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# Comprehensive analysis of ambient air quality during second lockdown in national capital territory of Delhi

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## ABSTRACT

The lockdown imposed in Delhi, due to the second wave of the COVID-19 pandemic has led to significant gains in air quality. Under the lockdown, restrictions were imposed on movement of people, operation of industrial establishments and hospitality sector amongst others. In the study, Air Quality Index and concentration trends of six pollutants, i.e. PM<sub>2.5</sub>, PM<sub>10</sub>, NO<sub>2</sub>, SO<sub>2</sub>, CO, and O<sub>3</sub> were analysed for National Capital Territory of Delhi, India for three periods in 2021 (pre-lockdown: 15 March to 16 April 2021, lockdown: 17 April to 31 May 2021 and post-lockdown: 01 June to 30 June). Data for corresponding periods in 2018–2020 was also analysed. Lockdown period saw 6 days in satisfactory AQI category as against 0 days in the same category during the pre-lockdown period. Average PM<sub>2.5</sub>, PM<sub>10</sub>, NO<sub>2</sub> and SO<sub>2</sub> concentrations reduced by 22%, 31%, 25% and 28% respectively during lockdown phase as compared to pre-lockdown phase, while O<sub>3</sub> was seen to increase. Variation in meteorological parameters and correlation of pollutants has also been examined. The significant improvement arising due to curtailment of certain activities in the lockdown period indicates the importance of local emission control, and helps improve the understanding of the dynamics of air pollution, thus highlighting policy areas to regulatory bodies for effective control of air pollution.

## 1. Introduction

The COVID-19 pandemic is an ongoing pandemic caused by severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2), with over 200 Million cases identified worldwide (Coronavirus Disease (COVID-19), 2021). In order to curb the transmission of COVID-19, governments across the world took measures to implement social distancing norms, and lockdowns were enforced in several countries such as Italy, China, United Kingdom, Argentina and South Africa, to name a few. The first positive case in India, was reported on January 30, 2020. Since then, over 30 million cases have been reported in India (MoHFW, 2020). As a preventive measure, the Government of India on March 24, 2020 announced a 21-day nationwide lockdown, which was extended till May 31 (Ministry of Home Affairs, 2020a, 2020b). Under the said lockdown, severe restrictions were imposed on major sectors such as public transport, construction & demolition activities (C&D), operation of commercial and industrial establishments, etc. This was followed by unlocking of the restricted activities in a phased manner, starting from June 01, 2020 (Ministry of Home Affairs, 2020c). Lockdown continued to be imposed in many parts of the world throughout 2021 as well, due to resurgence in COVID-19 cases.

One of the aspects of the COVID-19 induced lockdown that has been studied lately is its impact on air pollution. Air pollution is a major

concern in India. Central Pollution Control Board (CPCB) has identified 132 non-attainment cities i.e. cities where the ambient air quality exceeds the National Ambient Air Quality Standards (NAAQS) with respect to Particulate Matter (Central Pollution Control Board, 2021; CPCB, ENVIS CENTRE on Control of Pollution (Water, Air, 2021)). Delhi is also listed as one of the non-attainment cities. As per several source apportionment studies conducted for Delhi, emissions from transport sector, industrial sector, and dust (road and construction & demolition) are the major contributors to PM<sub>2.5</sub> and PM<sub>10</sub> in Delhi (CPCB, 2010; Guttikunda and Goel, 2013; Sharma and Dixit, 2016; TERI and ARAI, 2018).

Due to the restrictions on some of these major air pollution sources, widespread reduction in average levels of particulate matter and other pollutants have been reported. In Delhi, PM<sub>2.5</sub> was reported to have reduced by almost 50% during the lockdown imposed in 2020 (25th March– 3rd May 2020) as compared to the levels observed during the same period in 2019. During 20th April – 3rd May 2020 (one of the lockdown phases), PM<sub>10</sub>, NO<sub>2</sub>, Benzene and SO<sub>2</sub>, reduced by 60%, 64%, 62% and 35% respectively, as compared to levels observed in the same time period during 2019 (Central Pollution Control Board (CPCB), 2020). The impact on air quality, due to imposition of lockdown in cities across the world, has been reported in several studies/reports (Briz-Redón et al., 2021; Chen et al., 2020; Gao et al.,

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2021; IQAir, 2020; Jiabin et al., 2021; Liu et al., 2021; Malpede and Percoco, 2021; Nakada and Urban, 2020; Nigam et al., 2021; Roy and Balling, 2021; Sharma et al., 2020; Shukla et al., 2020; Venter et al., 2020).

Considering the rise in COVID-19 cases in Delhi, during the month of April 2021, i.e. in the second wave of the COVID-19 pandemic in India, the Government of NCT of Delhi ordered a weekend lockdown from 10:00 PM on April 16, 2021 to 5:00 AM on April 19, 2021, and subsequently announced a lockdown from 10:00 PM on April 19, 2021 to 5:00 AM on April 26, 2021, which was extended till May 31, 2021 (DDMA, 2020). This was followed by phased unlocking in which the restrictions were gradually lifted. Improvement in air quality in Delhi has been mentioned in a few media reports during this second lockdown. However, it has not been adequately studied. In this paper, we analyse the hourly concentration data for six criteria pollutants ( $PM_{2.5}$ ,  $PM_{10}$ ,  $NO_2$ ,  $SO_2$ ,  $CO$  and  $O_3$ ) along with Air Quality Index (AQI), for National Capital Territory of Delhi, during the lockdown imposed due to the second wave of the COVID-19 pandemic. The variation in air quality observed is compared to the periods, one month before and one month after the lockdown period, along with the data for the corresponding periods during 2018–2020. We also investigate the correlation of meteorological parameters (wind speed, relative humidity and temperature) with the criteria pollutants.

## 2. Data and methodology

### 2.1. Study area, data sources and period of study

The study focuses on the National Capital Territory of Delhi, located at 28.24°N – 28.53°N and 76.50°E - 77.20°E, with slightly over 75% area classified as urban and the rest as rural. Delhi has a population of 16.78 million as per Census of India 2011 (Government of NCT of Delhi, 2021). To monitor the air quality in the city, 40 Continuous Ambient Air Quality Monitoring Stations (CAAQMS) have been installed in Delhi by different agencies such as Central Pollution Control Board (CPCB), Delhi Pollution Control Committee (DPCC), India Meteorological Department (IMD) and Indian Institute of Tropical Meteorology (IITM). Location of these stations is depicted in Fig. 1. These stations monitor a number of pollutants including  $PM_{2.5}$ ,  $PM_{10}$ ,  $NO_2$ ,  $SO_2$ ,  $NH_3$  and Benzene using different analysers, and generate and transmit the air quality data online thereby, reducing the chances of manual error. The data generated is disseminated online. Methods for measurement of these pollutants have already been laid down in the National Ambient Air Quality Standards (National Ambient Air Quality Standards, 2009). CPCB has laid down guidelines for real-time sampling and analysis for measurement of ambient air pollutants, and has also developed a protocol for transmission of data from CAAQM stations (CPCB, 2011, 2015). These stations also record meteorological data at their respective sites on a continuous basis.

Hourly concentrations of  $PM_{2.5}$ ,  $PM_{10}$ ,  $SO_2$ ,  $NO_2$ ,  $O_3$ , and  $CO$  from CAAQMS installed in Delhi were obtained from Central Control Room (CCR) portal (CPCB 2021) (), a portal operated by CPCB where ambient air quality data from CAAQMS installed across India is available. Hourly data of relative humidity (RH), Precipitation, Wind speed (WS), Wind direction (WD) and Temperature (Temp) were obtained from two CAAQM stations, i.e. IHBAS (Latitude: 28.6811736, Longitude: 77.3025234) and East Arjun Nagar (Latitude: 28.655935, Longitude: 77.294904). These stations have data availability for several years and are operated by CPCB.

Air Quality Index (AQI) data has been obtained from CPCB website (CPCB, 2021). AQI is a dimensionless number that is decided based on ambient concentration values of air pollutants and their likely health impact. There are six AQI categories, namely Good, Satisfactory, Moderately polluted, Poor, Very Poor, and Severe (CPCB, n.d.-a). Calculation of AQI is discussed in detail in the next section.

The data is analysed for three periods of 2021, viz. pre-lockdown, during lockdown and post-lockdown. The pre-lockdown period has been considered from 15th March to 16th April 2021, lockdown period from 17th April to 31st May 2021 while the post-lockdown period has been considered from 1st June to 30th June 2021. The 'during lockdown' period described above has been mentioned as 'lockdown' in subsequent sections of the study. In order to draw comparison with previous years, air quality and meteorological data for the corresponding periods in 2018–2020 has also been considered in the study.

### 2.2. Methodology

#### 2.2.1. Air quality index

There are eight pollutants for which short-term (up to 24-hours) National Ambient Air Quality Standards have been prescribed, i.e.  $PM_{10}$ ,  $PM_{2.5}$ ,  $NO_2$ ,  $SO_2$ ,  $CO$ ,  $O_3$ ,  $NH_3$ , and Pb. (National Ambient Air Quality Standards, 2009) Though health breakpoints have been defined for each of these pollutants, the first six are usually considered for the calculation of Air Quality Index (CPCB, 2014). Sub-indices for individual pollutants at a monitoring location are calculated using 24-hourly average concentration value (8-hourly in case of  $CO$  and  $O_3$ ) and health breakpoint concentration range. The highest sub-index of all the calculated sub-indices is the AQI for that location.

The sub-index ( $I_p$ ) for a given pollutant concentration ( $C_p$ ), as based on 'linear segmented principle' is calculated as:

$$I_p = \left\{ \frac{(I_{HI} - I_{LO})}{(B_{HI} - B_{LO})} \right\} * (C_p - B_{LO}) + I_{LO}$$

$B_{HI}$  = Breakpoint concentration greater or equal to given concentration

$B_{LO}$  = Breakpoint concentration smaller or equal to given concentration

$I_{HI}$  = AQI value corresponding to  $B_{HI}$

$I_{LO}$  = AQI value corresponding to  $B_{LO}$ ; subtract one from  $I_{LO}$ , if  $I_{LO}$  is greater than 50

$AQI = \text{Max}(I_p)$  (where;  $p = 1, 2, \dots, n$ ; denotes  $n$  pollutants) (CPCB, 2014)

There are six AQI categories, namely Good, Satisfactory, Moderately polluted, Poor, Very Poor, and Severe, and each has an associated colour code, likely health impact, and AQI range. AQI is calculated only if data is available for minimum three pollutants out of which one should be either  $PM_{2.5}$  or  $PM_{10}$ , and a minimum of 16 hours' data is available for the pollutants.

#### 2.2.2. Statistical tests used

Normality of meteorological and air quality data were assessed using Shapiro-Wilk's test (Ghasemi and Zahediasl, 2012; Mohd Razali and Bee Wah, 2011). The null-hypothesis of this test is that the sample is normally distributed. If the  $p$ -value is less than 0.05, the distribution is said to be non-normal.

If the distribution is non-normal, Kruskal-Wallis One Way Analysis of Variance (ANOVA) on Ranks is performed. The same has been performed on pre-lockdown, during lockdown and post-lockdown datasets, as well as data for corresponding periods in previous years. This test is used to determine whether or not there is a statistically significant difference between the medians of three or more independent groups. If the  $p$ -value is less than 0.05, the null hypothesis is rejected, i.e. the difference between the medians of the groups considered is statistically significant. However, the test does not indicate which of the groups are different. Therefore, post-hoc tests are required to be performed. In our analysis, we have performed Dunn's test to ascertain whether pairwise differences between the groups are statistically significant. Since the null hypothesis for the test is that there is no difference between groups, a  $p$ -value of less than 0.05 indicates that the difference between the two groups is statistically significant.



Fig. 1. Location of CAAQMS in Delhi.

### 3. Results and discussion

#### 3.1. Variation in meteorological parameters

An increasing trend in temperature was seen during 2021 from pre-lockdown phase to lockdown phase (Fig. 2). As expected, temperatures were the highest in the post-lockdown period as against the earlier two phases because this period is usually termed as the summer season for Delhi. Relative humidity (RH) followed a similar trend as temperature (Fig. 2). There are two events during the study period, i.e. May 19, 2021 and June 20, 2021, when RH levels peaked, which may be due to rainfall or favourable conditions for rainfall, leading to high humidity levels, as shown in Fig. 2. Wind speed was higher during the lockdown period as compared to pre-lockdown and post-lockdown periods, with wide variation in wind direction. Fig. 3 shows the wind rose diagrams for the three phases in 2021. Hourly meteorological data was found to be non-normal as per Shapiro-Wilk's test (S. No. 1, Supplementary). Pairwise differences of temperature, RH and WD for the three phases were statistically significant (S. No. 2 & 3, Supplementary). However, pairwise difference for wind speed between pre-lockdown and during lockdown phases was not significant.

Mean wind speed during lockdown period was higher than the wind speed in the same period during 2018–2020, while wind direction was similar to that seen during 2018 and 2020. Mean RH during lockdown period was similar to average levels seen during the corresponding period of 2020 but higher than the levels seen in corresponding periods of 2018 and 2019. Descriptive statistics for meteorological variables for

lockdown period in 2021 and corresponding periods in 2018–20 is presented in Table 1.

Results of Dunn's tests reveal that temperature difference amongst the lockdown period of 2021 and corresponding periods of 2019 and 2020 was not significant ( $p > 0.05$ ). Differences in wind speed and wind direction between lockdown period and corresponding period of 2018 were not statistically significant. Differences in RH and wind direction between lockdown period and corresponding period of 2020 were also not significant (S. No. 4 & 5, Supplementary). Thus, while meteorological variations amongst the three phases in 2021 were significant in most cases, variation in meteorological factors over the corresponding periods in 2018–20 has been mixed at best.

#### 3.2. Variation in air quality index

Average AQI during the lockdown period was 25% lower than that observed during pre-lockdown phase (S. No. 6, Supplementary). Average AQI reduced further in the post-lockdown period with a 31% reduction as compared to the pre-lockdown period. Fig. 4 depicts the trend of AQI during the three study phases in 2021 and corresponding periods over 2018–2020. Average AQI during 2018–20 was observed to increase in the period corresponding to the lockdown phase as compared to the period corresponding to pre-lockdown phase, unlike the trend observed in 2021.

The pre-lockdown period saw 19 days in the poor-severe AQI categories, while the corresponding period in 2018, 2019 and 2020 saw 18, 14 and 0 days, respectively in poor-severe AQI categories (S. No. 7, Sup-

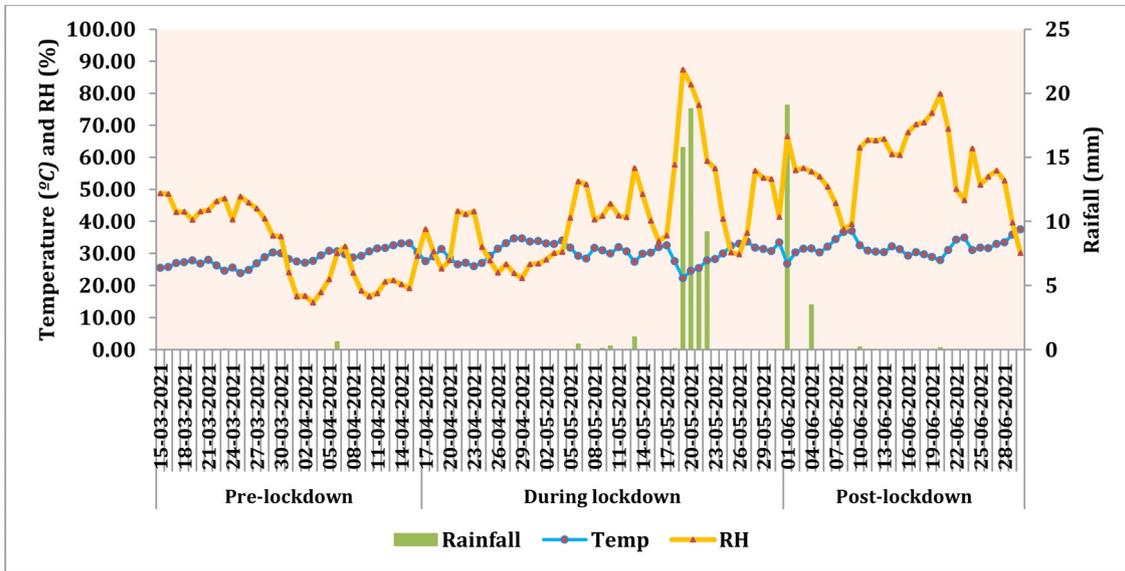


Fig. 2. Daily average temperature (Temp in °C), Relative Humidity (RH in%) and rainfall (in mm) during study period of 2021.

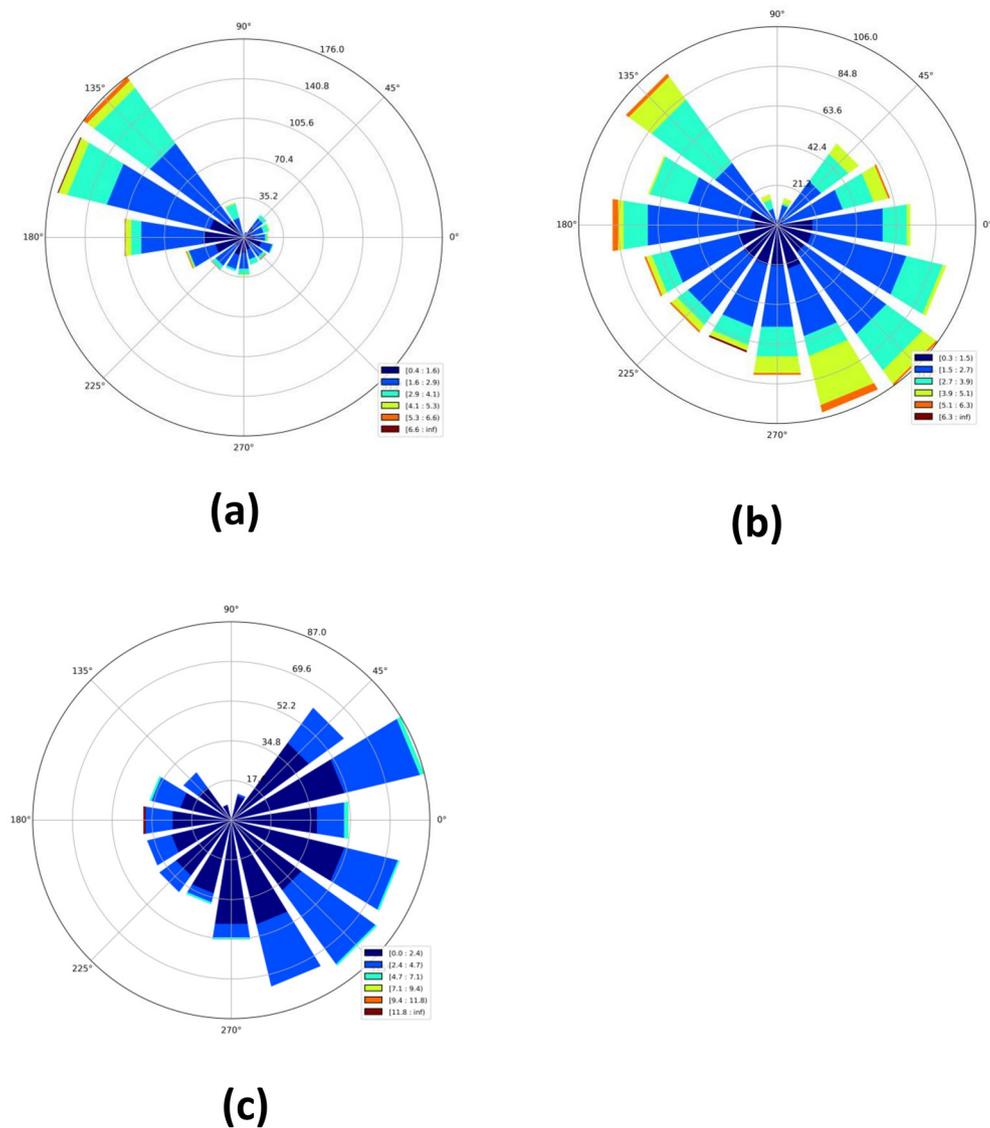


Fig. 3. (a) Wind rose for pre-lockdown period 2021, (b) Wind rose for during lockdown period 2021, (c) Wind rose for post-lockdown period 2021  
Note: Wind speed in m/s.

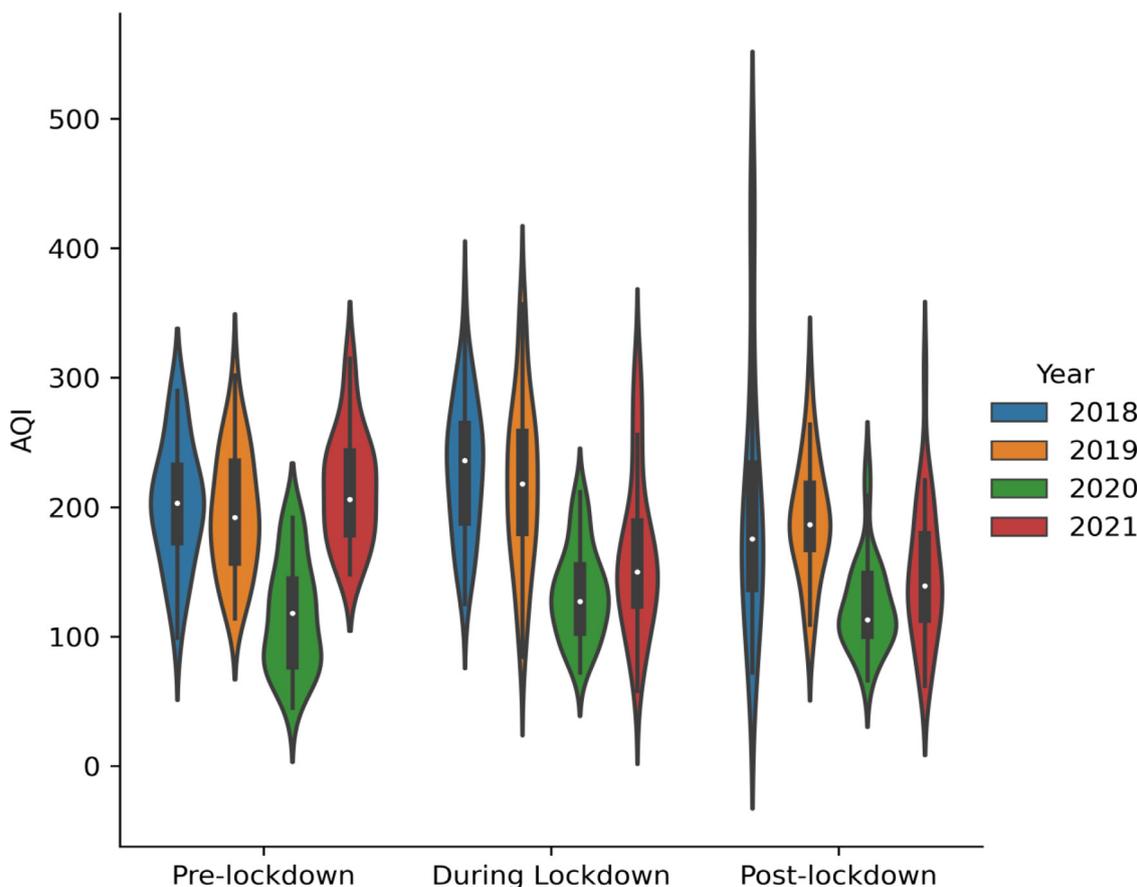


Fig. 4. Violin plot for AQI in Delhi for 2018–2021 under the three phases.

**Table 1**

Descriptive statistics for meteorological variables for lockdown period in 2021 and corresponding periods in 2018–21.

Parameter	Temp (°C)	RH(%)	WS (m/s)	WD (degrees)
<b>2018</b>				
Mean	33.49	33.81	2.18	175.89
Median	33.47	34.09	1.96	166.66
Min	28.69	14.98	1.27	74.65
Max	38.31	54.24	3.84	315.25
Std dev	2.69	12.10	0.67	67.03
<b>2019</b>				
Mean	30.85	32.33	0.99	213.39
Median	31.60	31.57	0.99	225.47
Min	22.19	9.39	0.48	91.37
Max	35.65	64.56	1.63	320.02
Std dev	2.95	14.87	0.28	58.25
<b>2020</b>				
Mean	31.11	42.27	1.93	178.45
Median	29.88	42.56	1.79	156.12
Min	25.07	20.39	1.17	92.10
Max	40.55	74.70	3.79	310.09
Std dev	4.03	13.63	0.57	64.42
<b>2021</b>				
Mean	30.23	41.75	2.35	184.60
Median	30.62	40.79	2.26	172.31
Min	22.22	22.23	1.19	76.82
Max	34.67	87.35	4.29	314.64
Std dev	2.91	15.19	0.62	62.01

plementary). Thus, air quality in the pre-lockdown phase was worse as compared to the air quality in the corresponding period of 2018–2020.

However, a greater number of satisfactory and moderate AQI days were observed during the lockdown and post-lockdown periods in 2020

and 2021 as against the corresponding periods in 2018 and 2019 (S. No. 8 & 9, Supplementary). It may also be noted that average AQI during the lockdown period was higher than the levels observed during the corresponding period in 2020, in all likelihood due to stricter restrictions imposed in 2020 due to the nation-wide lockdown.

### 3.3. Variation in pollutant concentrations

Concentrations of all criteria pollutants considered in the study, except O<sub>3</sub>, reduced during the lockdown phase as compared to the pre-lockdown phase. Concentrations of PM<sub>2.5</sub>, PM<sub>10</sub>, NO<sub>2</sub>, SO<sub>2</sub> and CO decreased further in the post-lockdown period (S. No. 10, Supplementary). The hourly concentrations of the pollutants were non-normally distributed as per Shapiro-Wilk's test (S. No. 11–14, Supplementary). Results of Kruskal-Wallis test indicates that the differences in medians between the three phases in 2021 for all six pollutants were statistically significant. Dunn's test was used to further determine whether pair-wise differences were significant (S. No. 15 & 16, Supplementary).

Descriptive statistics for these pollutants for pre-lockdown, lockdown and post-lockdown periods in 2021 are presented in Table 2. Average PM<sub>2.5</sub> concentration reduced from 85.5 µg/m<sup>3</sup> to 66.4 µg/m<sup>3</sup>, average PM<sub>10</sub> concentration from 241.4 µg/m<sup>3</sup> to 167.7 µg/m<sup>3</sup>, average NO<sub>2</sub> concentration from 45.3 µg/m<sup>3</sup> to 34.1 µg/m<sup>3</sup>, average SO<sub>2</sub> concentration from 19.4 µg/m<sup>3</sup> to 14 µg/m<sup>3</sup> and average CO concentration from 1.13 mg/m<sup>3</sup> to 1.03 mg/m<sup>3</sup>, in the lockdown phase from the pre-lockdown period. During the post-lockdown phase, Average PM<sub>2.5</sub>, PM<sub>10</sub>, NO<sub>2</sub>, SO<sub>2</sub> and CO concentration decreased to 53.6 µg/m<sup>3</sup>, 158.8 µg/m<sup>3</sup>, 29.7 µg/m<sup>3</sup>, 10 µg/m<sup>3</sup> and 1 mg/m<sup>3</sup>, i.e. a reduction of 37%, 34%, 34%, 48% and 11%, respectively as compared to the levels observed during pre-lockdown period.

**Table 2**  
Descriptive statistics for PM<sub>2.5</sub>, PM<sub>10</sub>, NO<sub>2</sub>, SO<sub>2</sub>, CO and O<sub>3</sub> for pre-lockdown, lockdown and post-lockdown periods in 2021.

Statistical measure	PM <sub>2.5</sub> (µg/m <sup>3</sup> )	PM <sub>10</sub> (µg/m <sup>3</sup> )	NO <sub>2</sub> (µg/m <sup>3</sup> )	SO <sub>2</sub> (µg/m <sup>3</sup> )	CO (mg/m <sup>3</sup> )	Ozone (µg/m <sup>3</sup> )
<b>Pre-lockdown</b>						
Mean	85.47	241.37	45.30	19.36	1.13	34.97
Median	81.93	237.42	44.20	19.21	1.13	36.22
Min	49.32	144.53	30.05	13.51	0.71	19.42
Max	125.86	365.45	65.35	24.47	1.47	51.09
Std dev	21.53	56.85	7.68	3.13	0.18	7.13
<b>During lockdown</b>						
Mean	66.36	167.70	34.06	13.96	1.03	43.35
Median	53.50	140.67	32.36	12.67	0.97	43.95
Min	22.35	57.16	24.95	8.15	0.75	19.79
Max	185.52	390.13	52.61	28.56	1.81	59.82
Std dev	39.04	86.76	7.61	5.40	0.20	8.30
<b>Post- lockdown</b>						
Mean	53.65	158.84	29.70	10.02	1.00	35.22
Median	50.78	148.68	29.12	9.86	1.00	36.13
Min	23.79	52.64	18.05	8.12	0.83	22.17
Max	89.11	374.43	42.46	13.28	1.24	49.44
Std dev	17.65	78.66	5.88	1.22	0.10	7.04

Pairwise difference of NO<sub>2</sub> and SO<sub>2</sub> levels for all three phases were statistically significant. Pairwise difference of PM<sub>10</sub> levels between lockdown and post-lockdown phases was not significant. Average O<sub>3</sub> levels increased by 24% in the lockdown phase to 43.4 µg/m<sup>3</sup> as against pre-lockdown phase concentration of 35 µg/m<sup>3</sup> but remained similar to the levels seen in pre-lockdown phase during the post-lockdown period (35.2 µg/m<sup>3</sup>). However, the pairwise differences between the three phases were statistically significant. There were more number of exceedance of the hourly O<sub>3</sub> NAAQS during the lockdown phase as compared to the pre-lockdown phase. While the focus of the NCAP presently is on control of particulate matter pollution, high O<sub>3</sub> concentrations, and its effects on health and ecosystem are often overlooked (Ministry of Environment Forests and Climate Change, 2019). Thus, there is a need to have more studies to assess ozone formation potential, so as to target reduction of VOCs in parallel with NO<sub>x</sub> and PM in future pollution abatement strategies.

During the lockdown, curbs were imposed on several activities, except for emergency activities/services. Further, movement of individuals was also restricted apart from certain exemptions. Thus, a large number of private and commercial establishments, markets, manufacturing units, along with construction activities were not permitted (DDMA, 2021). As per source apportionment study for Delhi, dust (soil, road, construction), industries and transport sector contribute about 77% of PM<sub>2.5</sub> and 79% of PM<sub>10</sub> during summers (TERI and ARAI, 2018). Further, transport sector is the most prominent contributor to NO<sub>x</sub> and CO emissions, while power plants and industries are the major contributor to SO<sub>2</sub> (TERI and ARAI, 2018). Due to restriction on movement of people, curbs on commercial and industrial establishments, and construction activities, a general reduction was seen in the levels of these pollutants during lockdown, as against pre-lockdown levels.

Even though power plants operating in the vicinity of Delhi were still in operation, few units have already installed Flue Gas Desulphurization technologies, while work is underway at many units with the deadline for thermal power plants within 10 km of the National Capital Region (NCR) and in cities with more than 1 million population, to comply with new emission norms, by the end of 2022.

Sustained reduction through the post-lockdown phase, may be due to gradual relaxation of curbs. However, meteorological variations may also have played a role as the difference between meteorological variables during the lockdown phase and the post-lockdown phase was statistically significant.

The reduction in emissions from transport sector is also indicated by Google's COVID-19 community mobility reports. Mobility trends for retail & recreation places, grocery & pharmacy places, and, parks, show a

decline of 75%, 47% and 68% respectively during the lockdown period as compared to the baseline (S. No. 21, Supplementary) (Google, 2022). The baseline is the median value, for the corresponding day of the week, during the five week period 3 Jan–6 Feb 2020. Reduction in emissions from transport sector and commercial establishments is also clearly reflected in the change in mobility trends for public transport hubs and workplaces, which fell by 68% and 70% respectively during the lockdown phase, with respect to the baseline. Mobility trends for residential places increased during the same period by 26%, as against the baseline.

Apple's mobility trends were also studied to observe the changes in requests for directions by transportation type (driving and walking for Delhi). Apple's mobility trends show relative volume of directions requests per country/region, sub-region or city compared to a baseline volume on January 13<sup>th</sup>, 2020 (COVID-19 - Mobility Trends Reports - Apple, 2022). In Delhi, during the lockdown period, requests for directions for driving and walking reduced by 64% and 65% respectively, as against the pre-lockdown period (S. No. 22, Supplementary). The reduction is in agreement with the mobility changes indicated by Google Mobility trends. During the post-lockdown period, the requests for directions for driving and walking increased as compared to the lockdown phase, but were still lower than the pre-lockdown phase.

The closure on operation of commercial and manufacturing units, along with restrictions on transport sector is also indicated by the rise in unemployment rate during this period. Unemployment Rates are produced by Centre for Monitoring Indian Economy Pvt. Ltd. (CMIE) using its Consumer Pyramids Household Survey machinery (CMIE, n.d.). The unemployment rate is computed as the number of persons not employed but willing to work and actively looking for a job as a per cent of the total labour force, where the total labour force is the sum of all those who are employed and those who are not employed but are willing and looking for a job. Monthly unemployment rate in Delhi increased from 9.4% in March 2021, to 27.3% in April 2021 and further to 45.6% in May 2021, before falling to 8.8% in June 2021 (S. No. 23, Supplementary). It may be noted that lockdown was in force from the middle of April to May, during which high unemployment rates have been reported. As per Delhi Human Development Report, 2013, most of the employment generation in Delhi (around 85%) has taken place in the unorganised informal sector (Institute for Human Development, 2013). Referring to the NSS survey of the 67th Round, 2010–11, pertaining to unincorporated non-agricultural enterprises data, the report noted that retail trade (except for motor vehicles and motorcycles) accounts for 28.2% of the employment in the unorganised sector, while manufacture of wearing apparel, wholesale trade (except motor vehicles and motorcycles), food and beverages, & service activities, and other personal service activi-

ties (maids, hairdressers, pet care, etc.) account for 8%, 7.3%, 6.4%, and 4.8%, respectively. The above subsectors together account for more than half of the employment in the 65 subsectors of unorganised sector and were affected during the lockdown, which may have led to higher unemployment rates and lower emissions.

Further, power supply position reports of Central Electricity Authority (CEA) depicts a reduction of 8% and 31% in energy supply for Delhi region during May 2021 as compared to May 2020 and May 2019 respectively (S. No. 24, Supplementary) (Central Electricity Authority, n.d.-b). It may be noted that lockdown was in place during the month of May in 2021.

Since almost 40% of Delhi's energy sales are to industrial and commercial units (Central Electricity Authority, n.d.-a), and mobility trends for residential places were seen to increase, it could be inferred that there was a considerable reduction in operation of industrial and commercial establishments during the lockdown period.

However, lowest 24-hourly  $PM_{2.5}$  and  $PM_{10}$  concentration during the lockdown period still remained above the 24-hourly WHO Global air quality guidelines (AQG) of  $15 \mu\text{g}/\text{m}^3$  and  $45 \mu\text{g}/\text{m}^3$  respectively (World Health Organization, 2021). On the other hand, lowest 24-hourly  $CO$ ,  $NO_2$  and  $SO_2$  levels were within WHO AQG. Moreover, these lowest levels of pollutants were seen during the days when rainfall was recorded (18–22 May) or when high wind speed was observed (29–30 May), suggesting the important role played by meteorological factors in deposition or dispersion of pollutants.

A source apportionment study for Delhi had suggested that only 36% and 26% of  $PM_{2.5}$  in Delhi during winters and summers respectively, was contributed by sources located within Delhi itself, with NCR region, upwind regions outside NCR and even upwind regions outside India contributing the rest (TERI and ARAI, 2018). This, read with the fact that  $PM_{2.5}$  levels did not meet the WHO AQG during the lockdown period, implies that even with strict curtailment of emissions in Delhi, achieving WHO AQG might be difficult, unless actions on a regional or sub-national scale are undertaken.

In order to tackle the problem of air pollution in a comprehensive manner, Ministry of Environment, Forest and Climate Change, Government of India has launched national clean air programme (NCAP) in January 2019 with targets to achieve 20 to 30% reduction in  $PM_{2.5}$  and  $PM_{10}$  concentrations by 2024 at the national level (Ministry of Environment Forests and Climate Change, 2019). Formulation of regional and trans-boundary plans is a part of NCAP, and may play a major role, especially in the Delhi-NCR region.

Fig. 5 depicts the violin plots for the six criteria pollutants during the three phases in 2018–2021. Average  $PM_{2.5}$ ,  $PM_{10}$ ,  $NO_2$  and  $CO$  levels were higher during all three phases in 2021 as compared to corresponding periods in 2020 (S. No. 25, Supplementary). However, average  $SO_2$  and  $O_3$  levels were lower during the lockdown period in 2021 as compared to the corresponding period in 2020. Notably, pairwise differences of concentration of the 6 pollutants between the lockdown period and the corresponding period in 2020 were statistically significant. (S. No. 26 & 27, Supplementary)

Average  $PM_{2.5}$ ,  $PM_{10}$ ,  $NO_2$  and  $CO$  levels during the lockdown period reduced by 22%, 32%, 33% and 25% respectively as against the levels observed in the corresponding period in 2019 (S. No. 28, Supplementary). When compared against the levels observed in the corresponding period in 2018, average  $PM_{2.5}$ ,  $PM_{10}$ ,  $NO_2$  and  $CO$  levels reduced by 26%, 37%, 32% and 30% respectively during the lockdown period (S. No. 29, Supplementary). Pairwise differences for the levels of above pollutants in lockdown period with respect to 2018 and 2019 were statistically significant. Average  $SO_2$  levels reduced to  $14 \mu\text{g}/\text{m}^3$  in the lockdown period from a concentration of  $20.3 \mu\text{g}/\text{m}^3$  (reduction of 31%) observed during the corresponding period in 2019 but increased by 6% when compared with the levels observed in the corresponding period of 2018. However, the pairwise difference in  $SO_2$  levels between lockdown period and the corresponding period in 2018 was not statistically significant. Average  $O_3$  levels reduced by 12% and 19% in the

lockdown period as against the corresponding period in 2019 and 2018 but the pairwise difference between  $O_3$  levels in the lockdown period and the corresponding period in 2019 was not statistically significant.

The lower average levels of  $PM_{2.5}$ ,  $PM_{10}$ ,  $NO_2$  and  $CO$  during the lockdown period, as compared to the levels observed in the corresponding period of 2018 and 2019, may be attributed to the restrictions imposed due to lockdown. However, average levels of these pollutants were still higher during lockdown period, when compared with the levels observed in the corresponding period of 2020. This may be due to the fact that during most of this period in 2020, a nationwide lockdown was in place, in which even more stringent curbs were imposed including restrictions on interstate travel and commercial transport, closure of government offices and institutions, curtailment of most industries, etc. This is supported by a larger reduction in Mobility trends provided by Google and Apple, in the period corresponding to the lockdown period in 2020, as against the lockdown period.

Average  $O_3$  levels in all three phases during 2021 were lower than the levels observed in corresponding periods of 2018–20. Reduction in  $O_3$  has also been observed in several other studies (Centre for Science and Environment, 2020; Chen et al., 2021; Deroubaix et al., 2021; Grange et al., 2020; Kang et al., 2021; Sicard et al., 2020; Siciliano et al., 2020). However,  $O_3$  levels were recorded at  $43.4 \mu\text{g}/\text{m}^3$  during the lockdown period, i.e. 24% higher as compared to pre-lockdown period ( $35 \mu\text{g}/\text{m}^3$ ). Ground-level  $O_3$ , being a secondary pollutant, forms due to the reaction of nitrogen oxides and volatile organic compounds in the presence of heat and sunlight.  $NO$  scavenges  $O_3$  and leads to formation of  $NO_2$  and  $O_2$ , thus leading to a reduction in  $O_3$  levels. Therefore, the rise in  $O_3$  levels during lockdown period may probably be due to the reduced levels of this reaction considering the reduction in  $NO_x$  levels resulting from restrictions on transport and industrial sectors.

It may be noted that though the levels of most pollutants were considerably lower during the lockdown period, further reduction in ambient concentrations to even lower levels was not seen, in all likelihood, due to operational thermal power plants, certain industries, regional sources, and, domestic sector emissions, during the said lockdown period, coupled with Delhi's geography and location in the Indo-Gangetic plain, along with unfavourable meteorology favouring accumulation of pollutants.

### 3.4. Variation in $PM_{2.5}/PM_{10}$ ratio

Ratio of  $PM_{2.5}/PM_{10}$  increased from 0.356 in the pre-lockdown period to 0.397 during the lockdown phase and then decreased to 0.364 during the post-lockdown phase, as depicted in Fig. 6. This is unlike the trend observed in the corresponding periods during 2019 and 2020 when the  $PM_{2.5}/PM_{10}$  ratio decreased monotonously from the pre-lockdown phase to the post-lockdown phases.

Since  $PM_{10}$  comprises of  $PM_{2.5}$  as well, an attempt was also made to understand the variation in levels of coarser particles, i.e.  $PM_{10}-PM_{2.5}$ . However, the ratio of  $PM_{2.5}/(PM_{10}-PM_{2.5})$  also followed the same trend. The increase in ratio of  $PM_{2.5}/(PM_{10}-PM_{2.5})$  from pre-lockdown phase to lockdown phase, despite decrease in average  $PM_{2.5}$ ,  $PM_{10}$  and  $PM_{10}-PM_{2.5}$  levels, indicates larger decrease in coarser particles ( $PM_{10}-PM_{2.5}$ ) than finer particles ( $PM_{2.5}$ ). This may be due to more restrictions on dust producing activities, such as C&D, road dust re-suspension, etc., while on the other hand, sectors contributing towards  $PM_{2.5}$  emissions such as domestic, industries including thermal power plants, certain types of vehicles were still operational, though in lesser quantities. The analysis suggests that fugitive dust may be the major pollutant in Delhi, and relevant emission reduction could be effective for coarse PM control in the future.

However, when  $PM_{2.5}/(PM_{10}-PM_{2.5})$  ratio declined from lockdown phase to post-lockdown phase, both average  $PM_{2.5}$  and  $PM_{10}$  levels were seen to decrease, while average  $PM_{10}-PM_{2.5}$  levels increased, indicating prominent role of coarse particles, i.e. dust. A recent study has also indicated the major component in the particulate matter in Delhi during

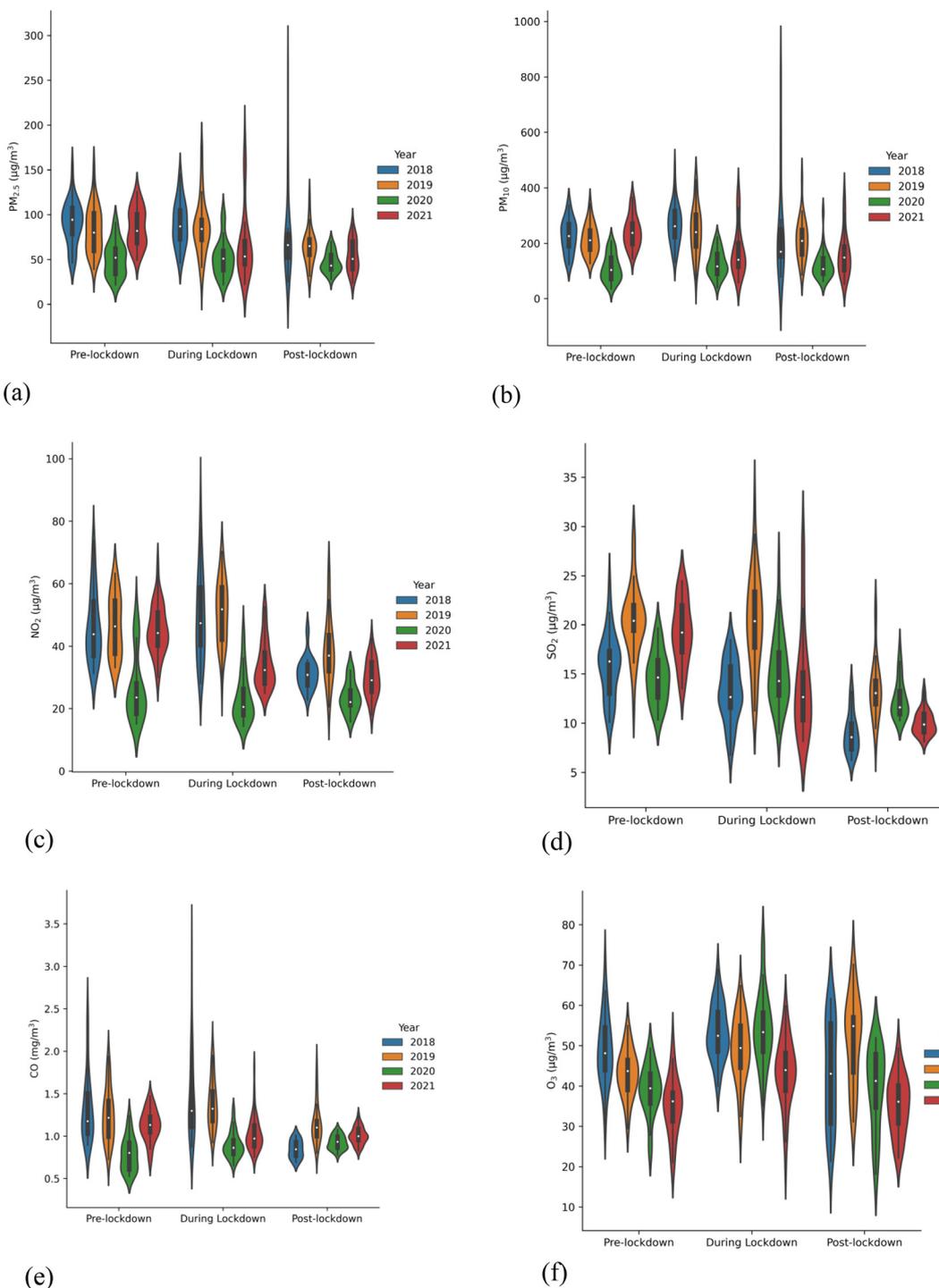


Fig. 5. Violin plots during the three phases in 2018–2021 for pollutants (a)  $PM_{2.5}$ , (b)  $PM_{10}$ , (c)  $NO_2$ , (d)  $SO_2$ , (e)  $CO$ , and (f)  $O_3$ .

summers is dust (Shukla et al., 2021). Thus, it is likely that localised lifting of dust due to dry conditions may have played a prominent role during the post-lockdown phase.

### 3.5. Episodic events during lockdown period

While there was an overall reduction during the lockdown phase in the average levels of five pollutants, i.e.  $PM_{2.5}$ ,  $PM_{10}$ ,  $NO_2$ ,  $SO_2$  and  $CO$ , there were some days during the lockdown period when an uncharacteristic rise in levels of these pollutants was witnessed. These incidences have been termed as episodic events. Since particulate matter is

the prominent pollutant for Delhi, we limit our analysis to those days in the lockdown period when  $PM_{2.5}$  or  $PM_{10}$  levels were abnormally higher (ENVIS, 2016). 24-hour averaged  $PM_{2.5}$  and  $PM_{10}$  levels for the lockdown period were studied and two episodic events, i.e. April 26–29, 2021 and May 23, 2021 were identified and further analysed (S. No. 30, Supplementary).

Average  $PM_{2.5}$ ,  $PM_{10}$ ,  $NO_2$ ,  $CO$  and  $SO_2$  levels during the first episodic event (26–29 April 2021) were 148%, 102%, 42%, 44% and 93% higher respectively than average of the corresponding pollutant for the entire lockdown period. Average  $PM_{2.5}$ ,  $PM_{10}$ ,  $NO_2$ ,  $CO$  and  $SO_2$  levels during the first episodic event were  $164.4 \mu g/m^3$ ,  $339 \mu g/m^3$ ,

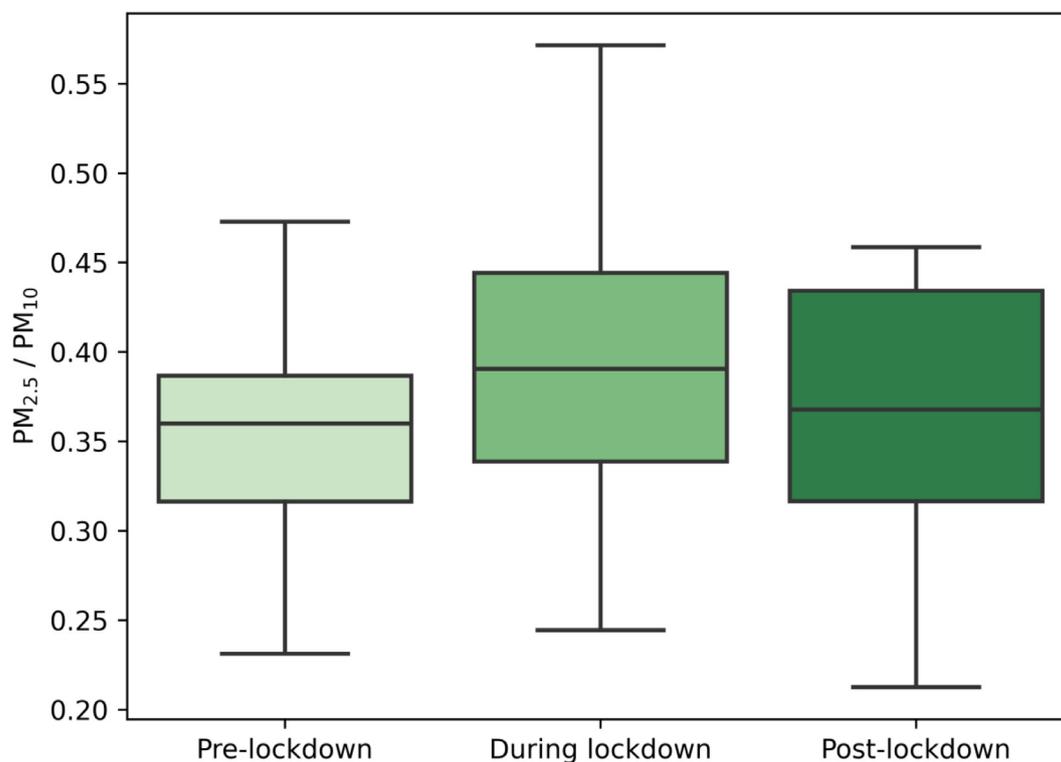


Fig. 6. Box plot depicting  $PM_{2.5}/PM_{10}$  ratio for the three phases during 2021.

48.5  $\mu\text{g}/\text{m}^3$ , 1.5  $\text{mg}/\text{m}^3$  and 26.9  $\mu\text{g}/\text{m}^3$  respectively. Backward air mass trajectories were computed using Hybrid Single-Particle Lagrangian Integrated Trajectory model (HYSPLIT version 5.1.0) (Rolph et al., 2017; Stein et al., 2015). Global Data Assimilation System (GDAS) one-degree dataset was used and New Delhi (28.58,77.20) was set as the source location. Backward trajectories were run for each day with a runtime of 72 h, with three arrival heights of 100 m, 500 m and 1000 m (above ground level) using a vertical velocity model. Results from backward trajectories show air masses originating from Punjab, Haryana and even from outside of India in this period. Fig. 7 shows the backward trajectories ending at 12 UTC on 26 April 2021 (S. No. 31, Supplementary).

It may be noted that during this time, wheat crop residue burning takes place in the northern/north-western parts of India. Several studies have shown that crop residue burning increases the concentration of air pollutants such as CO, NO<sub>x</sub>, SO<sub>x</sub>, non-methane hydrocarbons, volatile organic compounds, and particulate matter, and that these pollutants are also transported to Delhi during favourable meteorological conditions (Bhuvaneshwari et al., 2019; Gupta et al., 2004; Mittal et al., 2009; Ravindra et al., 2019).

NASA Fire Information for Resource Management System (FIRMS), detects active fire data from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Terra and Aqua satellites, NASA's Visible Infrared Imaging Radiometer Suite (VIIRS) aboard the joint NASA/NOAA Suomi national polar orbiting partnership (Suomi NPP) and, NOAA-20 satellites (NASA Fire Information for Resource Management System, 2021). FIRMS depicts a large number of fire events in the states of Punjab and Haryana and towards the west/northwest of India, during 24–30 April 2021, suggesting crop residue burning in these areas (S. No. 32, Supplementary). Thus, it is likely that crop residue burning in these areas may have played a part in the rise in average concentrations of multiple pollutants during the first episodic event in Delhi.

During the second episodic event (23 May 2021), the rise in level of air pollutants was witnessed for a couple of hours.  $PM_{10}$  levels suddenly shot up at 4 AM on 23 May 2021 (483.6  $\mu\text{g}/\text{m}^3$ ), reached a peak at 6 AM (1000  $\mu\text{g}/\text{m}^3$ , which is also the upper limit of the analyser) and

then subsequently started to decrease from 9 AM (950.1  $\mu\text{g}/\text{m}^3$ ), reaching pre-episodic levels by 10 PM (48.6  $\mu\text{g}/\text{m}^3$ ) on the same day (S. No. 33, Supplementary).  $PM_{2.5}$  followed a similar trend. Average levels of  $PM_{2.5}$  and  $PM_{10}$  on this day increased by 126% and 133% respectively as compared to the average  $PM_{2.5}$  and  $PM_{10}$  levels during the entire lockdown period. Moreover, average levels of coarser particles ( $PM_{10}-PM_{2.5}$ ) increased by 137% as compared to average levels of  $PM_{10}-PM_{2.5}$  during the lockdown period. However, average NO<sub>2</sub> (28.9  $\mu\text{g}/\text{m}^3$ ), SO<sub>2</sub> (8.7  $\mu\text{g}/\text{m}^3$ ) and CO (0.8  $\text{mg}/\text{m}^3$ ) levels during this event were lower than the average NO<sub>2</sub>, SO<sub>2</sub> and CO levels during the entire lockdown period. Ratio of  $PM_{2.5}/(PM_{10}-PM_{2.5})$  fell from 0.88 on 22.05.2021 to 0.52 on 23.05.2021 and then again increased to 0.74 on 24.05.2021. Thus, on 23.05.2021, coarser particles, i.e. dust was more prominent.

Meteorological data for this period indicate that surface winds were from Southwest (Wind direction between 180°-270°) for 19 out of 24 h between 12 noon on 22.05.2021 to 12 noon on 23.05.2021 (S. No. 34, Supplementary). Results of backward air mass trajectories computed using HYSPLIT model, run for 48 h with source at Delhi with three arrival heights of 10 m, 100 m and 500 m (above ground level), depicted in Fig. 8, also indicate air mass originating from Delhi's southwest (Rajasthan).

Though trajectories were also seen to arrive even from Punjab and Haryana, fire events had reduced to a large extent during 21–24 May 2021 (S. No. 35 & 36, Supplementary). Further, since there was no increase in gaseous pollutants, it may be reasonably stated that crop residue burning was not the primary reason behind this episodic event.

Emissions due to resuspension of dust in pre-monsoon season in Delhi along with dust storms from Arabian peninsula and Thar Desert have been studied in several previous studies (Hama et al., 2020; Kumar et al., 2014, 2014; Perrino et al., 2011; Rai et al., 2020; Sarkar et al., 2019). Thus, it seems that dust emissions from south-west of Delhi along with localised dust re-suspension may be responsible for this episodic event, and the high dust emissions subsided after a few hours as the day progressed, due to higher wind speed along with higher boundary layer height.

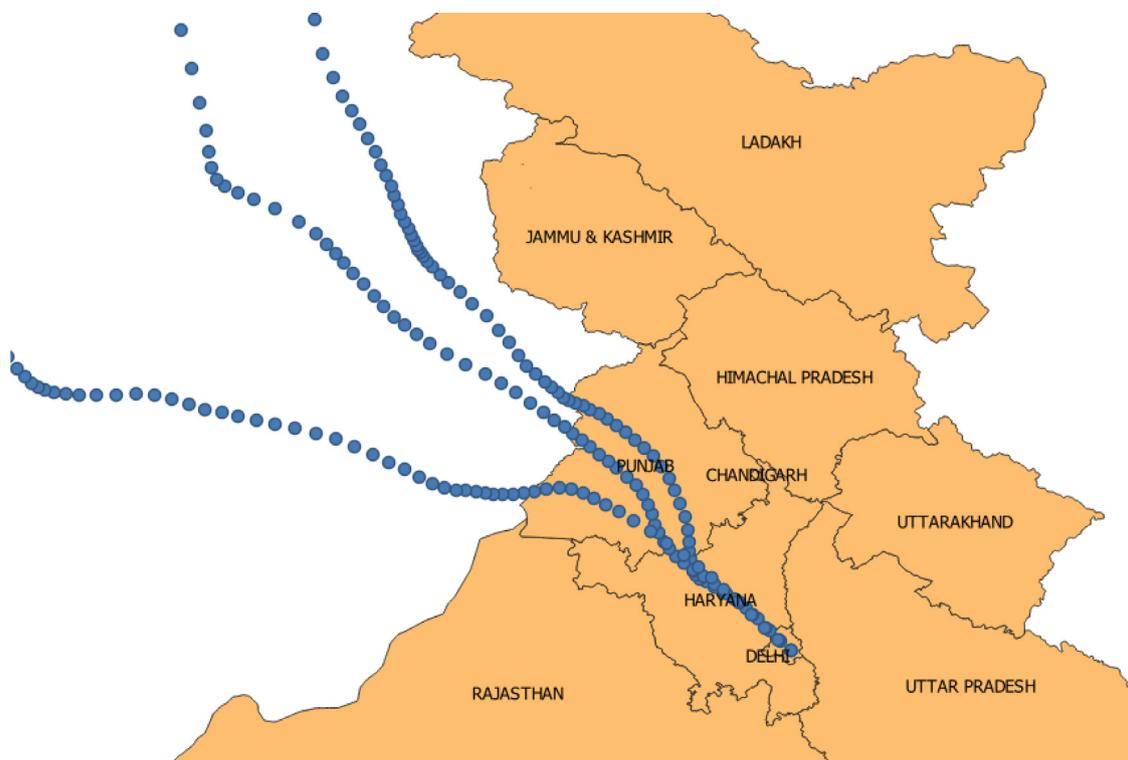


Fig. 7. Backward trajectories ending at 12 UTC on 26 April 2021 with source location at New Delhi.

From the above, it is evident that even with restrictions on emission sources, both natural and anthropogenic regional sources influenced Delhi's air quality during the lockdown period. While an airshed-based approach is being initiated by the Government of India to formulate comprehensive regional air quality management policies, natural events such as dust transport from dry arid regions in India and abroad, is a natural phenomenon on which no effective curbs can be placed. Such natural episodic incidences may not be considered for determination of compliance to NAAQS, so that emphasis remains on control of anthropogenic emission sources.

### 3.6. Correlation analysis of meteorological parameters and criteria pollutants

Spearman rank correlation test was performed on the six criteria pollutants and meteorological variables, considered in the study (S. No. 37.1, 37.2 and 37.3, Supplementary). In the pre-lockdown phase, temperature was positively correlated with all six pollutants with  $O_3$  showing the highest correlation (S. No. 38.1, Supplementary). The correlation with  $O_3$  was also statistically significant. In the lockdown and post-lockdown phases, all pollutants except  $O_3$  had statistically significant positive correlation with temperature (S. No. 38.2 & 38.3, Supplementary). Some studies have also reported negative correlation between high temperature and pollutants, stating that high temperature promotes convection of air, and brings about the dilution and dispersion of air pollutants (Yang et al., 2017). Further,  $O_3$  is very weakly correlated with temperature in post-lockdown phase, with the correlation not even significant, which is inconsistent with earlier studies (Ali et al., 2012; Jayaraman et al., 2007; Xie et al., 2021).

However, the correlation was not statistically significant. Correlation of temperature with  $PM_{2.5}$ , and  $PM_{10}$  saw a consistent increase from pre-lockdown to post-lockdown phase. The strong correlation of temperature with  $PM_{2.5}$  and  $PM_{10}$  during lockdown and post-lockdown phases may be due to photochemical production of particulate matter

or localised lifting of dust due to dry weather conditions amidst high temperature (Manju et al., 2018).

Average RH levels in the pre-lockdown period were lower than those seen in lockdown and post-lockdown periods. RH positively correlated with  $PM_{2.5}$  and  $PM_{10}$  during pre-lockdown phase but negatively correlated during lockdown and post-lockdown phases. All these correlations were statistically significant. It may be the case that  $PM_{2.5}$  concentration increased while humidity was low, but once humidity reaches a high enough value,  $PM_{2.5}$  concentrations decreased. This has also been reported in a few studies (Barmpadimos et al., 2011; Hernandez et al., 2017). Some studies suggest settling down of particulate matter in humid conditions due to the particles gathering mass (Giri et al., 2008; Islam et al., 2017; Jayaraman et al., 2007; Kayes et al., 2013).

$NO_2$ ,  $SO_2$  and CO also negatively correlated with RH in the lockdown and post-lockdown phases and the correlation was statistically significant. High humidity may also lead to rain, resulting in wet deposition and consequent reduction in ambient pollutant concentrations (Jayamurugan et al., 2013). RH inversely correlated with  $O_3$  in all three phases, and the results during pre-lockdown and lockdown phases were statistically significant. The negative correlation between  $O_3$  and relative humidity found in the current study is in agreement with the results of earlier studies (Chen et al., 2004; Jayaraman et al., 2007; Swamy et al., 2012). Increase in RH often results in increase in cloudiness, inhibiting  $O_3$  formation due to a reduction in photochemical process. Also, in polluted areas such as Delhi, increase in water vapour can restrict ozone formation, as  $NO_2$  gets converted to nitric acid (Camalier et al., 2007; Jacob and Winner, 2009).

Wind speed was negatively correlated with the 6 pollutants in all phases except  $O_3$  in the pre-lockdown phase. Correlation during the lockdown phase was significant for all pollutants except  $O_3$ . The negative correlation of wind speed and pollutants indicates improved dispersion of these pollutants, with a rise in wind speed (Zhang et al., 2015). Negative correlation of  $PM_{2.5}$ ,  $NO_2$  and CO with wind speed was the highest in pre-lockdown phase and decreased consistently from

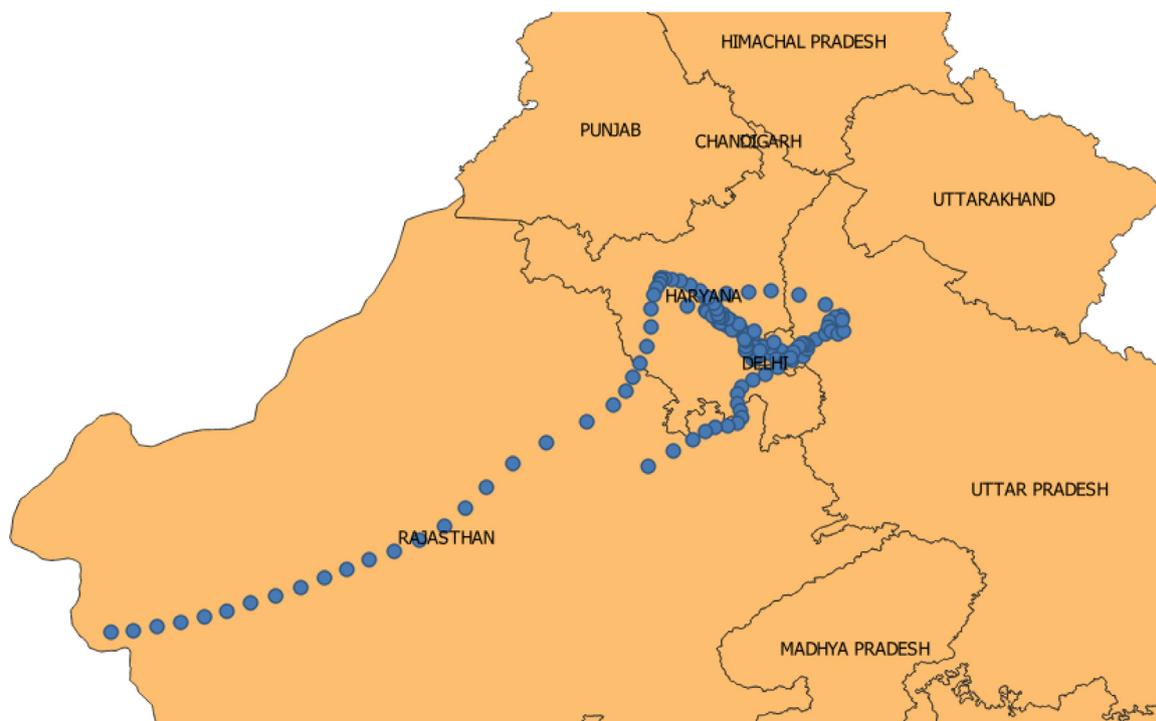


Fig. 8. Backward trajectories ending at 23 UTC on 22 May 2021 with source location at New Delhi.

lockdown phase to post-lockdown phase, suggesting the reducing dominance of local sources to ambient  $PM_{2.5}$ ,  $NO_2$  and CO concentrations (Manju et al., 2018).

In view of the changing association of meteorological parameters with the pollutants, from one phase to another, and that these phases are spread across different seasons, one single strategy for all seasons may not work, and air quality management plans may be required on seasonal basis.

Correlation tests were also performed amongst the six criteria pollutants. During the pre-lockdown period,  $PM_{2.5}$  was strongly and positively correlated with  $PM_{10}$  and CO (S. No. 38.4, Supplementary). The correlation of  $NO_2$  with  $SO_2$  was strong, and so was the correlation of CO with  $SO_2$ . All these correlations were significant.  $O_3$  was weakly correlated with  $NO_2$ , and the correlation was not significant.

Correlation between  $NO_2$  and CO was high ( $>0.75$ ) during the pre-lockdown and lockdown phases, since CO influences the oxidation of NO to  $NO_2$  in presence of sunlight (Environmental Protection Agency (EPA), 1999; Kovač-Andrić et al., 2013). During lockdown period,  $PM_{2.5}$  was strongly and significantly correlated with the other pollutants, while  $PM_{10}$  strongly correlated with  $SO_2$  (S. No. 38.5, Supplementary).  $NO_2$  was also strongly correlated with  $SO_2$  and CO.  $O_3$  was weakly correlated with other pollutants but the correlations of  $O_3$  were not significant (except with  $SO_2$ ). This is comprehensible considering the fact that  $O_3$  is a secondary pollutant, and one of its precursors, i.e.  $NO_x$  was reduced during the lockdown period because of curbs on vehicular movement and industrial operation.

In the post-lockdown period,  $PM_{2.5}$  was strongly correlated with all pollutants except  $O_3$ , and the correlations were significant (S. No. 38.6, Supplementary).  $NO_2$  was also strongly correlated with  $SO_2$ . Notably, the correlation of  $NO_2$  with  $O_3$  was higher in this phase, as compared to the previous two phases, and the correlation was also significant.

Since  $PM_{2.5}$ ,  $SO_2$ ,  $NO_2$ , and CO primarily originate from anthropogenic and combustion sources, and that gaseous pollutants are also related to formation of secondary particulate matter, the correlation is expected to be high for these pollutants with  $PM_{2.5}$  than with  $PM_{10}$ . This is consistent with the results of the analysis where the correlation

coefficients for  $PM_{2.5}$  with  $NO_2/SO_2/CO$  were higher than that between  $PM_{10}$  and  $NO_2/SO_2/CO$  in all three phases during 2021 (Yangyang et al., 2015).

### 3.7. Diurnal variation of criteria pollutants

The diurnal variation in the criteria pollutants during the three phases in 2021 were also studied. In the lockdown phase,  $PM_{2.5}$  and  $PM_{10}$  followed the same pattern as the pre-lockdown phase, though at lower levels (S. No. 39.1 & 39.2, Supplementary). In the post-lockdown phase,  $PM_{2.5}$  and  $PM_{10}$  had varying trends, with almost stable levels during the day but an increase during evening hours as compared to the levels observed during lockdown phase.  $NO_2$  and  $SO_2$  levels in lockdown phase were lower throughout the day but followed the same trend as in pre-lockdown phase (S. No. 39.3 & 39.4, Supplementary).  $NO_2$  levels during post lockdown-phase were lower than levels seen during lockdown and there was no noticeable peak in the morning.  $SO_2$  levels during post-lockdown phase were even lower, and remained stable throughout the day. CO levels had variable trends during the lockdown and post-lockdown phases (S. No. 39.5, Supplementary). Though CO levels were lower during the peak hours in both lockdown and post-lockdown phases, reduction in CO levels during non-peak hours was relatively less, resulting in higher levels than seen during pre-lockdown phase.  $O_3$  levels during the lockdown were higher throughout the day as compared to pre-lockdown levels (S. No. 39.6, Supplementary). However,  $O_3$  levels during post-lockdown phase were lower during the day when  $O_3$  is expected to peak, but were higher in early morning and late night hours as against pre-lockdown levels. Variation in  $O_3$  levels is indicative of the photochemistry and the complex relationship it shares with other pollutants, which has not been studied in detail, in this paper.

Diurnal variability of pollutants is primarily attributed to the diurnal variability of boundary layer height and emission sources (Liu et al., 2015). Relatively muted diurnal variation in the levels of  $PM_{2.5}$ ,  $PM_{10}$ ,  $NO_2$ ,  $SO_2$  and CO clearly indicates absence of major emission sources during the lockdown and post-lockdown periods. It is clear that increase in pollutant concentrations seen during night hours in the lockdown

period is dominated by role of boundary layer height and meteorological factors which require further study.

#### 4. Conclusion

Owing to the restrictions imposed on several activities during the second wave of the COVID-19 pandemic in Delhi, concentrations of the criteria pollutants analysed in the study, except O<sub>3</sub>, were seen to decrease during the lockdown period, with maximum reduction seen in PM<sub>10</sub> levels. During the lockdown period, O<sub>3</sub> levels were higher during all hours of the day and CO levels were higher during some non-peak hours, while PM<sub>2.5</sub>, PM<sub>10</sub>, NO<sub>2</sub> and SO<sub>2</sub> levels were lower during the entire day. Quantum of reduction in the average levels of these pollutants further increased during the post-lockdown phase. However, there was an increase in pollutant concentrations in all phases during 2021 when compared to corresponding periods in 2020. Correlation of PM<sub>2.5</sub> was high with SO<sub>2</sub>, NO<sub>2</sub>, and CO, hinting at their origin from anthropogenic and combustion sources. Curtailment of anthropogenic activities yielded considerable improvement in air quality, corroborating the fact that policy changes at local level can aid in achieving considerable reduction in air pollution. However, despite these restrictions, ambient concentrations of pollutants were far from ideal, hinting at the complex and multi-faceted nature of Delhi's air quality, involving Delhi's location in the densely populated Indo-Gangetic Plain and unfavourable meteorological conditions resulting in accumulation of pollutants.

While the analysis conducted in our study is limited to Delhi, our study carries significance for the entire Indo-Gangetic belt which has high levels of air pollution, urbanization and similar anthropogenic pollution sources. The data analysis is meaningful to understand the relationship between the air quality and emission, brings out possible areas of further research, and underscores the impact of regional sources on Delhi's air quality during low emission scenarios. Such data is novel for building upon policies to mitigate air pollution.

With quantifiable targets set under the National Clean Air Programme launched by the Government of India for reduction in particulate matter concentration by 2024, there is a need to identify prominent emission sources and make a transition to cleaner & greener alternatives, while establishing graded emission reduction targets, so as to attain sustainable and irreversible reduction in air pollution.

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#### 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.

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#### Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.hazadv.2022.100078.

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