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TECHNICAL PAPER

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Unprecedented reduction in air pollution and corresponding short-term premature mortality associated with COVID-19 lockdown in Delhi, India

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ABSTRACT

Countries around the world introduced strict restrictions on movement and activities known as 'lockdowns' to restrict the spread of the novel coronavirus disease (COVID-19) from the end of 2019. A sudden improvement in air quality was observed globally as a result of these lockdowns. To provide insight into the changes in air pollution levels in response to the COVID-19 restrictions we have compared surface air quality data in Delhi during four phases of lockdown and the first phase of the restriction easing period (25 March to 30 June 2020) with data from a baseline period (2018–2019). Simultaneously, short-term exposure of $PM_{2.5}$ and O_3 attributed premature mortality were calculated to understand the health benefit of the change in air quality. Ground–level observations in Delhi showed that concentrations of PM_{10}, $PM_{2.5}$ and NO_2 dropped substantially in 2020 during the overall study period compared with the same period in previous years, with average reductions of ~49%, ~39%, and ~39%, respectively. An overall lower reduction in O_3 of ~19% was observed for Delhi. A slight increase in O_3 was found in Delhi's industrial and traffic regions. The highest peak of the diurnal variation decreased substantially for all the pollutants at every phase. The decrease in $PM_{2.5}$ and O_3 concentrations in 2020, prevented 904 total premature deaths, a 60% improvement when compared to the figures for 2018–2019. The restrictions on human activities during the lockdown have reduced anthropogenic emissions and subsequently improved air quality and human health in one of the most polluted cities in the world.

Implications: I am submitting herewith the manuscript entitled "Unprecedented Reduction in Air Pollution and Corresponding Short-term Premature Mortality Associated with COVID-19 Forced Confinement in Delhi, India" for potential publishing in your journal.

The novelty of this research lies in: (1) we utilized ground-level air quality data in Delhi during four phases of lockdown and the first phase of unlocking period (25th March to 30th June) for 2020 as well as data from the baseline period (2018–2019) to provide an early insight into the changes in air pollution levels in response to the COVID-19 pandemic, (2) Chatarize the change of diurnal variation of the pollutants and (3) we assess the health risk due to $PM_{2.5}$ and O_3. Results from ground-level observations in Delhi showed that concentrations of PM_{10}, $PM_{2.5}$ and NO_2 substantially dropped in 2020 during the overall study period compared to the similar period in previous years, with an average reduction of ~49%, ~39%, and ~39%, respectively. In the case of O_3, the overall reduction was observed as ~19% in Delhi, while a slight increase was found in industrial and traffic regions. And consequently, the highest peak of the diurnal variation decreased substantially for all the pollutants. The health impact assessment of the changes in air quality indicated that 904 short-term premature deaths (~60%) were prevented due to the decline in $PM_{2.5}$ and O_3 concentrations in the study period. The restrictions on human activities during the lockdown have reduced the anthropogenic emissions and subsequently improved air quality and human health in one of the most polluted cities in the world.

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Introduction

The novel coronavirus disease COVID-19 caused by SARS-CoV-2 (severe acute respiratory syndrome coronavirus 2), was first identified in Wuhan province in mainland China in December 2019. By March 2020, the disease had spread rapidly to other countries and the

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outbreak was declared a global pandemic on 12 March 2020 (WHO 2020). The COVID-19 disease has affected 110 million people and caused more than 2.45 million deaths worldwide as of 18 February 2021. The United States of America (USA), Brazil, Mexico, India, and the United Kingdom (UK) have experienced the greatest impact to date (18 February 2021), with death tolls of around 505,000, 243,000, 178,000, 156,000and 119,000, respectively (https://coronavirus.jhu.edu/).

On 30 January 2020, India reported its first COVID-19 case in Kerala, which rose to three cases by 3 February 2020, all were students returning from pandemic zone Wuhan, China. No significant rise in transmissions was observed in India in February. After observing the COVID-19 rising cases in Europe and the USA, the Indian government announced "*Janta (People) Curfew*" on March 22, 2020, a 14 -h self-quarantine curfew to maintain social distance (PIB 2020). Three days later, on 25 March 2020, the Indian government announced a strict lockdown for the entire nation with 1.3 billion citizens. After 68 days of lockdown, the first phase of the unlock process started on 1 June 2020 with some restrictions still in place. The long-term lockdown was not able to prevent the spread of COVID-19 in India. As of 18 February 2021, the total number of positive cases in India stands at 10.96 million, with 10.66 million recoveries and 156,000 deaths. Maharashtra, Tamil Nadu, Karnataka and Delhi reported 51,100, 12,400, 12,200 and 10,900 thousand deaths from COVID-19 respectively (https://www.covid19india.org/).

COVID-19 has shown higher disease severity and death risk in patients with co-existing illnesses (comorbidities) (Cai 2020; Guan et al. 2020). In Italy, 60% of COVID-19 deaths occurred in people with hypertension (69%), type-2 diabetes (32%), chronic renal failure (21%) and ischemic heart disease (27%) (Michelozzi et al. 2020). The excess in mortality was higher among men than among women, with an increasing trend by age (Michelozzi et al. 2020). A meta-analysis of data from China, Italy, Spain, UK, and New York State by Bonanad et al. (2020), reported that the number of COVID-19 deaths among the infected population aged ≥60 years old was 12.6 times higher than for those aged <60 years. The number of COVID-19 cases and death rates tend to be higher in both high population density and high particulate matter (PM) exposure areas. The viral genome (SARS-COV-2 RNA) has been found on particulate matter (PM_{10} and $PM_{2.5}$) which may have increased the transmission and spread of COVID-19 (Setti et al. 2020). PM_{10} and $PM_{2.5}$ also suppress innate anti-viral immunity and enhance influenza virus replication via metabolic pathway gene modulation, amplifying the number of deaths from respiratory and cardiovascular disease in COVID-19 patients (Mishra et al. 2020). For example, Zhu et al. (2020) reported a 0.22% increase in COVID–19 positive cases for each 1 μg/m^3 increase in $PM_{2.5}$ concentrations in China. Cole, Ozgen, and Strobl (2020) found that a 1 μg/m^3 increase in $PM_{2.5}$ was associated with an increase of 13.0–21.4% in the COVID-19 death rate in the Netherlands, larger than the 8% increase in death rate reported for the same $PM_{2.5}$ increase in the USA (Wu et al. 2020).

The COVID-19 forced restriction in all public activities, except for essential sectors, throughout the world. This resulted in lowered anthropogenic emissions and consequent appreciable reductions in gaseous and PM concentrations across cities worldwide (Bauwens et al., 2020; Adams 2020; Berman and Ebisu 2020; Menut et al. 2020), except for O_3 concentrations which increased in some places in the UK (Semple and Moore 2020; Zoran et al. 2020). Studies in India show an appreciable reduction in air pollutants associated with the COVID–19 lockdown restrictions, although most of the studies focus on the first phase of lockdown (25 March – 14 April 2020) (Jain and Sharma 2020; Mahato, Pal, and Ghosh 2020; Singh and Chauhan 2020; Srivastava et al. 2020). A significant reduction was noted for PM_{10}, $PM_{2.5}$ and NO_x level by 44%, 21% and 51%, respectively, in Delhi during the "*Janta Curfew*" on March 22–23, 2020 compared to the previous day (Table 1). This sudden decrease in air pollution was brought about by the combination of reduced vehicles on the road, functioning of only essential commercial units and weather conditions.

The lockdown began in March which is early spring in northern India. Human activities generate the majority of aerosols in this area. Motor vehicles, coal-fired power plants, and other industrial sources around urban areas produce nitrates and sulfates, and coal combustion produces soot and other carbon-rich particles. Rural areas add smoke rich in black carbon and organic carbon from cooking and heating stoves, as well as smoke from the burning of crop stubble on farmland (though farming fires occur more often in late September and October each year) (NASA 2020).

This study aimed to investigate the impact of COVID–19 restrictions on air quality, during four phases of lockdown and the first phase of unlocking in Delhi, with respect to (a) the characteristics of PM_{10}, $PM_{2.5}$, NO_2, and O_3 based on daily data in 2020 and compared with the similar periods in 2018–2019; (b) the diurnal variation of identified pollutants in from 2018–2020, and (c) quantification of health benefits due to the reduction of pollutants concentrations in Delhi.

Table 1. Summary of the recent studies conducted on the effects of COVID–19 lockdown on air pollution in the urban city around the world.

City	Study phase	Pollutants	Findings
Delhi (Mahato, Pal, and Ghosh 2020)	2–21 March, 2020 (before lockdown); and 25 March-14 April, 2020 (LDP–1)	PM_{10}, $PM_{2.5}$, SO_2, NO_2, CO, O_3, NH_3	The reduction of concentrations were PM_{10} (53%), $PM_{2.5}$ (53%), SO_2 (18%), NO_2 (53%), CO (30%), O_3 (1%), NH_3 (12%) compairted to before lockdown.
Delhi and Mumbai (Chauhan and Singh 2020)	December 2019–March 2020, and compared with 2017–2019	$PM_{2.5}$	During March 2020, the highest percentage reductions in $PM_{2.5}$ were observed in Delhi (35%) and Mumbai (14%) compared to March 2019.
Megacity in India (Chauhan and Singh 2021)	10–31 March 2020, and compared with the same period in 2019	$PM_{2.5}$, HCHO, NO_2, SO_2, CO and O_3	The decline of 62, 26, 22, 40% were observed in tropospheric NO_2 concentration after the lockdown in Delhi, Mumbai, Chennai and Kolkata.
Ghaziabad (Kumari, Lakhani, and Kumari 2020)	24 March to 31 May in 2020 (LDP-1 to LDP–4) and compared with the same period in 2019	PM_{10}, $PM_{2.5}$, CO, SO_2, O_3 and NO_2	During lockdown period in 2020, average levels of PM_{10} (57%), $PM_{2.5}$ (48%), CO (41%), SO_2 (46%), O_3 (6%) and NO_2 (59%) showed reduction in comparison to 2019.
Shanghai, China (Filonchyk and Peterson 2020)	24 January to 6 February in 2020 and compared with the same period in 2019	$PM_{2.5}$, PM_{10}, SO_2, NO_2, and CO	The $PM_{2.5}$, PM_{10}, SO_2, NO_2, and CO concentration during the lockdown period were reduced by 9%, 77%, 31.3%, 60.4%, and 3% respectively compared to the same period in 2019.
New York City (NYC), USA (Zangari et al. 2020)	First 17 weeks of 2020, and compared with the same period in 2015–2019	$PM_{2.5}$ and NO_2	Daily average NO_2 concentration in the NYC region fell by approximately 51%. No significant difference was found for $PM_{2.5}$.
Naples (Italy) (Sannino et al. 2021)	13 March to 4 May in 2020 and compared with the same period in 2019	$PM_{2.5}$ and NO_2	The typical reduction in the range of 20–35% for $PM_{2.5}$ and 45–50% for NO_2.
41 city in India (Vadrevu et al. 2020)	25 March to 3 May 2020 and compared to the pre-lockdown (1 January – 24 March 2020) period	NO_2	The cities with the highest NO_2 pollution reduction were Delhi (60%), Bangalore (48%) and Ahmedabad (46%).
Delhi (Dhaka et al. 2020)	25 March to 14 April 2020 and compared with pre–lockdown (1 March to 24 March 2020	$PM_{2.5}$	Around 40–70% reduction of $PM_{2.5}$, depending upon the location in Delhi.
Megacities in India (Sathe et al. 2021)	25 March to 17 May 2020 and compared with the same period in 2017–2019	$PM_{2.5}$, PM_{10}, NO_2, SO_2, O_3 and CO	A significant reduction of NO_2 (46–61%) and $PM_{2.5}$ (42–60%). And PM_{10} (24–62%), O_3 (22–56%) showed a substantial reduction whereas CO (16–46%), exhibited a moderate decline.

Data description and methodology

Delhi is the second-largest megacity in the world and the largest urban agglomeration in India with an estimated population of 19.3 million in 2020 (https://www.census2011.co.in/census/state/delhi.html). The present study on air quality during COVID-19 restrictions has focused on Delhi which is the administrative capital and the second major financial city of India. The lockdown was renewed four times [Lockdown Phase 1 (LDP-1): 25 March– 14 April 2020; LDP-2: 15 April 2020–3 May 2020; LDP-3 (4 May 2020– 17 May 2020; LDP-3: 18 May 2020 – 31 May 2020; Unlock Phase 1 (ULP–1): 1 June 2020 – 30 June 2020] after observing the number of cases at the end of each phase. Each lockdown phase had a different level of restriction on public activity (more details are reported in Table 2).

Materials used

Hourly air quality data from 34 continuous ambient air quality monitoring stations covering different regions of Delhi have been taken into consideration to assess the air quality during the four phases of the lockdown period and the first month of the unlocking period. The organizations responsible for these air quality monitoring stations include CPCB (Central Pollution Control Board); DPCC (Delhi Pollution Control Committee) and SAFAR (System of Air Quality and Weather Forecasting and Research) and IITM Pune (Indian Institute of Tropical Meteorology). Hourly time series data of four air pollutants, $PM_{2.5}$, PM_{10}, nitrogen dioxide (NO_2), and ozone (O_3) from 25 March to 30 June in 2018–2020, were downloaded from the CPCB online portal Central Control Room for Air Quality Management – Delhi NCR (https://app.cpcbccr.com/ccr/#/caaqm-dashboard/caaqm-landing/data). Rigorous protocols for sampling, analysis and calibration are followed by CPCB to provide appropriate data quality assurance and quality control (QA/QC). Additional data criteria required for inclusion in this study were as follows (i) ≥ 80% hourly data capture for the period 25 March to 30 June; (ii) >12 h of available data in a day; (iii) spurious outliers in the data with z-scores exceeding an absolute value of 4 were removed and (iv) data below the detection limit of the measurement instruments were removed (Table S1). We observed that >93% of the hourly data at 11 monitoring stations was available for further calculation after our criteria and quality checks (Table 3 and Figure 1).

The daily average meteorological information was collected from OGIMET (www.ogimet.com), which uses freely available data from the National Oceanic

Table 2. The time frame of four phases of lockdown and unlock period and corresponding probable sources of air pollution in Delhi.

COVID-19 restriction Phases	Restriction-level in Delhi
Lockdown-1 [25 March – 14 April 2020 (21 days)] (LDP-1)	Except for the emergency sector, all sector remains closed. The possible source for air pollution (Ministry of Heavy Industry and Public Enterprises 2018): ● Power plants, household, diesel generator, sea salt and dust from trans-border. ● Goods vehicles, as all goods traffic was allowed to ply.
Lockdown-2 (15 April 2020 – 3 May 2020 (19 days) (LDP-2)	Except for the emergency sector, all sector remains closed and with a conditional relaxation for certain businesses. The possible source for air pollution: ● Power plants, household, diesel generator, sea salt and dust from trans–border. ● Goods vehicles, as all goods traffic was allowed to ply. ● Industry, as some manufacturing units in industrial estates and industrial township, were allowed to operate with a 30–40% workforce. ● Brick kilns in rural areas started to operate. Brick kilns in surrounding Delhi are responsible for air pollution in Delhi city. ● Open burning from agriculture (maybe), like all agricultural and horticultural activity, was fully functional. ● Dust from construction activity where workers are available on site.
Lockdown-3 (4 May 2020 – 17 May 2020 (14 days) (LDP-3)	National lockdown with some relaxation in the day time. The movements of individuals, for all non-essential activity, was strictly prohibited between 7 pm to 7 am. The possible source for air pollution: ● Power plants, household, diesel generator, sea salt and dust from trans-border. ● Vehicles: although some public transport was remain shut, private vehicles – four-wheelers and two-wheelers were ply. With the condition that public bus with 50% capacity and a maximum of 20 passengers, four-wheelers can carry two people and a driver and only one person on two–wheelers. ● Industry, as all manufacturing industry in the urban area, was allowed to operate with a 30–40% workforce. ● Brick kilns in rural areas started to operate. ● Open burning from agriculture (maybe), like all agricultural and horticultural activity, was fully functional. ● Dust from all construction activity where workers are available on site.
Lockdown-4 (18 May 2020 – 31 May 2020 (14 days) (LDP-4)	National lockdown with some relaxation in the day time. The movements of individuals, for all non-essential activity, was strictly prohibited between 7 pm to 7 am, except the essential activity. The possible source for air pollution: ● Same as Lockdown 3.
Unlock-1 (only for containment zones): 1 June 2020 – 30 June 2020 (30 days) (ULP-1)	All activity was normally operated. Although, the movements of individuals, for all non-essential activity, was strictly prohibited between 9 pm to 5 am, except the essential activity. Metro operations were remain suspended. The possible source for air pollution: ● Power plants, vehicles, industry, household, brick kilns, open burning, diesel generator sets, sea salt and dust (from construction, soil, re-suspended and trans–border)

and Atmospheric Administration (NOAA). Delhi typically has four seasons: winter (December-February), summer (March-May), monsoon (June-August) and post-monsoon (September-November) (Hama et al. 2020).

Methodology for quantifying air pollution changes

A differential approach was used to quantify air pollution changes coincident with COVID−19 during 2020 in comparison with the similar period in 2018–2019. For the March-June differential, we calculated daily average pollutant levels for March-June each year from 2018 to 2020. The differential was defined as the difference between 2020 values and the average of those for a 2–year baseline (2018–2019). We searched the central and Delhi state government websites to identify the dates for different phases of the lockdown and the unlocking periods in Delhi. Table 2 reports the details of lockdown and unlock phases and their different levels of restrictions. A paired t-test was used to determine whether, on average, there was a change in average pollutant levels during each of the identified subperiods. We considered a p-value higher than $\alpha = 0.05$, as not statistically significant (Table S4). The percentage variation of the average pollutant concentrations throughout the subperiods were examined. We also examined the role of different meteorological variables on the changes in air quality in Delhi during the period investigated.

Health impact assessment

We estimated short-term all-causes, cardiovascular diseases (CVD), ischemic heart disease (IHD), respiratory disease (RD) and stroke-related mortalities attributable to ambient $PM_{2.5}$ and O_3–exposure at Indian capital from 2018–2020, using the log-linear exposure-response function, described in past studies (Seltzer, Shindell, and Malley 2018; Stanaway et al. 2018) as:

Table 3. Brief description of monitoring sites operated by CPCB (Central Pollution Control Board) and DPCC (Delhi Pollution Control Committee).

Monitoring stations	Type of site	Latitude and Longitude
Ashok Vihar (AV)	Industrial + Residential (I + R)	Latitude: 28.695381, Longitude: 77.181665
Dwarka Sector (DS)	Commercial + Residential (C + R)	Latitude: 28.5710274, Longitude: 77.0719006
Delhi Technological University (DTU)	Industrial + Residential (I + R)	Latitude: 28.7500499, Longitude: 77.1112615
Jawaharlal Nehru Stadium (JNS)	Commercial + Residential (Road Side) (C + R + T)	Latitude: 28.580280, Longitude: 77.233829
Jahangirpuri (JP)	Commercial + Residential (C + R)	Latitude: 28.732820, Longitude: 77.170633
Major Dhyan Chand National Stadium (MDC)	Commercial + Residential (C + R)	Latitude: 28.611281, Longitude: 77.237738
Mandir Marg (MM)	Industrial + Residential (Traffic) (I + R + T)	Latitude: 28.636429, Longitude: 77.201067
Nehru Nagar (NN)	Industrial + Residential (I + R)	Latitude: 28.567890, Longitude: 77.250515
Rohini (RH)	Industrial + Residential (I + R)	Latitude: 28.732528, Longitude: 77.119920
Vivek Vihar (VV)	Industrial (I)	Latitude: 28.672342, Longitude: 77.315260
Wazirpur (WP)	Industrial (I)	Latitude: 28.699793, Longitude: 77.165453

$$\Delta C = \begin{cases} 0 & if\ [P_c] \le\ TMREL \\ [P_c] - TMREL & f\ [P_c] >\ TMREL \end{cases}$$

$$\beta = \ln(RR)/\Delta X$$

$$\Delta Mort = (1 - \exp^{-\beta \Delta C}) \times D_0 \times EP$$

where TMREL represents the theoretical minimum risk exposure level and ΔC is $PM_{2.5}$ or O_3-exposure relative to TMREL. β is the exposure-response coefficient derived from the reported relative risk (RR), which links incremental changes in $PM_{2.5}$ or O_3-exposure ΔX (10 μg/m^3 in average $PM_{2.5}$ concentrations or DMA8-h O_3). D_0 is the cause-specific death rate, obtained from

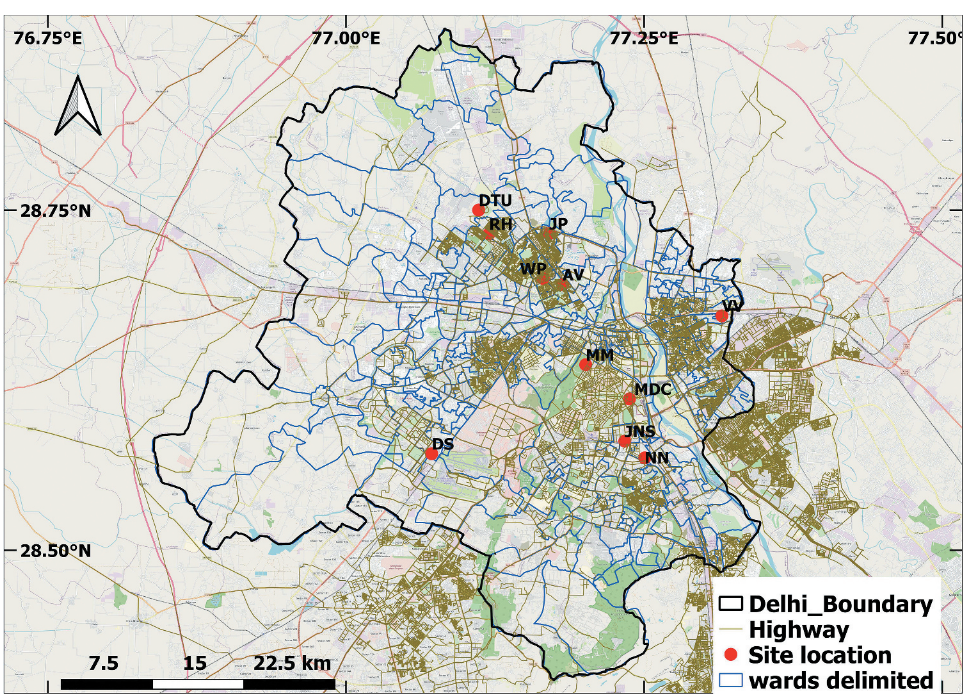

Figure 1. The spatial location of 11 continuous air quality monitoring stations in Delhi. [Figure has been made using QGIS (https://www.qgis.org/en/site/)]. Station abbreviations are shown in .Table 2.

the GHDx database (http://ghdx.healthdata.org/gbd-results-tool). *EP* is the exposed population age ≥ 25 years and *ΔMort* is the estimated number of cause-specific mortalities in a city. In this study, we used the average daily value of $PM_{2.5}$ and the average DMA8-h O_3 metric for short-term health risk analysis. We used TMRELs of 10 μg/m^3 for $PM_{2.5}$ (based on WHO guidelines) and 70 μg/m^3 for O_3 (as recommended in the HRAPIE project) (WHO 2013). In our $PM_{2.5}$-attributed short-term mortality, β was estimated using adopted relative risk (*RR*) from a Chinese epidemiological study as no cohort study was available for India (Chen et al. 2017; Yin et al. 2017) (S1.1).

Results and discussions

Overview of daily mean air quality levels

Figure 2 and Table S3 show daily average concentrations of pollutants monitored at the 11 monitoring sites for 2018–2020. The daily average of all monitoring stations showed that PM_{10} concentrations in 2020 were 119 ± 54 μg/m^3, reduced from 273 ± 140 μg/m^3 in 2018 and 242 ± 90 μg/m^3 in 2019, indicating a reduction of 49.0 ± 29.6% when compared with daily data those of the same period in 2018–2019. For the industrial background stations the magnitude of the decline of PM_{10} was as high as 56.8 ± 23.0% at location AV, 56.4 ± 20.4% at location MM and 58.4 ± 21.1% at location WP (Figure 3). During the entire study period, the daily average $PM_{2.5}$ was 90 ± 44 μg/m^3 in 2018 and 81 ± 34 μg/m^3 in 2019, which was reduced to 48 ± 20 μg/m^3 in 2020 showing a reduction of 38.6 ± 29.0% when compared to 2018–2019. Overall, at residential and traffic background sites the magnitude of the decline of $PM_{2.5}$ was as high as 43.4 ± 23.8% at JNS, 46.3 ± 20.9% at MDC and 42.8 ± 33.9% at MM, whereas in industrial and residential mix regions, the decrease was smaller, 28.6 ± 35.1% in RH and 30.0 ± 31.6% in DTU.

The NO_2 concentrations were high in 2019, 52.8 ± 20.4 μg/m^3, compared to 43.6 ± 27.9 μg/m^3 in 2018. Due to the COVID–19 lockdown in 2020, the overall concentrations of NO_2 came down to 24.9 ± 13.4 μg/m^3, showing a reduction of 38.8 ± 46.2% compared to the average daily value in 2018–2019. The monitoring sites in commercial and residential areas, JNS and MDC, demonstrated the greatest decrease in NO_2 (JNS: 66.6 ± 18.5% and MDC: 64.2 ± 17.8%) concentrations during the COVID-19 lockdown restrictions. Based on 11 monitoring stations, the highest level of maximum daily average 8–h (MDA8) O_3 concentrations were observed in 2019 (95.3 ± 35.1μg/m^3), an increase from 2018 (81.6 ± 39.0 μg/m^3), followed by a decrease to 65.2 ± 41.9 μg/m^{3}in 2020. The overall MDA8 O_3 concentrations decreased by 19.1 ± 67.6% in 2020 compared to the daily average value in 2018–2019, although the monitoring sites in the industrial-residential area DTU and NN indicate 103.9 ± 96.3% and 11.7 ± 44.2% increase of MDA8 O_3 (Figure 3).

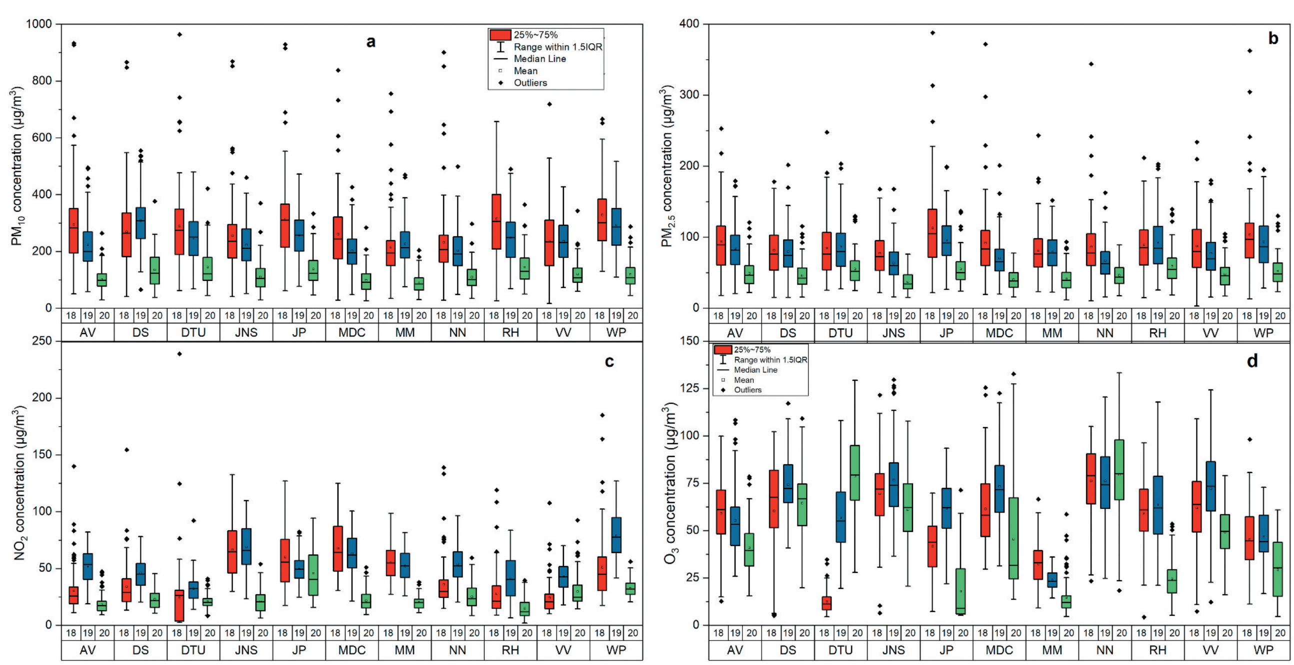

Figure 2. Boxplot of average concentrations of the analyzed pollutions (a) PM_{10}, (b) $PM_{2.5}$, (c) NO_2 and (d) O_3 at 11 monitoring sites in Delhi from 2018–2020 during the study period (25 March to 30 June). The mean (black square), median (horizontal black line), interquartile range (IQR) (box), and IQR ± 1.5*IQR (whiskers) represented the concentration of the pollutant in μg/m^3.

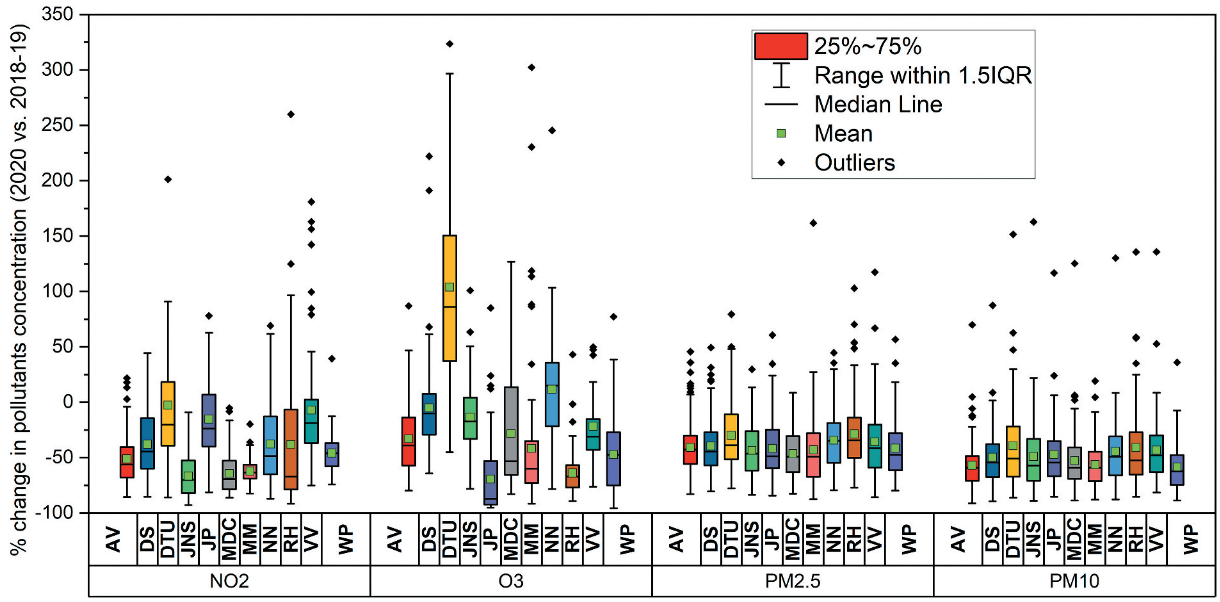

Figure 3. Boxplot of percentage (%) change of daily pollutants concentrations during the total study period in 2020 compared to 2018–19 of PM_{10}, $PM_{2.5}$, NO_2, and O_3 at 11 monitoring sites in Delhi.

In Delhi, the significant contributors to annual $PM_{2.5}$ emissions include road dust (38%), vehicle exhaust emissions (20%), domestic fuel burning (12%), and industries (11%) (Sharma and Dikshit 2016). Previous studies of the Delhi megacity have reported that vehicular emissions (exhaust and non-exhaust) provide a significant contribution (up to 60%) to Delhi's $PM_{2.5}$ load (Singh et al. 2020). Only essential service (like police, hospital, army, and other emergency transport) vehicles were permitted during lockdowns phase 1 and 2, all commercial vehicular movements were restricted. This restriction resulted in a significant reduction in both exhaust and non-exhaust emissions, both significant contributors to the total PM load.

Variation of air quality during different phases of lockdown and unlocking period

Table 4 presents the mean, standard deviation and median of $PM_{2.5}$ concentrations at 11 monitoring sites during the four lockdown phases (i.e., LDP-1, LDP-2, LDP-3, LDP-4) and first-phase of unlocking (i.e., ULP–1), and for the same periods in 2018 and 2019. The details of PM_{10}, NO_2 and O_3 concentrations in five phases in 2018–2019 and 2020 are reported in Table S4. Comparing data for the same seasonal period minimized the influence of confounding factors such as meteorological conditions. Pollutant concentrations (as % reduction) in 2020 compared with that of the previous two years in 11 monitoring stations in five phases are shown in Figure 4 to further demonstrate the impact of COVID-19 lockdown restrictions.

In 2020, generally, PM_{10} concentrations continuously increased from LDP-1 to LDP-4 (LDP1: 90.5 ± 33.6 μg/m^3; LDP4: 159.4 ± 69.7 μg/m^3) due to the gradual removal of lockdown restrictions for each phase. PM_{10} concentrations decreased in ULP-1 (123.9 ± 56.2 μg/m^3) compared to LDP-4. In LDP–4, PM_{10} concentrations reached their highest levels at monitoring sites DTU (214.3 ± 89.9 μg/m^3) and JP (212.8 ± 61.5 μg/m^3) (Table 4). However, when the 2020 levels are compared with those for the same period in 2018–2019, it was observed that overall PM_{10} concentrations reduced in 2020, and that the reduction varied for the four lockdown phases and unlock phase, ranging from 61.1 ± 17.6% (LDP-1), 55.8 ± 20.5% (LDP-2), 55.3 ± 18.4% (LDP-3), 34.4 ± 30.3% (LDP-4) to 40.1 ± 38.2% (ULP-1) (Table 5). Monitoring site-specific PM_{10} reductions are shown in Figure 4a.

The daily average $PM_{2.5}$ concentrations in 2020 were always below the Indian air quality standard (24 h: 60 μg/m^3), ranging from 44.2 ± 17.1 μg/m^3 (LDP-1) to 56.9 ± 31.8 μg/m^3 (LDP–4), whereas in 2018–2019, the average concentrations were observed to be above the standard (71.9 ± 31.4 μg/m^3 in ULP1 and 102.8 ± 33.1 μg/m^3 in LDP3). Although, in LDP4, the monitoring sites DTU (71.7 ± 37.5 μg/m^3), JP (71.7 ± 37.2 μg/m^3) and RH (73.1 ± 40.4 μg/m^3) showed higher $PM_{2.5}$ concentrations in 2020 when compared to the same period in 2018–2019 (Table 4). In 2018–2019

Table 4. The daily average $PM_{2.5}$ concentration (μg/m^3) at the 11 monitoring stations during the study period (25th March–30th June) during 2018–2019 and 2020 in different four phases of lockdown and first unlock phase across Delhi.

	2018–2019 [mean ± SD (median)] (μg/m^3)					2020 [mean ± SD (median)] (μg/m^3)				
Monitoring Site	LDP-1	LDP-2	LDP-3	LDP-4	ULP-1	LDP-1	LDP-2	LDP-3	LDP-4	ULP–1
AV	100.7 ± 35.5 (100.3)	92.9 ± 27.5 (97.2)	108.3 ± 37.2 (98.5)	89.6 ± 27.8 (86.7)	68.7 ± 38.9 (60.3)	45.2 ± 14.6 (38.7)	47.0 ± 17.5 (42.6)	54.2 ± 15.5 (53.0)	57.4 ± 32.0 (47.8)	46.4 ± 13.4 (47.0)
SD	87.0 ± 28.3 (87.0)	86.8 ± 33.8 (86.6)	96.6 ± 41.9 (86.0)	82.2 ± 21.5(82.8)	64.1 ± 26.0 (60.9)	48.5 ± 18.9 (45.6)	43.8 ± 16.2 (39.5)	51.5 ± 19.4 (47.5)	53.1 ± 29.1 (50.2)	39.8 ± 11.1 (37.3)
DTU	95.2 ± 36.4 (103.5)	83.3 ± 31.3 (78.9)	113.8 ± 49.0 (105.9)	83.2 ± 21.2 (84.8)	69.0 ± 36.4 (60.9)	51.9 ± 15.4 (47.1)	49.6 ± 19.8 (44.7)	62.0 ± 25.1 (54.4)	71.7 ± 37.5 (71.0)	50.4 ± 12.1 (49.7)
JNS	76.0 ± 25.2 (72.9)	70.9 ± 28.8 (71.4)	81.3 ± 32.5 (76.7)	70.0 ± 22.4 (70.3)	60.9 ± 28.5 (55.1)	33.6 ± 13.0 (31.0)	36.7 ± 12.7 (37.4)	43.6 ± 16.2 (42.7)	40.9 ± 20.1 (33.7)	36.0 ± 9.8 (33.9)
JP	120.3 ± 35.5 (125.0)	104.8 ± 34.3 (103.2)	117.0 ± 42.8 (111.5)	99.5 ± 30.2 (99.4)	89.4 ± 65.2 (74.7)	52.5 ± 14.1 (49.5)	49.8 ± 18.4 (48.0)	61.8 ± 22.7 (59.3)	71.7 ± 37.2 (73.4)	50.1 ± 12.3 (48.6)
MDC	77.4 ± 23.0 (74.4)	80.0 ± 31.7 (76.6)	91.4 ± 36.7 (82.1)	84.4 ± 30.8 (84.9)	77.7 ± 61.5 (61.0)	34.8 ± 12.8 (31.4)	40.2 ± 12.7 (42.1)	45.3 ± 14.4 (42.7)	43.6 ± 19.2 (37.6)	39.8 ± 9.9 (39.5)
MM	73.6 ± 26.4 (72.6)	87.7 ± 22.5 (86.4)	92.4 ± 29.4 (93.0)	84.7 ± 28.0 (79.2)	72.1 ± 37.5 (63.7)	33.5 ± 10.6 (30.4)	35.4 ± 13.9 (30.9)	46.1 ± 14.0 (40.8)	44.6 ± 25.4 (40.8)	46.8 ± 16.8 (43.6)
NN	79.4 ± 26.2 (78.3)	78.6 ± 30.9 (74.6)	90.5 ± 31.5 (82.9)	77.4 ± 25.6 (74.4)	66.7 ± 54.7 (58.1)	44.3 ± 17.0 (41.4)	47.8 ± 14.4 (50.3)	50.8 ± 13.5 (48.3)	49.7 ± 23.2 (44.3)	43.0 ± 11.8 (43.7)
RH	99.8 ± 34.9 (99.5)	91.0 ± 32.6 (87.0)	118.3 ± 43.7 (107.7)	87.7 ± 29.3 (88.1)	72.0 ± 34.1 (66.1)	57.1 ± 18.4 (55.8)	57.7 ± 20.0 (54.5)	65.2 ± 27.9 (58.7)	73.1 ± 40.4 (69.1)	52.2 ± 13.2 (51.6)
VV	99.9 ± 37.2 (93.0)	79.1 ± 27.9 (76.8)	99.8 ± 35.2 (92.5)	79.1 ± 25.7 (81.9)	65.8 ± 36.9 (58.9)	37.8 ± 18.1 (31.3)	47.1 ± 18.1 (46.1)	52.5 ± 14.9 (49.8)	55.9 ± 29.4 (48.1)	49.6 ± 14.3 (48.4)
WP	105.1 ± 35.4 (106.3)	99.5 ± 27.1 (101.3)	116.7 ± 41.1 (105.9)	98.6 ± 23.9 (97.6)	84.3 ± 61.5 (69.1)	47.2 ± 15.1 (44.1)	50.9 ± 18.2 (47.1)	57.7 ± 20.7 (53.5)	64.0 ± 35.3 (58.3)	47.8 ± 12.0 (45.9)

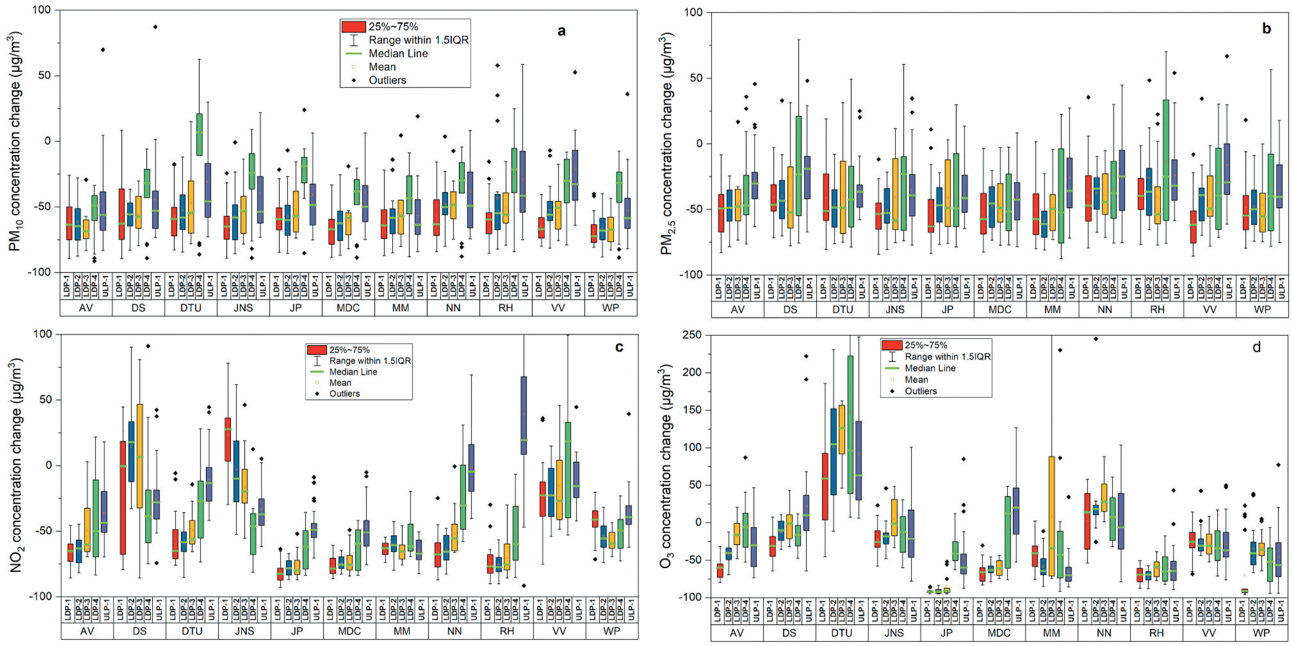

Figure 4. Boxplot of percentage (%) change of daily pollutants concentrations in 2020 compared to 2018–2019 of (a) PM_{10}, (b) $PM_{2.5}$, (c) NO_2 and (d) O_3 at 11 monitoring sites in Delhi in four phases of lockdown and the first phase of unlocking period. The mean represented as orange square, median as the horizontal green line, interquartile range (IQR) as solid box, and IQR ± 1.5*IQR as black whiskers.

Table 5. Average percentage change of pollutants concentration in different phases in 2020, compared to the same period 2018–2019.

	Percentage change in pollutants concentration (%)					
Pollutants	LDP-1	LDP-2	LDP-3	LDP-4	ULP-1	Overall study period
PM_{10}	−61.1 ± 17.6	−55.8 ± 20.5	−55.3 ± 18.4	−34.4 ± 30.3	−40.1 ± 38.2	−49.0 ± 29.6
$PM_{2.5}$	−48.0 ± 23.8	−44.6 ± 22.7	−42.6 ± 26.9	−31.6 ± 38.2	−29.8 ± 28.5	−38.6 ± 29.0
NO_2	−44.6 ± 66.0	−49.2 ± 34.4	−47.2 ± 34.2	−39.9 ± 35.6	−23.7 ± 42.1	−38.8 ± 46.2
DMA8-O_3	−41.6 ± 50.6	−26.4 ± 59.0	−7.1 ± 78.8	−4.0 ± 88.8	−14.1 ± 61.4	−19.1 ± 67.6

from 1 June to 30 June (same period of ULP-1), $PM_{2.5}$ concentrations were lower in all the monitoring sites in Delhi due to the rain in the pre-monsoon season. In 2020, $PM_{2.5}$ concentrations in ULP-1 were higher than LDP-1 in industrial monitoring sites like MM (LDP-1: 33.5 ± 10.6 μg/m^3 and ULP-1: 46.8 ± 16.8 μg/m^3), VV (LDP-1: 37.8 ± 18.1 μg/m^3 and LDP-1: 49.6 ± 14.3 μg/m^3), due to the removal of the restriction in the industrial activity. The average decrease in $PM_{2.5}$ was different in different phases, for example, about 48.0 ± 23.8%, 44.6 ± 22.7%, 42.6 ± 26.9%, 31.6 ± 38.2% and 29.8 ± 28.5% during LDP-1, LDP-2, LDP-3, LDP-4 and ULP-1, respectively (Table 5). The industrial monitoring site VV showed the highest decline for $PM_{2.5}$ (59.4 ± 20.9%) in LDP-1 and the lowest decline in ULP-1 (16.2 ± 37.9%). This is because, in LDP-1, all industries were fully shutdown whereas in ULP-1 industries were running again, though still not fully operational and with a limited workforce. The monitoring site-specific $PM_{2.5}$ concentrations changes in percentage are reported in Figure 4b.

The decrease of NO_2 concentrations has shown considerable variation between the four-phases of lockdown [NO_2: 49.2 ± 34.4% to 39.9 ± 35.6%], although the overall decline is lower in the unlock-phase (ULP-1), about 23.7 ± 42.1%. In Delhi, nearly 52% of NO_x emission is attributed to industrial point sources (largely from power plants) followed by vehicular sources (36%) (Nandi 2018). In LDP, the decline rate of NO_x is mainly due to full restrictions on vehicles, whereas in ULP, NO_x is still lower than the past year as there were comparatively fewer vehicles on the road. In LDI-1, the highest decline for NO_2 was observed at the traffic sites JNS and MM, 81.3 ± 8.8% and 63.8 ± 5.9% respectively. In ULP–1 these sites still had lower NO_2 levels compared to the average daily values in 2018–2019 for the same period, although at some industrial sites, like RH and VV, NO_2 concentrations increased by 39.1% and 8.2% in ULP-1 (Table S4).

The MDA8 O_3 concentrations declined in the four-phases of lockdown by 49.9 ± 35.2 μg/m^3, 64.1 ± 40.3 μg/m^3, 79.8 ± 45.4 μg/m^3 and 82.1 ± 42.5 μg/m^3 respectively with a further decrease in unlocking phase of 61.1 ± 40.3 μg/m^3, as compared to the levels of 88.9 ± 26.4 μg/m^3, 93.5 ± 27.6 μg/m^3, 97.1 ± 27.6 μg/m^3, 100.7 ± 32.4 μg/m^3 and 75.5 ± 30.1 μg/m^3 equivalent periods of LDP-1, LDP-2, LDP-3, LDP-4 and ULP–1 in 2018–2019 (Table 4). Overall, MDA8 O_3 concentrations declined by 19.1 ± 67.6% (Table 5) and the highest decline was observed in the LDP–1 period (39.4 ± 51.5%) compared to values in 2018–2019. Despite an overall decrease of MDA8-O_3 some monitoring sites like DTU, MM and NN showed an increase of MDA8 O_3 in different phases (Table S5). The MDA8 O_3 concentrations level increase in traffic and industrial sites could be due to the following reasons: (1) The continuous decrease of NO which is responsible for the gradual decrease of O_3 strength to titrate NO (titration, $NO + O_3 \rightarrow NO_2 + O_2$), causing an augment of O_3 concentrations; (2) Reduced $PM_{2.5}$ levels also plausibly cause an increase in O_3 level due to impacts on O_3 photochemistry and heterogeneous chemistry on aerosol surfaces. Primarily, $PM_{2.5}$ scavenges the hydroperoxy (HO_2) and NO_x radicals that would otherwise produce O_3 (Wang et al. 2019).

Delhi has a higher number of on-road vehicles. In March 2018, Delhi had 10.8 million registered vehicles, including 6.96 million motorcycles/scooters and 3.1 million motor-cars (private vehicles) (Transport Department Government of NCT of Delhi. 2018). Road traffic was strictly restricted in the first two phases of lockdown, however, this was relaxed to some extent in the next lockdown phases. In ULP-1, pollutants concentrations were still lower compared to the same period 2019 and even in LDP-4 in 2020, due to the fear of increasing rates of COVID-19 cases in Delhi during ULP-1, visits to workplaces reduced by 60%, while retail and recreation activities reduced by 84% (Shrangi and Pillai 2020). Three coal–based thermal power plants that continued to operate throughout the lockdowns operated can be expected to have a similar contribution during the study period in 2020 and the equivalent period in 2018–2019. Their previous contributions were estimated to be 9.0%, 10.9% and 7.2% of PM_{10}, $PM_{2.5}$ and NO_x load for Delhi (Ministry of Heavy Industry and Public Enterprises 2018) (Table S6). Switching-off of the main PM_{10} and $PM_{2.5}$ sources like transport, industries, agricultural burning, road dust, construction, restaurant and airport could be responsible for 80.4% and 72.8% reduction of PM_{10} and $PM_{2.5}$ (Table S6), although during LDP-1 the PM_{10} and $PM_{2.5}$ were reduced by only 61.1% and 48.0%, possibly due to the transport of PM into the city from surrounding states Haryana and Uttar Pradesh (Purohit et al. 2019). Additionally, these sources also emit secondary aerosol which could have contributed to the reduction of PM during lockdown (Kumar et al. 2020). In lockdown phases, biofuel burning from residential areas for cooking purposes, such as LPG, wood and coal has increased (IANS 2020), and could have contributed to overall air pollution.

The COVID-19 restrictions reduced urban anthropogenic emission activities across India by different amounts, due to the different anthropogenic sources of pollutants and different meteorological conditions. In the first phase of lockdown, Mahato, Pal, and Ghosh (2020) reported a 60%, 39% and 53% reduction of PM_{10}, $PM_{2.5}$ and NO_2, respectively, compared to 2019 in Delhi. Reductions in $PM_{2.5}$ concentrations, based on ground-level monitoring data, was 35% in Kolkata and 28% in Delhi during 22–31 March 2020 (Singh and Chauhan 2020). Sharma et al. (2020) reported a 43% decline of $PM_{2.5}$ from 16 March to 14 April, using a WRF-AERMOD modeling system, when compared with a similar period in previous years. Dhaka et al. (2020) observed that in the first week of lockdown (25–31 March 2020), $PM_{2.5}$ showed large reductions (by 40–70%) compared to the pre-lockdown conditions over the Delhi-NCR region (Table 1). In UK cities, the lockdown (23 March 2020) caused a sharp drop in NO_2 pollution (~60% after two weeks), however, no consistent reduction was seen in $PM_{2.5}$ over the same period. In the UK, $PM_{2.5}$ levels were higher in many areas during the UK lockdown than at any other time in 2020 to date (https://www.bbc.com/news/science-environment–52113695).

Meteorological conditions and change of pollution levels

The variations in meteorological parameters in 2020 during the study period are summarized in Table 6 (Table S2 for 2018–2019). The month of March marks the beginning phase of summer in Delhi and the month of May is the peak of the summer season, therefore, from LDP-1 to LDP-4, the temperature has increased by ~8.3°C. The start of the monsoon rain in June brings down the temperature, where the mean temperature during ULP-1 was ~1.0°C less than the temperature during LDP-4. In inland city Delhi, a continuous decrease of relative humidity (RH) was reported from March to May (LDP-1 to LDP-4) as temperatures increased, peaking in June, primarily due to the beginning of monsoon rain. The opposite pattern to RH was observed for wind speed (WS) with the highest reported WS of 10.4 ± 3.4 km/h in LDP-4 in 2020.

No systematic correlations were observed between pollutants and weather parameters from March to June (Figure S1). This was due to the interplay between two different weather and air pollution emission scenarios from March to June. The end of March represents the

Table 6. Summary of the meteorological parameters during the study phases in Delhi in 2020.

Year	Meteorological variables	LDP-1 Mean±SD (Min-Max)	LDP-2 Mean±SD (Min-Max)	LDP-3 Mean±SD (Min-Max)	LDP-4 Mean±SD (Min-Max)	ULP-1 Mean±SD (Min–Max)
2020	Temperature (°C)	25.8 ± 3.0 (20.8–32.2)	29.3 ± 2.1 (24.0–32)	30.9 ± 1.7 (27.3–33.6)	34.1 ± 4.1 (25.5–38.4)	33.1 ± 2.4 (28.6–37.2)
	Relative humidity (RH) (%)	44.8 ± 12.2 (29.9–74.4)	42.5 ± 11.1 (22.4–63.9)	41.8 ± 8.1 (29.2–53.9)	30.6 ± 19.8 (16.5–73.4)	53.1 ± 8.0 (39.6–71.8)
	Wind speed (WS) (km/h)	9.2 ± 2.3 (4.8–13.1)	9.3 ± 3.6 (5.0–17.8)	8.8 ± 2.3 (5.4–13.5)	10.4 ± 3.4 (5.2–18)	9.3 ± 2.9 (2.8–14.6)
	Visibility (km)	3.7 ± 0.4 (3.0–4.3)	3.9 ± 0.4 (3.1–4.6)	4.0 ± 0.6 (3.0–5.0)	4.1 ± 0.4 (3.1–4.8)	3.7 ± 0.5 (2.8–4.6)
	Precipitation (Prec) (mm)	0.3 ± 0.9 (0–3)	0.9 ± 2.3 (0–8.9)	0.4 ± 1.4 (0–5.1)	0.8 ± .6 (0–5.1)	1.0 ± 2.5 (0–10.9)

LDP-1, where all the services were closed and there were no active emission sources. However, June represents the ULP–1, where essential services were opened gradually. These scenarios lead to different emission patterns, which led to the inconsistencies observed in the correlation coefficients. Worthy of note is the negative correlation coefficient between RH and air pollutants, and the positive correlation coefficient between temperature and air pollution is increased in 2020, compared to 2018–2019. The higher variation in coefficient values between $PM_{2.5}$ and O_3, (2018: −0.11; 2019: 0.38 and 2020: 0.17) may be due to the sensitivity of O_3 formation in different $PM_{2.5}$ concentration levels (Figure S1). The sensitivity of O_3 formation in the Delhi city region is dominated by local traffic emissions, and O_3 and traffic emissions are anticorrelated. The response surfaces show that a reduction in local traffic emissions alone of 50% could decrease Delhi $PM_{2.5}$ loading by 15%-20%, but this would also increase O_3 by 20%–25%. To prevent the side effect of increasing O_3, controls on traffic emissions would be required to reduce only by 25–30%, which also permits a further reduction of $PM_{2.5}$ by 5%–10% (Chen et al. 2020).

The meteorological variables were divided into five equal intervals between minimum and maximum during the total study period from 2018–2020 and it was observed that the different range of meteorological conditions influenced the reduction of air pollution in 2020 differently, compared to 2018 and 2019. For example, in the average temperature of 22.8, 26.7, 30.6, and 34.5°C, the average percentage change of $PM_{2.5}$ decreased by 62.2, 42.6, 37.9 and 24.3% respectively. The further increase of the atmospheric temperature to 38.4°C, when the lockdown was in the fourth phase the $PM_{2.5}$ reduction level increased slightly (28.9%), due to the highest temperature reported in May. Similarly, RH and WS have significantly influenced the change of pollutants concentrations in COVID-19 lockdown phases in 2020, compared to 2019 (Figure 5). More details are reported in Figure S2 (supplemental material).

Diurnal variation in pollutant concentrations

Figures 6a, b show the average diurnal variation of PM_{10} and $PM_{2.5}$ concentrations in five-phases from 2018 to 2020 in Delhi. The diurnal variation of PM_{10} and $PM_{2.5}$ concentrations were largely characterized by a “W” type double wave. The morning peak occurred around 07:00 to 10:00, and an afternoon valley between 15:00 to 17:00. The peak in the night appeared after 20:00 or midnight and then gradually decreased in the early hours of the morning in 2018 and 2019. The higher concentrations of PM is consistent with the morning and evening rush-hour traffic pattern and the afternoon dip was mainly attributable to a higher atmospheric mixing layer, which enhanced air pollution diffusion (San Martini, Hasenkopf, and Roberts 2015). During COVID-19 pandemic restrictions, overall PM concentrations decreased and similar diurnal variation was observed in LDP-1 to LDP-3. The morning peak was followed by a gradual decrease in PM concentrations through the afternoon. This feature may be explained in part by the growth of the mixed layer depths and stronger atmospheric ventilation during the afternoon. The morning peak might be associated with the fumigation effect in the boundary layer, which brings aerosols from the nocturnal residual layer shortly after the sunrise. As the day advances, increased solar heating leads to increased turbulent effects and a deeper boundary layer, leading to faster dispersion of aerosols and hence dilution of PM concentrations occurs near to the surface after 15:00 (late-afternoon) (Tiwari et al. 2013). This suggests that meteorological processes such as vertical mixing, advection and transport are the dominant factors controlling PM in the daytime. In contrast, freshly emitted pollutants are trapped at night when the planetary boundary layer (PBL) is shallow, and concentrations are very sensitive to the emission flux so that the diurnal pattern of emissions is the dominant factor at night (Chen et al. 2020). In LDP–4 a different diurnal shape of PM was observed in 2020, PM_{10} concentrations continuously increased from 04:00 to 11:00 and for $PM_{2.5}$ the increase was observed between 04:00 to 08:00 and then gradually decreased in the afternoon. In ULP in June 2020, PM_{10} concentrations continuously increased from morning 07:00 to 21:00 and then gradually decreased, whereas $PM_{2.5}$ concentrations continuously decreased from midnight to late afternoon.

The diurnal variation in NO_2 concentrations in 2018–2019 can be represented by two peaks like a “U” shape (Figure 6c) with a deep valley. The first

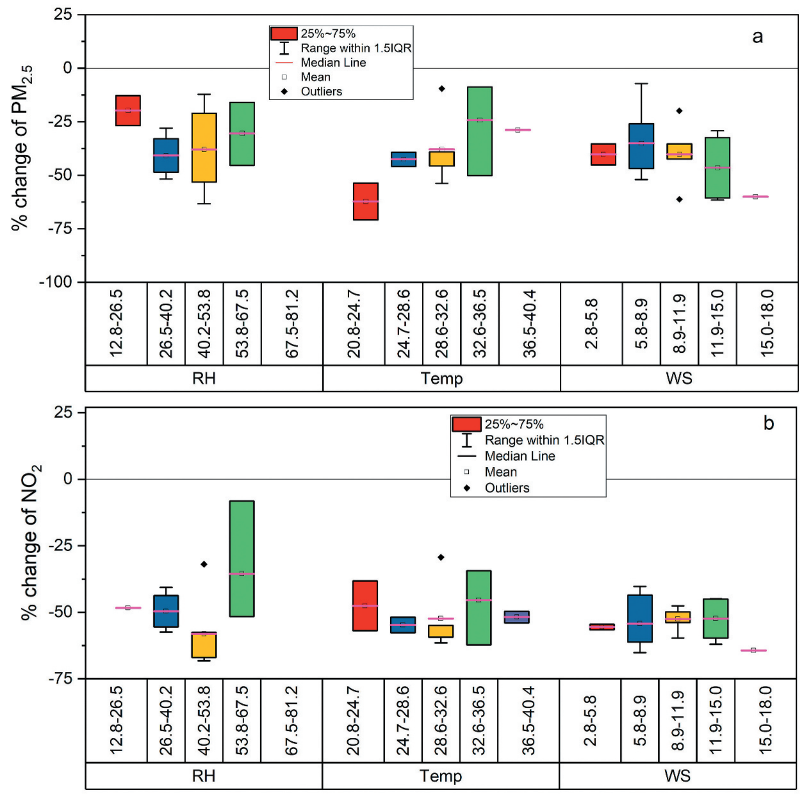

Figure 5. Boxplot of percentage (%) change of average (a) $PM_{2.5}$ and (b) NO_2 concentrations during the total study period in 2020 compared to 2019 at different interval of the meteorological parameter.

peak was at 06:00–8:00 and the second one appeared at 20:00–22:00; the second peak was sometimes significantly higher than the first one. The peak in the morning could be attributed to the rush hour traffic and a peak at night might be related to NO_2 accumulation caused by relatively unfavorable weather conditions and high NO emissions. Heavy diesel vehicles are allowed to enter the city at night, resulting in a large amount of NO emissions at night (Kaushika 2017). The decrease of NO_2 concentrations in the afternoon was related to the increase of boundary layer height and an increase in wind speed which results in the dilution of pollutants, whereas the NO decrease in the afternoon as NO convert to NO_2. The shapes of the diurnal variations in industrial to traffic sites are different although the overall NO_2 concentrations decreased across all the sites, as the vehicular source of NO_x were removed. In LDP–4, the diurnal curve of NO_2 moves upward as the vehicular restriction was removed, although still, the number of vehicles were low compared to last year at the same time. Late evening hour (20:00–22:00) peaks of PM_{10}, $PM_{2.5}$ and NO_2 were observed in Delhi (Figure 6). This could be linked to the decrease in night temperature and boundary level height (Ravindra et al. 2021).

Figure 6d shows the hourly average diurnal variation of O_3 concentrations during 2018–2020, which was opposite that of the other air pollutants with "∩" shape. O_3 concentrations reach a minimum value before sunrise. From 06:00 to 08:00, coinciding with the morning peak traffic, the NO_x concentrations increase rapidly in Delhi (Nandi 2018) and solar radiation is still weak during this period, which leads to a greater depletion of O_3 due to titration with NO. Around 09:00, along with increases in solar radiation and temperature, the photochemical reactions become more active and O_3 concentrations begin to increase, and they peak around 11:00–16:00. As time progress from LDP-1 to LDP-3, the peak of the diurnal curve in O_3 was increased where NO concentrations were decreased from LDP-1 to LDP-3 in 2020. Between 20:00 and 23:00, the O_3 concentrations decrease rapidly due to the decrease in solar radiation and titration with NO during evening peak traffic. With the decrease in NO_2 and CO concentrations in the afternoon, O_3 concentrations increased and it was suggested that the maximum O_3 concentrations in the afternoon were mainly due to photochemical reaction under intense solar radiation conditions, leading to the consumption of NO_2 and CO emissions (Shi et al. 2019).

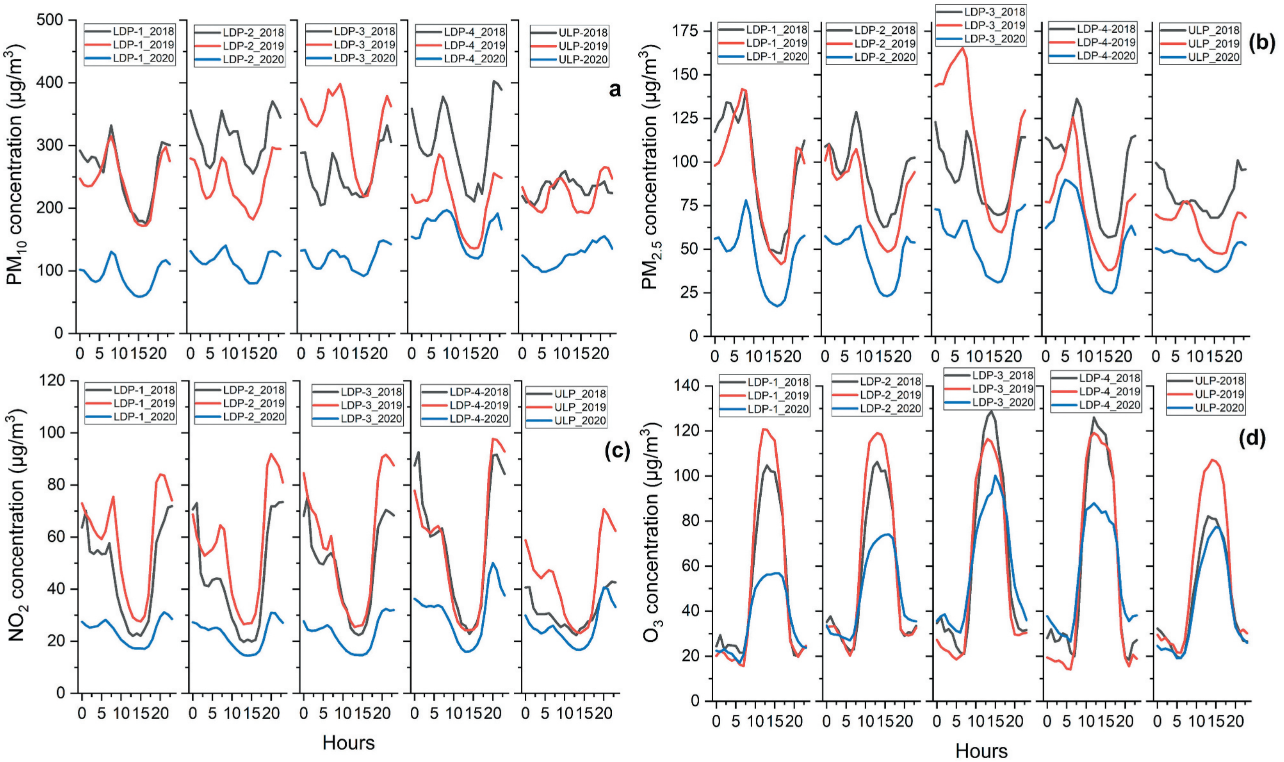

Figure 6. Average diurnal variation of the four analyzed pollutants from 2018 to 2020 during the lockdown and unlock period for Delhi city.

Health benefit

In this study, we estimated short-term $PM_{2.5}$ and O_3-exposure associated health risk only, as other pollutants concentrations are below the threshold value. The selected risk factor estimates for the Chinese population may not be applicable in India as, race, education background, marital status, food habit, alcohol consumption rate, cigarette-smoking status, socioeconomic status, body mass index (BMI) may be different. However, the range of ambient $PM_{2.5}$ and O_3 concentrations in Delhi is quite similar to those in the selected epidemiological study. The short-term $PM_{2.5}$ and O_3-exposure are associated with the increase of premature deaths among adults (≥25 years) from all-cause of nonaccidental, cardiovascular disease (CVD), ischemic heart disease (IHD), respiratory disease (RD) and stroke. Based on the log-linear model, the estimated $PM_{2.5}$ and O_3-related premature mortalities along with 95% confidence interval (CI), when the daily $PM_{2.5}$ and DMA8–h O_3 concentrations meet the threshold value in 2018–2019 and 2020. The averages short-term all-cause $PM_{2.5}$-attributed deaths were 1,186 (95% CI: 811–1,505) in which 33%, 21%, 13%, 8% and 26% were due to CVD, IHD, RD, stroke and 'other cause' of deaths during the study period in 2018–2019. The all–cause premature death decreased to 603 (95% CI: 412–767) in 2020 and CVD, IHD, RD, stroke and 'other cause' of deaths decline to 17%, 11%, 6%, 4% and 13%, respectively. The DMA8-h O_3 attributed all-cause premature mortality was 321 (95% CI: 174–467) in 2018–2019, in which CVD, IHD, RD, stroke and 'other cause' of deaths were contributed by 30%, 16%, 29%, 9% and 17% respectively, and in 2020, the O_3 exposure-related deaths were zero as O_3 concentrations were below the threshold. Overall avoided premature deaths due to the decline of $PM_{2.5}$ and O_3 were about 60% in Delhi during the overall study period (25 March to 30 June) as compared to similar periods of 2018 – 2019.

Bherwani et al. (2020) reported that reduction of $PM_{2.5}$ in LDP-1 alone is responsible for a 35.5% reduction of long-term all-cause total premature mortality compared to 2019. Venter et al. (2020) estimated that $PM_{2.5}$-related reductions in mortality (short-term) burden were 5,300 (1,000–11,700) for India during the first two weeks of lockdown as compared to similar periods of 2017 – 2019. A similar study in Delhi by Kumar et al. (2020) reported a 49% reduction of $PM_{2.5}$-attributed all-cause death (short-term) during the first 47 days of the lockdown.

While there were reports of clear pollution-free skies and long-distance views to Himalayan mountains as a result of COVID–19 lockdowns, it has been suggested that indoor air pollution might have increased during the same period as people spent more time indoors and burnt more fuel for cooking and heating. About 78% of India's 1.3 billion population uses solid fuels for their primary and secondary needs. It has been estimated that when solid biomass fuels are burnt for cooking or heating, $PM_{2.5}$ concentrations are in the range of 163–600 μg/m^3, about 6–23 times the safe level of daily air pollution exposure of 25 μg/m^3 recommended by the World Health Organization (WHO) (Tripathi 2020). Around 50% of the population that is usually out of the home during peak cooking hours (WHO 2018) were confined indoors during the lockdown periods, therefore the number of people affected (i.e., asthma, premature death) by indoor air pollution is likely to have increased significantly during the lockdown.

During the COVID-19 lockdown period, the present study and other recent studies highlighted the impact of restricted anthropogenic activities on air quality across Indian megacities and other megacities around the world (Table 1). In India, $PM_{2.5}$, PM_{10} and NO_2 show a significant reduction of up to 40–50% in many of its megacities during the lockdown period as highlighted by Mahato, Pal, and Ghosh (2020), Singh and Chauhan (2020), Srivastava et al. (2020) and Jain and Sharma (2020). The PM concentrations in Delhi were still above WHO guidelines, therefore a higher number of people will be affected by long-term exposure. Generally, air quality in megacities is affected by emission sources, atmospheric reactivity, and meteorology. In India, significant reduction of air pollution is primarily due to the decrease in major anthropogenic activities such as vehicles, industries, and other fugitive sources such as household cooking, emissions from local industries, street food vendors, semi-open cooking in restaurants (using coal for cooking), and other non-exhaust emissions. Meteorology also played an important role in emission reduction during the lockdown as intermittent rain events were also observed during the lockdown in some parts of India. Sharma et al. (2020) reported that meteorology was favorable during the lockdown, otherwise, the predicted $PM_{2.5}$ levels could be around 33% higher than levels reported during the lockdown.

In agreement with the current study and all the above studies also shed light on the factors leading to air quality improvement, where air pollution levels remain relatively high and attaining the standard norms is a challenge. Our study results indicate that temporary lockdown could be considered to mitigate environmental and public health damage to some extent. The lockdown gave us a rare opportunity to establish the baseline pollution level of air pollutants in Delhi, key information to set appropriate target limits. Learnings from this natural experiment will help us and develop effective management policies for achieving better air quality in urban centers like Delhi. In the past, measures like odd-even traffic restrictions and air pollution emergencies were implemented in megacities such as New Delhi, however, this failed to make a measurable impact on air pollution levels (Kumar et al. 2017). For location-specific policy development, source apportionment studies need to compare during the lockdown and non-lockdown periods to provide a better understanding of source contribution in each location (Ravindra et al. 2021).

Conclusion

The COVID−19 restrictions reduced the anthropogenic emissions during the lockdown and unlock phases in the megacity Delhi. This study provides evidence of the reductions using air quality monitoring data in 2020 (25 March to 30 June 2020) compared with the same period in the proceeding years 2018–2019. This study also analyzed the influencing factors including meteorology, the diurnal variation and the short−term health impact of the decrease of pollutants concentrations. The conclusions can be drawn as:

- Relatively high reductions of PM_{10}, $PM_{2.5}$, and O_3 (61%, 48%, and 42% respectively) in lockdown phase 1, whereas the highest reduction of NO_2 (49%) was observed in the lockdown phase 2. The restrictions on vehicular, industry, road dust and construction activities are mainly responsible for the overall reduction, although other sources like biomass burning for cooking, coal power plants, diesel generating sets, and waste incinerators can not be ignored as PM_{10} and $PM_{2.5}$ still exceeded the NAAQS.
- Even though the maximum restrictions were withdrawn in unlock phase 1, the levels of PM_{10}, $PM_{2.5}$, NO_2, and O_3 still declined by 40%, 30%, 24% and 14% respectively, as compared with 2018–19 levels, thus demonstrating the residual effect of restrictions in altering peoples behavior and activity patterns.
- Except for O_3, the highest decline of pollutant concentrations was observed at traffic and industrial monitoring sites. At some monitoring sites, like Delhi Technological University, Mandir Marg and Nehru Nagar, O_3 continuously increased during the study period perhaps due to the decrease in the levels of $PM_{2.5}$ and NO.
- Pollutants concentrations displayed a gradual decrease in the first three phases, however, after that pollutants concentrations gradually increased

as day by day the restrictions were removed. Analysis of diurnal variation revealed that the implementation of lockdown helped to suppress PM_{10} and $PM_{2.5}$ peaks during the daytime. And the diurnal variation of O_3 showed generally increased concentrations with the highest peak during the first to the third phase of lockdown in 2020.

- An appreciable reduction of $PM_{2.5}$ and O_3 concentrations during COVID-19 restriction led to a decrease of 903 premature deaths, which is about 60% lower compared to similar periods of 2018 – 2019. This demonstrates that if main emission generating activities are controlled systematically, significant pollution reduction and health gains can be achieved. This study has suggested that lockdowns have acted as a useful lens to identify the primary and secondary sources of air pollution which will help to develop future air quality management policy.

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