Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
Impact of lockdown during COVID-19 pandemic on the air quality of North Indian cities

Abhishek Saxena a,⁎, Shani Raj b

a Department of Physics, Pacific University Udaipur, 313001, Rajasthan, India
b Department of Botany, Mohanlal Sukhadia University Udaipur, 313001, Rajasthan, India

ARTICLE INFO

Keywords:
COVID-19
Lockdown
PM2.5 and PM10
CO
NO2
Surface O3

ABSTRACT

The World Health Organization, which proclaimed the COVID-19 a pandemic in early March 2020, imposed a partial lockdown by the Government of India on 21 March 2020. The aim of this investigation was to measure the change in air pollutants, including particulate matter (PM2.5 and PM10) and gaseous pollutants (NO2, CO and O3) during COVID-19 lockdown (25th March to 14th April 2020) across four major polluted cities in North India. In all region, PM2.5, PM10, NO2 and CO were significantly reduced while O3 has been shown mixed variation with increased in Agra and decreased in all other stations during lockdown. PM2.5 was reduced by ~20–50% and highly decreased in Noida. PM10 was most significantly decreased by 49% in Delhi. NO2 was reduced by ~10–70%, and high reduction was observed in Noida. Likewise, ~10–60% reduction was found in CO and most significantly decreased in Gurugram. However, an increased in O3 was observed in Agra by 98% while significantly reduced in other sites. Compared to the same timeframe in 2018–2019, PM2.5 and PM10 values for all sites were reduced by more than 40%.

1. Introduction

Pollution levels have emerged as an increasing concern globally, particularly in Asian economic countries such as India and China. In India, with increasing economic growth, industrialization and development of infrastructure since modernizing has also increased in Air pollution level to significant health hazards leading to a cause of premature death (Sharma et al., 2020). In India, almost one million people have died due to atmospheric particulate matter (PM2.5) pollution in 2015 (Guo et al., 2017). From the past few years, the big Indian cities have been listed in top 20 world’s most polluted cities as recommended by WHO and CPCB (Central Pollution Control Board) (Lawrence and Fatima, 2014; Sharma and Mandal, 2017). PM (PM2.5 and PM10) is the prominent pollutant and the households, transport and industries are the primary anthropogenic emission source of the PM (Guo et al., 2019). PM2.5 affects more, even in a low concentration in the air is linked to adverse impacts on human health according to WHO report comparing to other pollutants (Fann et al., 2012). NO (nitrogen oxide) and CO (carbon monoxide) and are gaseous pollutants, and their emission is by transport, industries, coal-based thermal power plants and incomplete burning of fossil fuels in any manner emits various forms of combustion or waste into the environment as fine particulates matter (Gurjar et al., 2016; Sharma and Dikshit, 2016). NO2 is a precursor element which leads to the production of O3 (ozone) in the existence of Sunlight and high temperatures via CO, CH4, and VOC reactions (Li et al., 2018). Unfavorably, surface ozone O3 is very harmful air pollutant affects the crop yield, human health and ecosystem as a third most imperative greenhouse gas (Li et al., 2020). Ozone is a popular oxidant gas in urban air, and ozone exposure

⁎ Corresponding author.
E-mail address: saxenaabhishek85@gmail.com (A. Saxena).

https://doi.org/10.1016/j.uclim.2020.100754
Received 29 July 2020; Received in revised form 21 October 2020; Accepted 29 November 2020
Available online 7 December 2020
2212-0955/© 2020 Elsevier B.V. All rights reserved.
can provoke oxidizing stress-causing respiratory and cardiovascular diseases and breathing mortality rates (Sujith and Sehgal, 2017). O$_3$ and PM$_{2.5}$ pollutants have a secondary origin and are produced by the gas and liquid phase oxidation of SO$_2$ as well as the photochemical reaction of the NOx (Nitrogen oxides) and VOCs (volatile organic compounds), therefore, both the secondary pollutant share similar precursors (Xiang et al., 2020). In several areas of the world, the environmental risk from exposure to these contaminants has increased as a result of anthropogenic activity (Lelieveld et al., 2015; Apte et al., 2015; Burnett et al., 2014). These pollutants and many other components such as some solvent used in washing, construction materials, painting, carbon monoxide, pathogens, food preparation, smoking, plastic materials, soft furnishings, and gasoline are also affecting the indoor air quality (Kotcher et al., 2019; Slezakova et al., 2013). Several studies have reported the impact of these air pollutants on people who could be sensitive to indoor air pollutants for longer periods are more susceptible to severe respiratory infections, mostly the children, senior citizens, and the severely exhausted, particularly those with respiratory or cardiovascular diseases, respiratory erythema, asthma, difficulty breathing and sneezing (Bergstra et al., 2018; Burnett et al., 2014).

This observation motivated us to seek different paths and variables that are accountable during COVID-19 (Corona Virus Disease 2019) in India. On the end of December 2019 WHO draws attention to China of several unusual pneumonia cases due to the highly contagious disease known as COVID-19. The cause of this disease, a new virus named SARS-CoV-2, was announced on 7 January 2020 (WHO, 2020) was initially identified in Wuhan, China. The first COVID-19 case in India was confirmed on January 30, 2020. The death toll crossed 200,000 in all parts of the world as the World Health Organization (WHO, Geneva, Switzerland) called this a pandemic on 26 April 2020. COVID-19 cases were identified in family and hospital cluster and transmission from one person to another was confirmed (Chan et al., 2020). COVID-19 disease produced respiratory symptoms, some patient experience significant cardiovascular damage. Furthermore, certain patients with underlying cardiovascular diseases (CVDs) may have an increased risk of death (Zheng et al., 2020). Because of COVID-19 contagion, a nationwide lockdown is enforced in India for three weeks from March 24th to April 14th and later extended to May 3rd. Nearly all commercially operations and public transit have been banned by this nationwide lockdown. As a result, the level of pollution in 88 cities across the country fell dramatically only after four days of the CPCB officially data beginning lockdown event (Sharma et al., 2020). Recent studies have reported improvement in the air quality during the lockdown over many Indian cities and regions (Navinya et al., 2020; Srivastava et al., 2020; Kumari and Toshniwal, 2020). A substantial reduction of NO$_2$ from space was observed by European Space Agency (ESA, 2020). The CPCB evaluate the data on air quality in real-time at 34 monitoring stations in Delhi between 3 March and 14 April 2020 and announced a substantial reduction in PM$_{10}$, PM$_{2.5}$ NO$_2$ and CO and a 40%–50% improvement in the national air quality index during the lockdown (Mahato et al., 2020).

In this paper, we analysed the variations in pollutant concentration and meteorological data obtained from a network of air quality monitoring in Agra, Noida, Delhi and Gurugram in India for the period of March 24th to April 14th from years 2018–2020. The analysis of observations over the past three years tends to explain the possible impact of pollution shifts over days of similar meteorological conditions.

![Fig. 1. Study area with the location of selected cities: Agra, Noida, Delhi and Gurugram.](image-url)
2. Data and methodology

2.1. Data sources

During the lockdown time, data from four cities covering different areas of India, i.e., Agra, Noida, Gurugram and Delhi were collected to determine air quality improves. The concentration levels of the various pollutants for the period of 24 March to 14 April from 2018 to 2020, were analysed. The CPCB online database for air quality data collected daily average concentrations of four pollutants including PM$_{2.5}$, PM$_{10}$, NO$_2$ and CO and at 8 h average for surface O$_3$ (https://app.cpcbcrcc.com/ccr/#/caaqm-dashboard-all/caaqm-landing). Meteorology data i.e. air temperature, relative humidity (RH), wind Speed, PBLH (planetary boundary layer height) from NOAA Air Resources Laboratory’s (ARL) NASA web (https://ready.arl.noaa.gov/index.php).

2.2. Study area

In this report, four major north Indian cities have selected for the study of variation in the pollutant’s concentration during lockdown Fig. 1. Agra about 206 km south of New Delhi, the national capital. The Agra climate is semi-arid, bordering on a humid subtropical climate. The mean rainy season is 628.6 mm from June to September. The daytime temperature during summer is about 46–50 °C. Nights are slightly colder, and the temperature drops to 30 °C. Noida is a centre of industry. Noida is situated in Uttar Pradesh state district of Gautam Buddha Nagar. Noida is approximately 25 km southeast of New Delhi, about 20 km northwest of the district headquarters-Greater Noida and 457 km northwest of the state capital, Lucknow. Noida city is situated in the Indian State of Uttar Pradesh district of Gautam Buddha Nagar. Gurugram is a city located in Haryana, a northern Indian state. It is located close to the Delhi-Haryana border, approximately 30 km southwest of the national capital New Delhi and 268 km south of the state capital Chandigarh. Delhi is considered among the most polluted megacities of the globe based on environment performance index (WHO, 2016). According to the environmental monitoring database for the world-leading megacities encompassing 100 countries published in April 2018 by WHO for the period of 2011 and 2016 Delhi ranks high in the list of PM$_{2.5}$ pollution (WHO, 2018). The detail of emission sources, vehicle etc. of the observed station are given in Table 1. A recently release IQAir 2019 World Air Quality study showed that 14 out of the 20 most polluted cities in the world are from India. In 2019, the concentration of PM$_{2.5}$ levels in Delhi, Noida and Gurugram was 98.6 μg/m$^3$, 97.7 μg/m$^3$ and 93.1 μg/m$^3$ compared to the allowable maximum of 60 μg/m$^3$ (daily average) (IQAir report, 2019). This suggests a significant degree of air pollution, which even after many attempts could not be regulated by state and central government.

2.3. Description of air pollutants and meteorological parameters

A table showing the list of selected cities in present study.

| City      | Coordinates       | Area (km$^2$) | Population (census 2011) | Emission sources                                                                 |
|-----------|-------------------|---------------|--------------------------|---------------------------------------------------------------------------------|
| Agra      | 27.17° N, 76° E   | 4041          | 43,80,793                | 580,396 licensed motor vehicles, 27,462 of which were transportation vehicles. Two big thermal power plants, leather goods and iron manufacturing factories, two coal-based railway marshalling yards industries i.e. Rubber, chemical, electronics equipment and brick are the main industries in Agra. Despite all these manufacturing units, the Mathura Refinery and Firozabad glass factory is also very near to Agra, leads to Air pollution in Agra. |
| Noida     | 28.53° N, 77.39° E| 1442          | 642,381                  | The number of motor vehicles licensed in the city in 2019 were 89,625, up slightly from 85,628 in 2018 and 66,582 in 2017. The total number of four-wheelers licensed at Noida rose from 21,135 in 2017 to 23,761 in 2018 and rose to 25,537 in 2019. While, two-wheelers rose from 39,811 in 2017 to 51,657 in 2018 and only slightly enhanced to 55,000 in 2019 |
| Gurugram  | 28.45° N, 77.02° E| 732           | 876,900                  | The Gurugram city is situated on the northeastern border of Delhi. Gurugram had 4,791,825 licensed motor vehicles. There are numerous reasons why Gurugram is populated, i.e. Building projects dust, industrial waste, vehicle pollution, industrial hub (several textile fabrication units, automotive industries, food processing units and IT companies) |
| Delhi     | 28.65° N, 77.3° E | 1484          | 16.8 million             | On March 31, 2018, the total number of license vehicles on Delhi Roads was 109.86 lakh, growing fast of 5.81% over the past year. The number of four wheels was 32,46,637 although the number of autorickshaws was 1,13,074. |
Table 2
24 h average concentration of PM$_{2.5}$, PM$_{10}$, NO$_2$ and 8 h average concentration for Surface O3 and CO variation of pollutants and meteorological parameter from 2nd March to 21st March (before the lockdown) and 24th March to 14th April (during the lockdown) for North Indian cities.

| Air Pollutants & Meteorological Parameters | Before Lockdown (2 Mar-21 Mar 2020) | During Lockdown (24 Mar-14 Apr 2020) | Overall change and percentage |
|------------------------------------------|-------------------------------------|--------------------------------------|------------------------------|
|                                          | Agra  | Noida | Delhi | Gurugram | Agra  | Noida | Delhi | Gurugram | Agra  | Noida | Delhi | Gurugram |
| PM$_{2.5}$ (μg/m$^3$) 24 h               | 56.1  | 60.2  | 79.4  | 55.9  | 42.6  | 33.6  | 45.1  | 34.6  | –13.5 | –29.9 | –34.3 | –21.3  |
|                                          |       |       |       |        |       |       |       |       | –24%  | –49.6 | –43.1 | –38.1 |
| PM$_{10}$ (μg/m$^3$) 24 h               | 144.6 | 145.2 | 122.2 | 86.8  | 81.5  | 72.7  |       |       | –57.8 | –63.7 | –49.5 | –40.0  |
|                                          |       |       |       |        |       |       |       |       | –39.9 | –43   | –40.6 | –40.0  |
| Ozone (μg/m$^3$) 8 h                    | 6.5   | 29.6  | 28.8  | 43.7  | 12.9  | 18.7  | 28.5  | 32.5  | 6.4   | 10.9  | 0.3   | –11.2  |
|                                          |       |       |       |        |       |       |       |       | 98%   | –36   | –1    | –25%   |
| CO (mg/m$^3$) 8 h                       | 1.1   | 0.9   | 0.7   | 1.5   | 1     | 0.4   | 0.4   | 0.6   | –0.1  | –0.5  | –0.3  | –0.9   |
|                                          |       |       |       |        |       |       |       |       | –9%   | –55   | –42.8 | –60.0  |
| NO$_2$ (μg/m$^3$) 24 h                  | 50.4  | 42.3  | 42.4  | 17.4  | 45.4  | 12    | 14.8  | 10.7  | –5    | –30.3 | –27.4 | –6.7   |
|                                          |       |       |       |        |       |       |       |       | –9.9% | –71.8 | –64.6 | –38.5  |
| Temperature (°C)                         | 22.2  | 20.3  | 20.1  | 20.3  | 29    | 27.4  | 27.3  | 27.5  | 6.8   | 30%   | 7.2   | 7.2    |
|                                          |       |       |       |        |       |       |       |       | 34.9% | 35.8  | 35.4  | 35.4   |
| RH (%)                                   | 41.7  | 53    | 53.8  | 50.8  | 25.5  | 29.7  | 30.2  | 29.5  | –16.2 | –23.3 | –23.6 | –21.3  |
|                                          |       |       |       |        |       |       |       |       | –38%  | –44   | –44   | –42%   |
| PBL (m)                                  | 585.8 | 513.6 | 507.2 | 532.7 | 1013.8| 959.8 | 955.5 | 972.7 | 428   | 446.2 | 448.3 | 440    |
|                                          |       |       |       |        |       |       |       |       | 73%   | 86%   | 88%   | 82%    |
| WS (m/s)                                 | 2.46  | 2.41  | 2.46  | 2.46  | 2.88  | 3.18  | 3.24  | 3.08  | 0.41  | 0.77  | 0.77  | 0.61   |
|                                          |       |       |       |        |       |       |       |       | 16%   | 32%   | 32%   | 25%    |
3. Results and discussion

3.1. Variation in PM$_{2.5}$ and PM$_{10}$

The variation in the average concentration of PM$_{2.5}$ and PM$_{10}$ in Agra, Delhi, Noida and Gurugram before and during the lockdown have shown in Fig. 2a-b. In Agra, the average concentration of PM$_{2.5}$ is 56.1 $\mu$g/m$^3$ before the lockdown and the linear reduction ($-24\%$) was noticeable during the lockdown. Though in Noida, PM$_{2.5}$ decreases are $-49.6\%$ and $-40\%$ in PM$_{10}$ during lockdown which was observed at 145.2 $\mu$g/m$^3$ before lockdown. Similarly, in Delhi and Gurugram, the concentration of PM$_{2.5}$ is about 45.1 $\mu$g/m$^3$ and 34.6 $\mu$g/m$^3$ were noted during lockdown were significantly declined by $-43.1\%$ and $-38.1\%$ respectively Fig. 2a. Likewise, the PM$_{10}$ was also reduced during the lockdown in Delhi and Gurugram by $-43\%$, and $-40\%$ which were observed 145.2 mg/m$^3$ and 122.2 mg/m$^3$, (Fig. 2b) respectively before lockdown (Table 2). The most visible declines in PM$_{2.5}$ are in Noida>Delhi>Gurugram>Agra and PM$_{10}$ are in Delhi>Gurugram>Noida. PM$_{2.5}$ at Noida (from 60.2 $\mu$g/m$^3$ to 33.6 $\mu$g/m$^3$) and PM$_{10}$ at Delhi (145.2 $\mu$g/m$^3$ to 81.5 $\mu$g/m$^3$) recorded the largest decrease during lockdown (Table 2).

![Fig. 2. Variation of air pollutant (a) PM$_{2.5}$ and (b) PM$_{10}$ before and after lockdown.](image-url)
Table 3
Basic statistics of average concentration of PM$_{2.5}$, PM$_{10}$, NO$_2$ of 24 h and surface O$_3$ and CO of 8 h for North Indian cities, the period of 24th March to 14th April from 2018 to 2020.

| Air Pollutants | 24 March to 14 April-18 | 24 March to 14 April-19 | 24 March to 14 April-20 | Average of 2018-19 | Variation (2020 and avg. of 2018-19) | Variation (2020 and avg. Of 2019) |
|----------------|-------------------------|-------------------------|-------------------------|-------------------|--------------------------------------|----------------------------------|
|                | Agra Noida Delhi Gurugram | Agra Noida Delhi Gurugram | Agra Noida Delhi Gurugram | Agra Noida Delhi Gurugram | Agra Noida Delhi Gurugram | Agra Noida Delhi Gurugram | Agra Noida Delhi Gurugram | Agra Noida Delhi Gurugram |
| PM$_{2.5}$ (24 h) ($\mu$g/m$^3$) | 75.2 83.4 101 73.9 | 74.8 91.2 97 70.7 | 42.6 33.6 41.5 34.6 | 75 87.3 99 72.3 | -32,- 42% | -53,- 61% | -53,- 53% | -36.6,- 50% | -31.6,- 42% | -57.6,- 63% | -53,- 53% | -36.1,- 51% |
| PM$_{10}$ (24 h) ($\mu$g/m$^3$) | 313 265 172 | 239 183 213 | 86.8 81.5 72.5 | NIL 276 224 192.5 | -189,- 68% | -142,- 63% | -119.5,- 62% | -152,- 63% | -102,- 61% | -140.8,- 65% |
| Surface O$_3$ (8 h) ($\mu$g/m$^3$) | 13.4 57 60 27 | 13.4 5.6 50.8 44 | 12.9 18.7 28.5 32.5 | 13.4 31.3 55.4 35.5 | -0.5,- 3.7% | -12.6,- 40% | -26.9,- 8% | -3,- 8% | -0.5,- 3% | 13.1,- 23% | -22.3,- 43% | -11.5,- 26% |
| NO$_2$ (24 h) ($\mu$g/m$^3$) | 45 44.7 30 24.7 | 28.7 59.6 59.8 8.3 | 45.4 12 14.8 10.7 | 36.85 51.85 45 16.5 | 8.5, 23% | -39.5,- 76% | -30,- 66% | -5.8,- 35.1% | -30.5,- 58% | -16.7,- 79% | -47.5,- 74% | 2.4, 28.9% |
| CO (8 h) (mg/m$^3$) | 0.8 | 1 | 0.6 | 3.5 | 0.54 | 0.6 | 1.2 | 0.44 | 1 | 0.4 | 0.4 | 0.4 | 0.6 | 0.8 | 0.9 | 1.97 | 0.4, 6% | -0.3,- 45% | -0.5,- 55% | -1.3,- 49% | 0.46, -45% | -0.16,- 85% | -0.8,- 26% | 0.16, 36% |
Fig. 3. Variation of air pollutant (a) NO$_2$, (b) surface O$_3$ and (c) CO before and after lockdown.
Owing to lockdown, air pollutant levels were significantly higher in 2019 relative to the same period in 2020 from 24 March to 14 April (Table 3). In Noida, the average PM$_{2.5}$ concentration declined by 63% from 24 March to 14 April 2020 (33.6 μg/m$^3$), compared to 25 March to 14 April 2019 (91.2 μg/m$^3$). In Agra, Delhi and Gurugram, a similar trend has been found as PM$_{2.5}$ levels are 42.6 μg/m$^3$, 41.5 μg/m$^3$, 34.6 μg/m$^3$ from March 24 to April 14, 2020, which were declined by −42%, −53% and −51% in comparison to the previous year. The average concentration of PM$_{2.5}$ during 24 March to 14 April (2018–2019) is approximately 75 μg/m$^3$, 87.3 μg/m$^3$ 99 μg/m$^3$ and 72.3 μg/m$^3$ also higher than in comparison to 2020 (Fig. 4a), which are declined by 42%, 61%, 53% and 51% in Agra, Noida, Delhi and Gurugram respectively shown in Table 3. Similarly, in Noida, Delhi and Gurugram PM$_{10}$ concentration were also reduced by 68%, 63% and 62% respectively during 24 March to 14 April 2020 in comparison to average concentration were 276 μg/m$^3$, 224 μg/m$^3$ and 192.5 μg/m$^3$ in 2018–2019 (Fig. 4b) (Table 3). Another measure of air quality is particulate matter PM$_{2.5}$ and PM$_{10}$ which comes directly from various pollution sources such as industrial sectors, thermal power plant, burning waste, road dust through vehicular activity etc., although the lockdown blocked all the countries operational activities, it is the significant reason of reduction in particulate matter (Srivastava et al., 2020; Agarwal et al., 2020).

3.2. Variation in NO$_2$

Fig. 3a depicted the changes in concentration of NO$_2$ before and during the lockdown in the four cities. In Agra, Delhi, Noida and Gurugram NO$_2$ level have been dropped by - 9.9%, −64.6%, −71.8% and −38.5% respectively (Table 2) during lockdown time. In Delhi, the NO$_2$ concentration decreased more than half (from 42.4 to 14.8 μg/m$^3$) compare to three other cities. The most visible declines are in Noida > Delhi > Gurugram > Agra. The average concentration of NO$_2$ from 24 March to 14 April 2020 is highly reduced in Delhi (−45 μg/m$^3$) and Noida (−47.6 μg/m$^3$) which corresponds to a variation of 75% and 79% in comparison to the same duration in the previous year (2019) while increasing in Agra and Gurugram by 58% and 28% (Table 3). Similarly, in comparison to the previous two years (2018–2019) during 24 March to 14 April the NO$_2$ level decline by −76%, −66% and −35.1% in Noida, Delhi and Gurugram while a slight increase in Agra by 23% (Fig. 4d, Table 3). NO$_2$ is emitted from biogenic sources such as soil and rain, pyrogenic sources such as natural explosions, and anthropogenic sources such as vehicle emissions and power plants dependent on fossil fuel (Reddy et al., 2012). Though transport and industrial operations were limited during the lockout, power generation and biomass burning remained operational, contributing to the NO2 pollution from the atmosphere. It is identified in the Ghude et al. (2008) report that the industrial and thermal power plant region in India are major sources of NO2 emissions. This drop-in NO$_2$ may be mainly due to decreased automobile emissions. Sharma et al. (2020) also recorded the approximately 18% decrease in NO$_2$ in the IGP (Indo-Gangetic

Fig. 4. Mean concentration of (a) PM$_{2.5}$, (b) PM$_{10}$, (c) CO, (d) NO$_2$ and (e) surface O$_3$ during 24 March to 14 April of year from 2018 to 2020.
Table 4
(a-d). Correlation (Pearson Correlation) and P-value between Air pollutants and Meteorology data in cities of the different regions during the analysis period.

|      | Agra | PM$_2.5$ (µg/m$^3$) | CO (mg/m$^3$) | Ozone (µg/m$^3$) | NO$_2$ (µg/m$^3$) | Temperature (°C) | Relative Humidity (%) | Wind Speed (m/s) | PBL Height (m) |
|------|------|---------------------|---------------|------------------|------------------|------------------|----------------------|-----------------|---------------|
| PM$_2.5$ (µg/m$^3$) | 1 |  |  |  | 1 |  |  |  |  |
| CO (mg/m$^3$) | 0.66 | 1 |  |  |  |  |  |  |  |
| Ozone (µg/m$^3$) | 0.26 | 0.77 | 0.33 | 1 |  |  |  |  |  |
| NO$_2$ (µg/m$^3$) | 0.40 | -0.23 | -0.33 | 1 |  |  |  |  |  |
| Temperature (°C) | 0.086 | -0.16 | 0.73 | -0.25 | 1 |  |  |  |  |
| Relative Humidity (%) | -0.20 | 0.35 | -0.56 | -0.082 | 0.79 | 1 |  |  |  |
| Wind Speed (m/s) | -0.54*** | 0.05 | -0.12 | 0.17 | 0.67*** | 1 |  |  |  |
| PBL Height (m) | -0.013 | -0.20 | 0.75*** | -0.17 | 0.87*** | 0.73*** | 1 |  |  |

|      | Noida | PM$_2.5$ (µg/m$^3$) | PM$_{10}$ (µg/m$^3$) | CO (mg/m$^3$) | Ozone (µg/m$^3$) | NO$_2$ (µg/m$^3$) | Temperature (°C) | Relative Humidity (%) | Wind Speed (m/s) | PBL height (m) |
|------|-------|---------------------|---------------------|---------------|------------------|------------------|------------------|----------------------|-----------------|---------------|
| PM$_2.5$ (µg/m$^3$) | 1 |  |  |  |  |  |  |  |  |  |
| PM$_{10}$ (µg/m$^3$) | 0.62*** | 0.92*** | 1 |  |  |  |  |  |  |  |
| CO (mg/m$^3$) | 0.50*** | 0.37** | -0.58*** | 1 |  |  |  |  |  |  |
| Ozone (µg/m$^3$) | 0.76*** | 0.73** | 0.80*** | -0.55*** | 1 |  |  |  |  |  |
| NO$_2$ (µg/m$^3$) | -0.20 | -0.07 | -0.46*** | -0.54** | -0.60*** | 1 |  |  |  |  |
| Temperature (°C) | 0.14 | 0.01 | 0.45*** | 0.45*** | 0.54*** | -0.88*** | 1 |  |  |  |
| Relative Humidity (%) | -0.62*** | -0.62*** | -0.36*** | -0.38*** | -0.46*** | 0.10 | 0.05 | 1 |  |  |
| Wind Speed (m/s) | -0.28* | -0.19 | -0.52*** | -0.52*** | -0.59*** | 0.84*** | -0.77*** | 0.31** | 1 |  |
| PBL height (m) |  |  |  |  |  |  |  |  |  |  |

|      | Delhi | PM$_2.5$ (µg/m$^3$) | PM$_{10}$ (µg/m$^3$) | CO (mg/m$^3$) | Ozone (µg/m$^3$) | NO$_2$ (µg/m$^3$) | Temperature (°C) | Relative Humidity (%) | Wind Speed (m/s) | PBL height (m) |
|------|-------|---------------------|---------------------|---------------|------------------|------------------|------------------|----------------------|-----------------|---------------|
| PM$_2.5$ (µg/m$^3$) | 1 |  |  |  |  |  |  |  |  |  |
| PM$_{10}$ (µg/m$^3$) | 0.89*** | 1 |  |  |  |  |  |  |  |  |
| CO (mg/m$^3$) | 0.72*** | 0.76*** | 1 |  |  |  |  |  |  |  |
| Ozone (µg/m$^3$) | 0.34** | 0.33** | -0.55 | 1 |  |  |  |  |  |  |
| NO$_2$ (µg/m$^3$) | 0.79*** | 0.80*** | 0.77*** | 0.08 | 1 |  |  |  |  |  |
| Temperature (°C) | -0.27** | -0.18 | -0.30** | 0.36 | -0.58*** | 1 |  |  |  |  |
| Relative Humidity (%) | 0.16 | 0.08 | 0.34** | -0.47*** | 0.51*** | -0.89*** | 1 |  |  |  |
| Wind Speed (m/s) | -0.62*** | -0.67*** | -0.50*** | -0.26** | -0.52*** | 0.078 | -0.02 | 1 |  |  |
| PBL height (m) | -0.36** | -0.29** | -0.36** | 0.26* | -0.59*** | 0.84*** | -0.76*** | 0.30** | 1 |  |

|      | Guru gram | PM$_2.5$ (µg/m$^3$) | PM$_{10}$ (µg/m$^3$) | CO (mg/m$^3$) | Ozone (µg/m$^3$) | NO$_2$ (µg/m$^3$) | Temperature (°C) | Relative Humidity (%) | Wind Speed (m/s) | PBL height (m) |
|------|-----------|---------------------|---------------------|---------------|------------------|------------------|------------------|----------------------|-----------------|---------------|
| PM$_2.5$ (µg/m$^3$) | 1 |  |  |  |  |  |  |  |  |  |
| PM$_{10}$ (µg/m$^3$) | 0.89*** | 1 |  |  |  |  |  |  |  |  |
| CO (mg/m$^3$) | 0.52*** | 0.49*** | 1 |  |  |  |  |  |  |  |
| Ozone (µg/m$^3$) | 0.26 | 0.17 | -0.55*** | 1 |  |  |  |  |  |  |
| NO$_2$ (µg/m$^3$) | 0.68** | 0.67** | 0.69*** | -0.31*** | 1 |  |  |  |  |  |
| Temperature (°C) | -0.06 | -0.07 | -0.70*** | -0.57*** | -0.35 | 1 |  |  |  |  |
| Relative Humidity (%) | -0.02 | -0.09 | 0.71*** | 0.54*** | 0.26* | -0.86*** | 1 |  |  |  |
| Wind Speed (m/s) | -0.66*** | -0.65*** | -0.36 | -0.17 | -0.41*** | 0.04 | 0.03 | 1 |  |  |
| PBL height (m) | -0.18 | -0.16 | -0.68*** | -0.38*** | 0.83*** | -0.74*** | 0.23 | 1 |  |  |
3.3. Variation in CO

Changes in the CO concentration shown in Fig. 3c. Before lockdown from 2 March to 24 March the CO average concentration 1.1 mg/m$^3$, 0.9 mg/m$^3$, 0.7 mg/m$^3$ and 1.5 mg/m$^3$ in Agra, Noida, Delhi and Gurugram respectively, were decrease at 1 mg/m$^3$, 0.4 mg/m$^3$, 0.4 mg/m$^3$ and 0.5 mg/m$^3$ due to the lockdown from 24 March to 14 April which corresponds to variation of $-9\%$, $-55\%$, $-42.8\%$ and $-60\%$ (Table 2). The sequence of declines is Gurugram > Noida > Delhi > Agra and the most visible drop was observed in Gurugram (from 1.5 to 0.6 mg/m$^3$). Though the CO concentration decreased at all observing stations during lockdown time, in the previous two years (2018-2019) the average concentration of CO from 24 March to 14 April has declined in Noida, Delhi and Gurugram by $-45\%$ $-55\%$ and $-69\%$ as decreased NO$_2$ in the same station. While the CO level increased in Agra by (6%) (Fig. 4c, Table 3) due to two thermal power plant (coal-based) was continued during the lockdown (Saini et al., 2014). CO has mostly emitted from incomplete combustion processes vehicular sources and biomass burning as well as oxidation of hydrocarbons. However, other sources include forest fires, agricultural waste burning, biofuel burning, (Holloway et al., 2000). Road vehicles, airlines, trains and all types of transport activities are mostly banned during the lock-down period which decreases CO concentration overall observation sites. Higher levels can be attributed to the use of biofuels in heavily populated areas, while the levels in central India may be due to forest fires and farm burning, as reported by Sahu et al. (2015), prevalent during this season.

3.4. Variation in surface ozone

The variation in the concentration of surface ozone at 8 h average daily maximum is shown in Table 2. Fig. 3b shows, the significant decrease in the O$_3$ level is observed in Noida, Delhi and Gurugram during lockdown by $-36\%$, $-1\%$ and $-25\%$ respectively. In contrast, the surface O$_3$ level is increased in Agra by 98% compared to prior lockdown. Fig. 3b (Table 2) indicates a decrease in the trend of surface O$_3$ in Agra, Delhi and Gurugram by $-3\%$, $-43\%$ and $-26\%$ in 2020 compared to 2019, while in the Noida concentration of surface ozone is increased dramatically by 233% in 2020. Similarly, average O$_3$ concentration was significantly lower during lockdown from 24 March to 14 April 2020 than the average of the same duration in 2018-2019 in all observed stations. The average concentration of O$_3$ approximately 13.4 µg/m$^3$, 31.3 µg/m$^3$ 55.4 µg/m$^3$ and 35.5 µg/m$^3$ in Agra, Noida, Delhi and Gurugram respectively in 2018-2019 in compare to 2020 average of approximately 12.9 µg/m$^3$, 18.7 µg/m$^3$, 28.5 µg/m$^3$ and 32.5 µg/m$^3$ respectively reduced by $(-3.7\%$, $-40\%$, $-48\%$ and $-8\%)$ (Fig. 4e, Table 3). O$_3$ is a secondary pollutant and its increase in the atmosphere due to the presence of its precursors such as NOx and VOCs and sunlight. During the lockdown, the concentration of the precursors may vary based on physical and chemical elimination, photochemistry and transportation on local, regional and global scales can increase the O$_3$ (Filonchyk et al., 2020; Filonchyk and Yan, 2019; Sharma et al., 2016). It is also documented that a decrease in the concentration of PM causes more infiltration of solar radiation through the atmosphere. The existence of much more solar radiation helps to increase the photochemical activity, thus increasing the production of surface O$_3$ in the atmosphere (Oang and Liao, 2019; Li et al., 2019). The temperature began to rise due to the onset of summers, also causing an increase in surface O$_3$ concentrations. On the contrary, a decrease in the O$_3$ in mainly due to reduction in NO$_2$ and CO concentration. The reduction in concentration of O$_3$ precursor such as NO$_2$ by $-71.8\%$, $-64\%$, $-38.5\%$ and CO by $-55\%$, $-42\%$, $-66\%$ in Noida, Delhi and Gurugram, respectively whereas in Agra very less reduction in NO$_2$ ($-9\%$) and CO ($-9.9\%$) were found. Due to the high reduction in NO$_2$ and CO at Noida, Delhi and Gurugram, the O$_3$ concentration was decreased compare to Agra. The level of NO$_2$ and CO declined sharply (Table 3) due to restrictions in all the sectors mentioned, leading to a reduction in the concentration of NO$_2$ and CO emissions in the VOC-limited region which could be correlated with the rise in O$_3$ concentration in the most selected city while in Agra two thermal power plant were continued during the lockdown.

3.5. Relationship between meteorological parameters and air pollutants

In the Pearson correlation test, data of meteorological variables were used to evaluate the relationship between pollutants PM$_{2.5}$, PM$_{10}$, and O$_3$, CO, NO$_2$ during the lockdown period are summarized in Table 4 a-d. The coefficient of Pearson correlation is an indicator of the linear association between two variables. In Agra the PM$_{2.5}$ concentration was highly correlated with NO$_2$ ($r = 0.40$) and CO ($r = 0.66$). In Noida, the concentration of PM$_{2.5}$ was strongly correlated with NO$_2$ ($r = 0.76$), CO ($r = 0.62$) and O$_3$ ($r = 0.50$) likewise, PM$_{10}$ was correlated with NO$_2$ ($r = 0.73$) and CO ($r = 0.92$). The concentration of PM$_{2.5}$ significantly correlated with CO ($r = 0.72$) and NO$_2$ ($r = 0.79$) and similarly PM$_{10}$ is correlated with CO ($r = 0.76$) and NO$_2$ ($r = 0.80$) found in Delhi. In Gurugram PM$_{2.5}$ concentration was significantly correlated with NO$_2$ ($r = 0.62$), CO ($r = 0.52$) and PM$_{10}$ was correlated with NO$_2$ ($r = 0.67$), CO ($r = 0.49$) and least correlated with O$_3$ ($r = 0.17$). The average daily temperature for all stations has substantially positive correlations with the average daily PBL height (correlation $\approx 0.83$) and daily average wind speed (correlation $\geq 0.04$) for all stations, and negative correlations with the average daily relative humidity were (correlation $\approx -0.83$).
and then concentrated close to the ground, even as air pollutants are stuck close to the ground in the days with lower PBL levels (Levi et al., 2020). During the winter season, low PBL height may be partly responsible for several pollutants such as Anthropogenic: burning of fossil fuel, wood burning, natural sources (e.g., pollen), conversion of precursors (NOx, SOx, VOCs) and Biogenic: dust storms, forest fires, dirt roads in the air of the urban area associated with fog and can increase human cardiovascular risk (Al-Delaimy et al., 2020). O3 has a positive Pearson correlation with air temperature in Agra and Delhi, it is evident that the O3 variation is directly correlated to air temperature in Agra and Delhi. There is an increase in O3 concentration, predicted mainly because of the reduction in NOx and particulate matter (PM2.5 and PM10) concentrations. The positive correlation between O3 and Temperature is because the radiation controls the temperature and therefore the photolysis effectiveness will be higher. It points out that apart from the photochemical reaction, some other mechanism might also be contributing to O3 mixing ratio whereas surface O3 has negative Pearson correlation with temperature in Noida and Gurugram indicate that Surface O3 is not directly correlated to air temperature, a lower concentration of NO2 makes it impossible for the O3 generated during the day to be further effectively converted (Zhao et al., 2018). It is seen from Figs. (2–3), in most of the days no breach of the National Ambient Air Quality Standards (NAAQS) for NO2 = 80 μg/m3, PM10 = 100 μg/m3, PM2.5 = 60 μg/m3 based on the 24-h and CO = 2 mg/m3 and surface O3 = 100 μg/m3 at 8-h average during the lockdown period in the observing cities.

For Delhi, the correlations between different air pollutants concentration in Delhi during the study period (2nd March to 14th of April) are shown in Table 4 a-d. The daily (24 h) average concentration of PM2.5 is highly correlated with the daily average concentration of PM10 (r = 0.89), NO2 (r = 0.79) as well as 8 h average concentration of CO (r = 0.72). Likewise, the daily average concentration of PM10 is also strongly correlated with the daily average concentration of NO2 (r = 0.8), as well as 8 h average concentration of CO (r = 0.76) and surface ozone (r = 0.24). This visibly implies that the augmented control of regional transport activity compared to local contributions in the megacity is the key responsible factor for the reduction of pollutants concentration (Sharma et al., 2020) as during the lockdown period the regional transportation has been restricted completely. Besides these, CO (r = 0.77) is strongly associated with NO2. The correlation between O3 and NO2; O3 and CO is not evident (Mahato et al., 2020).

For Delhi, Noida and Gurugram, there is a very poor or negative correlation between temperature and PBL with O3 concentrations, but humidity and wind speed correlate negatively with O3 concentrations. Significant factors influencing the dispersion, aggregation and chemical transition processes of ambient air pollutants are atmospheric conditions, spatial structure, and urban settlement problems (Dandotiya et al., 2020). A correlation analysis demonstrates a good association between ozone and PBL height only in Agra, indicating that surface ozone enhancement could be due to its mixing in a deeper boundary layer with the ozone-rich air aloft, but rather poor or negative correlation found for all observation sites (Ojha et al., 2012). For all observation sites, NO2 and CO concentrations correlated very well, which could indicate that CO and NO2 generated from similar sources (vehicular activities) (Kerimray et al., 2020). A correlation analysis demonstrates a good association between ozone and PBL height only in Agra, indicating that surface ozone enhancement could be due to its mixing in a deeper boundary layer with the ozone-rich air aloft, but rather poor or negative correlation found for all observation sites (Ojha et al., 2012).

A substantial reduction of NO2, CO, PM2.5 and PM10 concentration in the atmosphere for Delhi, Noida and Gurugram due to the restriction of all anthropogenic emissions, thus reducing NO2 concentrations (Table 2) during the lockdown, could be a reason for the reduction in ozone concentration during lockdown (Mahato et al., 2020). Correlation coefficients between air pollutants (NO2, O3, PM2.5 and PM10) for the observation sites during the study period are presented in Table 4a-d. Air pollutants are correlated significantly with each other. For all observation sites, the concentrations of PM2.5 and PM10 correlated well, which may suggest that PM2.5 and PM10 emerged from similar sources. But on the other hand, O3 and NO2 were negatively or weakly correlated with PM2.5 and PM10 for all observing sites. The observations indicate that local transportation control and restricted industrial operations have reduced the overall air pollution burden (Hashim et al., 2020).

Air temperature, PBL height and wind speed are significant factors that influence air pollutant dispersion. The rise in air temperature due to the start of the summer season directly reduces the atmospheric balance and thus raises the planetary boundary layer height of the pollutants and hence the vertical mixing height of the pollutants in the troposphere. (Ravindra et al., 2019; Cichowicz et al., 2017; Akpinar et al., 2008). The increase in air temperature attributed to the rise in solar radiation also increases the strength of atmospheric photochemical reactions. During the lockdown period, the average temperature raised by 6 °C to 7 °C compared to the pre-lockdown time due to the start of the summer season. Therefore, the rise in temperature can be linked to a small fraction of the overall decrease in pollution levels during the lockdown time. This rise is due to the presence of powerful solar radiation for the production of photochemical reactions, leading to the formation of O3 at ground level. The rise in wind speed is also beneficial to air pollutants dispersion and local suspension of the PM2.5 and PM10 sources. During the lockdown, the wind speed marginally increased from 4.1 m/s before lockdown to 0.7 m/s. The comparison between the daily mean wind speed and the variance of the air pollutants indicates a decrease in the concentrations of NO2, CO, PM and O3 during the peaks of wind speed during the entire study period (Mor et al., 2020).

4. Conclusion

This research analyses the impact of national air quality lockdown during COVID-19 as well as the correlation of contaminants in four northern Indian cities. From 24 March to 14 April 2020 during lockdown the concentration of pollutant highly declined by −49.6% (Noida), −43% (Delhi), −71.8% (Noida) and −60% (Gurugram) for PM2.5, PM10, NO2 and CO respectively while O3 has increased drastically 98% in Agra. In 2020, during the lockdown, the concentration of pollutant is also reduced significantly in comparison to 2018–2019. Important variables affecting air pollutant dispersion are air temperature, PBL and wind direction. For surface ozone production, the different meteorological conditions such as high temperature, low relative humidity and high solar
radiation are favourable. The results are especially important for areas where epidemics of COVID-19 and air pollution are both currently elevated, reinforcing the importance of mitigation and enhancing air quality not just in the short term but also in the long term. The analysis reported here only highlights trends in air quality during the period of lockdown. However, to impose short-term (2–4 day) lockdown as an effective policy mechanism for emissions control, and its effect on the economy needs to be rigorously studied. Therefore, lockdown is the important alternate mechanism to be adopted to control air emissions and the existing study is planned to examine the degree of improvement in air quality during the lockdown.

**Author contributions**

**Abhishek Saxena:** Conceptualization; Investigation; Methodology; Software; Writing an original draft. **Shani Raj:** Writing original draft; Writing - review & editing; Figure preparation; Formal analysis.

**Declaration of Competing Interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**Acknowledgements**

The authors would like to thank the Central Pollution Control Board (CPCB) and NOAA (National Oceanic and Atmospheric Administration) Air Resources Laboratory’s (ARL) NASA. Authors also grateful to Mr. Hanwant Singh (M.L. Sukhadia University) for their help in graphical draw.

**References**

Agarwal, A., Kaushik, A., Kumar, S., Mishra, R.K., 2020. Comparative study on air quality status in Indian and Chinese cities before and during the COVID-19 lockdown period. Air Qual. Atmos. Health 13 (10), 1167–1178.

Alpinar, S., Oztop, H.F., Alpinar, E.K., 2008. Evaluation of relationship between meteorological parameters and air pollutant concentrations during winter season in Elazig, Turkey. Environ. Monit. Asses. 146 (1–3), 211–224.

Al-Delaimy, W., Ramanathan, V., Sánchez Sorondo, M., 2020. Health of People, Health of Planet and Our Responsibility: Climate Change, Air Pollution and Health, p. 419.

Apte, J.S., Marshall, J.D., Cohen, A.J., Brauer, M., 2015. Addressing global mortality from ambient PM2.5. Environ. Sci. Technol. 49 (13), 8057–8066.

Bergsträsser, E., Brunekreef, B., Burdorf, A., 2018. The effect of industry-related air pollution on lung function and respiratory symptoms in school children. Environ. Health. 17 (1), 30.

Bennett, R.T., Pope, I.C., Ezzati, M., Olives, C., Lim, S.S., Mehta, S., Shin, H.H., Singh, G., Hubbell, B., Brauer, M., Anderson, H.R., 2014. An integrated risk function for estimating the global burden of disease attributable to ambient fine particulate matter exposure. Environ. Health Pers. 122 (4), 397–403.

Chan, J.F.W., Yuan, S., Kok, K.H., To, K.K.W., Chu, H., Yang, J., Xing, F., Liu, J., Yip, C.C.Y., Poon, R.W.S., Toi, H.W., 2020. A familial cluster of pneumonia associated with the 2019 novel coronavirus indicating person-to-person transmission: a study of a family cluster. Lancet 395 (10223), 514–523.

Cichowicz, R., Wielgosiński, G., Fetter, W., 2017. Dispersion of atmospheric air pollution in summer and winter season. Environ. Monit. Asses. 189 (12), 605.

Dandotiya, B., Sharma, H.K., Jadon, N., 2020. Ambient Air Quality and Meteorological Monitoring of Gaseous Pollutants in Urban Areas of Gwalior City India. Environmental Claims 1–16.

Dang, R., Liao, H., 2019. Radiative forcing and health impact of aerosols and ozone in China as the consequence of clean air actions over 2012–2017. Geophys. Res. Lett. 46 (21), 12511–12519.

ESA, 2020. Air Pollution Drops in India Following Lockdown. https://www.esa.int/Applications/Observing_the_Earth/Copernicus/Sentinel5P/Air_pollution_drops_in_India_following_lockdown.

Fenn, N., Lamson, A.D., Anenberg, S.C., Wesson, K., Risley, D., Hubbell, B.J., 2012. Estimating the national public health burden associated with exposure to ambient PM 2.5 and ozone. Risk Anal. Int. J. 32 (1), 81–95.

Filonchyk, M., Yan, H., 2019. Urban Air Pollution Monitoring by Ground-Based Stations and Satellite Data: copyright: 97–127. Springer International Publishing AG, part of Springer Nature.

Filonchyk, M., Hustychny, V., Yan, H., Yang, S., 2020. Atmospheric pollution assessment near potential source of natural aerosols in the South Gobi Desert region. China. Gl Sci. Remote Sensing. 57 (2), 227–244.

Ghude, S.D., Jain, S.L., Arya, B.C., Beig, G., Ahammed, Y.N., Kumar, A., Tyagi, B., 2008. Ozone in ambient air at a tropical megacity, Delhi: characteristics, trends and cumulative ozone exposure indices. J. Atmos. Chem. 60 (3), 237–252.

Guo, H., Kota, S.H., Sahu, S.K., Hu, J., Ying, Q., Gao, A., et al., 2017. Source apportionment of PM2.5 in North India using source-oriented air quality models. Environ. Pollut. 231, 426–436.

Guo, H., Kota, S.H., Sahu, S.K., Zhang, H., 2019. Contributions of local and regional sources to PM2.5 and its health effects in North India. Atmos. Environ. 214, 116857.

Gurjar, B.R., Ravindran, K., Nagpure, A.S., 2016. Air pollution trends over Indian megacities and their local-to-global implications. Atmos. Chem. Phys. 16, 11783–11790.

Holloway, T., Levy, H., Kasibhatla, P., 2000. Global distribution of carbon monoxide. J. Geophys. Res. Atmos. 105 (D10), 12123–12147.

Kerimray, A., Baimatova, N., Ibragimova, O.P., Bangiev, B., 2020. Assessing air quality changes in Baghdad, Iraq. Sci. Total Environ 756, 436–443.

Kotcher, J., Maibach, E., Choi, W.T., 2019. Fossil fuels are harming our brains: identifying key messages about the health effects of air pollution from fossil fuels. BMC Public Health 19 (1), 1079.

Kumari, P., Toshniwal, D., 2020. Impact of lockdown measures during COVID-19 on air quality a case study of India. Int. J. Environ. Health Res. 1–8.

Lawrence, A., Fatima, N., 2014. Urban air pollution & its assessment in Lucknow City—the second largest city of North India. Sci. Total Environ. 488, 447–455.

Lelevedel, J., Evans, J.S., Piaiek, M., Giannadaki, D., Pozzer, A., 2015. The contribution of outdoor air pollution sources to premature mortality on a global scale. Nature 525 (7569), 367–371.

Levi, Y., Dayan, U., Levy, I., Broday, D.M., 2020. On the association between characteristics of the atmospheric boundary layer and air pollution concentrations. Atmos. Res. 231, 104754.
Li, Q., Zhang, L., Wang, T., Wang, Z., Fu, X., Zhang, Q., 2018. “New” reactive nitrogen chemistry reshapes the relationship of ozone to its precursors. Environ. Sci. Technol. 52, 2810–2818.

Li, K., Jacob, D.J., Liao, H., Zhu, J., Shah, V., Shen, L., Bates, K.H., Zhang, Q., Zhao, S., 2019. A two-pollutant strategy for improving ozone and particulate air quality in China. Nat. Geosci. 12 (11), 906–910.

Li, X., Song, Y., Song, G., Cui, J., 2020. Bat origin of a new human coronavirus: there and back again. Sci. China Life Sci. 63 (3), 461–462.

Mahato, S., Pal, S., Ghosh, K.G., 2020. Effect of lockdown amid COVID-19 pandemic on air quality of the megacity Delhi, India. Sci. Total Environ. 139086.

Mor, S., Kumar, S., Singh, T., Dogra, S., Pandey, V., Ravindra, K., 2020. Impact of COVID-19 lockdown on air quality in Chandigarh, India: understanding the emission sources during controlled anthropogenic activities. Chemos.127978.

Navinya, C., Patidar, G., Phuleria, H.C., 2020. Examining effects of the COVID-19 national lockdown on ambient air quality across urban India. Aerosol Air Qual. Res. https://doi.org/10.4209/aaqr.2020.05.0256.

Ojha, N., Naja, M., Singh, K.P., Sarangi, T., Kumar, R., Lal, S., Lawrence, M.G., Butler, T.M., Chandola, H.C., 2012. Variabilities in ozone at a semi-urban site in the indo-Gangetic plain region: association with the meteorology and regional processes. Journal of Geophys. Res.: Atmos. 117 (D20).

Ravindra, K., Singh, T., Mor, S., Singh, V., Mandal, T.K., Bhatti, M.S., Gahlawat, S.K., Dhanakhar, R., Mor, S., Belg, G., 2019. Real-time monitoring of air pollutants in seven cities of North India during crop residue burning and their relationship with meteorology and transboundary movement of air. Sci. Total Environ. 690, 717–729.

Reddy, B.S.K., Kumar, K.R., Balakrishnaiah, G., Gopal, K.R., Reddy, R.R., Sivakumar, V., Ahammed, Y.N., 2012. Analysis of diurnal and seasonal behavior of surface ozone and its precursors (NOx) at a semi-arid rural site in southern India. Aerosol and Air Quality Research 12 (5), 1081–1094.

Saha, L.K., Sheel, V., Pandey, K., Yadav, R., Saxena, P., Gunthe, S., 2015. Regional biomass burning trends in India: analysis of satellite fire data. J. Earth Syst. Sci. 124, 1377–1387. https://doi.org/10.1007/s12040-015-0616-3.

Saini, R., Singh, P., Awasthi, B.B., Kumar, K., Taneja, A., 2014. Ozone distributions and urban air quality during summer in Agra—a world heritage site. Atmospheric Pollution Research 5 (4), 796–804.

Sharma, M., Dikshit, O., 2016. Comprehensive study on air pollution and green house gases (GHGs) in Delhi. In: A report submitted to Government of NCT Delhi and DPCC Delhi., pp. 1–394.

Sharma, S.K., Mandal, T.K., 2017. Chemical composition of fine mode particulate matter (PM2.5) in an urban area of Delhi, India and its source apportionment. Urban Clim. 21, 106–122.

Sharma, S., Chatani, S., Mahtta, R., Goel, A., Kumar, A., 2016. Sensitivity analysis of ground level ozone in India using WRF-CMAQ models. Atmos. Environ. 131, 29–40.

Sharma, S., Zhang, M., Gao, J., Zhang, H., Kota, S.H., 2020. Effect of restricted emissions during COVID-19 on air quality in India. Sci. Total Environ. 728, 138878.

Slezakova, K., Castro, D., Delerue-Matos, C., da Conceiçã,˜o Alvim-Ferraz, M., Morais, S., do Carmo Pereira, M., 2013. Impact of vehicular traffic emissions on particulate-bound PAHs: Levels and associated health risks. Atmos. Res. 127, 141–147.

Srividasta, S., Kumar, A., Baudddh, K., Gautam, A.S., Kumar, S., 2020. 21-day lockdown in India dramatically reduced air pollution indices in Lucknow and New Delhi, India. Bull. Environ. Contam. Toxicol. (1).

Sujith, B., Sehgal, M., 2017. Characteristics of the ozone pollution and its health effects in India. Inte. J. Med. Public Health. 7 (1).

World Health Organization, 2016. Ambient Air Pollution: A Global Assessment of Exposure and Burden of Disease. World Health Organization (ISBN: 9789241511353).

World Health Organization,2018. Ambient outdoor air quality and health. Downloaded from www.who.int/news-room/factsheets/detail/ambient-(outdoor)-air-qualityand- health, on 30.

WHO, 2020. World Health Organization. Novel coronavirus (2019-nCoV). http://www.euro.who.int/en/health-topics/health-emergencies/novel-coronavirus-2019 ncoy_old (accessed April 02 2020).

Xiang, S., Liu, J., Tao, W., Yi, K., Xu, J., Hu, X., Liu, H., Wang, Y., Zhang, Y., Yang, H., Hu, J., 2020. Control of both PM2.5 and O3 in Beijing-Tianjin-Hebei and the surrounding areas. Atmos. Environ. 224 (117259).

Zhao, T., Markevych, I., Romanos, M., Nowak, D., Heinrich, J., 2018. Ambient ozone exposure and mental health: a systematic review of epidemiological studies. Environ. Res. 165, 459–472.

Zheng, Y.Y., Ma, Y.T., Zhang, J.Y., Xie, X., 2020. COVID-19 and the cardiovascular system. Nat. Rev. Cardiol. 17 (5), 259–260.