COVID-19 lockdown: a rare opportunity to establish baseline pollution level of air pollutants in a megacity, India

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Abstract

This paper analyses air quality data from megacity Delhi, India, during different periods related to the COVID-19, including pre-lockdown, lockdown and unlocked (post-lockdown) (2018–2020) to determine what baseline levels of air pollutants might be and the level of impact that could be anticipated under the COVID-19 lockdown emission scenario. The results show that air quality improved significantly during the lockdown phases, with the most significant changes occurring in the transportation and industrially dominated areas. A pronounced decline in $PM_{2.5}$ and PM_{10} up to 63% and 58%, respectively, was observed during the lockdown compared to the pre-lockdown period in 2020. When compared to 2018 and 2019, they were lower by up to 51% and 61%, respectively, dropping by 56% during unlock. Some pollutants (NO_x and CO) dropped significantly during lockdown, while SO_2 and O_3 declined only slightly. Moreover, when compared between the different phases of lockdown, the maximum decline for most of the pollutants and air quality index occurred during the lockdown phase 1; thus, this period was used to report the COVID-19 baseline threshold values (CBT; threshold value is the upper limit of baseline variation). Of the various statistical methods used median + 2 median absolute deviation (mMAD) was most suitable, indicating CBT values of 143 and 75 $\mu g/m^3$ for PM_{10} and $PM_{2.5}$, respectively. This results although preliminary, but it gives a positive indication that temporary lockdown can be considered as a boon to mitigate the damage we have done to the environment. Also, this baseline levels can be helpful as a first line of information to set future target limits or to develop effective management policies for achieving better air quality in urban centres like Delhi.

Keywords COVID-19 lockdown · Air quality · Baseline threshold value · Delhi · India

Introduction

COVID-19 was reported first in Wuhan City, China (December 2019), and quickly spread around the World (WHO 2020a; Gautam Hens 2020) to 213 countries by March 2020, becoming a global pandemic (WHO 2020b; Buono et al. 2020). The disease has a high community spreading rate via expiratory activities (Ningthoujam 2020), which can be attenuated by breaking the transmission chain through isolation (WHO 2020a, 2020b). The Govt. of India began the first 21-day “Curfew/Lockdown” in March 2020 (The Hindu 2020), limiting activities for industries, businesses (non-essential services), airways, roadways and railways; three more lockdowns extended through May 2020. The positive impact of the lockdowns included surface water quality (Yunus et al. 2020) and air quality (Xu et al. 2020) from fewer emissions (Muhammad et al. 2020; Zambrano-Monserrate et al. 2020), but there were also negative societal and economic ramifications (Mackolil and Mackolil 2020; Muhammad et al. 2020; Jain and Sharma 2020).

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The National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) were the first to report significant regional reduction in NO_2 (up to 30%) in Asian and European countries due to lockdown (Gautam 2020; ESA 2020). Similar results on reduction of major air pollutants were reported from China, Italy, Spain, Brazil, USA, India and others (Krecl et al. 2020; Tobías et al., 2020; Zambrano-Monserrate et al. 2020; Bashir et al. 2020; Nakada and Urban 2020; Berman and Ebisu 2020; ESA 2020^a; Gautam 2020; Sharma et al. 2020; Sahoo et al. 2020a, 2021; Mahato et al. 2020; Jain and Sharma 2020; ESA 2020b). Scientists predict that these lockdowns will produce the cleanest urban atmospheres in recent history, providing an opportunity to study baseline level of air pollutants for future policy development (Beig et al. 2020; Sahoo et al. 2020a, 2021). Moreover, site-specific regional/local baseline levels are also favoured over large/global-scale for risk assessment (EPA 2016). However, information on local/regional scale baseline pollution levels of air pollutants are highly deficient in many countries (Fonatana 2000; Das et al. 2006; Ghauri et al. 2007; Gómez-Losada 2018). This may be due to a lack of control study areas or it was impossible to halt most of the major anthropogenic activities during normal days in large cities like Delhi.

India's capital city Delhi is one of the most severely polluted megacity (air pollution) in the world (WHO 2016, 2018; Biswas and Cecila 2017), with $\text{PM}_{2.5}$ and PM_{10} levels in the National Capital Region (NCT) of Delhi consistently higher than the National Ambient Air Quality Standards (NAAQS; CPCB 2009). Delhi's growing urbanization, industry/manufacturing, transportation, crop burning and dust storm have contributed significantly to extreme pollution levels by emitting particulate matter (PM), CO, O_3 , SO_2 , NO_x , NH_3 , benzo(a)pyrene (BaP) and other pollutants to its atmosphere (Goyal et al. 2013; Rizwan et al. 2013; WHO 2016; Gulia et al. 2018), with serious toxicological effects (Ghorani-Azam et al. 2016; Pani et al. 2020). Identifying sources and defining baseline pollution levels in Delhi's atmosphere during this lockdown will greatly relevant to epidemiological research and will also play an important role in framing future air quality standards/policies for air quality management.

The present study was conducted in NCT Delhi, India, from 1 January to 6 June 2020, with the objectives: 1) to evaluate the changes in major criteria ($\text{PM}_{2.5}$, PM_{10} , CO, SO_2 , O_3 , NH_3 and NO_x) and other pollutants from pre- to -post lockdown periods; 2) to understand the impact of meteorology on their behaviour; and 3) to establish the COVID-19 baseline threshold values of these pollutants in Delhi.

Materials and methods

Study area

As the capital of India, Delhi has been divided into nine districts including North, North-west, West, South-west, South, New Delhi, Central, North-east and East, jointly administered by the Central and State governments. NCT Delhi is the largest urban agglomeration in India with a population of 16.8 million (decadal growth rate of 21%) (Census 2011; <http://census2011.co.in>) and pollution density of 29,259 people per square mile (<https://worldpopulationreview.com/world-cities/delhi-population>). The state has a total 129,000 registered industries and 5.7 million vehicles enter Delhi daily (The Hindu 2016). The climate is semi-arid; summer is March–September; winter is October–February; monsoon includes pre-monsoon (Mar–May), heavy monsoon (June–Sept.) and post-monsoon (Oct–Nov.). Temperatures range from summer highs of $\approx 48^\circ\text{C}$ to winter lows of $\approx 4^\circ\text{C}$ (Kumar et al. 2017; Mahato et al. 2020). The majority of annual precipitation occurs during the monsoon season (July and August) (Perrino et al. 2011).

Data collection

The daily averaged air quality and meteorological data from 34 continuous ambient air quality monitoring stations (Fig. 1) were collected between 1 January 2018 and 6 June 2020 from the Central pollution control board's online portal (<https://app.cpcbcr.com/ccr/#/caaqm-dash-board-all/caaqm-landing>) (CPCB 2020). The 2020 data are represented as pre-lockdown (PL₁: 1 January–31 January; PL₂: 1 February–29 February; PL₃: 1 March–23 March), during lockdown (LD₁: 24 March–14 April; LD₂: 15 April–3 May; LD₃: 4 May–17 May; LD₄: 18 May–31 May) and unlock periods (UL₁: 1 June–6 June). The parameters collected include $\text{PM}_{2.5}$, PM_{10} , NO_x , CO, SO_2 , O_3 , NH_3 , benzene, toluene, ambient temperature (AT), wind speed (WS), temperature (Temp) and relative humidity (RH). The air quality index (AQI) was calculated using an Excel-based tool obtained from CPCB (2014). This tool allows the user to input the concentration of major pollutants, with a minimum of three pollutants required; one of them should be PM_{10} or $\text{PM}_{2.5}$ and defines six categories: “good” (0–50), “satisfactory” (51–100), “moderate” (101–200), “poor” (201–300), “very poor” (301–400) and “severe” (> 401) (CPCB 2014).

Data analyses

Before statistical treatment, zero values (which supposedly occurred during instrument calibration) were stripped from the datasets. Statistical treatments included descriptive statistics such

Fig. 1 Location map showing the administrative regions, ground monitoring stations and land use pattern in the NCT Delhi

as minimum, maximum and mean $\pm$ standard deviation (SD) and multivariate analysis such as Spearman correlation matrix (visualized in heat-plots) and principal component analysis (PCA)], carried out following standard methods (Reimann et al. 2018; Sahoo et al. 2020b). The COVID-19 baseline threshold (CBT) levels (i.e., the upper limit of COVID-19 baseline variation) were calculated using a percentile-based approach (75th, 95th, 98th), median + 2 median absolute deviation (mMAD), mean + 2 standard deviation (SD), Tukey inner fence (TIF; 3rd quartile + 1.5* interquartile range) and cumulative frequency distribution using log-transformed data (Reimann et al. 2018; Salómao et al. 2019; Sahoo et al. 2020b). The cumulative frequency distribution plots were also used to define the baseline range by analysing curve reflection points. All statistical treatments and calculations were performed with the open statistical software R version 3.5 (R Core Team 2018).

Spatial distribution maps of air pollutants were constructed using Geographic Information System (GIS) (ArcGIS 10.6) under the World Geodetic System 1984 (WGS84) datum. The distribution maps of air pollutants were obtained using the spatial interpolation method by Inverse Distance

Weighted (IDW). The power function “3” was chosen for the prediction and cubic convolution for the resampling display (Wong et al. 2004).

Results and discussion

Changes in air quality parameters: pre- to -post COVID-19 lockdown

Temporal variations of selected air quality pollutants in pre-lockdown (PL), lockdown (PL₁₋₄) and unlock (UL₁) phases in 2020 and the same periods (dates) in 2018 and 2019 are shown in Fig. 2 (Fig. SM1) and all data are given in Table 1S. The per cent change in the given pollutants during the lockdown periods with respect to the pre-lockdown periods of 2020 and the historical periods in 2018 and 2019 is given in Table 1. The results show that the levels of most of the pollutants reduced significantly throughout Delhi during the lockdown periods. PM₁₀ and PM_{2.5} are the most severe air pollutants in Delhi. Average concentrations of PM_{2.5} in LD₁₋₄ phases were 41.45, 46.75, 55.74 and 58 $\mu\text{g}/\text{m}^3$

Fig. 2 Trend of average air quality parameters and meteorological parameters in different pre-lockdown (PL₁₋₃), lockdown (LD₁₋₄) and unlock (UL₁) periods in 2020 in Delhi. This is compared with the same time periods of 2018 and 2019

m³, respectively, and in UL₁ 44.02 µg/m³. All these levels were much lower as compared to PL₁₋₃ phases (156, 121, 65.5 µg/m³, respectively). Similarly, PM₁₀ levels remained considerably lower in LD₁, followed by LD₂₋₄ (85.7, 113.4, 124, 158 µg/m³, respectively), as well as in UL₁ (91.3 µg/m³) compared to PL₁₋₃ (240, 222, 145, respectively). In both cases, LD₁ witnessed the maximum reduction in both PM₁₀ and PM_{2.5} levels, which were well below their NAAQS permissible limits, i.e. 100 and 60 µg/m³, respectively. Sudden increases in PM levels after LD₁, especially in LD₄, could be due to some relaxation in the lockdown rules. For LD₁₋₃, the level of PM_{2.5} was below the permissible limit, but in the case of PM₁₀ exceeded the limit. However, when compared with the WHO standards (PM_{2.5} = 25 µg m⁻³, PM₁₀ = 50 µg m⁻³; 24-h averages), the pollutants were within the limits. Similar decreasing trends continued even after the restrictions were lifted. When compared to the PL periods, PM_{2.5} and PM₁₀ in LD phases reduced up to 62.6% and 57.8%, respectively, and 56.5% and 50.9%, respectively, during UL (Table 1). When compared to the same periods in the year 2018 and 2019, the levels of PM_{2.5} were as low as 51.4% and 51.7%, respectively (Table 1), while PM₁₀ dropped to 59% and 61%, respectively. The most significant reduction of PM₁₀ and PM_{2.5} was noticed in LD-1, which is likely due to stricter lockdown enforcement that drastically reduced emission from vehicle exhaust (mainly diesel), road dust, industrial activities and construction work (major sources of PMs; CPCB 2016). Considerable decreases in both fractions of PM levels during lockdown have also been reported in cities in China, Italy, Spain, USA and Brazil, etc. (Xu et al. 2020; Krecl et al. 2020; Zambrano-Monserrate et al. 2020; Tobías et al. 2020), as well as in India (Sahoo et al. 2020a, 2021; Sharma et al. 2020; Singh and Chauhan 2020; Mahato et al. 2020; Jain and Sharma 2020). Particulate matter also decreased significantly during the UL period, which may be due to the additive role of weather (mainly rainfall and temperature) with the lockdown conditions.

Atmospheric NO_x mainly occur due to industrial activities, transportation, energy production, biomass burning and others (He et al. 2020; Sharma et al. 2020). In urban areas, NO_x consists of NO and NO₂, with the latter leading to serious health hazards (Mills et al. 2015). A potential benefit of the LD₁₋₄ was the reduction in NO₂ levels, which reduced to 20.41, 19.7, 21.99, 30.18 µmol/m², respectively, compared to PL₃ (39.4 µmol/m²); the trend was also lower in the immediate UL₁ (24.3 µmol/m²) (Table 1). The lowest NO₂ level recorded occurred in LD₁, but the level slowly increased in the subsequent lockdown periods, LD₃₋₄, possibly due to

relaxation of some restrictions. When compared to the PLs (Jan to March 2020), NO₂ in LD phases reduced up to 55% (Table 1). When compared to the same periods in the year 2018–2019, the concentration of NO₂ is dropped by as much as 59.1% and 58.2%, respectively. Though the NO₂ levels were less than the permissible limit (80 µg/m³) even before COVID-19, it is evident that the levels further decreased during the lockdown. Similar to PM, maximum reductions of NO₂ were witnessed in LD₁. A significant decrease in NO₂ levels (20–30%) was also reported in France and Italy during lockdowns (ESA 2020a). In India, 40–70% drops in NO₂ during lockdowns were reported for Mumbai, Delhi, Chandigarh, Kolkata, etc. (Gautam 2020; Sharma et al. 2020; Mahato et al. 2020; Jain and Sharma 2020). This increased reduction in Indian cities, compared to European countries, may indicate that the efficiency of lockdown in India was more stringent. The level of NO_x reduced significantly in LDs compared to the PLs and declined up to 64% during the UL in 2020. When compared to the same periods in 2018 and 2019, the levels of NO_x dropped to 61% and 62%, respectively. Also, the lowest level of NO_x was recorded during LD₁. These significant drops are the consequence of nearly 99% of vehicles being off the road, which was also evident at ground stations and visible from satellites' columnar observations over China, Italy and the USA (Science Wire 2020).

The level of CO significantly varied between pre- to post-lockdown periods and followed a similar pattern to NO_x. During the LDs, CO levels in LD₁₋₄ averaged 0.68, 0.87, 0.87 and 1.01 mg/m³, respectively, and were 46.3, 32.1, 30.2 and 21.5% lower compared to PLs (2020), respectively (Table 1). The CO concentration also remained lower (almost 28%) during UL₁, with respect to the PL. When compared to the same periods in the year 2018 and 2019, CO levels dropped during LDs up to 56.9% and 48.3%, respectively. Despite the significant differences of CO levels between the PL and LD phases, the levels remained well below the permissible limit (2.0 mg/m³) and the maximum reduction occurred in LD₁. A comparatively lower level of CO reduction is possibly due to its longer tropospheric life-time (approximately two months), relative to the other pollutants. According to the CPCB, restrictions on vehicular activity led to a 56% reduction in NO₂ level compared to a 37% reduction in CO levels.

In contrast, O₃ witnessed an increase in all phases of lockdown and unlock compared to pre-lockdown. The concentrations in LD₁₋₄ were 39.2, 49.04, 59.4 and 51.88 µg/m³, respectively, and 43.29 µg/m³ in UL₁, compared to PL₁₋₃ (19.8, 31.22, 35.5 µg/m³, respectively). O₃ increased by 39.4%, 73.3%, 109% and 77.8% in LD₁₋₄, respectively, compared to the PL (2020), but when compared to the same time period in 2018 and 2019, it increased up to 8% and 25%, respectively. Sicard et al. (2020) also reported an increase

Table 1 Percent (%) change in average (over all 34 stations) pollution levels of air quality parameters during the lockdown and unlock phases with respect to their corresponding time period in 2018 and2019 and the average value of January, February and March for 2020. **Bold** values indicate the pollution level increases during the lockdown and unlock phases

% change during COVID-19 lockdown and unlock phases

Parameters	2018				2019				2020				
	LD-1	LD-2	LD-3	LD-4	LD-1	LD-2	LD-3	LD-4	LD-1	LD-2	LD-3	LD-4	UL-1
PM _{2.5}	−51.4	−47.5	−33.7	−38.4	−51.7	−38.3	−48.1	−16.6	−62.6	−59.0	−50.0	−47.3	−56.5
PM ₁₀	−59.3	−56.4	−45.1	−41.9	−61.1	−49.3	−55.8	−18.6	−57.8	−42.4	−36.6	−20.1	−50.9
Ozone	−18.1	−1.1	8.0	5.8	−11.0	0.3	25.4	3.7	39.7	73.3	109.1	77.8	53.6
SO ₂	−4.1	15.8	21.6	27.3	−35.6	−26.2	−27.7	−5.4	1.4	14.6	9.1	25.8	9.5
CO	−56.9	−41.0	−53.6	−19.6	−48.3	−35.1	−39.5	−21.2	−46.3	−32.1	−30.2	−21.5	−28.4
NO	−62.8	−59.6	−50.9	−70.2	−67.6	−63.5	−62.7	−62.6	−72.5	−73.6	−64.5	−71.6	−79.9
NO _x	−64.8	−61.7	−57.2	−58.0	−62.2	−57.6	−57.3	−50.8	−64.3	−62.5	−57.3	−55.9	−64.0
NO ₂	−54.6	−59.1	−51.0	−51.1	−55.8	−58.2	−56.1	−40.0	−52.6	−55.9	−49.4	−33.8	−44.3
NH ₃	−32.7	−17.3	−36.4	−49.1	−21.5	3.4	−13.1	−13.4	−28.5	−16.9	−22.6	−23.8	−8.2
Benzene	−64.4	−36.8	−36.5	−53.9	−63.3	−61.9	−59.8	−58.4	−58.1	−50.9	−54.9	−50.5	−47.3
Black carbon	−25.5		−71.0	−74.8	−77.2		−89.5	−64.4	−84.7		−88.6	−81.0	−73.4
Toluene					−41.4	−52.9	−53.0	−39.6	−27.7	−46.1	−39.1	−25.6	−21.2
Xylene					−36.1	−92.8	−85.0	−82.1	−61.1	−85.6	−82.0	−68.2	−70.3

LD1-4: lockdown phase 1 to 4; UL-1: unlock phase 1

in O₃ concentrations during lockdowns in cities like Wuhan (36%), Valencia (2.4%), Rome (14%) and Turin (27%). Similar trends were reported in Indian cities during lockdowns (Sharma et al. 2020; Jain and Sharma 2020; Sahoo et al. 2020a, 2021). Ozone is the only secondary pollutant covered here; it is formed indirectly in the troposphere by the action of sunlight and destroyed in the presence of NO_x, CO and volatile organic compounds (VOCs) (Lu et al. 2019; Sicard et al. 2020). Consequently, when most vehicles were off the road and there were little industrial activities, NO_x emissions drastically reduced, which lead to lower O₃ consumption ($\text{NO} + \text{O}_3 = \text{NO}_2 + \text{O}_2$) (Kim et al. 2018; Tobías et al. 2020; Sicard et al. 2020). Ozone levels are also influenced by seasonal temperatures. High temperatures give rise to O₃ formation during summer months, compared to the winter/monsoon (Lu et al. 2019). O₃ levels were well within the prescribed USEPA limit (120 ppb) irrespective of climatic or pre- to post-lockdown periods.

The NH₃ reduced (8.2–28.5%) during LDs compared to PL (2020), but to a lesser degree as compared to the other pollutants. Unlike the other pollutants, SO₂ increased between 1.4% and 25.8% during LD and 9.5% during UL compared to the PL (2020); all levels were consistently below NAAQS limits. Rising SO₂ level was possibly from coal and natural gas-based thermal power plants, which continued to operate during the LD periods. The principal sources of SO₂ are diesel and coal combustion and even though Delhi has made strides in S removal by flue gas desulfurization (FGD) of all fossil fuel-based energy (Parry and Tongia 2019) sources still remain. The cause of the SO₂

increase is not explained by the data but these findings are in agreement with Sharma et al. (2020).

The volatile organic compounds (VOCs) like benzene, toluene and xylene are generally higher in ambient urban air (Gaur et al. 2016). Among these compounds, benzene, which is a component of crude oil and petrol, demands special attention as it is a “known human carcinogen” (Category A; USEPA 1986). The average benzene level in the ambient air during LD₁₋₄ decreased up to 58% with respect to the pre-lockdown (2020) due to restriction on transport and industrial operations. When compared to 2018 and 2019, a significant reduction (64% and 61.9%, respectively) in benzene was observed. This reduction even remained during UL₁ (47%). Toluene and xylene were also significantly reduced during the lockdown and unlock phases.

Air quality index (AQI): pre-to-post lockdown

The air quality index (AQI) is generally used to express the magnitude of air pollution in a particular region (CPCB 2014; Sharma et al. 2020). This has been widely used by government agencies to inform citizens of the current status of air pollution. In India, the National AQI has been developed by the CPCB (2014). The AQI for Delhi in pre-, during and post-lockdown periods in 2020 and historical periods 2018–2019 is shown in Fig. 3. Before lockdown, the AQI was mostly “poor” to “very poor”; however, immediately after lockdown, it improved to “good” or “satisfactory” (except for a few samples); the “moderate” category was observed in the subsequent lockdown periods. This could

Fig. 3 Air quality index (AQI) for pre-lockdown (PL), lockdown (LD₁₋₄) and unlock (UL₁) periods in 2020 and the historical periods with respect to their corresponding time period in 2018 and 2019

be due reopening some essential services, as well as the change in temperature and onset of dry conditions. Overall, the most improvement was observed during LD₁. The “satisfactory” air quality also remained in the UL₁. AQI during LD compared to the same period in 2018 and 2019 (Fig. 3); reduction of almost 30 to 42% compared to the previous two years. This was corroborated with the CPCB, which showed 78% of cities recorded “good” to “satisfactory” AQI during LD. Since PM_{2.5} and PM₁₀ contribute significantly to the AQI, controlling these pollutants is crucial to maintaining acceptable air quality levels. Air quality on some days was impacted by dust storms unrelated to COVID-19 and/or perturbations due to weather.

Spatiotemporal analysis of air quality parameters

Spatiotemporal analyses of air pollutants during the pre-lockdown and lockdown periods are shown in Fig. 4 (additional data provided in Fig. 2SM and Table 2SM). Air pollutants, such as PM_{2.5}, PM₁₀, NO_x and CO were reduced significantly across Delhi during the lockdown periods. Before lockdown the North-west and Eastern part of Delhi, mainly Bawana, Mundka, Anand Vihar, Rohini, Nehru Nagar, Ashok Vihar, Wazirpur, Jahangirpuri, D Sector 8 and DTU had considerably higher levels of PM_{2.5}, PM₁₀, but decreased in South Delhi at Lodhi road, Pusa, Aya Nagar and RK Puram, etc. This may be because the former areas are either closer to industrial/semi-industrial clusters or experience more vehicular traffic, while the latter are mainly residential areas. PMs may be blown into the city through dust storms or are related to road traffic (nearly 30% of the annual mean), with industry, construction and dust re-suspension being minor sources (CPCB 2016; Mahato et al., 2020). Considerably higher drops in pollution level (up to 76%) in the former regions, except Bawana, during lockdown indicate that curbing vehicular and industrial emissions could be used as mechanisms to decrease air pollutants in urban centres (CPCB 2011, 2016), even if for only certain periods

of the day or days of the week, which has been effective in other parts of the World. Bawana is a major industrial area that remains polluted round the year and is also affected by open waste burning. However, reduced PM (up to 53%) in this area is possibly due to continuation of some industrial activities during the lockdown. Moreover, major PM reduction (83%) was observed at IHBAS, Dilshan Garden, likely due to very low vehicular traffic and almost no industry near this location. Interestingly, the maximum decline in both PMs was observed in LD₁, rising again towards LD₄, in the Northern regions, which may reflect a relaxation of curfew in the latter phase. NO₂ has a short lifespan and does not travel very far. During pre-lockdown, NO_x (NO₂, NO), were mostly enriched in Jahangirpuri, Jawaharlal Nehru Stadium, Major Dhyani Chand National Stadium, CRRI, IGIT3, Anand Vihar areas of East Delhi. As NO_x primarily gets into the air from burning petroleum based fuel (mostly emissions from cars, trucks and buses, as well as industries), it is a first-level indicator of traffic dominated pollution (CPCB 2016). Thus, these locations showed more pronounced drops in NO_x during the lockdown, even though the drop occurred across Delhi. The southern part of Delhi witnessed the best air quality for NO_x relative to other regions. In the case of SO₂, the concentrations were higher in Vivek Vihar, Jawaharlal Nehru Stadium and East Arjun Nagar in South and East Delhi during the pre-lockdown period. At these locations, higher levels of SO₂ during the lockdown phases are possibly due to the functioning of thermal power plants and other industries. The distribution of CO was different than the other pollutants, being higher in central and Eastern Delhi.

Overall, the maximum drop in some of the pollutants (PM_{2.5}, PM₁₀, NO₂ and CO) during the lockdown phases was observed during LD₁, even though they increased again at the same locations during LD₄, which may be due to relaxation of vehicular use during LD₄. Globally, there have been significant quantitative differences in pollution response to lockdown and subsequent relaxation. China, for example, noted a reduction of 40% in urban areas

Fig. 4 Spatial distribution of air pollutants ($PM_{2.5}$, PM_{10} , NO_x , NO_2 , CO , SO_2 and O_3) during immediate pre-lockdown (PL; 1st March to 23rd March) and lockdown (LD) phase 1 and 4 in Delhi

while the USA dropped 19–40% (Sharma et al. 2020). These inconsistent effects of lockdowns on air quality between cities might be due to each country's methodology for tackling the coronavirus pandemic. These differences have not been compared, but they are certainly due to differences in sources/types of pollutants, climate, methods of pollution sampling/evaluation, analytical methods and reporting. With time, a review of these differences may be possible.

Influence of meteorological factors on air quality

Apart from the industrial and vehicular emissions, local meteorological factors can also influence air quality (Jain and Sharma 2020; Dhaka et al. 2020; CPCB 2016). Delhi experiences significant variability in local weather patterns with extremely high temperatures and rainfall during summer compared to chilly winters with moderate rainfall (CPCB 2016). It has been shown that very high wind

Fig. 4 (continued)

Fig. 5 (a) PCA shows air quality pollutants in pre-lockdown and lockdown periods and (b) heat-plots depict the Spearman correlation coefficient matrices for parameters in pre-lockdown and lockdown period

speed and temperature and low relative humidity generally play a positive role in dispersing air pollutants relative to calmer winds or stagnant days (Sharma et al. 2020). This study shows that before the lockdown from January to March 2020, absolute temperature (AT) was 12.3–20.34 °C and wind speed (WS) was 1.11–1.29 m s⁻¹, against the AT (25.8–33.97 °C) and WS (1.11–1.29 m s⁻¹) (Table 1M). The lower temperature in pre-lockdown (Fig. 2; Table 1M) may

not be favourable for dispersion of air pollutants and could be one of the causes of increasing concentrations for all the pollutants. On the other hand, increasing AT at the beginning of the lockdown period may have contributed to the dispersion of pollutants and significant improvement in air quality. Similar observations have been made by Sharma et al. (2020). Although overall trends for wind speed were less varied between the pre and lockdown period (Fig. 2),

scattered rains in Delhi-NCR during March-end could have led to further improvement in air quality during lockdown periods. This could also be more effective during the unlock period that further reduced particulate matters. A negative correlation between $PM_{2.5}$ and PM_{10} and WS also further substantiates the role of wind speed in controlling particulate matter. Thus, this study shows that a rise in temperature and an increase of wind speed could be an additional factor in dispersing pollutants during lockdown phases. This is different for China because the first phase of lockdown there, which did not result in significant improvement in air quality, might have been due to unfavourable meteorology (Wang et al. 2020). Recently, Sharma et al. (2020) modelled the behaviour of air quality parameters using WRF-AER-MOD modelling and predicted that $PM_{2.5}$ might increase due to unfavourable meteorology, but they found that this reason might not be applicable for the air pollution during the month of November, even though similar restrictions on human activities were imposed, as the residential emissions significantly increase in North India, mainly due to space heating (Guo et al. 2017). This information would be helpful for providing key information to regulatory bodies or policymakers when executing stricter air quality control plans. Furthermore, excessive reduction of some pollutants ($PM_{2.5}$, PM_{10} , SO_2 , NO_2 and CO) may be one of the causes of lower surface air temperature in 2020 compared to 2019 and 2018. While meteorological factors were favourable for reducing pollutants, it is likely that the largest factor was reduced transportation and industrial activity.

Source and factor controlling air pollutants during pre-post lockdown

Principal component analyses (PCA) were applied separately for pre- and during lockdown periods on 16 parameters including air pollutants and meteorological parameters to identify the major sources and factors controlling air pollutants. Based on eigenvalues (> 1), three principal components (PC1, PC2 and PC3) were selected; they explain 65% of the total variance. Projection on to the first two PCs is given in Fig. 5a. In the pre-lockdown period, four groups are identified: Group-1: $PM_{2.5}$, PM_{10} , NO_x and black carbon; Group-2: CO, O_3 and AT; Group-3: NH_3 , SO_2 and WS; Group-4: xylene, benzene, toluene. These relationships are consistent with heat-plots (Fig. 5b), which suggests a good association and a common source possibly from automobiles combustion and industrial sources, which are common sources for both fractions of PMs and NO_x . However, in this group, $PM_{2.5}$ is strongly positively correlated with PM_{10} and both share a similar spatial distribution and only moderate correlation with NO_x , indicating that although both subgroups have shared a common source, PMs were contributed additionally from others source such as crustal dust.

Furthermore, since $PM_{2.5}$, PM_{10} and NO_x concentrations are correlated in the pre-lockdown period, the same relationship would be expected during lockdown. SO_2 is loaded positively on PC2 during the pre-lockdown period, but it was differently distributed during the lockdown period. Although the concentration of SO_2 could be the direct result of motor vehicles, particularly from diesel engines of buses and lorries and industrial emissions, the poor relationship between SO_2 and NO_2 could be due to having different sources and the ban of diesel engines in Delhi as well as the additional input from coal-fired power plants for the former (Pereira et al. 2007). Organic parameters such as benzene, toluene and xylene show positive association in pre-lockdown periods, indicating their common sources, such as burning petroleum-based fuels and other industrial activities. However, a weak association of these parameters in the lockdown period is possibly due to influence of restriction on anthropogenic activities. Ozone is closely associated with AT, but distributed differently from other major pollutants in both periods. Also, the Spearman correlation analysis shows a negative correlation between O_3 and NO_x . It has been reported that the variation of O_3 can be influenced by a number of O_3 precursors, especially by NO_x , as discussed above, because these compounds are undergoing photochemical reactions by absorbing solar radiation to produce ozone (Sicard et al. 2020), which is supported by the positive relation between O_3 and AT.

Defining COVID-19 baseline level for air quality parameters

As discussed earlier, the current COVID-19 lockdown that attenuated many anthropogenic factors producing inputs of atmospheric pollution resulted in substantial decreases in pollutants in Delhi. This is consistent with several other studies; thus, this period can represent the lowest levels of ambient pollution in major cities worldwide over the past decades (Krecl et al. 2020; Bashir et al. 2020; Zambrano-Monserrate et al. 2020; Gautam 2020; Sharma et al. 2020; Mahato et al. 2020; Jain and Sharma 2020; Sahoo et al. 2020a, 2021). Researchers have also postulated that this period is historic and represents the cleanest air quality in Delhi for the past 2 decades. Among the four phases of lockdown, the maximum reduction in atmospheric pollutants was achieved in the first lockdown period. Thus, this period has been considered as the most appropriate for defining the baseline levels of air pollutants under the COVID-19 lockdown scenario. This baseline level is representative of minimum level of air pollution when most of the major air polluting sources are shut. However, baseline level is not a single value, rather it should correspond to a range taking into account the natural variability (Reimann et al. 2005). The upper limit of baseline variation is known as threshold value. In this

Fig. 6 Frequency distribution curve showing the COVID-19 baseline threshold level–CBT (upper limit, based on mMAD) for air quality parameters in whole Delhi

study, the COVID-19 baseline threshold values (CBT; upper limit) were estimated using the recently developed statistical technique such as mMAD, TIF and percentiles, which are commonly used in geochemical studies (Sahoo et al. 2020b; Salāmao et al. 2019). Table 2 presents the CBT values for air quality parameters in Delhi by different methods. The results show that CBT values vary widely, in the order: TIF > 98th > mMAD > 95th > 75th, except in a few cases. The lowest values achieved by 75th and 90th were more conservative, thus not adequate for the present assignment of baseline values. TIF is a good method, but it sometimes exceeds the maximum concentration, as shown in Table 2. This may depend on data distribution that does not indicate the presence of outliers (Reimann et al., 2018; Sahoo et al. 2020b); thus, this technique may

not be suitable. mMAD, which is more robust and relies on the median and the median absolute deviation (MAD) of the data distribution and is inherently stable against outliers and deviations, may be more suitable (Salomão et al. 2019; Reimann et al. 2018). Also, this method provides more realistic values occurring between the 95th and 98th percentiles and often coincides with a break in the CP distribution (Fig. 6). Thus, mMAD was considered as the most appropriate for defining CBT level of air pollutants. Furthermore, as shown in the spatial maps (Fig. 4), the occurrence and distribution of parameters are quite different between stations, making it necessary to establish zone-wise CBT values. The CBT varied significantly with higher values in the North and West zones and the lowest in the East zone of Delhi (Table 2); using CBT values,

Table 2 COVID baseline threshold values (CBT; upper limit) of air quality parameters estimated by different methods

Parameter	Zone	Q75	Q90	Q95	Q98	mMAD	TIF	mSD	Max
PM ₁₀ (ug/m ³)	Central	89.24	103.44	109.05	113.72	115.11			116.87
PM ₁₀ (ug/m ³)	East	87.84	121.27	131.38	139.45	108.44	126.40	140.07	144.94
PM ₁₀ (ug/m ³)	North	127.29	143.00	163.89	177.96	164.63		176.68	187.3
PM ₁₀ (ug/m ³)	South	94.64	109.73	122.38	131.23	120.63		131.36	137.1
PM ₁₀ (ug/m ³)	West	134.37	172.55	192.36	208.04	187.88	205.58	204.55	218.7
PM₁₀(ug/m³)	Total	105.18	129.95	145.83	171.52	143.46	172.07	154.58	233.0
PM _{2.5} (ug/m ³)	Central	49.14	56.79	60.97	63.73	59.22		66.40	65.56
PM _{2.5} (ug/m ³)	East	37.37	42.40	55.06	62.56	44.35	58.91	60.16	67.51
PM _{2.5} (ug/m ³)	North	62.34	71.11	76.99	79.52	79.78			81.21
PM _{2.5} (ug/m ³)	South	47.18	54.98	58.03	64.78	57.29	78.32	64.77	69.46
PM _{2.5} (ug/m ³)	West	61.57	74.22	77.05	81.67	83.10		84.39	84.92
PM_{2.5}(ug/m³)	Total	52.95	67.47	77.79	89.85	74.77	91.33	79.45	105.4
CO(mg/m ³)	Central	0.94	1.09	1.16	1.25	1.13		1.24	1.31
CO(mg/m ³)	East	0.89	1.00	1.10	1.16	1.09		1.17	1.20
CO(mg/m ³)	North	0.59	0.68	0.70	0.78	0.76		0.78	0.83
CO(mg/m ³)	South	0.60	0.67	0.72	0.76	0.70		0.77	0.79
CO(mg/m ³)	West	0.56	0.64	0.68	0.70	0.71			0.72
CO(mg/m³)	Total	0.80	1.29	1.53	1.76	1.12	1.40	1.53	4.03
NH ₃ (ug/m ³)	West	37.64	43.44	50.93	52.65	43.54	45.81	49.62	53.64
NH ₃ (ug/m ³)	Central	24.85	28.58	30.39	31.51	31.33			32.27
NH ₃ (ug/m ³)	east	8.28	9.04	9.64	10.26	9.04	9.76	9.94	10.67
NH ₃ (ug/m ³)	north	8.65	9.40	10.15	10.62	9.78		10.70	10.94
NH₃(ug/m³)	Total	29.04	41.54	52.21	79.46	39.98	44.51	57.93	157.9
NO(ug/m ³)	Central	24.85	28.58	30.39	31.51	31.33			32.27
NO(ug/m ³)	East	8.28	9.04	9.64	10.26	9.04	9.76	9.94	10.67
NO(ug/m ³)	North	8.65	9.40	10.15	10.62	9.78		10.70	10.94
NO(ug/m ³)	South	5.40	7.52	9.91	12.81	6.97	9.27	11.14	14.82
NO(ug/m ³)	West	4.19	4.89	5.13	5.48	4.97	5.52	5.39	5.72
NO(ug/m³)	Total	7.77	23.63	35.11	72.98	10.40	16.16	44.34	145.6
NO ₂ (ug/m ³)	Central	30.50	34.27	37.08	40.65	38.76		41.16	43.05
NO ₂ (ug/m ³)	East	21.51	25.18	26.51	28.67	23.29		28.66	30.14
NO ₂ (ug/m ³)	North	29.19	35.53	42.33	47.66	34.45	39.82	46.92	51.28
NO ₂ (ug/m ³)	South	15.33	18.60	20.14	22.31	19.49		22.05	23.83
NO ₂ (ug/m ³)	west	18.85	21.93	22.65	24.14	23.01		24.58	25.19
NO₂(ug/m³)	Total	22.55	33.88	47.58	78.53	31.71	38.01	51.98	129.5
NO _x (ppb)	Central	37.63	40.53	43.49	46.33	44.08		46.83	48.24
NO _x (ppb)	East	15.98	19.79	21.30	23.11	17.39	23.82	22.64	24.32
NO _x (ppb)	North	22.96	25.68	29.72	33.18	26.81	30.82	32.57	35.55
NO _x (ppb)	South	16.82	19.99	22.06	26.62	21.32	28.20	25.80	29.83
NO _x (ppb)	West	13.37	15.28	15.84	16.56	15.67	19.53	16.95	17.06
NO_x(ppb)	Total	20.50	39.11	59.84	87.94	28.06	37.24	60.50	167.9
SO ₂ (ug/m ³)	Central	16.90	19.19	20.38	21.35	21.31		22.00	22.02
SO ₂ (ug/m ³)	East	13.66	16.22	18.11	19.95	16.35	19.58	19.19	21.19
SO ₂ (ug/m ³)	North	14.40	16.74	17.57	18.33	17.53	19.70		18.86
SO ₂ (ug/m ³)	South	15.54	17.76	18.92	20.79	18.76	21.50	20.68	22.10
SO ₂ (ug/m ³)	West	15.92	18.96	21.31	22.93	20.29	22.60	22.17	24.03
SO₂(ug/m³)	Total	18.02	22.41	25.80	29.72	27.21	32.11	27.46	39.16
CO(mg/m ³)	Central	0.94	1.09	1.16	1.25	1.13		1.24	1.31
CO(mg/m ³)	East	0.89	1.00	1.10	1.16	1.09		1.17	1.20
CO(mg/m ³)	North	0.59	0.68	0.70	0.78	0.76		0.78	0.83
CO(mg/m ³)	South	0.60	0.67	0.72	0.76	0.70			0.79

Table 2 (continued)

Parameter	Zone	Q75	Q90	Q95	Q98	mMAD	TIF	mSD	Max
CO(mg/m ³)	West	0.56	0.64	0.68	0.70	0.71			0.72
CO(mg/m³)	Total	0.80	1.29	1.53	1.76	1.12	1.40	1.53	4.03
Ozone(ug/m ³)	Central	32.62	36.44	38.26	40.02	41.24			41.25
Ozone(ug/m ³)	East	44.40	48.18	48.59	49.32	43.71		53.38	49.81
Ozone(ug/m ³)	North	43.39	47.82	50.44	52.32	52.95			53.59
Ozone(ug/m ³)	South	60.72	66.25	68.68	71.02	72.43			72.63
Ozone(ug/m ³)	West	60.35	64.37	65.50	66.39	60.96			66.99
Ozone(ug/m³)	Total	55.24	68.65	78.65	91.52	84.20	105.3	85.82	146.4
Benzene(ug/m ³)	Central	1.05	1.27	1.44	1.53	1.42		1.57	1.59
Benzene(ug/m ³)	East	3.32	4.79	5.11	5.50	3.18		5.45	5.77
Benzene(ug/m ³)	North	1.86	2.13	2.33	2.45	2.62		2.63	2.53
Benzene(ug/m ³)	South	1.57	2.10	2.22	2.33	1.64	2.22		2.40
Benzene(ug/m ³)	West	1.93	2.54	2.94	3.24	2.55		3.08	4.71
Benzene(ug/m³)	Total	1.92	3.53	5.19	6.25	2.91	3.71	4.76	13.26
Toluene(ug/m ³)	Central	3.82	4.54	5.24	5.75	4.79		5.78	6.09
Toluene(ug/m ³)	East	15.80	19.90	22.55	24.07	13.05		23.62	25.04
Toluene(ug/m ³)	North	19.34	22.22	24.34	25.64	25.45			26.50
Toluene(ug/m ³)	South	17.42	19.69	20.57	21.56	18.78		21.49	22.23
Toluene(ug/m ³)	West	8.43	13.60	16.76	19.07	10.79	16.27	16.18	20.81
Toluene(ug/m³)	Total	14.02	28.20	39.20	49.30	19.89	31.82	35.58	57.09

mMAD, median + 2median absolute deviation; *TIF*, Tukey inner fence; *mSD*, mean + 2standard deviation; percentile-based approach percentile (75th, 95th, 98th); *Max*, maximum; Empty cells, overestimated values; Total, whole Delhi. For zone (central, east, north, south, and west) classification please see Table 2SM

Fig. 7 Schematic diagram shows the establishment of COVID-19 baseline level of air pollutants for Delhi (one example is shown for PM_{2.5})

AQI was classified “good” to “satisfactory”. This gives an indication of how air quality in cities might improve if we switched to a lower-carbon economy. This baseline level should be kept in mind when framing the national

ambient air quality standards and may be considered in the new management guidelines/control strategies to reduce air pollution in the future. Furthermore, as transportation is the key driver of air pollution, it is crucial to

think of implementing more electrical systems not based on fossil fuels; this will be difficult in a country like India, which relies so heavily of coal. This mandate is critical for improving quality of life and longevity, in India (Jain et al. 2016).

Conclusions

The restrictions placed on transport, industry and construction activities due to COVID-19 lockdown have significantly improved air quality throughout Delhi, which is known as one of the most polluted megacities in the world. The $PM_{2.5}$ and PM_{10} levels reduced by as much as 58.9 and 57.1%, respectively, in the lockdown periods and even stayed significantly lower (as much as 52%) in the early unlock phase 1, which may have been aided due to favourable climatic change (e.g. increased rainfall). Other pollutants such as NO_x and CO and AQI also improved significantly during lockdown (as much as 61 and 49%, respectively). By location, North-west and Eastern Delhi experienced the maximum improvement in air quality. This viral scenario has shown that shutting down a city can significantly improve atmospheric pollution loads in urban areas, but is that a realistic solution to the problem; there are untested economic drawbacks. Based on the levels of pollution reduction, the lockdown phase 1 was considered as most appropriate for establishing COVID-19 baseline threshold values of air pollutants (CBT; Fig. 7). However, these CBT values should be used with caution as they are subjected to some uncertainty which may be due to the influence of meteorological conditions and presence of other anthropogenic emission. Moreover, this baseline levels can provide a steady response to overall air quality of a city and it may inform policymakers to set new target limits to fine-tune air quality standards and develop strategies for possible attenuation of atmospheric pollution, keeping in mind that the solutions must be realistic from an economic/development sense and in the context of managing the World's largest democracy. There are models for personal vehicle operation reduction (hours or days of the week that a person may drive their car) and pollution reduction strategies (for industry and construction) that have been implemented elsewhere, but India has its own reality. We believe the following science-driven efforts will address atmospheric benefits in the context of a growing economy:

1. Adopt an “airshed approach” to strengthen interstate collaboration including regional efforts to look beyond the city-centric or sector-centric approach (Guttikunda et al. 2019). This decentralization of goods and services will reduce migration and transportation (move-

ment of raw materials and finished products) emissions and will allow rural areas to improve their economic situations.

2. Reduce dependence on fossil fuel-based transportation/energy (promote electric/hybrid, CNG, wind energy, battery technology, etc. Vigorously promote existing State and Central Government of India policies related to use of electric mobility in metros to rural India.
3. Accept the harsh reality and educate citizens that under extreme conditions (like winter pollution in Delhi-NCR), it is better to legislate partial lockdowns and take other emergency measures such as banning construction and vehicles. This partial solution has been proposed by the emergency Graded Response Action Plan (GRAP) of Delhi (Shrangi 2020).
4. Promote working remotely (e.g. from home) rather than congested offices as has the IT sector. This will require policy to improve the digital infrastructure/internet scenario.
5. Increase education related to the benefits of public transport: improvements in the public transportation sector; reduction of individual cars.
6. Decrease vehicular density in all cities by implementing odd–even numbered license operation on alternating days, as is currently done in Delhi (and many other parts of the World).
7. Promote (possibly by tax incentives or fines) carpooling/sharing.
8. Deter the use of outdated four-wheel/three-wheel vehicles through government-based loan guarantee schemes to allow owners to upgrade to more environmentally friendly transports.
9. Replace fossil fuel-based energy with solar/wind/hydro.
10. Consider the use of particulate/smog reducing technologies (smog towers, mist cannons) in the most severely affected parts of the city.
11. Force interstate/intrastate movement of goods to take outer belts, bypassing metro areas.
12. Strict enforcement of existing regulations and tougher regulations, related to the locations of highly polluting industries and, more importantly, the regulations restricting emissions/effluents. This is a critical step to improve all of India.
13. Strict enforcement of existing and new, regulations related to construction activities and dust control (covers, spraying) in all cities.

Failure to act will certainly result in a return to “business as usual” and further deterioration of the urban atmosphere, with known/anticipated health/welfare impacts. Furthermore, the scenarios covered here do not take into account how biomass burning (a major source of household energy

in both urban and rural settings) should be dealt with if India expects to achieve a “liveable” atmosphere for future generations!

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

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