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Effect of COVID-19-induced lockdown on NO_2 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 (NO_2) 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 NO_2 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 NO_2 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 NO_2 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 NO_2 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 NO_2 · Air pollution · TROPOMI · CPCB · COVID-19

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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 phasewise 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 (NO_2). NO_2 is generally studied in conjunction with nitric oxide (NO) and is a resultant of fuel burning process 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 NO_2 and the capability of 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 NO_x contributes to its increase in the atmosphere, ultimately leading to climate change.

Additionally, long-term exposure to canopy level high levels of 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 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 NO_2 during and after lockdown phases. (Siddiqui et al., 2020) linked the long-term 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 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 NO_2 by 1×10^{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 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 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 NO_2 in Barcelona and Spain during the two-week lockdown. Several other studies (Table 1) have indicated a reduction in NO_2 and other pollutants across Indian cities (Biswal et al., 2020; Biswas & Ayantika, 2021; Dumka 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 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_6H_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_6H_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 PM10 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/m3 in the North East India and Indi Gangetic Plain as compared to 8.72 ± 5.19 μg/m3 and 5.5 ± 3.1 μg/m3, 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)

Table 1 (continued)

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 PM2.5 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%, NO2 (-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)

Table 1 (continued)

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 PM2.5 for Ahmedabad (68%), PM10 for Delhi (71%), NO2 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 SO2 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	NO_2	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 NO_2 values. As per ground station data, during the lockdown NO_2 in Delhi dropped to 12–25 μg/m^3 as compared to 30–65 μg/m^3	(Sarfraz et al., 2020)
India	PM_{10}, $PM_{2.5}$, NO_2, SO_2	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% PM_{10}, 44% $PM_{2.5}$, 51% NO_2 and 21% SO_2	(Sekar et al., 2020)
22 cities in India	PM_{10}, $PM_{2.5}$, NO_2, SO_2, CO, O_3	Central Pollution Control Board's (CPCB) ground station data	Maximum reduction was observed in $PM_{2.5}$ values across the cities. Overall, around 43, 31, 10, and 18% decreases in PM2.5, 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. Correlation	(Sharma et al., 2020)

Table 1 (continued)

Study area	Criteria air pollutant	Dataset used	Major findings	Reference
Eight 5-million plus cities, India	NO_2	Sentinel-5P TROPOMI satellite datasets	An average of 46% reduction in average NO_2 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 NO_2 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 NO_2 values as compared to pre-lockdown phase	(Siddiqui et al., 2020)
Delhi, India	PM_{10}, $PM_{2.5}$, NO_2	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)

Table 1 (continued)

Study area	Criteria air pollutant	Dataset used	Major findings	Reference
India	PM_{10}, $PM_{2.5}$, NO_2, CO, SO_2, O_3	Central Pollution Control Board's (CPCB) ground station data (134 stations)	Studied the temporal and diurnal changes of six criteria air pollutants. PM_{10}, $PM_{2.5}$, NO_2 and CO reduced during lockdown, SO_2 and O_3 increased at some sites (IGP) and decreased in other sites (south). Decrease in daytime O_3 is found in Indo Gangetic Plain (IGP) and Central India, while nighttime O_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_2, AOD	Sentinel-5P TROPOMI and MODIS satellite datasets	13% reduction in NO_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_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/km^2 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 76^0 48′24″ E and 77^0 31′14″ E longitude, and 28^0 54′19″ N and 28^0 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 ℃ in winters to 42–48 ℃ 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.

Fig. 1 Study Area: Delhi Urban Area

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

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

Parameter	Unit	Resolution	Source
Nitrogen-dioxide	μg/m^3	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/m^2	Daily Average	

Source: https://app.cpcbccr.com

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 NO_2 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 NO_2 concentration in the Delhi Region. To quantify the impact of lockdown on NO_2 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 NO_2 concentration and meteorological parameters. *Paired t-test* was also performed to determine the change in NO_2 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 NO_2 for the month.

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

Parameter	Unit	Resolution	Source
Nitrogen-dioxide	mol/m^2	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/m^2	Daily/Monthly Average	ERA-5/Copernicus Climate Data Store

Table 4 Statistics of CPCB ground station NO_2 (μg/m^3) data during lockdown phases for 2019 and 2020

Time Period	∑μ 2019(a)	∑μ 2020(b)	t	Δ in %	p	Δ = b-a	SE Diff	95% CI for Mean Diff Lower	Upper
1stJan-24thMar (Pre-LD)	52.3	45.1	-11.6	-14%	< 0.001	-6.8	0.59	-7.98	-5.67
25thMar-14thApr (LD-1)	48.1	18.8	-33.0	-61%	< 0.001	-26.9	0.82	-28.53	-25.33
15thApr-3rdMay (LD-2)	48.5	18.8	-29.6	-61%	< 0.001	-25.9	0.87	-27.61	-24.18
4thMay-31stMay (LD-3)	52.3	24.6	-29.9	-53%	< 0.001	-26.1	0.87	-27.81	-24.39
1stJun-31stDec (Post-LD)	42.9	39.3	-6.1	-8%	< 0.001	-2.0	0.33	-2.67	-1.38

Results and analysis

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 5 Statistics of satellite-retrieved TROPOMI data for NO_2 (μg/m^3) data during lockdown phases for 2019 and 2020

Time Period	∑μ 2019(a)	∑μ 2020(b)	t	Δ in %	p	Δ = b-a	SE Diff	95% CI for Mean Diff Lower	Upper
1**st**Jan-24**th**Mar (Pre-LD)	115.1	97.8	-1.8	-15%	< 0.01	-15.5	8.49	-32.50	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	-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	-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	-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	-2.76

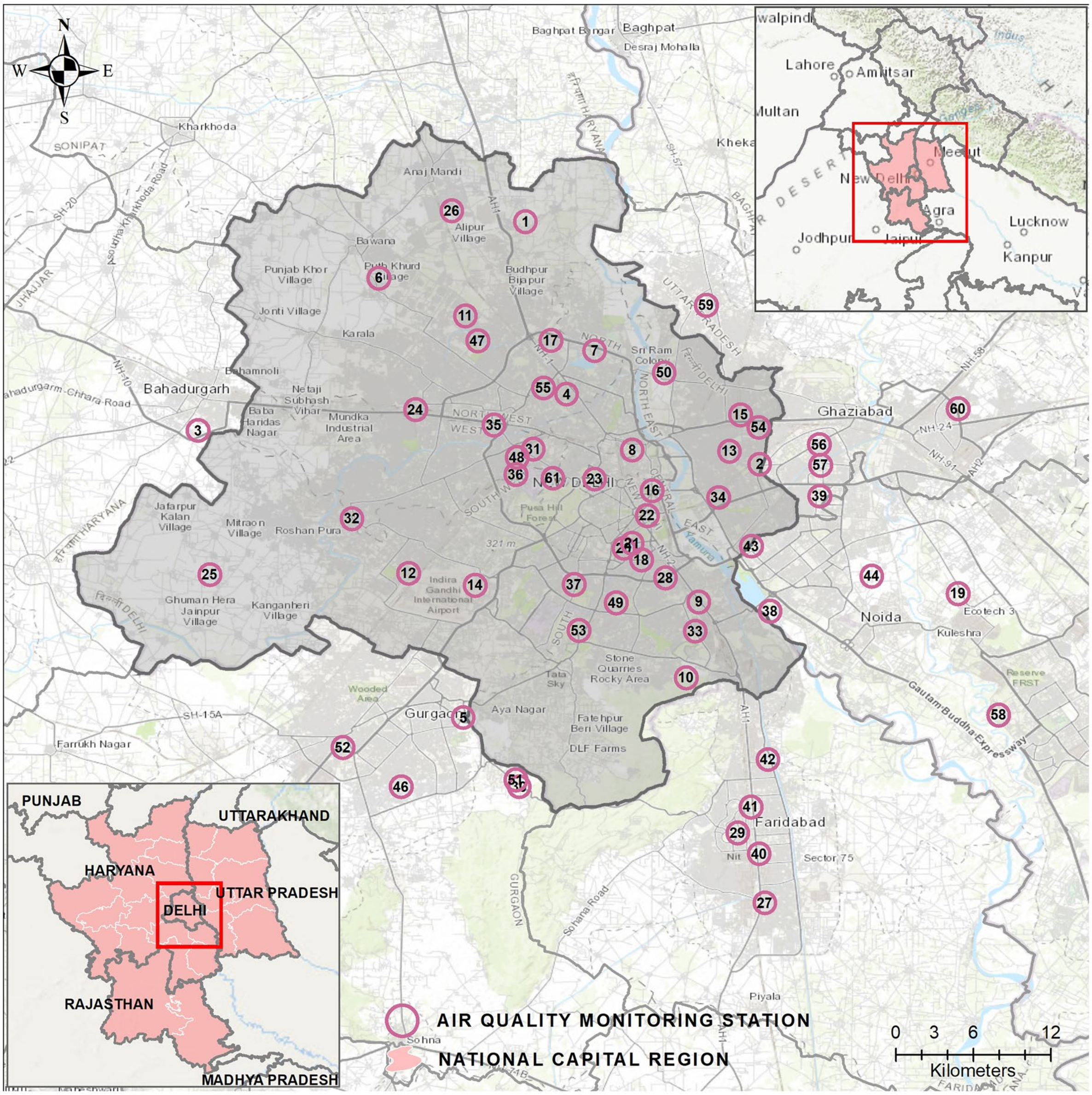

Fig. 2 CPCB stations in the study area. For details of CPCB stations used for the study, please refer Annexure VI

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_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_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

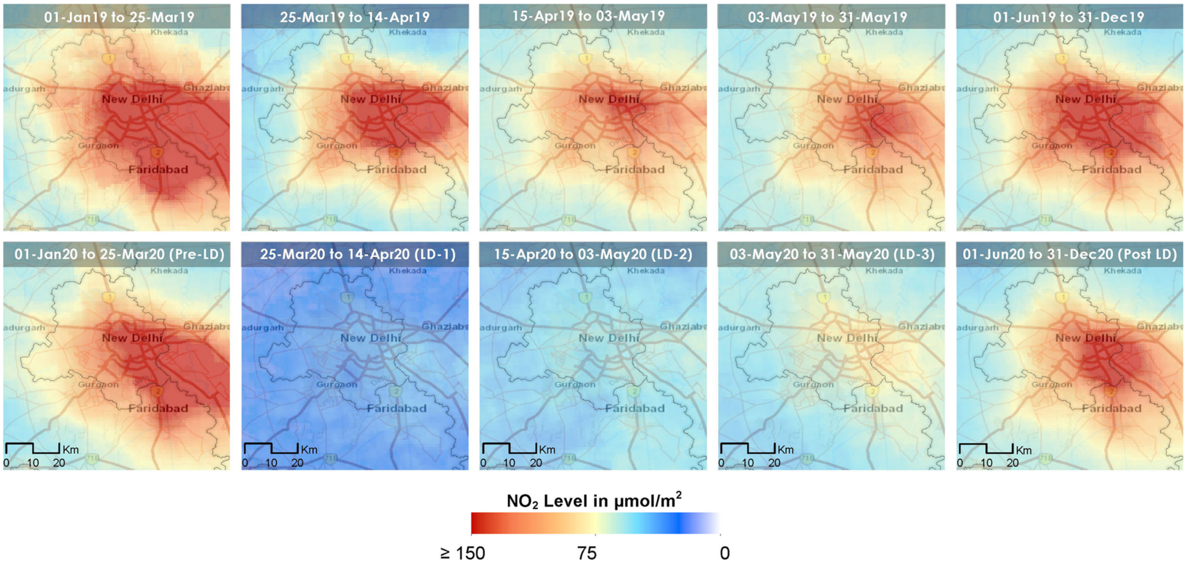

Fig. 3 Comparison between Pre-Lockdown, Lockdown-1, Lockdown-2, Lockdown-3, Post-Lockdown period of 2020 with concurrent periods in 2019 using satellite-based Tropomi-5P observation data

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

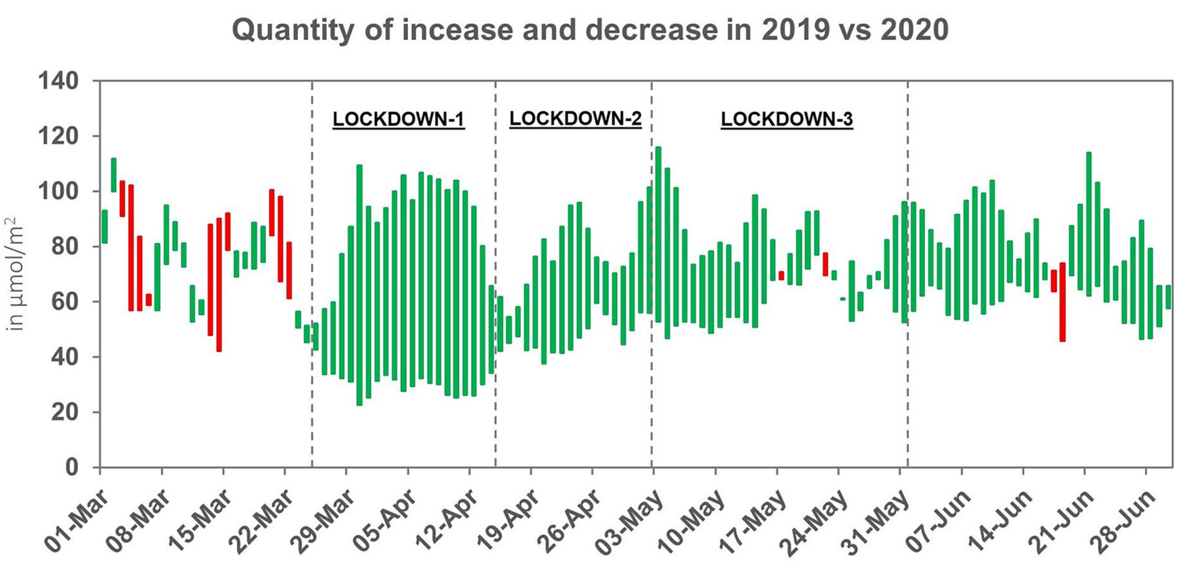

Fig. 4 Daily increase and decrease in NO_2 concentration from 2019 to 2020. The red vertical lines represent the increase in concentration in 2020 compared to 2019 and green vertical line decrease in concentration in 2020 compared to 2019

Table 6 Statistics of CPCB ground station monthly NO_2 (μg/m³) data for 2019 and 2020

								95% CI for Mean Diff	
Month	**∑μ 2019 (a)**	**∑μ 2020 (b)**	***t***	**Δ in %**	**p**	**Δ = b-a**	**SE Diff**	**Lower**	**Upper**
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	-5.85	-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	-4.663	-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

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 7 Statistics of satellite-retrieved Sentinel-5P TROPOMI monthly NO_2 (μmol/m²) data for 2019 and 2020

								95% CI for Mean Diff	
	∑μ 2019(*a*)	**∑μ 2020(*b*)**	***t***	**Δ *in %***	***p-Value***	**Δ = *b-a***	**SE Diff**	**Lower**	**Upper**
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

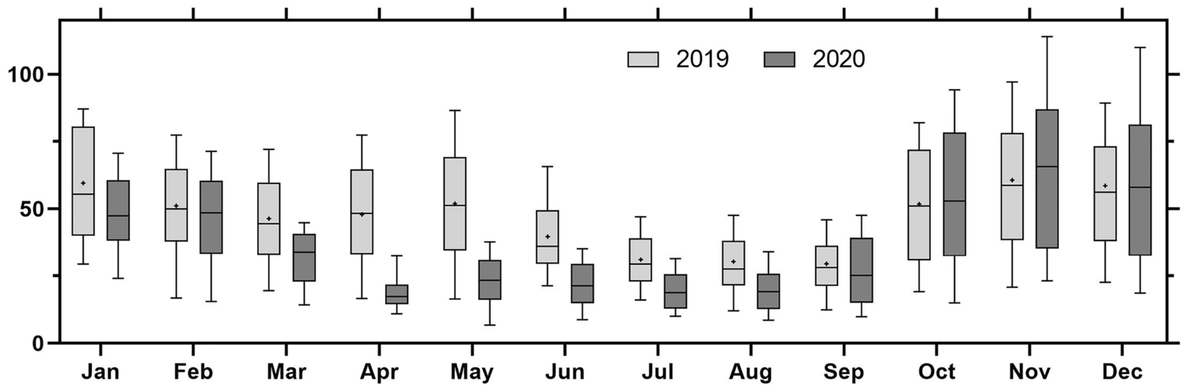

Fig. 5 Mean monthly variation in NO_2 based on CPCB station data

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

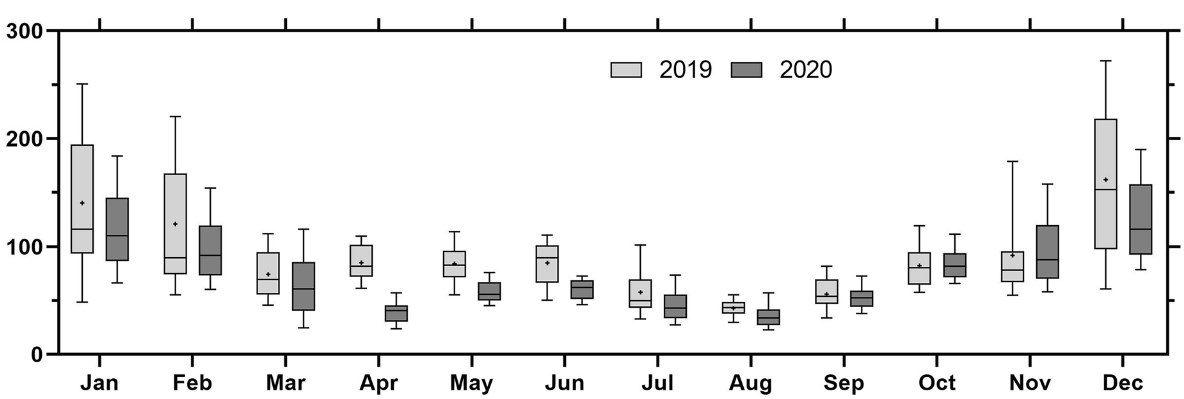

Fig. 6 Mean monthly variation in NO_2 based on TROPOMI Sentinel-5P data

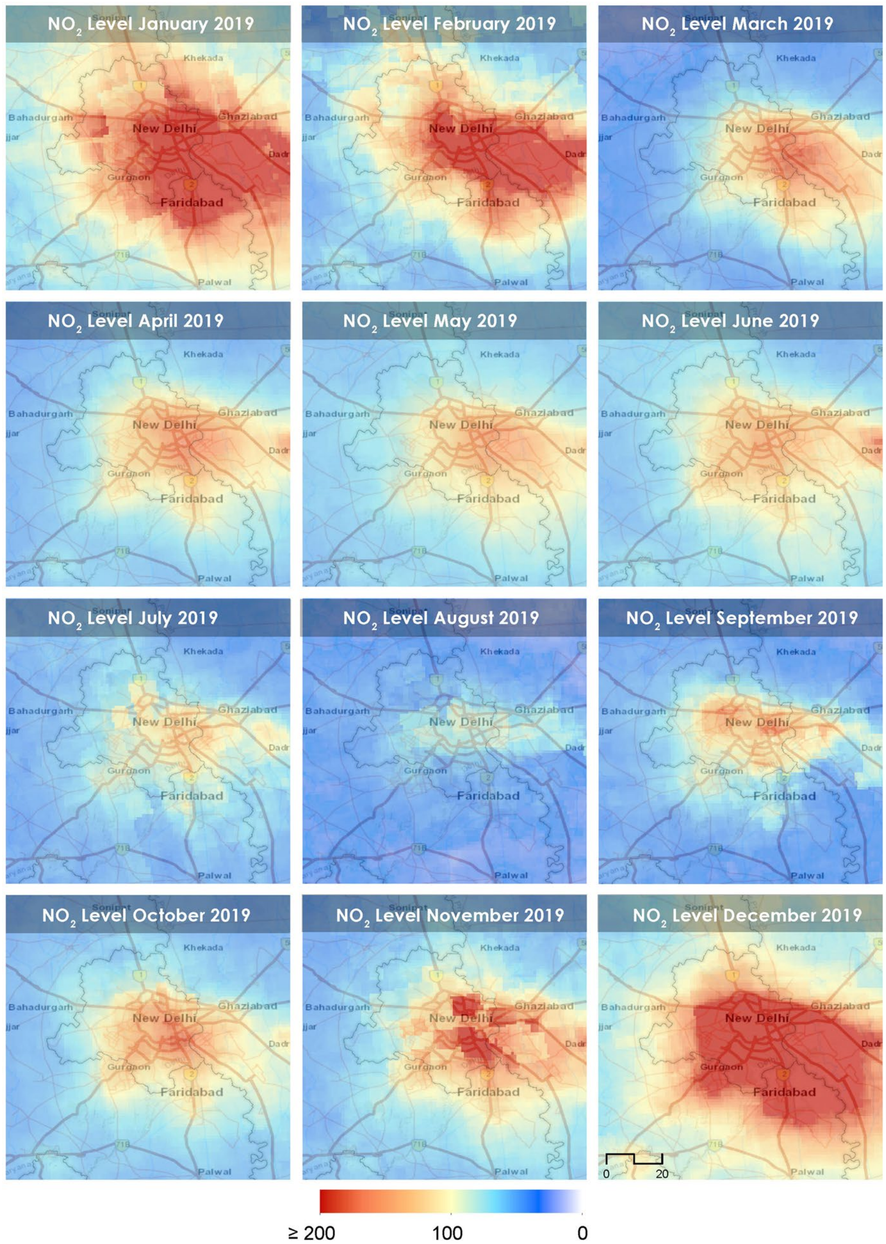

Fig. 7 Monthly Mean of NO_2 concentration in μmol/m^2 for the year 2019

as low as 20.5 μg/m^3 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 NO_2 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 NO_2 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 NO_2 levels for satellite data for 2019 and 2020. The mean monthly NO_2 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 NO_2 reductions are evident over the Delhi region during the lockdown months of April (~54%),

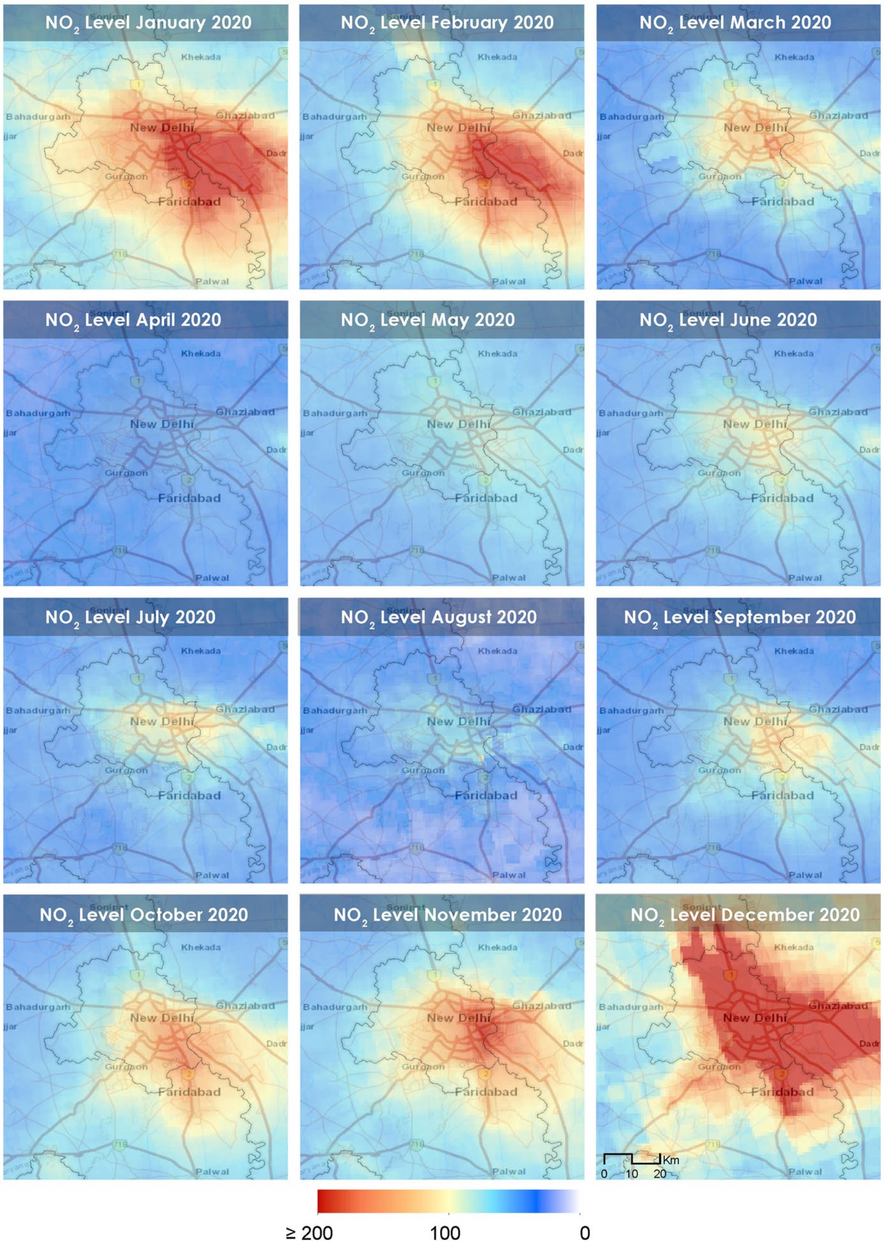

Fig. 8 Monthly Mean of NO_2 concentration in μmol/m.^{2} for the year 2020

Table 8 Statistics of CPCB ground station seasonal NO_2 (μg/m^3) data for 2019 and 2020

Season	∑μ 2019(a)	∑μ 2020(b)	t	Δ in %	p	Δ = b-a	SE Diff	95% CI for Mean Diff	
								Lower	Upper
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

Table 9 Statistics of satellite-retrieved Sentnel-5P TROPOMI seasonal NO_2 (μmol/m^2) data for 2019 and 2020

								95% CI for Mean Diff	
Season	**∑μ 2019(a)**	**∑μ 2020(b)**	**t**	**Δ in %**	**p**	**Δ = b-a**	**SE Diff**	**Lower**	**Upper**
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

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 NO_2 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 NO_2 concentrations. Spatial analysis of near-surface NO_2 (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 NO_2 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

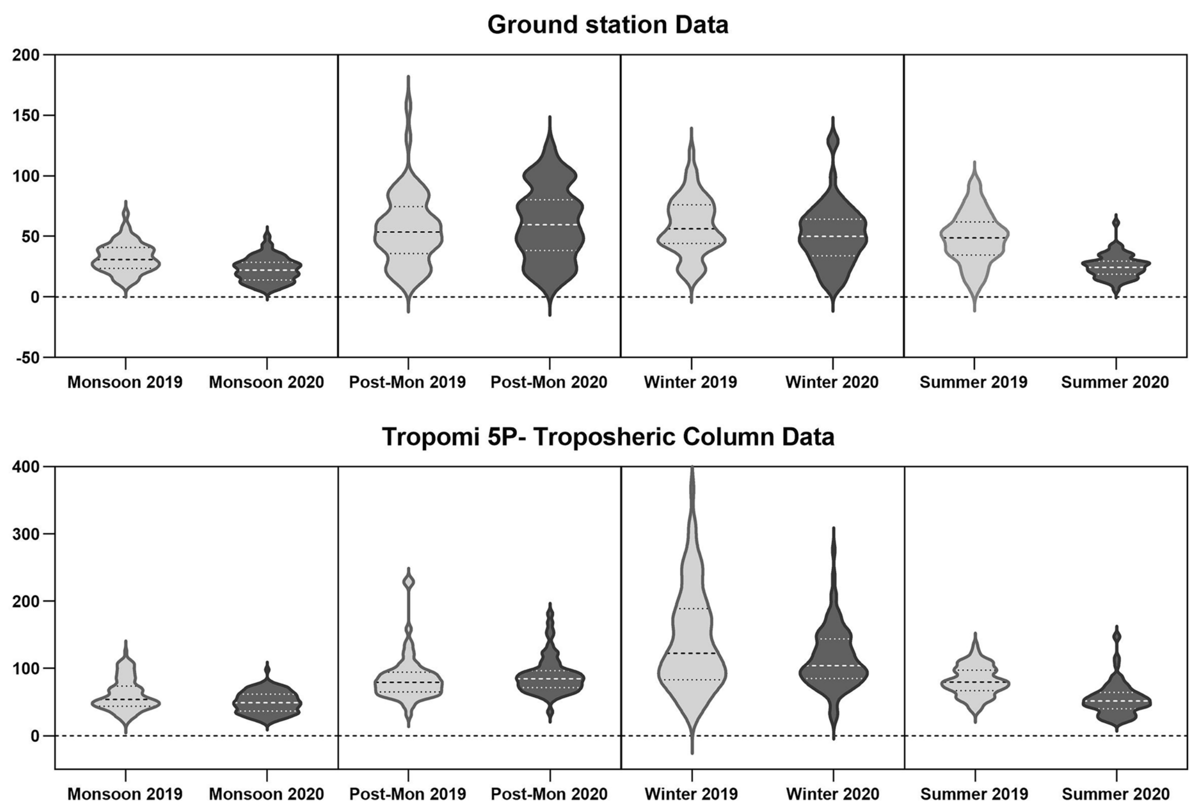

Fig. 9 Violin plot of seasonal variation in (**a**) near surface ground-based observations of NO_2 measured at 61 stations in the Delhi region (in μg/m^3), (**b**) Sentinel-5P TROPOMI tropospheric NO_2 (μmol/m^2), in 2019 and 2020

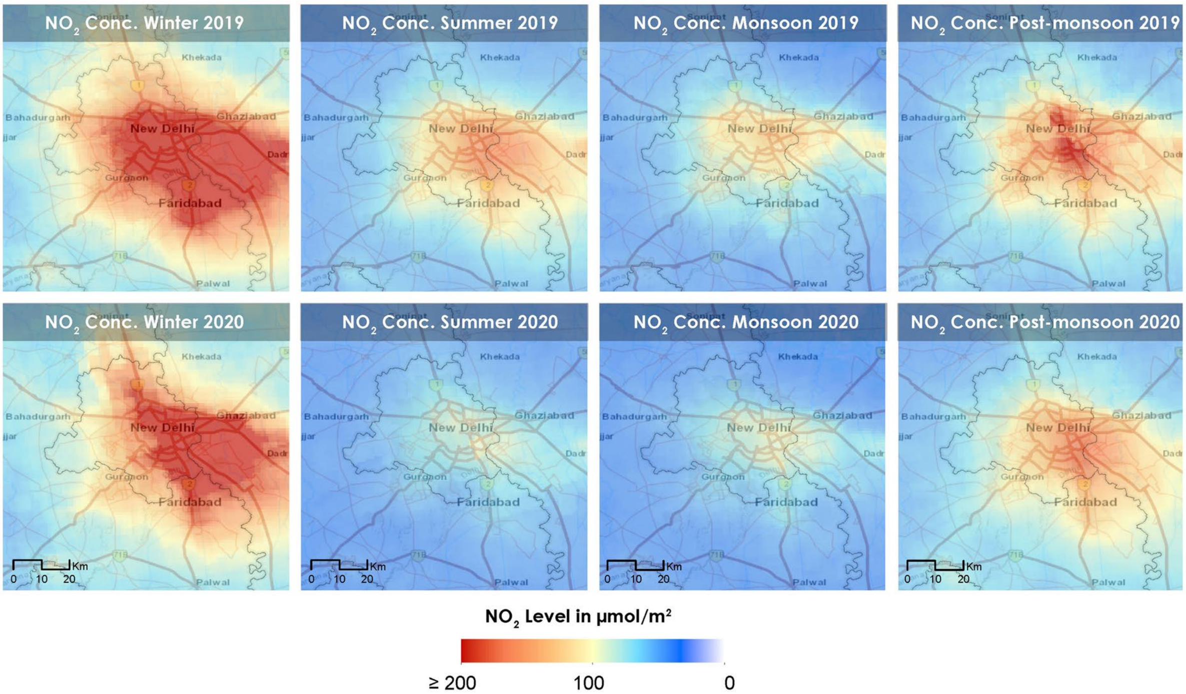

Fig. 10 Map showing seasonal variation in NO2 concentration (in µmol/m2) for the year 2019 and 2020

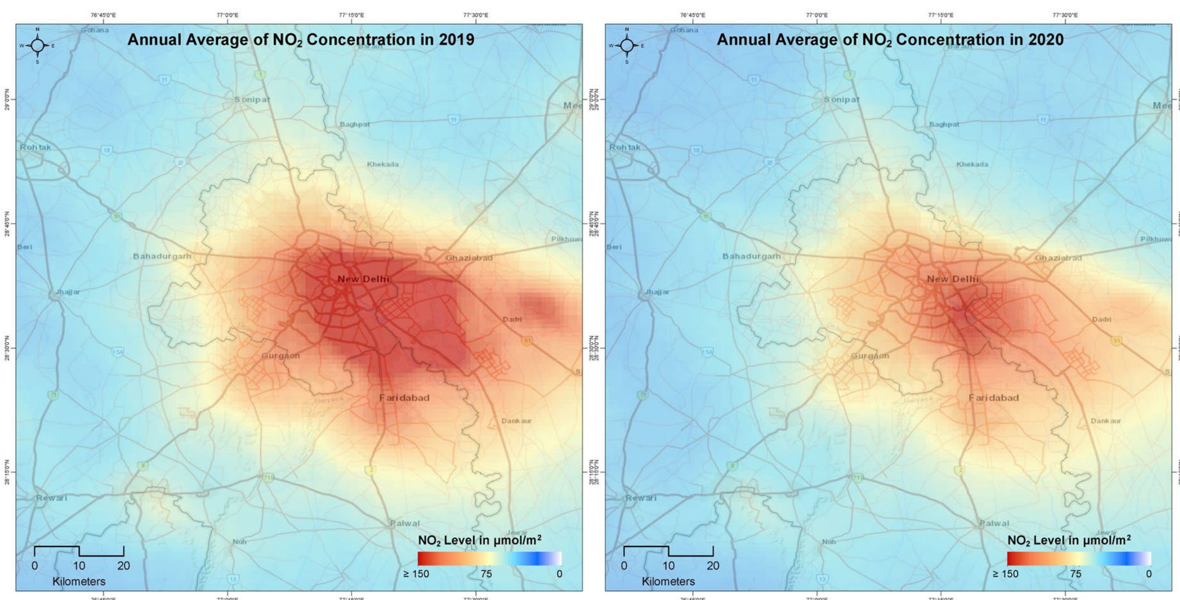

Fig. 11 Annual NO_2 concentration as observed from Sentinel-5P TROPOMI data (in µmol/m.[2]) for the year 2019 and 2020

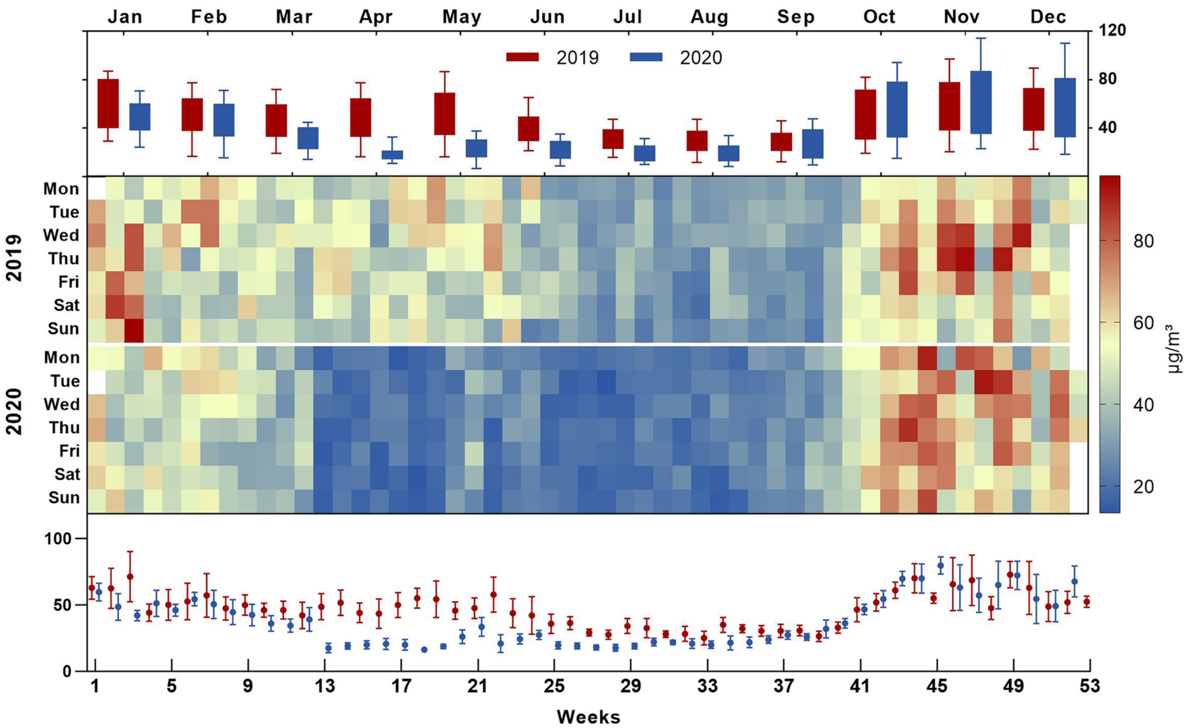

Fig. 12 Heat matrix showing the daily, weekly and monthly mean values of ground-based CPCB monitoring stations

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 dataset 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

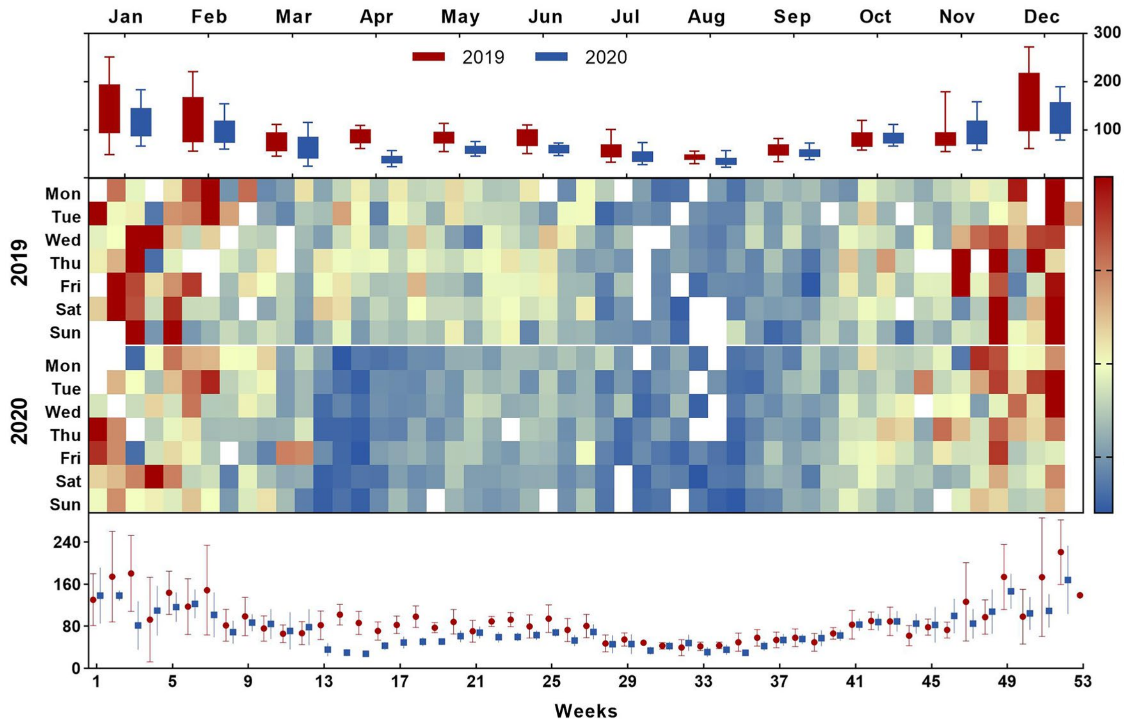

Fig. 13 Heat matrix showing the daily, weekly and monthly mean values of satellite-based Sentinel-5P TROPOMI tropospheric column NO_2 data

is 46.54 μg/m^3 and 37.11 μg/m^3, whereas satellite observed data annual concentration is 90.24 μmol/m^2 and 74.02 μmol/m^2 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 NO_2 in Delhi region

A Pearson correlation was estimated to examine the relationships between NO_2 concentration, air temperature, solar radiation, barometric pressure and wind speed using satellite-retrieved scatterplots of correlation which are presented in Fig. 14. NO_2 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 NO_2 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 NO_2 molecules into two other hazardous gases, i.e., ozone (O_3) and nitric oxide (NO), in the presence of sunlight resulting in a decrease in NO_2 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 NO_2 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 NO_2 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 negligent role in

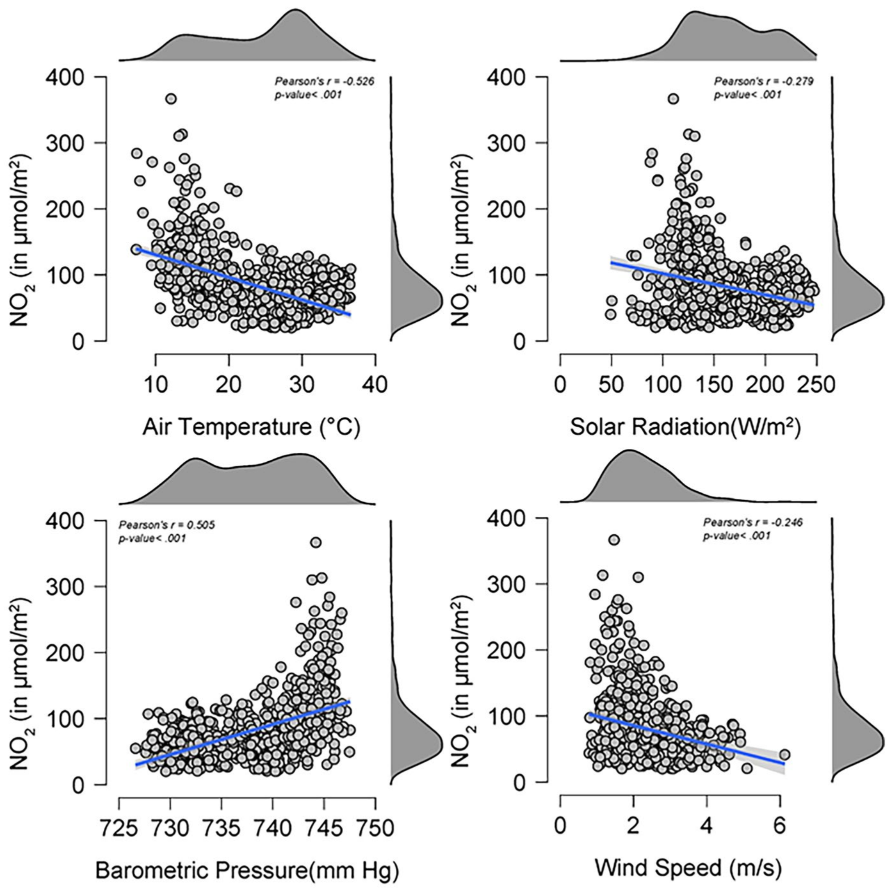

Fig. 14 Pearson r Correlation of NO_2 with air temperature, solar radiation, barometric pressure and wind speed for satellite-retrieved statistics. (The blue line show linear regression line and shaded portion indicates 95% CI, $p < 0.001$)

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 ~ 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 ~ 58% average NO2 was observed in LD-1 phase (March 25th to April 14th). Additionally, the concentrations reduced the maximum in the month of April (~ 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 (~ 48%) in ground measured NO_2 concentration for Delhi region covering Delhi NCT, Gurgaon, Faridabad, Gautam Budh Nagar, Ghaziabad, Baghpat, Sonepat, Rohtak and Jhajjhar. However, no study has comprehensively discussed the monthly,

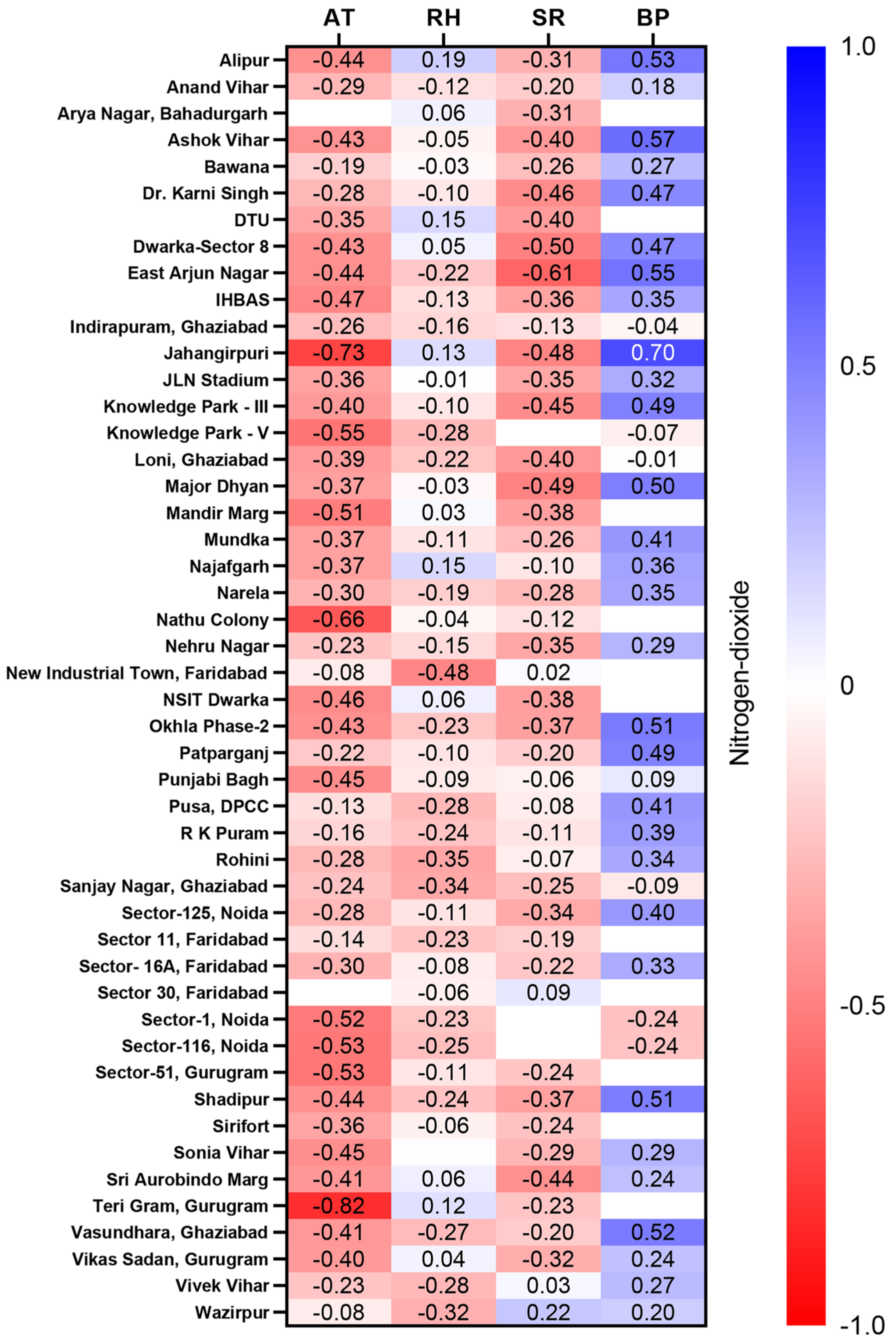

Fig. 15 Pearson's r correlation of NO_2 with air temperature (AT, in °C), relative humidity (RH, in %), solar radiation (SR, in W/m^2) and barometric pressure (BP, in mm Hg) for all ground-based CPCB stations with availability of meteorological parameters in Delhi and surrounding for the data points in 2019 and 2020

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 ~ 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 25th to April 25th) 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 °C and 25.40 °C as observed from ground-based data and 24.31 °C and 23.96 °C 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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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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