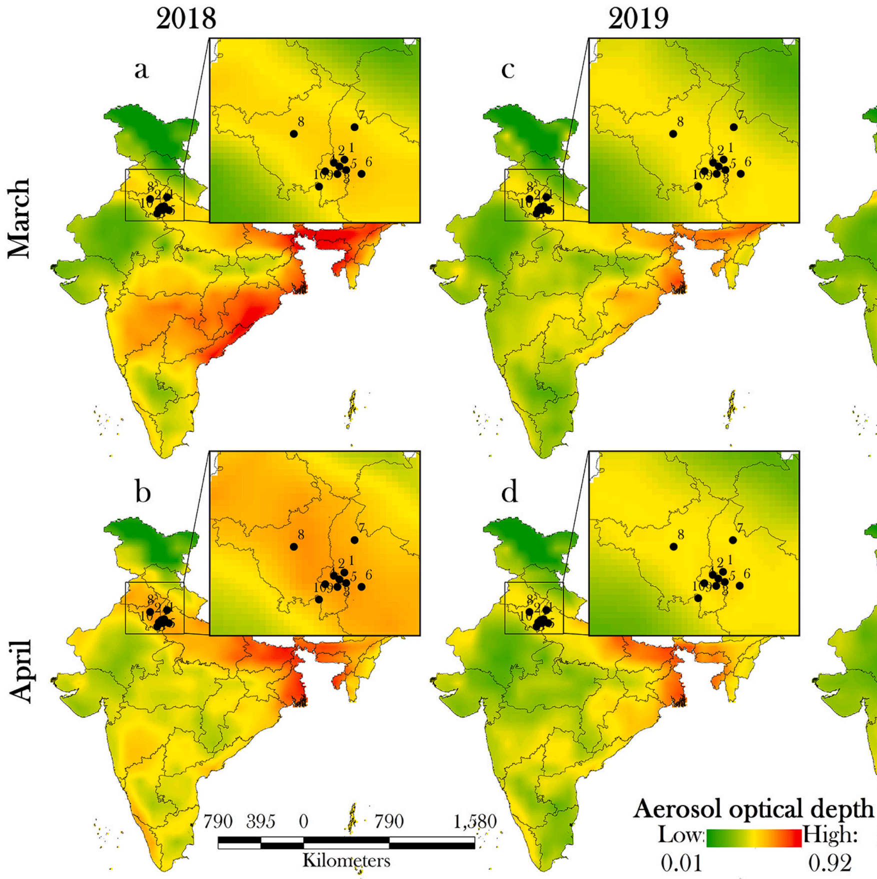

Fig. 7. Temporal profile of the monthly averaged aerosol optical depth (AOD) for the month of March and April for the year 2018, 2019 and 2020. ***Note:*** Region over which the 10 most polluted urban centers are located are shown in the inset.

3.6. Discussion and conclusion

The lockdown has had significant impacts on the air quality of the 10 most polluted urban centers located within NCR region with enhanced NAQI ratings. The NAQI outcome also conveys that about 70% of the cities across India air quality have restored to either good or satisfactory categories during the lockdown episode. Combining all the selected cities, among the selected pollutants PM_{10} and $PM_{2.5}$ have witnessed maximum reduction during the three week lockdown period counting as much as −49% and −46.9% respectively. Pollutants like CO and NO_2 have reduced to about −30% and −57% respectively during the full-fledged lockdown period. On the contrary there is insignificant decrease in SO_2 and slight increase in O_3 concentration during the period. Drastic drop in the diurnal concentration of PM_{10} and $PM_{2.5}$ to almost −70% can be noticed in 27th of March (Lockdown period) in contrast to that of the 10th of March (Pre-lockdown phase). Real-time concentration of aerosols as revealed from the profile of the monthly averaged AOD for the month of April in the year 2018 and 2019 show much higher value throughout India than this year. The observation again reveals lessening of the pollutant concentration. The framework adopted in this study can be easily transferred to not only examine similar lockdown effects on the air quality of other urban centers as well as industrial clusters, but also for continuous monitoring and image-extracted datasets, which can extend and improve spatio-temporal air quality assessments.

The policy planning and its implementation in this country in most of the cases are limited to the Tier-1 and Tier-2 cities. Yet, several medium and small urban centers of this country are enlisted in the world's most polluted cities. Therefore, there is a need for a closer look at the state of air pollution, particularly the most polluted Tier-3 cities in order to quantify the extent of pollution. Moreover, with the boosting of population and ever-rising urbanization trend particularly in and around the metropolitan cities, especially over the industrial clusters of the Indo-Gangetic Plain there is a need for revisiting the policy planning to combat the air pollution threat. The lockdown amid the COVID-19 pandemic has given us a rare window when the atmospheric pollution and particles are far less than at any point in the last 2–5 years especially for the industrial sites. Although the air quality have bettered yet, this improvement does not necessarily guarantee sustained purer air quality and there is a high likelihood that the environment shall return to its former degraded status once all lockdown measures are lifted and industrial production is increased to make up the economic losses engendered by such a period of closure. Therefore, integrative plans to recover the air quality are sorely required, together with better regulatory and sound technological interventions. The spate of newspaper articles, blogs and tweets about the cleanlier air quality during this lockdown must be used to press on for coordinated and augmented efforts to truly improve and sustain the environmental health, critically reexamining current management practices, which are quite unsustainable and exclusionary.

Of course lockdown has brought threat to the national economy but certainly the environmental refurbishment process also goes on hand by hand. Consequently if a city lockdown undeniably improved the air quality, it could be taken as an effective unconventional measure to restrain air pollution. The baseline report outlined in the present manuscript will definitely add on the researcher, planners and people at large to think for alternative policy interventions so as to manage the ever rising air pollution. However, an increase in the ground level monitoring network for these most polluted cities may support reporting air quality in finer terms. In these selected cities and all other resembling cities across India urbanization along with population boost is an increasing trend accompanied by ever rising automation and industrialization. Hence, these cities need to start pollution control planning by anticipating the possible environmental threat. There is a dearth of study devoted to emission inventory for most of these polluted Tier-3 cities. Therefore, detailed inventory for these medium and small cities having environmental threats need to be focused in order to assess the pollution trend and identify localized pollution hotspots (source contribution).

Credit statement

Susanta Mahato: Conceptualization, Methodology, Investigation, Data processing, Formal analysis, Visualization, Validation and Revision, Krishna Gopal Ghosh: Conceptualization, Methodology, Data processing, Investigation, Formal analysis, Visualization; Writing-Original Draft, Editing and Revision.

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.

Appendices

Appendix 1. Indian National Ambient (Outdoor) Air Quality Standards (INAQS)

Pollutants	Time weighted average	Industrial, residential and rural and other areas	Ecologically sensitive area (Notified by the central government)	WHO Standard
		Concentration of ambient air		
PM_{10} (μg/m^3)	24 h	100	100	50
$PM_{2.5}$ (μg/m^3)	24 h	60	60	25
SO_2 (μg/m^3)	24 h	80	80	20
NO_2 (μg/m^3)	24 h	80	80	–
O_3 (μg/m^3)	8 h	100	100	100
	1 h	180	180	
CO (mg/m^3)	8 h	02	02	–
	1 h	04	04	
NH_3 (μg/m^3)	24 h	400	400	–

Source: CPCB, 2015; WHO 2006.

Appendix 2. NAQI categories, their range, associated health impacts, criteria pollutants and corresponding health breakpoints.

NAQI Class (Range)	Associated Health impacts	PM_{10} 24 h (μg/m^3)	$PM_{2.5}$ 24 h (μg/m^3)	SO_2 24 h (μg/m^3)	NO_2 24hrs (μg/m^3)	O_3 8hrs (μg/m^3)	CO 8 h (mg/m^3)	NH_3 24 h (μg/m^3)
		Concentration Range						
Good (0–50)	Minimal Impact	0–50	0–30	0–40	0–40	0–50	0–1	0–200
Satisfactory (51–100)	Minor breathing and uneasiness to receptive people	51–100	31–60	41–80	41–80	51–100	1.1–2	201–400
Moderately polluted (101–200)	Breathing discomfort to the people with lung disease	101–250	61–90	81–380	81–180	101–168	2.1–10	401–800
Poor (201–300)	Breathing discomfort to people on prolonged exposure	251–350	91–120	381–800	181–280	169–208	10–17	801–1200
Very poor (301–400)	Respiratory illness to the people on prolonged exposure	351–430	121–250	801–1600	281–400	209–748*	17–34	1200–1800
Severe (401–500)	Respiratory illness to the people on prolonged exposure	> 430	> 250	> 1600	> 400	> 748	> 34	> 1800

Source: Compiled from CPCB (2015).

Appendix 3. A comparison of the 24 h/8h mean concentration of the criteria pollutants in the selected cities amid the pre-lockdown; 1st phase lockdown period and second phase partial lockdown period

Phase	Pollutants	All cities	Ghaziabad	Delhi	Noida	Gurugram	Greater Noida	Bulandshahr	Muzaffarnagar	Jind	Faridabad	Bhiwadi
		Avg. ± SD [% Change]	Avg. [% Change]	Avg. [% Change]	Avg. [% Change].	Avg. [% Change].	Avg. [% Change].	Avg. [% Change].	Avg. [% Change].	Avg. [% Change]	Avg. [% Change]	Avg. [% Change]
1	2	3	4	5	6	7	8	9	10	11	12	13
Pre-lockdown 10th Mar-23 Mar	PM_{10}	163.7 ± 57.9	171.5	225.3	148.7	136.3	201.2	151.1	131.4	94.9	192.6	184.3
1st Phase of lockdown 24Mar-06Apr		83.6 ± 33.4 [-48.9]	81.6 [-52.4]	95.5 [-57.6]	74.7 [-49.8]	71.3 [-47.7]	91.8 [-54.4]	110.4 [-26.9]	91.1 [-30.7]	62.3 [-34.4]	86.7 [-55]	71.1 [-61.4]
Partial lockdown 14 Apr to 20 April		143.7 ± 61.4 [-12.2]	147.2 [-14.1]	142.8 [-36.6]	136.1 [-8.4]	119.7 [-12.2]	168.7 [-16.1]	212 [40.3]	142 [8]	106.3 [11.9]	148.8 [-22.7]	113.5 [-38.4]
Pre-lockdown 10th Mar-23 Mar	$PM_{2.5}$	73.3 ± 22.9	82.5	79.4	68.1	62.5	67.6	71.4	63.8	61.1	77.3	99.2
1st Phase of lockdown 24Mar-06Apr		38.9 ± 17.3 [-46.9]	42.1 [-49]	47.2 [-40.6]	38.3 [-43.8]	35.3 [-43.5]	32.5 [-52]	47.8 [-33]	37.6 [-41.1]	39.9 [-34.6]	31.9 [-58.7]	36.5 [-63.2]
Partial lockdown 14 Apr to 20 April		50.1 ± 26.1 [-31.5]	52.9 [-35.8]	49.4 [-37.7]	42.9 [-36.9]	40.2 [-35.8]	44.6 [-33.9]	64.2 [-10]	47.4 [-25.7]	55.5 [-9.2]	51.5 [-33.5]	52.7 [-46.7]
Pre-lockdown 10th Mar-23 Mar	NO	14.1 ± 11.4	16	23.8	14.3	8.8	10.4	9.8	6.6	3.5	27.1	21.3
1st Phase of lockdown 24Mar-06Apr		5.1 ± 5.7 [-63.7]	3.7 [-76.7]	3.4 [-85.7]	0.7 [-95.5]	9.2 [4.3]	1.3 [-87.8]	2.9 [-70]	7.7 [16.7]	3.3 [-6.2]	12.9 [-52.1]	6.2 [-70.8]
Partial lockdown 14 Apr to 20 April		4.1 ± 3.1 [-70.5]	1 [-93.4]	4.4 [-81.6]	1.2 [-91.6]	7.9 [-10.2]	1.6 [-84.9]	2.2 [-77.3]	9.1 [37.2]	3.2 [-7.3]	8 [-70.4]	3.1 [-85.5]
Pre-lockdown 10th Mar-23 Mar	NO_2	34.6 ± 23.1	48.9	48.3	52.7	17.1	42.9	31.8	10.2	19.4	7.5	68.1
1st Phase of lockdown 24Mar-06Apr		14.8 ± 7.2 [-57.1]	26.6 [-45.6]	17.5 [-63.6]	15.9 [-69.8]	10.8 [-36.9]	15.4 [-64.1]	15.2 [-52.4]	4.8 [-52.9]	10.7 [-44.7]	9.6 [28.5]	22.3 [-67.3]
Partial lockdown 14 Apr to 20 April		17.1 ± 8.5 [-50.4]	34.7 [-28.9]	20.4 [-57.7]	19.9 [-62.1]	10.3 [-40]	20 [-53.3]	16.8 [-47]	6.9 [-31.7]	14.5 [-25.2]	11 [47.2]	17 [-74.9]
Pre-lockdown 10th Mar-23 Mar	NH_3	35.3 ± 12.6	31.3	34.2	38.7	20.3	33.5	35.3	17.5	50.9	52.7	39.1
1st Phase of lockdown 24Mar-06Apr		28.7 ± 11.5 [-18.7]	24.5 [-21.6]	29.5 [-13.7]	34.1 [-11.9]	35 [72.9]	27.5 [-17.9]	33.4 [-5.3]	16.9 [-3.5]	30 [-41.1]	38.8 [-26.3]	17.5 [-55.3]
Partial lockdown 14 Apr to 20 April		28.6 ± 10.9 [-19.1]	31.4 [0.1]	29.6 [-13.3]	42.1 [8.8]	22 [8.6]	35.5 [6]	42.7 [21.2]	18.2 [4.2]	22.6 [-55.7]	27.9 [-46.9]	13.7 [-64.9]
Pre-lockdown 10th Mar-23 Mar	SO_2	20.5 ± 14.6	23.2	23.2	14.6	4.3	10.3	32.9	21.7	27.3	5.9	42.1
1st Phase of lockdown 24Mar-06Apr		16.3 ± 10.2 [-20.6]	24.4 [5.2]	18.1 [-22.1]	14.3 [-2.4]	5.9 [39]	10.7 [3.3]	25.8 [-21.4]	16.4 [-24.3]	26.6 [-2.2]	5.8 [-2.3]	15.1 [-64.3]
Partial lockdown 14 Apr to 20 April		15.2 ± 9 [-25.9]	14.9 [-35.6]	19.5 [-16.4]	14.2 [-2.8]	7.9 [85.6]	11 [7]	24.5 [-25.5]	19.5 [-10.1]	26.7 [-1.9]	5.4 [-9.7]	8.7 [-79.4]
Pre-lockdown 10th Mar-23 Mar	CO	1.1 ± 0.8	1.1	0.3	2.8	1.3	1.1	1.3	1.2	0.4	0.8	0.7
1st Phase of lockdown 24Mar-06Apr		0.7 ± 0.5 [-30.5]	0.7 [-33]	0.4 [41.5]	1.8 [-36.4]	0.6 [-54.7]	0.6 [-43.9]	1.3 [-5.5]	0.9 [-18.9]	0.3 [-20.1]	0.5 [-36.2]	0.5 [-37.2]
Partial lockdown 14 Apr to 20 April		0.8 ± 0.4 [-21.7]	0.8 [-17.8]	0.5 [64.5]	1.5 [-46.7]	0.7 [-44.7]	1.1 [2.7]	1.2 [-11.1]	1.1 [-9.6]	0.5 [18.1]	0.7 [-20.7]	0.5 [-27.9]
Pre-lockdown 10th Mar-23 Mar	O_3	42 ± 18.7	40.1	42.3	53.3	44.0	42.7	77.1	18.6	49.6	26.6	25.9
1st Phase of lockdown 24Mar-06Apr		46.7 ± 22.9 [11.3]	55.6 [38.4]	52.5 [24.3]	59.6 [11.9]	32.9 [-25.3]	56.5 [32.4]	79.5 [3]	18.5 [-0.6]	52.9 [6.7]	23.6 [-11.2]	36.1 [39.5]
Partial lockdown 14 Apr to 20 April		42.8 ± 19.8 [1.9]	34.4 [-14.2]	59.27 [40.2]	59.2 [11.1]	26 [-40.9]	55 [29]	67 [-13]	18.6 [0]	52.3 [5.4]	22.7 [-14.5]	33.9 [31.1]

Appendix 4. Temporal (2018–2020) variation of Aerosol Optical Depth (AOD) for the month of March and April in the selected urban centers

Cities/Month & Year	March			April			Variation (April 2018 & April 2020)		Variation (April 2019 & April 2020)	
	2018	2019	2020	2018	2019	2020	Net	%	Net	%
Ghaziabad	0.53	0.49	0.56	0.64	0.52	0.42	−0.22	−34.38	−0.10	−19.23
Delhi	0.52	0.48	0.57	0.64	0.51	0.42	−0.22	−34.38	−0.09	−17.65
Noida	0.53	0.50	0.58	0.64	0.52	0.43	−0.21	−32.81	−0.09	−17.31
Gurugram	0.49	0.46	0.57	0.63	0.48	0.39	−0.24	−38.10	−0.09	−18.75
Greater Noida	0.54	0.51	0.58	0.64	0.53	0.43	−0.21	−32.81	−0.10	−18.87
Bulandshahr	0.52	0.49	0.55	0.63	0.50	0.42	−0.21	−33.33	−0.08	−16.00
Muzaffarnagar	0.47	0.41	0.41	0.59	0.45	0.38	−0.21	−35.59	−0.07	−15.56
Jind	0.48	0.45	0.52	0.64	0.47	0.40	−0.24	−37.50	−0.07	−14.89
Faridabad	0.51	0.49	0.58	0.64	0.50	0.41	−0.23	−35.94	−0.09	−18.00
Bhiwadi	0.45	0.43	0.53	0.59	0.43	0.35	−0.24	−40.68	−0.08	−18.60
Average	0.50	0.47	0.55	0.63	0.49	0.41	−0.22	−35.51	−0.09	−17.52

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2020.109835.

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