Effect of COVID-19-induced lockdown on NO₂ pollution using TROPOMI and ground-based CPCB observations in Delhi NCR, India

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Abstract The present study investigates the reduction in nitrogen dioxide (NO₂) levels using satellite-based (Sentinel-5P TROPOMI) and ground-based (Central Pollution Control Board) observations of 2020. The lockdown duration, monthly, seasonal and annual changes in NO₂ were assessed comparing the similar time period in 2019. The study also examines the role of atmospheric parameters like wind speed, air temperature, relative humidity, solar radiation and atmospheric pressure in altering the monthly and annual values of the pollutant. It was ascertained that there was a mean reduction of ~61% (~66.5%), ~58% (~51%) in daily mean NO₂ pollution during lockdown phase 1 when compared with similar period of 2019 and pre-lockdown phase in 2020 from ground-based (satellite-based) measurements. April month with ~57% (~57%), summer season with ~48% (~32%) decline and an annual reduction of ~20% (~18%) in tropospheric NO₂ values were observed (p < 0.001) compared to similar time periods of 2019. It was assessed that the meteorological parameters remained almost similar during various parts of the year in 2019 and 2020, indicating a negligent role in reducing the values of atmospheric pollution, particularly NO₂ in the study area. It was concluded that the halt in anthropogenic activities and associated factors was mainly responsible for the reduced values in the Delhi conglomerate. Similar work can be proposed for other pollutants to holistically describe the pollution scenario as an aftermath of COVID-19-induced lockdown.

Keywords Tropospheric NO₂ · Air pollution · TROPOMI · CPCB · COVID-19

Introduction

The World Health Organization (WHO) declared coronavirus disease a global pandemic on March 11, 2020. India witnessed a total of > 10.286 million cases and > 0.149 million deaths as of Dec 31, 2020 (World Health Organization, 2020). Delhi was one of the hardest-hit states in the nation with 6,24,795 cases and 10,523 deaths in the UT territory alone by December 2019. The countries across the globe were dramatically impacted by the pandemic and adapted the mitigation measures employing a phasewise lockdown of
essential services and activities in countries across the globe. The first countrywide curfew was announced on March 22, 2020, followed by phase-wise lockdowns. Phase 1 of the lockdown lasted for 21 days from March 25 to 14 April, phase 2 from April 15 to May 3 (19 days), phase 3 from May 4 to May 17 (14 days) and finally May 18 to May 31 (14 days) of 2020. It was followed by twelve unlock phases starting from June 1, 2020, until the second wave of the COVID-19 infections affected the country. The lockdown phases successfully slowed the growth of active infections within the country and proved vital in uplifting the environmental regime of the nation in terms of factors like air and water pollution. (Bao & Zhang, 2020; Garg et al., 2020a, b; Girdhar et al., 2021; Gkatzelis et al., 2021; Kumar et al., 2020b; Lokhandwala & Gautam, 2020; Putaud et al., 2020; Sekar et al., 2020; Selvam et al., 2020; Vadrevu et al., 2020). Restricted transportation and other anthropogenic activities restrained the emissions and brought a considerable reduction in air pollutant concentration, especially nitrogen dioxide ($\text{NO}_2$). $\text{NO}_2$ is generally studied in conjunction with nitric oxide (NO) and is a resultant of fuel burning processes from industries, thermal power plants, vehicular activity, etc. (Angelevska et al., 2021; Central Pollution Control Board, 2011). The increase in criteria pollutants like NO and $\text{NO}_2$ and the capability of $\text{NO}_x$ in producing secondary criteria air pollutants (like ozone) have been an important area of research in climatic studies (Chakraborty et al., 2020; He et al., 2020; Krotkov et al., 2016; Nidhi & Jayaraman, 2007; Smith et al., 2015). Ozone is a greenhouse gas and has a high global warming potential and positive radiative forcing effect (Hoegh-Guldberg et al., 2018), and $\text{NO}_x$ contributes to its increase in the atmosphere, ultimately leading to climate change.

Additionally, long-term exposure to canopy level high levels of $\text{NO}_2$ can have severe health impacts (Abbey & Burchette, 1996; Balakrishnan et al., 2019; Faustini et al., 2014; He et al., 2020). A slew of studies indicated a close relationship between the number of COVID-19 cases and mortality with exposure to $\text{NO}_2$ (Kaur, 2017; Naqvi et al., 2020; Ogen, 2020; Siddiqui et al., 2020; Sikarwar & Rani, 2020). Many researchers have elaborated their findings on the reduced levels of $\text{NO}_2$ during and after lockdown phases. (Siddiqui et al., 2020) linked the long-term $\text{NO}_2$ levels with COVID-19-related mortality and found 53% corona positive and 61% fatality cases due to the pandemic in eight five-million plus cities in the country alone. They indicated an overall reduction of $\text{NO}_2$ by 46% in the cities across India during the lockdown phase (March 11–March 23, 2020) when compared to the pre-lockdown (March 11–March 23, 2020) phase using Sentinel-5P TROPOMI data. (Srivastava et al., 2021) noted a reduction of $\text{NO}_2$ by $1 \times 10^{15}$ molecules/cm$^2$ in 2020 over the Indo Gangetic Plain, eastern and southern India due to lockdown w.r.t. average between 2017 and 2019 using Aura Ozone Monitoring Instrument (OMI) measurements. 20 to 30% reductions in $\text{NO}_2$ were observed in different regions across the globe like China, Europe, Italy, France, Spain and the USA (Muhammad et al., 2020). Using ground station pollution data (Central Pollution Control Board’s Continuous Ambient Air Quality Monitoring System data) from in and around Delhi $\text{NO}_2$ showed a reduction of 17.04% to 65.18% during 25 March–1 April compared to 17 March–24 March duration in 2020. The highest reduction in values was found at Noida (65.18%) followed by Delhi (58.1%), while the lowest decline was observed in Faridabad (Garg et al., 2021). (Tobías et al., 2020) reported a 51% decrease in $\text{NO}_2$ in Barcelona and Spain during the two-week lockdown. Several other studies (Table 1) have indicated a reduction in $\text{NO}_2$ and other pollutants across Indian cities (Biswal et al., 2020; Biswas & Ayantika, 2021; Dinka et al., 2021; Ganguly et al., 2021; Jain & Sharma, 2020; Kumar et al., 2020b; Mahato et al., 2020; Navinya et al., 2020; Selvam et al., 2020; Sharma et al., 2020; Singh et al., 2020a, b) and other cities around the world as an effect of partial and complete lockdown (Acharya & Sreekesh, 2013). Studies indicated that ambient concentrations of pollutants were significantly curtailed as an after effect of the pandemic-related lockdown compared to before lockdown scenarios and last year status.

The present study assesses the spatio-temporal variations in $\text{NO}_2$ concentrations due to decline in anthropogenic activities in the Delhi region compared with pre-lockdown, during the lockdown and post-lockdown scenarios in 2020 and 2019. The study also investigates the role of atmospheric parameters like wind speed, wind direction, air temperature, solar radiation and pressure in altering the monthly and annual values of the pollutants (Feistel & Hellmuth, 2021) using satellite-based measurements derived from Sentinel-5P onboard TROPOMI datasets. Also,
Table 1  Few noteworthy COVID-19-related air pollution studies in India

| Study area           | Criteria air pollutant | Dataset used                                      | Major findings                                                                                                                                                                                                 | Reference                  |
|----------------------|------------------------|--------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------|
| Delhi, India         | PM$_{10}$, PM$_{2.5}$, NOx, NO, NO$_{2}$, SO$_{2}$, NH$_{3}$, SO$_{2}$, CO, and C$_{6}$H$_{6}$ | Central Pollution Control Board’s (CPCB) ground station data | PM$_{10}$ and PM$_{2.5}$ levels decreased up to 55–65%, NOx and NO (50–78%), SO$_{2}$ (33%), CO (45%), NH$_{3}$ (27%), C$_{6}$H$_{6}$ (53%) during lockdown phase (25 March-1 April, 2020)). During first week of lockdown, O$_3$ decreased, but later it increased by 19–27%                                                                 | (Garg et al., 2021)         |
| 57 urban agglomerations, India | PM$_{2.5}$, PM$_{10}$, SO$_{2}$, NO$_{2}$ and O$_3$ | Central Pollution Control Board’s (CPCB) ground station data | Highlighted the reduction in various pollutants across the urban agglomerations with special emphasis on six representative zones of India across the 4 lockdown phases                                                                 | (Das et al., 2021)          |
| Delhi NCR, India     | PM$_{10}$, PM$_{2.5}$, NO$_{2}$, NO, NH$_{3}$, SO$_{2}$ | Central Pollution Control Board’s (CPCB) ground station data | Impact of COVID-19 lockdown at 63 locations in and around Delhi was examined. Average reductions in PM$_{10}$ (-46 to -58%), PM$_{2.5}$ (-49 to -55%), NO$_{2}$ (-27 to -58%), NO (-54 to -59%), NH$_{3}$ (-2 to -38%) and increase in average O$_3$ (4 to 6%) during the lockdown compared to same periods in previous years. WRF-CHIMERE model simulations suggest reductions in Indian subcontinent due to traffic and industrial sector especially in urban areas | (Dumka et al., 2021)        |
| Delhi, Mumbai, Kolkata, India | PM$_{10}$ and NO$_{2}$ | Central Pollution Control Board’s (CPCB) station data | Overall decrease in PM$_{10}$ concentration is 30–60% and NO$_{2}$ is 52–80% during lockdown in comparison to 2019 and pre-lockdown period (Feb 14-Mar 24, 2020). Highest decline observed in Kolkata, followed by Mumbai and Delhi for PM$_{10}$ and NO$_{2}$ highest in Mumbai. | (Ganguly et al., 2021)      |
Table 1 (continued)

| Study area                        | Criteria air pollutant | Dataset used                                         | Major findings                                                                                                                                                                                                 | Reference                      |
|-----------------------------------|------------------------|------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------|
| Delhi, Mumbai, Kolkata and Chennai| PM$_{10}$              | Landsat 8 OLI derived pollution                     | The study assessed the environmental quality following COVID-19 pandemic through environmental quality index using PM$_{10}$ concentration, Land surface temperature (LST), Normalized Difference Moisture Index (MDMI), Normalized Difference Vegetation Index (NDVI) and Normalized Difference Water Index (NDWI) prepared using fuzzy-Ah multi criteria decision making process. The lockdown is capable of minimizing environmental degradation. | (Ghosh et al., 2020)            |
| India                             | Black Carbon (BC)      | Aerosol Radiative Forcing over India Network (ARFINET) | Significant decline of BC in all stations during March 25 to 14 April, 2020 in comparison to 4–24 March, 2020. It reduced to <4 µg/m$^3$ in the North East India and Indi Gangetic Plain as compared to 8.72±5.19 µg/m$^3$ and 5.5±3.1 µg/m$^3$, respectively, in pre-lockdown period. Majority stations showed a 40–70% reduction in BC values from pre-lockdown to lockdown phase 1 | (Gogoi et al., 2021)            |
| Delhi, Mumbai, Chennai, Kolkata, and Bangalore | PM$_{10}$, PM$_{2.5}$, NO$_2$, CO | Central Pollution Control Board’s (CPCB) ground station data | A statistically significant decline in all the pollutants during the lockdown (25 March to 6 April, 2020) was observed 41%, 52%, 51% and 28% for the criteria pollutants PM$_{2.5}$, PM$_{10}$, NO$_2$, CO, respectively, as compared to before lockdown phase in Delhi. Similar decline observed in other study area cities. | (Jain & Sharma, 2020)            |
| Study area | Criteria air pollutant | Dataset used | Major findings | Reference |
|------------|------------------------|--------------|----------------|-----------|
| Delhi, India | PM$_{10}$, PM$_{2.5}$, NO$_2$, SO$_2$, CO | Central Pollution Control Board’s (CPCB) ground station data | Kendall and Spearman’s rank correlation established between weather indicators and COVID-19 cases. High positive correlation between air temperature with COVID-19 cases and negative with humidity | (Singh & Agarwal, 2021) |
| Chennai, Delhi, Hyderabad, Kolkata, Mumbai | PM$_{2.5}$ and aerosols | Beta-attenuation monitors maintained by US EPA | Substantial reduction in PM$_{2.5}$ observed during lockdown period (25 March-11 May) for Chennai (19–43%), Delhi (41–53%), Hyderabad (26–54%), Kolkata (24–36%) and Mumbai (10–39%). Reductions observed mostly in cities with larger traffic volume counts. Aerosols also decreased by 29%, 11%, 4% and 1% in Chennai, Delhi, Kolkata and Mumbai, respectively | (Kumar et al., 2020a) |
| Delhi, India | PM$_{10}$, PM$_{2.5}$, SO$_2$, NO$_2$, CO, O$_3$ and NH$_3$ | Central Pollution Control Board’s (CPCB) ground station data | PM$_{10}$ and PM$_{2.5}$ witnessed maximum reduction of > 50%, NO$_2$ (-52.68%), CO (-30.35%) during lockdown as compared to pre-lockdown phase. As compared to 2019, a reduction of 60% and 39% was observed for PM$_{10}$ and PM$_{2.5}$. For Central, Eastern, Southern, Western and Northern parts of the city, there was reduction of 54%, 49%, 43%, 37% and 31% in Air Quality Index | (Mahato et al., 2020) |
| Study area | Criteria air pollutant | Dataset used | Major findings | Reference |
|------------|------------------------|--------------|----------------|-----------|
| 17 cities in India | PM$_{10}$, PM$_{2.5}$, NO$_2$, SO$_2$, CO | Central Pollution Control Board's (CPCB) ground station data | Highest decline is observed in PM$_{2.5}$ for Ahmedabad (68%), PM$_{10}$ for Delhi (71%), NO$_2$ for Bangalore (87%) and CO for Nagpur (63%). The Northern region shows the highest decline for all the pollutants with most days below NAAQS during lockdown 86%, 68%, and 100% compared to 18%, 0%, and 38% in 2019 for PM$_{2.5}$, PM$_{10}$, and NO$_2$, respectively. > 40% reduction is observed during 7–10 am and 7-10 pm hours of the day for all criteria air pollutants | (Navinya et al., 2020) |
| India | NO$_2$, CO, AOD | Aura/OMI, Terra/MOPITT, Sentinel-5P/TROPOMI and Aqua/Terra MODIS satellite sensors | Mean NO$_2$ levels saw an overall 17% decline during the lockdown phase (25 March-3 May, 2020) as compared to pre-lockdown and 18% as compared to last 5 year average. Delhi showed an average decline by 62% in NO$_2$ compared to 2019 and 54% compared to preceding 5 year (2015–2019). AOD declined in the country by 24% as compared to last 5 years. CO levels showed an increase due to longer life span in the atmosphere | (Pathakoti et al., 2020) |
| Delhi, Mumbai, Bangalore, Chennai and Kolkata | NO$_2$, SO$_2$, CO, AOD | Sentinel-5P TROPOMI satellite datasets | NO$_2$ column mean concentration decreased to 0.0001201 mol/m$^2$ in April 2019 to 0.0000703 mol/m$^2$ in April 2020 in Bangalore. The highest decrease was observed in SO$_2$ in Chennai (81.2%), while for other cities it ranged from 9 to 56.6%. AOD levels decreased in four cities (2 to 18.6%) during April 2020 as compared to 2019, while for Bengaluru it was 32.49% | (Prakash et al., 2021) |
Table 1 (continued)

| Study area            | Criteria air pollutant | Dataset used                                                                 | Major findings                                                                                                                                                                                                                   | Reference                  |
|-----------------------|------------------------|------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------|
| Delhi and Mumbai      | NO₂                    | European Space Agency (ESA) Sentinel-5P TROPOMI and CPCB ground station data   | Mumbai and Delhi have observed a considerable decrease of 40–50% compared to same period (March 25 to April 20) in 2019 in NO₂ values. As per ground station data, during the lockdown NO₂ in Delhi dropped to 12–25 µg/m³ as compared to 30–65 µg/m³. | (Sarfraz et al., 2020)     |
| India                 | PM₁₀, PM₂₅, NO₂, SO₂    | Central Pollution Control Board’s (CPCB) ground station data (193 stations)    | 40% improvement in air quality index was observed after analyzing 193 ground stations distributed in the country contributed by 40% PM₁₀, 44% PM₂₅, 51% NO₂ and 21% SO₂.                                                                 | (Sekar et al., 2020)       |
| 22 cities in India    | PM₁₀, PM₂₅, NO₂, SO₂, CO, O₃ | Central Pollution Control Board’s (CPCB) ground station data                  | Maximum reduction was observed in PM₂₅ values across the cities. Overall, around 43, 31, 10, and 18% decreases in PM₂₅, PM₁₀, CO, and NO₂ in India were observed during lockdown period compared to previous years. While, there were 17% increase in O₃ and negligible changes in SO₂. The air quality index (AQI) reduced by 44, 33, 29, 15 and 32% in north, south, east, central and western India, respectively. | (Sharma et al., 2020)      |
| Study area                     | Criteria air pollutant | Dataset used                                      | Major findings                                                                                                                                                                                                 | Reference                        |
|-------------------------------|------------------------|--------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------|
| Eight 5-million plus cities, India | NO₂                   | Sentinel-5P TROPOMI satellite datasets            | An average of 46% reduction in average NO₂ values and 27% improvement in AQI was observed in the eight cities during the first lockdown phase with respect to pre-lockdown phase. Also, 53% of Corona positive cases and 61% of fatality cases were observed in the eight major cities of the country alone, coinciding with locations having high long-term NO₂ exposure. In Delhi the maximum and average values dropped by 70% followed by Bengaluru (63%), Mumbai (57%), Ahmedabad (56%), Hyderabad (49%), Pune (37%), Kolkata (34%) and Chennai (33%) in maximum NO₂ values as compared to pre-lockdown phase. | (Siddiqui et al., 2020)          |
| Delhi, India                  | PM₁₀, PM₂.₅, NO₂       | Central Pollution Control Board’s (CPCB) ground station data | The average PM₂.₅ concentration in the city has reduced from 122.48 µg/m³ on 25 February 2020 to 17.71 µg/m³ on 21 April 2020. On 21 April, 2020, 29 stations out of the 35 have recorded PM₂.₅ concentration below the WHO standards | (Sikarwar & Rani, 2020)          |
| Study area    | Criteria air pollutant | Dataset used                                                                 | Major findings                                                                                                                                                                                                 | Reference                    |
|--------------|------------------------|-----------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------|
| India        | PM\textsubscript{10}, PM\textsubscript{2.5}, NO\textsubscript{2}, CO, SO\textsubscript{2}, O\textsubscript{3} | Central Pollution Control Board’s (CPCB) ground station data (134 stations) | Studied the temporal and diurnal changes of six criteria air pollutants. PM\textsubscript{10}, PM\textsubscript{2.5}, NO\textsubscript{2} and CO reduced during lockdown, SO\textsubscript{2} and O\textsubscript{3} increased at some sites (IGP) and decreased in other sites (south). Decrease in daytime O\textsubscript{3} is found in Indo Gangetic Plain (IGP) and Central India, while nighttime O\textsubscript{3} increased due to less loss of the secondary pollutant. 40–60% reduction in particulate matter (highest in north-west and IGP followed by South and Central region). CO reduced by 20–40% during the lockdown in majority sites | (Singh et al., 2020a, b)     |
| 41 cities in India | NO\textsubscript{2}, AOD          | Sentinel-5P TROPOMI and MODIS satellite datasets                             | 13% reduction in NO\textsubscript{2} observed during the lockdown (March 25-May 3, 2020) as compared to pre-lockdown (Jan 1-Mar 24) and 19% reduction when compared with similar period of lockdown during 2019. The maximum reduction was recorded in New Delhi (61.74%), Delhi (60.37%), Bangalore (48.25%), Ahmedabad (46.20%), Nagpur (46.13%), Gandhinagar (45.64%) and Mumbai (43.08%). An unusual increase in NO\textsubscript{2} was observed in North-eastern cities attributed to forest and biomass burning | (Vadrevu et al., 2020)       |
no comprehensive study has been undertaken so far to the best of the authors’ knowledge incorporating the monthly, seasonal, annual and lockdown effects on air quality of the Delhi region for the years 2019 and 2020. The complex biophysical and physiographic setup of the state of Delhi further alleviates the problem of air pollution and is a challenging piece of research undertaken in the present work.

Study area

Delhi National Capital Territory (NCT), spanning an area of 1484 sq. km, is the capital of India. With a population density of 11,297 persons/km² in 2011, Delhi is one of the most populated and highly dense cities in the world (Gaurav et al., 2018; Jena et al., 2021). The city has an average annual growth rate in the population of 37.60% (The Census of India, 2011). The study is carried over Delhi and surrounding region (covering parts of Faridabad, Gautam Budh Nagar, Ghaziabad, Baghpat, Sonepat, Rohtak, Jhajjhar and Gurgaon) situated between 76° 48’ 24” E and 77° 31’ 14” E longitude, and 28° 54’ 19” N and 28° 16’ 11” N latitude covering an area of 4921.6 sq. km (refer Fig. 1). The study area was chosen keeping in view the urbanized area in and around Delhi delineated using satellite imagery. The city is developed along the river Yamuna and is on an average altitude of 213 to 305 m. It is divided into three main segments physically, viz. the flood plain, the ridge and the plain (Das & Das, 2017; Grover & Singh, 2015). The city and the surrounding falls under the monsoon influenced humid subtropical climate (Cwa) and bordering hot semi-arid climate as per Köppen classification system (Bsh) (Chakraborty et al., 2015; Mallick et al., 2008). As per the land use distribution of Delhi represented in the Master Plan document, it has nearly 15–20% recreation/green space allotted, while majority area 45–55% is covered by residential land use. The city experiences four major seasons pre-monsoon summer (March through May), monsoon (June through September), post-monsoon (October and November) and winter (December through February) where the air temperature varies from 4–10 °C in winters to 42–48 °C in summers (Guttikunda & Gurjar, 2012).

With a surging population (16.79 million), the city regularly accommodated the increasing number of vehicular traffic from 3.59 million registered vehicles in 2001 to 6.93 million in 2011 and 11.89 million vehicles in 2020 (Ramachandran et al., 2013; Romanos et al., 2005). The uncontrolled population and vehicle growth have environmental repercussions in the form of degrading air quality (Ramasammy, 2002). The recorded level of air pollution in Delhi is beyond the standards defined as per National Ambient Air Quality Standards (NAAQS) or WHO and is regarded as one of the most polluted cities across the globe (Dahiya et al., 2016; Goyal et al., 2006). The COVID-19 pandemic has reportedly improved the air quality regimes of various cities across the globe, including Delhi and its purlieu (Garg et al., 2021; Singh & Agarwal, 2021).

Material and methods

The air quality parameters listed in Table 2 were collected from ground-based monitoring stations of Central Pollution Control Board (CPCB). The datasets can be retrieved from collective network of a continuous monitoring system of air quality called Continuous Ambient Air Quality Monitoring System (CAAQMS) (Source:https://app.cpcbccr.com/ccr/#/ caaqm-dashboard-all/caaqm-landing/data). Data contributors to this network are different central and state agencies like the Central Pollution Control Board, State Pollution Control Boards, India Meteorological Department (IMD) and Indian Institute of Tropical Meteorology (IITM). For this study, the CPCB, Delhi Pollution Control Committee, IMD, IITM, Uttar Pradesh Pollution Control Board and Haryana State Pollution Control Board have provided the data compiled by the CAAQMS portal. Continuous monitoring stations measure air quality data along with meteorological parameters including air temperature, wind speed, wind direction, atmospheric pressure and solar radiation. Daily average data are used for monthly, seasonal and annual analysis as well as for analyzing and comparing COVID lockdown periods. All the parameters and their measuring units are mentioned in Table 2. Since ground station data do not provide wind speed and wind direction for all sites, four other meteorological parameters have been taken for analysis based on the availability of satellite data.
The satellite-based tropospheric (up to ~10 km from the surface) NO$_2$ concentration was retrieved from European Space Agency’s (ESA) Sentinel-5 Precursor (Sentinel-5P) TROPOspheric Monitoring Instrument (TROPOMI). TROPOMI has a swath of ~2600 km and provides a near-global surface coverage of tropospheric NO$_2$ concentration at a spatial resolution of 3.5 × 5.5 km$^2$. The TROPOMI instrument works in the ultraviolet-near infrared region (270–500 nm and 675–775 nm, respectively) and shortwave infrared region (2305–2385 nm) with a total of three spectrometers. NO$_2$ retrievals through TROPOMI utilize the similar algorithm as used by its predecessor OMI with improvements. Differential optical absorption spectroscopy (DOAS) method is used for extracting the NO$_2$ slant...
column density (Boersma et al., 2011; Vadrevu et al., 2020). Using a data assimilation system and an air mass factor (obtained from look up table from a radiative transfer algorithm approach)-based separation algorithm, the total slant column density is separated into the two components, viz. stratospheric and tropospheric. The offline stream (OFFL) tropospheric vertical column density of the number of NO₂ molecules per unit area was extracted using cloud based system like Google Earth Engine (GEE). Data processing and statistical analysis were performed using the GEE API platform (Gorelick et al., 2017).

European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis v5 (ERA-5) meteorological data has been used as satellite derived meteorological input for the study and has been collected from the Copernicus Climate data store (https://cds.climate.copernicus.eu/). Both, hourly and monthly meteorological parameters including air temperature (at 2 m), wind speed (at 10 m), wind direction (at 10 m), and surface pressure, have been retrieved and analyzed on python and GRADS platforms. Details of all parameters are listed in Table 3.

The paper is mainly focused at understanding the impact of COVID-19-induced lockdown on NO₂ concentration in the Delhi Region. To quantify the impact of lockdown on NO₂ concentration, the entire analysis consists of four sections: assessing COVID lockdown period with the previous year by understanding the monthly changes, seasonal variation and annual change in concentration compared to last year. In addition, to understand this phenomenon Pearson correlation has been performed on NO₂ concentration and meteorological parameters. Paired t-test was also performed to determine the change in NO₂ concentration with the corresponding period. Yearly, seasonal and monthly mean composites for 2019 and 2020 were prepared using an area weighted average technique for satellite data while for ground-based data simple averaging method has been adopted to obtain the mean (Thangjai et al., 2021). Moreover, to minimize the bias, stationwise monthly average approach has been adopted for the study. For instance, there are total 61 ground observed stations; to obtain monthly mean, daily data have been aggregated for each station to obtain the mean value of NO₂ for the month.

### Table 2  Meteorological parameters used for the study derived from ground-based monitoring stations

| Parameter             | Unit       | Resolution         | Source                                                                 |
|-----------------------|------------|--------------------|------------------------------------------------------------------------|
| Nitrogen-dioxide      | µg/m³      | Daily Average      | Continuous Ambient Air Quality Monitoring Station (CAAQMS), Central Pollution Control Board (CPCB) |
| Air Temperature       | °C         | Daily Average      |                                                                        |
| Wind Speed            | m/s        | Daily Average      |                                                                        |
| Wind Direction        | ° from North | Daily Average  |                                                                        |
| Atmospheric Pressure  | mm Hg      | Daily Average      |                                                                        |
| Relative humidity     | in %       | Daily Average      |                                                                        |
| Solar Radiation       | W/m²       | Daily Average      |                                                                        |

Source: https://app.cpcbccr.com

### Table 3  Meteorological parameters used for the study derived from satellite-based platform

| Parameter             | Unit       | Resolution         | Source                                                                 |
|-----------------------|------------|--------------------|------------------------------------------------------------------------|
| Nitrogen-dioxide      | mol/m²     | Daily Average      | GEE/Copernicus Sentinel-5P                                            |
| Air Temperature (at 2 m) | Kelvin    | Daily/Monthly Average | ERA-5/Copernicus Climate Data Store                                  |
| Wind Speed U component (at 10 m) | m/s     | Daily/Monthly Average | ERA-5/Copernicus Climate Data Store                                  |
| Wind Speed V component (at 10 m) | m/s     | Daily/Monthly Average | ERA-5/Copernicus Climate Data Store                                  |
| Surface Pressure      | Pascal (Pa) | Daily/Monthly Average | ERA-5/Copernicus Climate Data Store                                  |
| Solar Radiation       | J/m²       | Daily/Monthly Average | ERA-5/Copernicus Climate Data Store                                  |
Due to rising cases of COVID-19 in the major Indian cities, Govt. of India had to impose lockdowns for the entire country to curb the spread of the virus. As a result, there is a major improvement in air quality due to the reduction in vehicular traffic during the countrywide lockdown. There is a several-fold decrease in the concentration as compared to last year using both satellite-retrieved pollution and ground-based observation data.

Observed variation in NO$_2$ during COVID-19-related lockdown

The effect of nationwide lockdown due to COVID-19 is investigated in the Delhi region using CPCB ground station data and satellite-based data for 2020 and compared to the values observed during the same period in 2019 for NO$_2$. Tables 4 and 5 describe the NO$_2$ status during the three-lockdown phases spanning from March 25 to May 31, 2020, along with one pre-lockdown (Jan 1st to March 24th) and a post-lockdown phase (June 1st to December 31st) in the year 2020 compared to 2019, as observed from ground-based in situ station data and satellite-based TROPOMI observations, respectively. It is observed that the ground-based measurements from 61 sites across the Delhi region (Fig. 2) show absolute reductions in NO$_2$ concentrations across all the locations, since and during the lockdown. There is a mean decrease of ~61% in daily NO$_2$ during LD-1 and ~61% during LD-2 compared to 2019. Similarly, concentration was reduced in the third phase of lockdown to ~53% compared with the same time period in 2019. The effect of lockdown can also be witnessed during the post-LD phase (June to December 2020) indicating a decrease of ~8% w.r.t. 2019. However, mean NO$_2$ reduced by ~58% during LD-1 as compared to pre-LD phase. Subsequently, the reduction remained constant in LD-2 and gradually decreased to ~45.5% and ~13% in LD-3 and post-LD compared to pre-LD.

Similarly, the Sentinel-5P TROPOMI data were observed and recorded for daily average for the year 2019 and 2020 (Table 5). Satellite observations indicate a reduced daily mean NO$_2$ concentration by ~66.5%, ~40% and ~27% in LD-1, LD-2

Table 4 Statistics of CPCB ground station NO$_2$ (µg/m$^3$) data during lockdown phases for 2019 and 2020

| Time Period               | $\Sigma \mu$ 2019(a) | $\Sigma \mu$ 2020(b) | t    | $\Delta$ in % | p     | $\Delta = b-a$ | SE Diff | 95% CI for Mean Diff |
|---------------------------|-----------------------|-----------------------|------|---------------|-------|----------------|---------|---------------------|
| 1$^{st}$Jan-24$^{th}$Mar (Pre-LD) | 52.3                  | 45.1                  | -11.6| -14%          | <0.001| -6.8          | 0.59    | -7.98 to -5.67       |
| 25$^{th}$Mar-14$^{th}$Apr (LD-1)          | 48.1                  | 18.8                  | -33.0| -61%          | <0.001| -26.9         | 0.82    | -28.53 to -25.33     |
| 15$^{th}$Apr-3$^{rd}$May (LD-2)          | 48.5                  | 18.8                  | -29.6| -61%          | <0.001| -25.9         | 0.87    | -27.61 to -24.18     |
| 4$^{th}$May-31$^{st}$May (LD-3)          | 52.3                  | 24.6                  | -29.9| -53%          | <0.001| -26.1         | 0.87    | -27.81 to -24.39     |
| 1$^{st}$Jun-31$^{st}$Dec (Post-LD)       | 42.9                  | 39.3                  | -6.1 | -8%           | <0.001| -2.0          | 0.33    | -2.67 to -1.38       |

Table 5 Statistics of satellite-retrieved TROPOMI data for NO$_2$ (µg/m$^3$) data during lockdown phases for 2019 and 2020

| Time Period               | $\Sigma \mu$ 2019(a) | $\Sigma \mu$ 2020(b) | t    | $\Delta$ in % | p     | $\Delta = b-a$ | SE Diff | 95% CI for Mean Diff |
|---------------------------|-----------------------|-----------------------|------|---------------|-------|----------------|---------|---------------------|
| 1$^{st}$Jan-24$^{th}$Mar (Pre-LD) | 115.1                 | 97.8                  | -1.8 | -15%          | <0.01 | -15.5         | 8.49    | -32.50 to 1.42       |
| 25$^{th}$Mar-14$^{th}$Apr (LD-1)          | 89.7                  | 30.0                  | -9.5 | -67%          | <0.001| -59.7         | 6.28    | -72.84 to -46.64     |
| 15$^{th}$Apr-3$^{rd}$May (LD-2)          | 79.4                  | 47.9                  | -6.5 | -40%          | <0.001| -31.5         | 4.84    | -41.62 to -21.29     |
| 4$^{th}$May-31$^{st}$May (LD-3)          | 82.0                  | 60.0                  | -4.5 | -27%          | <0.001| -22.5         | 4.98    | -32.71 to -12.22     |
| 1$^{st}$Jun-31$^{st}$Dec (Post-LD)       | 83.4                  | 73.7                  | -2.7 | -12%          | <0.01 | -10.0         | 3.68    | -17.26 to -2.76      |
and LD-3, respectively, as compared to 2019 concurrent time periods. Statistics indicate a reduction of ~51%, ~39% and ~24.5% in the values during LD-1, LD-2 and LD-3, respectively, compared to the pre-LD phase in 2020 (Fig. 3). These reductions in the NO\textsubscript{2} values can be attributed to the restricted anthropogenic activities including vehicular movement and controlled industrial activities. LD-1 phase saw the maximum decrease due to stringent lockdown norms, which were liberalized during the LD-2 and further relaxed during LD-3. Description statistics of the datasets can be found in Annexure Ia and Ib.

Independent paired t-test performed on NO\textsubscript{2} values from ground-based and satellite-derived measurements for all lockdown periods in 2020 with the same time periods in 2019 was performed and measured the significant change. It was indicated...
that the CPCB sites show a statistically significant ($p < 0.001$) difference in NO$_2$ concentration between the mean concentrations in all lockdown phases to the mean of the same period in 2019. However, for satellite measurements, the lockdown phases (LD-1, LD-2 and LD-3) showed a statistically significant difference ($p < 0.001$) and pre-LD and post-LD phases showed significant differences ($p < 0.01$) between the mean NO$_2$ concentration and respective time periods in 2019. The

**Fig. 3** Comparison between Pre-Lockdown, Lockdown-1, Lockdown-2, Lockdown-3, Post-Lockdown period of 2020 with concurrent periods in 2019 using satellite-based Tropomi-5P observation data

**Fig. 4** Daily increase and decrease in NO$_2$ concentration from 2019 to 2020. The red vertical lines represent the increase in concentration in 2020 compared to 2019 and green vertical line decrease in concentration in 2020 compared to 2019
significant drop in tropospheric column NO$_2$ values during the lockdown phase can also be understood by analyzing the daily decrease and increase in the NO$_2$ concentration. Figure 4 displays satellite-based data retrieved from Sentinel-5P and averaged out for the study area-specific region. The value extracted from satellite data by Area Average Time Series using GEE (Google Earth Engine) offers spatial average data on a daily scale. The figure shows four-month data including a 67-day lockdown period and the amount of decrease and increase in NO$_2$ concentration on a daily scale. Maximum reduction in the pollutant concentration can be observed during LD-1.

### Monthly variation in NO$_2$ during 2019 and 2020

The effect of nationwide lockdown was investigated using monthly NO$_2$ values extracted through ground-based CPCB observations (Table 6) and Sentinel-5P TROPOMI (Table 7) datasets. The monthly analysis can help us understand the extent

#### Table 6: Statistics of CPCB ground station monthly NO$_2$ (µg/m$^3$) data for 2019 and 2020

| Month | $\sum\mu$ 2019 (a) | $\sum\mu$ 2020 (b) | $t$ | $\Delta$ in % | $p$   | $\Delta = b-a$ | SE Diff | 95% CI for Mean Diff |
|-------|-------------------|-------------------|-----|--------------|------|---------------|--------|---------------------|
| Jan   | 59.6              | 49.3              | -3.451 | -17%         | <0.001 | -12.011       | 3.48   | (-19.021, -5.001)   |
| Feb   | 51.1              | 48.1              | -0.999 | -6%          | 0.323  | -3.499        | 3.502  | (-10.54, 3.542)     |
| Mar   | 46.3              | 32.1              | -6.85 | -31%         | <0.001 | -11.977       | 2.047  | (-16.094, -7.861)   |
| Apr   | 47.9              | 20.5              | -7.982 | -57%         | <0.001 | -24.863       | 3.115  | (-31.126, -18.6)    |
| May   | 51.9              | 23.6              | -7.751 | -55%         | <0.001 | -26.077       | 3.365  | (-32.842, -19.312)  |
| Jun   | 39.7              | 22.0              | -7.781 | -45%         | <0.001 | -16.042       | 2.062  | (-20.181, -11.903)  |
| Jul   | 31.1              | 19.4              | -5.702 | -38%         | <0.001 | -10.417       | 1.827  | (-14.085, -6.75)    |
| Aug   | 30.4              | 21.0              | -3.663 | -31%         | <0.001 | -9.251        | 1.984  | (-13.235, -5.268)   |
| Sep   | 29.5              | 27.5              | -0.165 | -7%          | 0.869  | -0.357        | 2.159  | (-4.692, 3.977)     |
| Oct   | 51.8              | 55.7              | 1.433 | 8%           | 0.158  | 5.524         | 3.854  | (-2.213, 13.261)    |
| Nov   | 60.7              | 66.2              | 1.685 | 9%           | 0.1    | 8.002         | 4.749  | (-1.531, 17.536)    |
| Dec   | 58.6              | 59.9              | 0.767 | 2%           | 0.447  | 3.285         | 4.283  | (-5.314, 11.885)    |

#### Table 7: Statistics of satellite-retrieved Sentinel-5P TROPOMI monthly NO$_2$ (µmol/m$^2$) data for 2019 and 2020

| Month | $\sum\mu$ 2019(a) | $\sum\mu$ 2020(b) | $t$ | $\Delta$ in % | $p$  | $\Delta = b-a$ | SE Diff | 95% CI for Mean Diff |
|-------|-------------------|-------------------|-----|--------------|-----|---------------|--------|---------------------|
| Jan   | 140.3             | 114.7             | -1.126 | -18%         | 0.271 | -21.822       | 19.381 | (-61.823, 18.178)   |
| Feb   | 121.0             | 97.7              | -1.791 | -19%         | 0.088 | -22.092       | 12.334 | (-47.743, 3.558)    |
| Mar   | 74.3              | 65.3              | -1.912 | -12%         | 0.067 | -13.598       | 7.113  | (-28.193, 0.997)    |
| Apr   | 85.1              | 39.5              | -8.884 | -54%         | <0.001 | -45.652       | 5.139  | (-56.162, -35.142)  |
| May   | 84.3              | 59.2              | -5.317 | -30%         | <0.001 | -25.498       | 4.796  | (-35.306, -15.689)  |
| Jun   | 84.8              | 60.7              | -4.921 | -28%         | <0.001 | -24.011       | 4.879  | (-34.04, -13.982)   |
| Jul   | 57.6              | 47.5              | -2.015 | -18%         | 0.057 | -8.824        | 4.38   | (-17.932, 0.284)    |
| Aug   | 42.7              | 36.1              | -1.836 | -16%         | 0.082 | -6.59         | 3.59   | (-14.104, 0.924)    |
| Sep   | 55.8              | 52.7              | -0.736 | -5%          | 0.468 | -3.019        | 4.102  | (-11.408, 5.37)     |
| Oct   | 82.4              | 84.4              | 0.334 | 3%           | 0.741 | 1.67          | 5.005  | (-8.582, 11.922)    |
| Nov   | 92.1              | 95.7              | 0.376 | 4%           | 0.71  | 5.559         | 14.767 | (-24.989, 36.107)   |
| Dec   | 161.9             | 129.6             | -1.832 | -20%         | 0.078 | -31.488       | 17.192 | (-66.763, 3.787)    |
of change compared to 2019. Figure 5 characterizes the monthly aggregation of daily distribution in NO$_2$ levels for all ground-based station data. This analysis enabled to compare the trend with satellite-retrieved data in Delhi region for 2019 and 2020. The mean monthly NO$_2$ values for 2019 and 2020 are attached in Annexure IIa and IIb, respectively. The effect of the pandemic can be seen in the monthly variation in the values especially in March, April and May of 2020. To understand the statistical significance in the monthly concentration of NO$_2$ between 2019 and 2020, paired t-test was performed on all ground-based datasets for each site. The t-test is a statistical testing tool that can help to understand the significant difference/change between two datasets. As compared to 2019, the NO$_2$ concentration in 2020 reduced by ~31%, ~57%, ~55% and ~45% in the months of March, April, May and June months, respectively (refer Table 6). Due to COVID-19-induced lockdown, the thermal power plants near Delhi were non-operational and the vehicular movement was highly restricted in the capital city leading to a major decline in the criteria air pollutant’s concentration. During relaxed lockdown phases, the concentration of NO$_2$ increased gradually from October through December. However, the monsoon and post-monsoon months of July through September also showed a marginal decline in concentration as compared to 2019. Overall, when compared with the monthly mean NO$_2$ concentration of February 2020 (~48 in µg/m$^3$), there is an average reduction of ~33%, ~57%, ~51% and ~60% in March, April, May and June months of 2020, respectively. The mean concentration was

![Fig. 5 Mean monthly variation in NO$_2$ based on CPCB station data](image)

![Fig. 6 Mean monthly variation in NO$_2$ based on TROPOMI Sentinel-5P data](image)
as low as 20.5 µg/m³ in the month of April. April month saw the maximum reduction due to strict adherence in lockdown norms in Delhi and the surrounding region. The NO₂ concentration rises in the latter part of the year and amidst lockdown relaxation due to crop residue burning (paddy crop harvesting) and changing meteorological conditions (restricted wind speed and reduced air temperature), thereby contributing to the increased level of NO₂ in the region during October and November.

Similarly, the reduced values can also be analyzed in satellite-derived monthly analysis. Figures 6, 7 and 8 characterize the monthly aggregation of daily distribution in NO₂ levels for satellite data for 2019 and 2020. The mean monthly NO₂ values for 2019 and 2020 are attached in Table 7, and detailed observations are mentioned in Annexure IIIa and IIIb, respectively. Statistically significant tropospheric column NO₂ reductions are evident over the Delhi region during the lockdown months of April (~54%),
Fig. 8 Monthly Mean of NO₂ concentration in µmol/m² for the year 2020

Table 8 Statistics of CPCB ground station seasonal NO₂ (µg/m³) data for 2019 and 2020

| Season      | \( \Sigma \mu_{2019(a)} \) | \( \Sigma \mu_{2020(b)} \) | t     | \( \Delta \) in % | p          | \( \Delta = b - a \) | SE Diff | 95% CI for Mean Diff |
|-------------|--------------------------|--------------------------|-------|-----------------|------------|---------------------|--------|---------------------|
| Monsoon     | 32.7                     | 22.5                     | -8.41 | -31%            | <0.001     | -9.0                | 1.1    | -11.1              | -6.9    |
| Post-Monsoon| 56.2                     | 61.0                     | 2.221 | 8%              | 0.029      | 6.8                 | 3.0    | 0.7                | 12.8    |
| Winter      | 56.4                     | 52.7                     | -1.675| -7%             | 0.096      | -3.8               | 2.2    | -8.2              | 0.7     |
| Summer      | 48.7                     | 25.4                     | -12.025| -48%           | <0.001     | -21.0              | 1.7    | -24.4             | -17.5   |
May (~30%) and June (~28%) as compared to similar months in 2019. The values are in concurrence with CPCB ground-based observations. It is interesting to note that NO₂ observations before April show marginal concentration changes as compared to 2019, indicating the role of reduced anthropogenic emissions thereby contributing to a reduction in surface-level NO₂ concentrations. Spatial analysis of near-surface NO₂ (Figs. 7 and 8) also suggests that COVID-19-induced lockdown controlled the contributing factors to pollution, predominantly sectors like vehicles, industries, thermal power plants, generator sets, biomass burning, domestic fuel burning, construction activities, etc.

Seasonal variation in NO₂ during 2019 and 2020

To understand the seasonal changes in near-surface air pollution related to the COVID-19 pandemic, the analysis has been carried out on the dataset by

Table 9  Statistics of satellite-retrieved Sentinel-5P TROPOMI seasonal NO₂ (µmol/m²) data for 2019 and 2020

| Season   | $\Sigma \mu$ 2019(a) | $\Sigma \mu$ 2020(b) | t   | $\Delta$ in % | p       | $\Delta = b-a$ | SE Diff | 95% CI for Mean Diff  |
|----------|----------------------|----------------------|-----|---------------|---------|----------------|---------|-----------------------|
| Monsoon  | 61.5                 | 49.6                 | -4.808 | -19%          | <0.001  | -11.258        | 2.341   | (-15.905, -6.612)     |
| Post-monsoon | 86.6              | 87.9                 | 0.247  | 2%            | 0.806   | 1.712          | 6.936   | (-12.206, 15.63)      |
| Winter   | 141.5                | 115.4                | -2.472 | -18%          | 0.016   | -23.94         | 9.686   | (-43.235, -4.645)     |
| Summer   | 81.3                 | 55.3                 | -7.912 | -32%          | <0.001  | -28.37         | 3.586   | (-35.498, -21.242)    |

Fig. 9 Violin plot of seasonal variation in (a) near surface ground-based observations of NO₂ measured at 61 stations in the Delhi region (in µg/m³), (b) Sentinel-5P TROPOMI tropospheric NO₂ (µmol/m²), in 2019 and 2020

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Fig. 10  Map showing seasonal variation in NO2 concentration (in µmol/m²) for the year 2019 and 2020

Fig. 11  Annual NO2 concentration as observed from Sentinel-5P TROPOMI data (in µmol/m²) for the year 2019 and 2020
dividing the year into four seasons viz. Monsoon (Jun-Sep), Post-monsoon (Oct & Nov), Winter (Dec-Jan-Feb) and Summer (March–April–May). Seasonal variation analysis has been performed on both ground-based data (Table 8) and TROPOMI-5P (Table 9). Violin plot has been used as summary statistics for understating the data distribution for each season in each year (Fig. 8). High Kernel density shows a higher frequency or mode of the data-set which corresponds to the width of the violin plot. There is a reduction of ~48% and ~31% as observed from ground-based data, and ~32% and ~19% as observed from Sentinel-5P data, in summer and monsoon months, respectively. The summer season coincides with the pandemic induced lockdown period affected by the ceased anthropogenic activities. The monsoon season in 2020 has also shown a decline in NO$_2$ concentration due to self-imposed precautions administered by authorities and the common public as a preventive measure toward the spread of COVID-19. Spatial variations in seasons are shown in Figs. 9 and 10. A detailed description of values is shown in Annexure IVa and b.

**Annual variation in NO$_2$ during 2019 and 2020**

COVID-19-induced nationwide lockdown not only had a short-term impact on improving the air quality of the region for a few days, weeks and months; it also affected the overall air quality of the entire year (refer Fig. 11). In previous sections using monthly and seasonal analysis, it is quite evident that due to the immediate effect of country-wide lockdown, the city has witnessed a significant amount of decrease in NO$_2$ concentration, especially in the months of March, April and May. Figures 12 and 13 illustrate the daily, weekly and monthly change in NO$_2$ concentration using ground-based and satellite measurements in the Delhi region. Week 13 in 2020 showed a significant decline in the NO$_2$ values which marks the beginning of the nationwide lockdown to control the surge of COVID-19 cases in India. Overall the annual concentration dropped by 20% measured from ground-based data while satellite Tropomi-5P data reveal an 18% drop in NO$_2$ concentration from 2019 to 2020. The annual concentration of NO$_2$ observed in ground-based data during 2019 and 2020...
is 46.54 µg/m³ and 37.11 µg/m³, whereas satellite observed data annual concentration is 90.24 µmol/m² and 74.02 µmol/m² for the year 2019 and 2020, respectively. The entire daily, weekly, monthly analysis is shown in Figs. 13 and 14 for CPCB ground station and satellite-retrieved datasets.

Effect of meteorology in regulating the level of NO₂ in Delhi region

A Pearson correlation was estimated to examine the relationships between NO₂ concentration, air temperature, solar radiation, barometric pressure and wind speed using satellite-retrieved scatterplots of correlation which are presented in Fig. 14. NO₂ was negatively related to air temperature \( r = -0.526 \ p < 0.001 \), solar radiation \( r = -0.279 \ p < 0.001 \) and wind speed \( r = -0.246 \ p < 0.001 \), whereas NO₂ was positively related to barometric pressure \( r = 0.505 \ p < 0.001 \) (refer Fig. 14). These findings indicate that due to high solar radiation, air temperature increases during daytime; hence, it breaks down the NO₂ molecules into two other hazardous gases, i.e., ozone (O₃) and nitric oxide (NO), in the presence of sunlight resulting in a decrease in NO₂ level. This decrease is observed in 2020, where the mean solar radiation was observed to be higher than 2019. Similarly increase in wind speed decreases the concentration of NO₂ gases. For monthly mean values of solar radiation, wind speed, air temperature and barometric pressure observed from ground-based station data and European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis v5 (ERA-5) meteorological data, plz refer Annexure Va and b, respectively. The correlation coefficients were also determined for CPCB ground-based stations for all the locations with valid meteorological data availability (48 stations) represented in Fig. 15. A moderate to high negative correlation was observed between tropospheric NO₂ and surface air temperature/solar radiation, and a moderate to high positive correlation was observed with barometric pressure. These results are in accordance with the satellite-based findings. It was also observed that the meteorological parameters remained unaltered for almost all the months in 2020 as compared to 2019, indicating a negligible role in
reducing the values of atmospheric pollution, particularly NO$_2$ in the study area.

**Discussion**

The present study analyzes the impact of COVID-19 led lockdown on the status of air pollution (NO$_2$) through a weekly, lockdown period, monthly, seasonal and annual mean concentration analysis using both ground-based and satellite-based NO$_2$ statistics. There is a reduction in pollution levels in the Delhi region. Sentinel-5P TROPOMI tropospheric NO$_2$ observation shows a high correlation with CPCB ground-based measurements from 61 stations within the region. Satellite-based measurements indicate an advantage of demonstrating spatial and temporal variability over ground-based fixed station data. Considering the health impacts and the source of the major criteria air pollutants, NO$_2$ was primarily observed in the Delhi region. NO$_2$ concentration increased rapidly in the Indian subcontinent, and its ability to produce other secondary pollutants like ozone, etc. makes it inevitable for climatic studies.

Ground-based measurements’ analysis revealed a $\sim$61% mean reduction in daily NO$_2$ during lockdown phases as compared to the similar time period in 2019, i.e., March 25th to May 3rd. Also, when compared to pre-LD phase (Jan 1st to Mar 24th), a reduction of $\sim$58% average NO$_2$ was observed in LD-1 phase (March 25th to April 14th). Additionally, the concentrations reduced the maximum in the month of April ($\sim$57%) in 2020 when compared to the same month in 2019 and February of 2020. This made summer month represent the season with maximum reduction ($\sim$48%) in ground measured NO$_2$ concentration for Delhi region covering Delhi NCT, Gurgaon, Faridabad, Gautam Budh Nagar, Ghaziabad, Baghpat, Sonepat, Rohtak and Jhajjar. However, no study has comprehensively discussed the monthly,
seasonal and annual changes in NO$_2$ concentration in Delhi; few studies have detailed the lockdown period reductions w.r.t. pre-lockdown periods using ground-based data. (Garg et al., 2021) reported a reduction of $\sim$50–78% in NOx/NO in Delhi region including Delhi NCT, Gurgaon, Noida, Ghaziabad and Faridabad. In another study, a reduction of 81% was reported in NO$_2$ values for Delhi during the lockdown period (March 25$^{th}$ to April 25$^{th}$) in 2020 as compared to mean value of the same period in 2018 and 2019 (Garg et al., 2020a, b). Similar results were also presented for Delhi region in several studies for NO$_2$ and other pollutants like SO$_2$, O$_3$, PM$_{2.5}$, PM$_{10}$, etc.(Das et al., 2021; Dumka et al., 2021; Ganguly et al., 2021;
Jain & Sharma, 2020; Mahato et al., 2020; Navinya et al., 2020; Sharma et al., 2020; Sikarwar & Rani, 2020; Singh et al., 2020a, b).

Sentinel-5P TROPOMI datasets were also used to understand the level of pollution in the region for the year 2019 and 2020. NO$_2$ mean concentration decreased by ~66.5% in the LD-1 phase as compared to 2019 and ~51% as compared to pre-LD phase of 2020. Similar to ground-based measurements, April month showed the maximum reduction in the pollutant concentration (~57%) as compared to 2019 and the month of February of 2020 using satellite-based tropospheric measurements of NO$_2$. As compared to ground-based measurements, satellite-based measurements (48% reduction observed) showed only a 32% reduction in the summer months of 2020 as compared to 2019. Overall, an 18% drop in the concentration values were recorded for the year 2020 as compared to 2019, which helped cleaner air to the residents of Delhi and its surrounding. Majority studies have analyzed CPCB daily datasets; however, few studies have also analyzed the satellite-based measurements to decipher the spatio-temporal decline in the pollutants concentration. Mean NO$_2$ levels saw an overall 17% decline during the lockdown phase (25 March-3 May, 2020) as compared to pre-lockdown and 18% as compared to last 5 year average in India, whereas Delhi showed an average decline by 62% in NO$_2$ compared to 2019 and 54% compared to preceding 5 year (2015–2019) using various sensors like Aura/OMI, Terra/MOPITT, Sentinel-5P/TROPOMI and Aqua/Terra MODIS satellite sensors (Pathakoti et al., 2020). Similar results were presented by several studies across cities like Delhi, Bangalore, Chennai, Mumbai, Kolkata, etc. (Prakash et al., 2021; Sarfraz et al., 2020; Siddiqui et al., 2020; Vadrevu et al., 2020). (Siddiqui et al., 2020) reported a reduction of ~70% in mean NO$_2$ values during March 24 h to April 7th of 2020 as compared to two weeks average before March 24, 2020. Majority studies have analyzed the TROPOMI datasets due to its accuracy and higher spatial resolution facilitating inter-city and intra-city detailed analysis.

The synoptic local meteorology (short-term and long-term) can affect the geographical variations in emissions as they may enable pollution dispersion. Meteorological parameters like wind speed, solar radiation, air temperature, barometric pressure and relative humidity were studied using ground-based station data and satellite derived products from ERA-5 reanalysis product. It was, however, inferred that the meteorological parameters remained almost the same during the years 2019 and 2020 indicating no influence in altering the NO$_2$ levels during the aforementioned years. The mean annual air temperature was 25.41 ºC and 25.40 ºC as observed from ground-based data and 24.31 ºC and 23.96 ºC as observed from satellite data in 2019 and 2020, respectively. Similar findings were observed for barometric pressure, relative humidity and wind speed. Solar radiation, however, showed a marginal increase in annual values from 134.1 W/m$^2$ to 150.73 W/m$^2$ observed in ground station data. Wind speed remained almost the same, i.e., 2.27 m/s in both the years. Similar observations were made during lockdown periods and monthly data also. The dramatic decrease in the values can be attributed to the halt in anthropogenic activities and reduction in industrial activities. It was inferred in several studies that the meteorology in the nation including Delhi and its surrounding remained similar during 2017 to 2020 (Kant et al., 2020; Navinya et al., 2020; Sharma et al., 2020; Singh et al., 2020a, b).

Conclusion

In this study, the impact of restricted human activities on tropospheric NO$_2$ was studied for the years 2019 and compared with 2020 over Delhi region. It was inferred that anthropogenic activities and halt in industrial activities (particularly thermal power plants) have driven the decrease in NO$_2$ concentration over the Delhi urban region with almost unaltered meteorological conditions during the years under study. Further studies can evaluate the changes in other gaseous pollutants (SO$_2$, CO and CO$_2$) due to COVID-19-induced lockdown in Indian cities. This will provide a multi-pollutant holistic picture of the impact of lockdown on associated socio-economic factors in urban conglomerates. Trajectory and source apportionment studies can also play a pivotal role in understanding the underlying contributions of meteorological factors along with anthropogenic activities.

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Availability of data and materials The data that support the findings of the study are retrieved and worked using Google Earth Engine platform free of cost. Central Pollution Control Board (CPCB) data for Delhi and its surroundings can be accessed at https://app.cpcbccr.com/ect/#/caaqm-dashboard-all/caaqm-landing/data. The data can be made available upon suitable request.

Declarations

Competing of 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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