Air Quality during the COVID–19 Lockdown and Unlock Periods in India Analyzed Using Satellite and Ground-based Measurements

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Abstract

A nationwide lockdown was imposed in India from 24 March 2020 to 31 May 2020 to contain the spread of COVID-19. The lockdown has changed the atmospheric pollution across the continents. Here, we analyze the changes in two most important air quality related trace gases, nitrogen dioxide (NO₂) and tropospheric ozone (O₃) from satellite and surface observations, during the lockdown (April–May 2020) and unlock periods (June–September 2020) in India, to examine the baseline emissions when anthropogenic sources were significantly reduced. We use the Bayesian statistics to find the changes in these trace gas concentrations in different time periods. There is a strong reduction in NO₂ during the lockdown as public transport and industries were shut during that period. The largest changes are found in IGP (Indo-Gangetic Plain), and industrial and mining areas in Eastern India. The changes are small in the hilly regions, where the concentrations of these trace gases are also very small (0–1 × 10¹⁵ molec./cm²). In addition, a corresponding increase in the concentrations of tropospheric O₃ is observed during the period. The analyses over cities show that there is a large decrease in NO₂ in Delhi (36%), Bangalore (21%) and Ahmedabad (21%). As the lockdown restrictions were eased during the unlock period, the concentrations of NO₂ gradually increased and ozone deceased in most regions. Therefore, this study suggests that pollution control measures should be prioritized, ensuring strict regulations to control the source of anthropogenic pollutants, particularly from the transport and industrial sectors.

Highlights

• Most cities show a reduction up to 15% of NO₂ during the lockdown
• The unlock periods show again an increase of about 40–50% in NO₂
• An increase in tropospheric O₃ is observed together with the decrease in NO₂

Keywords COVID-19 lockdown · Air pollution · Ozone · NO₂ · India · Satellite measurements · CPCB
1 Introduction

Increasing pressure on natural resources is scraping their quality by hindering their self-healing mechanism (UNEP 2015). Air quality is an emerging concern as enough evidence points out the adverse health effects and ecosystem damage from the accumulation of toxic pollutants in the atmosphere. India has witnessed a rapid expansion of its economy, infrastructure and industries, since the economic liberalisation in the 1990s. However, at the same time, air pollution has also emerged as the fourth important risk factor for premature deaths globally (McMichael 2000).

Air pollution hampers economic development and increases human health issues. For instance, a study suggests that about 5.5 million people died worldwide due to outdoor and household air pollution, and it made an equivalent estimated loss of around $225 billion in 2013 (World Bank Report 2016). Air pollution strikes to the backbone of developing economies like India. Evidently, around 1.4 million people lost their lives and an additional $505 billion was spent towards the welfare loss due to air pollution in India (World Bank Report 2013). Therefore, a series of policy measures have also been adopted by India to control air pollution (Badami 2005; Guttiikunda and Mohan 2004). However, recent studies conducted for Indian cities report that many of them exceed permissible air quality limits set by Central Pollution Control Board (CPCB) and World Health Organization (WHO) (e.g., Kota et al. 2018; Mukherjee and Agarwal 2018). The situation might become more serious when the atmospheric trace gases classified as ‘oxidative stressors for organisms’ start competing each other to outplay.

Nitrogen Oxides (Nitrogen dioxide – NO2 and Nitrous oxide – N2O) are among few essential trace gases present in the troposphere. N2O is a strong atmospheric oxidant that plays a major role in tropospheric photochemistry involved in scavenging of tropospheric ozone (Portmann et al. 2012), while NO2 and NO might react with volatile organic compounds to produce ozone (Wood et al. 2009). However, it is also one of the critical air pollutants (Burnett et al. 2004), if it exceeds a certain limit. The source of NO2 in the atmosphere is primarily NO, which results from the combustion of fossil fuels, power plants and vehicle emissions. In addition, biomass burning, microbial reactions and lightning also contribute to NO2 emissions. The atmospheric sinks of NO2 are primarily the wet deposition and photolysis reactions (Finlayson-Pitts and Pitts 1999). Similarly, Ozone (O3) is also important among the trace gases in troposphere having crucial roles in atmospheric chemistry. In the troposphere, O3 acts as an effective cleansing agent at lower concentrations, but is harmful to humans, animals and vegetation at high concentrations (Devlin et al. 1997). On top of these, tropospheric ozone is also an important greenhouse gas that contributes to global warming (Mohnen et al. 1993).

The COVID-19 disease was first reported in Wuhan, China in December 2019 (Holshue et al. 2020), which spread to almost all countries of the world within a month (WHO 2020). It is caused by the severe acute respiratory syndrome coronavirus (SARS-CoV-2) that has the potential to cause serious infection related morbidity and mortality in human beings (Sohrabi et al. 2020). The first COVID-19 infection in India was detected in Kerala in late January 2020, and the infected person was a student who returned from China (Gautam and Hens 2020). Most patients affected by COVID-19 have acute symptoms or are asymptomatic, and a small number of patients develop severe health issues that warrants public attention (Ashour et al. 2020; Ayres 2020; Batah and Fabro 2020; Huang et al. 2020; Song et al. 2020; Zafer et al. 2021).
According to a report by International Monetary Fund, the pandemic has also played a crucial role in affecting the global economy into a recession, about 4% during the period of pandemic in 2020 (Dhar 2021). The unemployment rate was also very high during this period, which left about 100 million people jobless by the end of 2020 (International Labour Organization, ILO 2020). The pandemic has also disturbed the basic water resources and their distribution, and reduced the ability of consumers to pay water bills due to unemployment and economic inconsistency (Liu et al. 2021; Allaire and Dinar 2022). Balamurugan et al. (2021) discussed the impact of COVID-19 on water resources of India, particularly the river water quality, water use and wastewater management in the domestic, commercial and agriculture sectors. Many states and cities within the United States even placed a moratorium on the water supply during the pandemic period (Warner et al. 2020; Nath et al. 2022). This suggests that the water megaprojects should be planned carefully to ensure the economic and social balance (Ma et al. 2020).

As a precautionary measure to contain the spread of COVID-19 infection, nearly every government imposed a national level lockdown in their country by closing all the public places, transport modes and public gatherings. The lockdown has improved the air quality around the cities or urban areas in the world. For instance, Venter et al. (2020) studied the air quality in 34 different countries and found a significant decline in NO$_2$ (13–44%) and ozone (2–20%) during the first two weeks of lockdown, using the satellite measurements from TROPOMI. It is also reported that there was a noticeable reduction of NO$_2$ (0.00002 mol m$^{-2}$), AOD (0.1–0.2) and CO (<0.03 mol m$^{-2}$) between February and March 2020 over the major COVID-19 hotspots in Europe (e.g., Spain, Italy and Germany) compared to their concentration in 2019 as analyzed from TROPOMI and MODIS data (Lal et al. 2020). Pei et al. (2020) showed a significant reduction in NO$_2$, PM$_{2.5}$ and SO$_2$ in three cities of China (Beijing, Wuhan and Guangzhou) during the COVID-19 lockdown (23 January – 10 February 2020) as assessed from the observations of TROPOMI. Collivignarelli et al. (2020) reported a decrease in NO$_2$, PM$_{2.5}$, PM$_{10}$, BC, Benzene and CO in Milan, Italy during the lockdown period (7 February – 5 April 2020) using the regional data.

There are also studies conducted for different regions and cities in India on air pollution changes during the lockdown. For instance, Jain and Sharma (2020) examined different trace gases over Indian cities during the lockdown period (25 March – 6 April 2020) and found that the reduction in particulate matter (PM) was highest in Delhi. However, the decline in NO$_2$ and CO was highest in Mumbai and reduction of O$_3$ was highest in Kolkata as compared to their concentration during the same period in 2019 over these cities. This suggests that the decrease in different pollutant concentration during the lockdown is not similar in all urban regions. Nigam et al. (2021) studied the air quality in two major industrial cities Vapi and Ankleshwar in Gujarat, and observed a reduction (up to 50%) in PM$_{2.5}$ and PM$_{10}$ during the lockdown (25 March – 31 May 2020) period, but their concentrations increased when the restrictions were eased. They also report 80% reduction in NO$_2$ during the period in comparison to that of 2019 in these regions. Sahoo et al. (2021) found a decrease of about 51 and 47% for PM$_{2.5}$ and PM$_{10}$, respectively, during the first phase of lockdown (25 March – 14 April 2020) in India. They also reported an enhancement in air quality with respect to PM$_{2.5}$ and PM$_{10}$, which were reduced up to 80% in this period. Pandey et al. (2021) examined the changes in air quality for 34 months (January 2018 – October 2021) using CPCB measurements from eight locations across Delhi and observed a decrease of about 50% in PM$_{2.5}$ and PM$_{10}$ during the lockdown. However, the study also found a significant increase in NO$_2$, PM$_{2.5}$ and PM$_{10}$ when the lockdown restrictions were lifted. Srivastava et al. (2020) reported significant decline in PM$_{2.5}$, NO$_2$ and CO over Delhi and Lucknow in the first
21 days of lockdown (25 March – 14 April 2020) in India. A high reduction in PM$_{10}$ (3–4 times) near stone-crashing sites in the Dwaraka river basin of Eastern India was also reported during the first 18 days of lockdown (25 March – 11 April 2020) in India (Mandal and Pal 2020). Allu et al. (2021) made a comparative study of surface ozone, NO$_2$ and CO for Hyderabad using automatic analyzers and reported a decrease of 33.7, 53.8 and 27.25% for NO$_2$, NO and CO, respectively, during the lockdown (24 March – 30 April 2020) compared to that in the pre-lockdown (01 February – 23 March 2020) period in India. They also found an increase in surface O$_3$ from 26 ppb to 56.4 ppb during the same period.

Many other studies also observe similar changes in pollutants during the COVID-19 period (Abdullah et al. 2020; Tobías et al. 2020; Bashir et al. 2020; Chauhan and Singh 2020; Muhammad et al. 2020; Dutheil et al. 2020; Isaifan 2020; Filippini et al. 2020; Fan et al. 2020; Li et al. 2020; Ryan et al. 2020). Therefore, it is a challenge to include all studies, and thus, we have mentioned those related to air quality, particularly ozone and NO$_2$. Also, more analysis and assessment are provided in the results and discussion sections.

In India, the nationwide lockdown came into effect on 25 March 2020. Later, several lockdown phases continued and strict restrictions were progressively eased through a process termed as unlock, which started on 1 June 2020. Although the lockdown and phase-wise unlock periods were tough and challenging, it gave an opportunity to analyze the atmospheric load of vehicular pollution in a graded approach. However, most studies conducted so far lack a comparative analysis of pre- and post-lockdown periods that could otherwise assist the policymakers in regulating the vehicular norms for a long-term solution to automobile pollution. It would really be interesting to observe the variation of mutually commiserating trace gases (e.g., O$_3$ and NO$_2$) in atmosphere in relation to the audacity of their anthropogenic sources. Such studies over India are sparse and thus, the pandemic mediated lockdown proved as a blessing in disguise to analyse natural cleansing mechanisms of the atmosphere.

The improvements in air quality reported during the lockdown period can provide respite in the COVID-19 distress situation. A consensus of reasonable restrictions on the transport and industrial sectors to cut trace gas emissions from various anthropogenic sources throughout the country is built through the published studies on air quality (e.g., Biswas and Ayantika 2021; Kuttippurath et al. 2020; Kuttippurath and Raj 2021; Gopikrishnan and Kuttippurath 2021, Raj et al. 2020). This study, therefore, provides further insights into the atmospheric pollution during the lockdown period and compares that with unlock periods for pollution loading attributable to phased plying permissions given to commercial and private vehicles.

Furthermore, it also provides policy relevant information related to the air quality achievements that can be targeted. The uniqueness of this study is that it discusses the air quality during the lockdown, unlock and the current scenarios after the lockdown restrictions were gradually lifted. There is no other study conducted for all regions of India using satellite and ground-based measurements during lockdown and unlock periods to make a comprehensive assessment on the air quality changes yet, which make our analysis stronger and conclusions robust. This study would provide different context of air quality changes with and without the restrictions for better policy discussions, which is extremely important for a vast country like India. Since similar air pollution conditions are there in many world cities and towns, the analyses presented here has a global significance and wider applications. Henceforth, this study would add more insights into the air pollution related policy decisions.
2 Materials and Methods

2.1 Region of Study

We analyze the air quality changes during the lockdown and unlock periods in India. Since the severity of air pollution is different in different regions, we have divided the study area into six sub-regions, namely: (i) Peninsular India, which consists of six states (Kerala, Tamil Nadu, Karnataka, Goa, Andhra Pradesh and Telangana). Out of the first 10 most populated states in India, three of them are located in this region (Andhra Pradesh, Tamil Nadu and Karnataka). This region also houses a major forest area, the Western Ghats. (ii) Central India has five states: Maharashtra, Madhya Pradesh, Chhattisgarh, Jharkhand and Odisha. This region is sparsely populated, and has many thermal power stations, coal mines and steel plants. Many major cities of India including Mumbai and Pune are in this region. Also, the western central India is highly populated, industrialized and is known as the economic hub of India. (iii) North West India consists of Rajasthan and Gujarat, and much of its land is arid that includes the Thar Desert. (iv) North East India consists of Tripura, Mizoram, Manipur, Nagaland, Meghalaya and Assam. This region has small population density and high vegetation cover. (v) Indo Gangetic Plain (IGP) consists of West Bengal, Bihar, Uttar Pradesh, Haryana and Punjab, and this region lies between Central India and the Himalaya. Population density of this region is very high, more than 1000 per km², and is highly urbanized and industrialized. (vi) The hilly Indian states are Jammu Kashmir, Himachal Pradesh, Uttarakhand, Sikkim and Arunachal Pradesh. These regions are ecologically fragile and their economy depends primarily on agro-horticulture and forestry.

Apart from these, we have considered 8 major cities of India (Bangalore, Hyderabad, Lucknow, Kolkata, Ahmedabad, Chennai, Delhi and Mumbai) to find the impact of lockdown on air quality in highly urbanized areas using the ground-based CPCB measurements there. The analysis is performed particularly to examine the contribution from the transport sector since most of the pollution across the cities arise from the vehicular emissions. Therefore, this will help us to segregate the baseline emissions from sources other than transport and industries. This is also the reason that we diagnose changes in NO2 as much of its emissions in urban region is contributed by vehicles. Figure 1 shows different regions and major cities of India, and Supplementary Material (SM) Figure SM1 shows the energy map with industrial and economic clusters of India.

2.2 Satellite and Ground-based Measurements

We have used the tropospheric Vertical Column Density (VCD) of NO2 from GOME-2B (TM4NO2A v. 2.3 datasets). GOME-2B sensor uses the backscattered and the extraterrestrial solar irradiance in the spectral bands of 240–790 nm wavelengths (UV and Visible) at a high spectral resolution. The NO2 Slant Column Density (SCD) is retrieved by applying the differential optical absorption spectroscopy (DOAS) method (Platt 1994). Then, data assimilation is used to compute the tropospheric and stratospheric contribution to the VCD of NO2 (Dirksen et al. 2011). An air mass factor (AMF) is applied to convert the tropospheric SCD to tropospheric VCD (Boersma et al. 2004). The assimilated total SCD retrieved using DOAS method is fed to the TM4 chemical transport model to differentiate the tropospheric and stratospheric SCDs (Dirksen et al. 2011). These are available at 0.25°×0.25° latitude – longitude grids as monthly averaged data.
The O₃ data are taken from the ozone monitoring Instrument (OMI) and microwave limb sounder (MLS) onboard the Aura satellite, which is in a sun-synchronous polar orbit at 705 km altitude. OMI is a nadir-scanning instrument, which operates in the wavelength regions 270–314 nm and 306–380 nm. It detects the backscattered solar radiance to measure the total column ozone (TCO). The instrument has global coverage with a horizontal resolution of 13×24 km². The MLS instrument is a thermal-emission microwave sounder that measures vertical profiles of temperature, ozone and other atmospheric constituents. The MLS measurements lag by seven minutes before those of OMI at the same location during daytime. The OMI/MLS daily tropospheric ozone is determined by subtracting the OMI TCO from the MLS stratospheric column ozone on each day. Monthly mean TCO is computed by averaging all the available daily data in each month. The OMI TCO is filtered for clear-sky conditions by including only the pixels of OMI reflectivity measurements that are less than 0.3 and coincide with the MLS measurements (Ziemke et al. 2006).

The daily NO₂ data from 2019 to 2021 are considered from the satellite observations of Sentinel-5 Precursor (S5-P), which was launched by the European Space Agency on 13 October 2017 (Veefkind et al. 2012). The sensor is also termed as TROPOMI (TROPOspheric Ozone Monitoring Instrument), which operates in the UV and Visible (270–500 nm), near Infrared (675–775 nm) and short-wave infrared (2305–2385 nm) spectral bands. We have used the S5-P offline data with measurements from a single orbit for
a hemisphere, as the other half is in complete darkness in the same period. The source data are filtered to remove the quality assessment (QA) values of less than 75% for NO2. Harp Convert tool along with bin spatial operations are applied to obtain the tropospheric NO2 column in number density. The TROPOMI NO2 processing is based on the algorithm developed for the EU QA4ECV NO2 for OMI (Eskes et al. 2019).

The daily averaged NO2 and O3 data from the ground-based CPCB measurements at the cities Ahmedabad, Bangalore, Chennai, Delhi, Hyderabad, Kolkata, Mumbai and Lucknow for the past 3 years (2019, 2020 and 2021) are also considered to supplement the satellite-based analysis. The technical details of these data can be found in CPCB (2019).

2.3 Methods

Monthly data from GOME 2B and OMI-MLS are used to study the changes in ozone and NO2 during pre-lockdown (March), lockdown (April–May) and unlock (June–September) periods. In addition, the monthly changes of these trace gases over the past 5 years (2015) are also estimated. We use the daily NO2 observations from TROPOMI to evaluate the impact of lockdown on air quality, because TROPOMI has better spatial resolution than that of GOME 2B. The TROPOMI data are available from 2019 onwards. The percent change is calculated using the equation:

\[ D = \frac{Yc - Yr}{Yr} \times 100 \]

where D is the percent change, Yr is the mean of the pollutant during 2019 and 2021, and Yc is the average of the pollutant in the region during pre-lockdown, lockdown and unlock periods of 2020.

3 Results and Discussion

3.1 Air Pollution Change during the Lockdown and Unlock Periods

Figure 2a shows the mean NO2 before, during and after lockdown in India in 2020. The analyses performed for the pre-lockdown period show that Delhi, Ahmedabad, Surat, Chennai, Dhanbad, Tata, Visakhapatnam, Hyderabad and Kolkata are the hotspots of pollution (shown as the circles in the figure). The primary sources of NO2 are vehicular and industrial emissions, and other anthropogenic activities such as agriculture, biomass burning and aquaculture (Garg et al. 2002; Beirle et al. 2003). These cities show about 7–8 × 10^{15} molec./cm^2 of NO2, whereas the rural regions (other than the urban areas) have concentrations of about 0–2 × 10^{15} molec./cm^2. During the lockdown period, there was a significant reduction in the number of vehicles on roads, and as a result, the NO2 concentration is highly reduced in India. However, a few mining and industrial activities were still running during the lockdown period with some restrictions (Ray and Subramanian 2020). The industrial regions continued to contribute similar amounts of NO2 during the lockdown. The overall concentration also decreased to very low values over the whole country (0–3 × 10^{15} molec./cm^2) except for IGP, where it is about 4–5 × 10^{15} molec./cm^2 during the unlock period.

Figure 2b and c show the concentrations of NO2 during the same periods of 2019 together with the climatology (2015–18) of NO2, respectively. There are high values of
NO₂ during the pre-lockdown period of 2020 compared to that of 2019 and the average concentration during 2015–18 amounts to 1–2 × 10¹⁵ molec./cm² (regions marked in black circles). However, there is a reduction in NO₂ in these regions during the lockdown, and it again increased by 1–2 × 10¹⁵ molec./cm² during the unlock phases as compared to that in the previous years.

The tropospheric O₃ (Fig. 3) concentration is about 35–40 DU in the northern India before the lockdown period (March 2020) and it increased to 42.5–47.5 DU during the lockdown. Peninsular region shows about 30–32.5 DU during the pre-lockdown and it increased to 35–37.5 DU in the lockdown. The IGP has the highest levels of O₃ during the lockdown, as the pollution is very high there. However, ozone decreased substantially during the unlock period, about 30–35 DU in peninsular India (lowest during the unlock period) and 40–42.5 DU in the hilly regions. The NE and IGP regions also exhibit a significant decrease in O₃ during the unlock phase (40–45 DU), making a difference of about 5–15 DU from the lockdown to the pre-lockdown period. Furthermore, in general, ozone shows high values in northern India as compared to that in the south, due to the severe pollution in the north.

We have also compared the tropospheric O₃ and NO₂ during the pre-lockdown, lockdown and unlock periods in 2020 to those in 2019, as illustrated in Fig. 4. A significant increase in NO₂ is observed over the industrial regions of central India (e.g., Chhota-Nagpur
and Jamshedpur) and cities (e.g., Delhi and Mumbai) in the pre-lockdown period. However, these regions show lower NO$_2$ during the lockdown (1–1.5 $\times$ 10$^{15}$ molec./cm$^2$), but it again increased (about 1–1.5 $\times$ 10$^{15}$ molec./cm$^2$) during the unlock period. Cities of Delhi, Mumbai, Ahmedabad, Hyderabad and Kolkata also show similar changes in NO$_2$. The NO$_2$ concentrations were higher during the pre-lockdown and it suddenly decreased during the lockdown, and eventually increased to much higher levels in the unlock phases. The tropospheric O$_3$ shows a significant increase over NW prior to the lockdown (3–5 DU) and a decrease by 2–5 DU during lockdown, except for the hilly regions, as compared to that in 2019. In the unlock phase, O$_3$ increased from that of the lockdown by 2–4 DU, but still was lower by 0–2 DU from the previous year (2019) values. The NO$_2$ and O$_3$ concentrations show a similar pattern of reciprocal changes in most regions.

Figure SM2 shows the percent change in NO$_2$ and O$_3$ during the pre-lockdown, lockdown and unlock periods compared to those in 2019. As discussed above, the NO$_2$ concentrations show high reduction during lockdown (10–20%) except in the hilly regions, where pollution is also very small. Conversely, the NO$_2$ concentrations increased by 40–50% in most cities and northern India during the unlock phases, although some areas in the south still show a reduction of about 10%. Similarly, O$_3$ concentrations show negative change during the lockdown phase in most regions, except in Kashmir (about 5–10%). This reduction in ozone spread to almost all regions across India during the unlock periods, with values up to 10%, analogous to the changes in NO$_2$. 

Fig. 3 The average concentration of O$_3$ during the pre-lockdown, lockdown and unlock periods in India for a [upper panel] 2020, b [middle panel] 2019, and c [bottom panel] 2015–2018
3.2 Regional Progression of NO\(_2\) and O\(_3\)

Table 1 lists the regional changes in ozone and NO\(_2\) during each lockdown phase as a percent difference from the previous year (2019). Figure 1 shows the topographic divisions of India, which are used to differentiate the changes in the trace gases during the period of study. A clear reduction in NO\(_2\) is observed during the lockdown in the central, IGP and peninsular regions, whereas the other regions show an overall increase from the previous year. The NO\(_2\) concentrations in the industrial regions are mostly around 5–7 × 10\(^{15}\) molec./cm\(^2\) during the lockdown. Air quality improved over IGP during the lockdown (6%) and worsened during the unlock (18%) in terms of NO\(_2\) concentrations. This sharp increase in NO\(_2\) during the unlock period suggests the rise in pollution as soon as the restrictions were eased. In addition, the hilly regions show NO\(_2\) concentration of about 0–1 × 10\(^{15}\) molec./cm\(^2\) during the entire lockdown period. The NE regions show 3–4 × 10\(^{15}\) molec./cm\(^2\) during the lockdown, which significantly reduced in the subsequent unlock phases. The central India that includes the major industrial areas (e.g., Jamshedpur and Chandrapur) also shows a decline in NO\(_2\) concentration during the lockdown with a decrease of about 5.3% from the previous year values. Nevertheless, the concentration over peninsular region shows a consistent increase during the lockdown (4%), although the NW region exhibits a mixed response of positive and negative drifts from the previous year concentrations.

During the lockdown, high concentrations of O\(_3\) were found in IGP (45–47.5 DU), while the rest of the regions show lower concentrations of about 35–40 DU. We also observe the highest O\(_3\) in IGP compared to the other regions during the lockdown. Most regions show a decrease in O\(_3\) concentrations with respect to that in 2019 in the pre-lockdown period. The highest decrease is observed in NE (-17.3%) and the lowest in the hilly region (+3%) during the lockdown. The O\(_3\) concentrations are much smaller than the previous year values for the same period, although O\(_3\) started to increase in all regions as soon as the lockdown restrictions were relaxed (Table 1). This is evident from the increase of O\(_3\) concentrations
from the beginning of unlock phase, for which the hilly regions show the largest reduction (2.51%) from the 2019 levels.

Since the regional averages are estimated over large areas, it is difficult to find changes in the distribution of a pollutant with respect to industrial activities and transport sectors. Therefore, we examine the change in NO$_2$ and O$_3$ concentrations in the major cities of India before (March), during (April–May) and after (June–September) the lockdown in 2020 (Table 1). Our results show a decrease in NO$_2$ over the major cities. However, the areas with heavy traffic demonstrate a substantial increase in O$_3$ concentrations during the lockdown (e.g., Delhi). The NO$_2$ concentrations are relatively lower in many cities even before the lockdown because of the local lockdown imposed in a few places (e.g., Kerala, Pune and Mumbai). Therefore, the difference in NO$_2$ concentration with the pre-lockdown (March) is very small, for which the smallest change is observed at Ahmedabad (-1%) and the largest at Lucknow (-15.74%). On the other hand, the highest reduction in NO$_2$ is observed in Delhi (36%) and the smallest in Kolkata (6%) in the lockdown period. During the unlock period, the NO$_2$ concentrations in all cities show the same levels as observed during the pre-lockdown; indicating decrease in air quality and the impact of ease in restrictions. Meanwhile, the ozone concentrations show a similar pattern to the changes in NO$_2$, as its concentration decreased in most cities. The minimum and maximum decrease in O$_3$ during the lockdown are observed in Delhi (2%) and Kolkata (18.73%), respectively.

### 3.3 Air Quality in 2020 Compared to that during 2015–2020

Figure 5 shows the monthly mean of NO$_2$ and O$_3$ for the period 2015–2020. The analyses show a general increase in tropospheric O$_3$ from January to June and a gradual decrease thereafter. The NO$_2$ concentrations peak during March–April–May and show the minimum...

| Table 1 Percent difference in NO$_2$ and O$_3$ concentrations over different regions of India with respect to the 2019 scenario |
|---------------------------------------------------------------|
| **Regions** | NO$_2$ | O$_3$ |
| | Pre LD | LD | Unlock | Pre LD | LD | Unlock |
| Central | 3.32 | -5.31 | 10.23 | -8.68 | -10.57 | -2.08 |
| Hilly | 25.87 | 13.28 | 40.32 | -12.14 | 3.05 | -2.51 |
| IGP | 3.48 | -5.92 | 18.23 | -6.27 | -6.06 | -0.75 |
| NEI | 27.69 | 9.74 | 57.48 | -4.86 | -17.34 | -2.19 |
| NW | 8.32 | 1.92 | 36.83 | 5.61 | -1.97 | -0.02 |
| Peninsular | -8.35 | -3.99 | 7.44 | -8.19 | -13.79 | -2.25 |
| **Cities** | | | | | | |
| Bangalore | -15.66 | -21.34 | 4.94 | -8.50 | -13.79 | -2.59 |
| Hyderabad | -9.23 | -9.31 | -33.72 | -8.29 | -13.76 | -2.57 |
| Lucknow | -15.74 | -10.18 | 27.31 | -3.30 | -4.72 | 0.86 |
| Kolkata | -15.42 | -6.04 | -8.78 | -14.57 | -18.73 | -2.70 |
| Ahmedabad | 1.07 | -21.26 | 18.24 | -0.14 | -6.70 | 0.82 |
| Chennai | -14.61 | -9.08 | -4.48 | -8.16 | -15.17 | -0.31 |
| Delhi | -2.36 | -35.72 | -7.33 | -4.40 | 2.02 | -0.90 |
| Mumbai | -12.11 | -11.76 | 21.75 | -8.43S | -12.13 | -0.21 |
in June–July–August. A record decrease in O₃ is observed during the lockdown in all regions except in the peninsular India, with its lowest values in April 2015. As soon as the country entered the unlock phase, O₃ in all regions started to increase, particularly from October onwards, which is higher than that during the same months of previous years. The monthly mean NO₂ (April–May) also shows lower values in the lockdown period in all regions. All regions except NE show significant decrease in April 2020 as compared to that in 2019. However, NO₂ exhibits slightly higher values in May 2020 to that of previous year. During the unlock phase, NO₂ increased noticeably in all regions and it shows the highest concentrations in NEI, NW, IGP and hilly regions during June–September 2020, in comparison to previous year values.

### 3.4 Comparison of Daily NO₂ in 2020 with that of 2019 and 2021

Figure 6 shows the difference (in percent) of NO₂ during the pre-lockdown, lockdown and unlock periods of 2020 with the corresponding time periods in 2021. Figure SM3 shows the mean NO₂ distribution over India during the pre-lockdown, lockdown and unlock periods of last 3 years (2019–2021). An increase of 43, 60, 15, 38, 16 and 31% in NO₂ prior to the lockdown period of 2020 (pre-lockdown) is observed in IGP, Central, Hilly, North
East, North West and Peninsular India, respectively. This suggests increase in pollution during the same period of 2021 without any lockdown. India was hit by the largest wave of COVID-19 in February 2021 and the government imposed lockdown in different states again during this period. For instance, Maharashtra had 4 phases of lockdown from April to June 2021, during which the schools and public places remained closed, public gatherings were restricted and offices remained shut. Several states, like Tamil Nadu, Kerala, Karnataka, Rajasthan, Bihar, UP and Odisha enforced complete lockdown in the same period. In contrast, several other states, like Punjab, Chandigarh, Andhra Pradesh, Arunachal Pradesh and Nagaland had partial lockdown. However, most states started to lift the restrictions and moved to the unlock phase from 15 June 2021 onwards. This situation caused the increase in NO2 in some states, and the decrease in the states with complete lockdown.

Comparing the lockdown phases of 2020 with the same period in 2021, there is again a clear increase in the amount of NO2. We find an increase in NO2 during lockdown and unlock periods of 2020, at about 24, 21, 17, 31, 8 and 5.5% during lockdown (25 March – 31 May) and 20, 11, 7.5, 12.5, 2.5 and 8% during unlock (01 June – 30 September) in IGP, Central, Hilly, NE, NW and Peninsular India, respectively. We also observe a rapid increase in NO2 over IGP and Central India during the period. Figure 6 (bottom panel) shows the daily mean NO2 concentrations in these regions compared to those in 2019 and 2021. The results show very high levels of NO2 over Central India and IGP during the pre-lockdown period of 2021; it should be noted that the second wave of COVID-19 also occurred during the same period in India. Local restrictions were imposed from 15 April to 15 June, and therefore, significant decrease in NO2 is apparent until July 2021. The NO2 concentrations again increased during the unlock period and they outcompeted the overall NO2 concentrations observed in 2019 and 2020.

Figure 7 shows the CPCB ground-based NO2 and O3 measurements from 2019 to 2021 during the pre-lockdown, lockdown and unlock periods in India. The measurements from
CPCB show an overall reduction of NO\textsubscript{2} in all cities during the lockdown. Among the cities, except Kolkata, NO\textsubscript{2} levels increased during the same period of lockdown in 2021 compared to that in 2020. For example, NO\textsubscript{2} shows high values (40.61 ug/m\textsuperscript{3}) in 2019, which reduced significantly in 2020 (22.15 ug/m\textsuperscript{3}) due to the lockdown restrictions in Delhi. However, the NO\textsubscript{2} concentrations increased to 30.18 ug/m\textsuperscript{3} during the same period in 2021 because of the relaxation of restrictions. On the other hand, NO\textsubscript{2} concentrations are lower in 2021 (7.75 ug/m\textsuperscript{3}) than those in 2020 (11.88 ug/m\textsuperscript{3}) during the lockdown in Kolkata. A similar change in NO\textsubscript{2} concentrations is observed during the unlock period in all cities, except Delhi and Kolkata, where NO\textsubscript{2} concentrations are higher in 2021 and lower in 2019 with respect to the values in 2020. Table SM1 shows the change (in %) in surface O\textsubscript{3} and NO\textsubscript{2} in different cities of India.

Conversely, the ground-level ozone shows a significant increase during the lockdown period as compared to the ozone levels in pre-lockdown and unlock periods. Mahato et al. (2020) also reported an increase (10%) of O\textsubscript{3} over the industrialized and transport dominated regions of India because of the slowdown in atmospheric titration of NO\textsubscript{2}. The increased ozone in April–August can also be due to the higher solar radiation during the period in the Indian sub-continent (Gorai et al. 2017).

### 3.5 Assessment of Different Studies on Air Pollution in India and the World

#### 3.5.1 Studies Using the CPCB Data in India

Several studies have been performed using the CPCB NO\textsubscript{2} and O\textsubscript{3} concentrations during the lockdown (before and after 25 March 2020) in India. For example, Mahato et al. (2020) found a decrease of 53% in NO\textsubscript{2} and an increase of 1% of O\textsubscript{3} in Delhi for the period from 3 March to 14 April 2020. Sharma et al. (2020a, b) found a decrease of 18% for NO\textsubscript{2} and an increase of 17% in O\textsubscript{3} in India from 10 March to 17 May 2020. In a similar study, Kumari and Toshniwal (2020) reported a decrease of 60 and 78% of NO\textsubscript{2} and an increase of 27 and 30% of O\textsubscript{3} in Delhi and Mumbai, respectively, during the period 01 March – 15 April 2020. Singh et al. (2020) studied the air quality in 134 sites of India and found a
significant decline in NO₂ (30–70%). They also found a marginal increase in ground-level O₃ over Delhi. Kumari and Toshniwal (2020) found a decrease in NO₂ and SO₂ during the lockdown period (50–80%) in Delhi, Mumbai and Singrauli. Navinya et al. (2020) studied the air quality across 17 cities (e.g., Delhi, Bangalore and Ahmedabad) in India and reported a decline of NO₂ in Bangalore (86%), Delhi (70%) and Ahmedabad (67%). Our analysis with CPCB measurements in the respective cities during the lockdown period also shows comparable changes in NO₂ and O₃, although small variations due to the differences in time periods are there. However, our study is more comprehensive as it discusses the NO₂ and O₃ distribution together for the whole India and during the complete pre-lockdown, lockdown and unlock periods.

3.5.2 Comparison with Satellite Measurements in India

Sathe et al. (2021) used satellite derived tropospheric column NO₂ during the lockdown period (25 March – 17 May) and reported a decrease of about 46–61% over selected cities in India (e.g., Bangalore, Chennai, Delhi and Kolkata). Shehzad et al. (2020) observed a reduction of about 40 and 50% of NO₂ at Mumbai and Delhi, respectively, from 01 January to 05 April 2020, using the Sentinel-5P observations. Kumar (2020) used the OMI data and found a notable decrease in NO₂ in the period of 29 February – 30 May 2020 (with a difference of 45% from the average of 2017–2019) in six megacities in India. Prakash et al. (2021) studied NO₂ concentrations across India using the TROPOMI measurements and found a decrease of about 35–43% during the lockdown period compared to that in previous years in the megacities (Delhi, Mumbai and Bangalore). Siddiqui et al. (2020) also used TROPOMI to examine the changes of NO₂ during the lockdown (20 March 2020 – 3 May 2020) and observed a noticeable reduction in metro cities (34% in Kolkata, 33% in Chennai, 70% in Bangalore and 57% in Mumbai). We also find comparable results, as there are changes of around -40% in NO₂ and 5–10% in ozone at different regions and cities of India during the lockdown.

3.5.3 Global Analysis of Pollution Changes during COVID-19 Periods

Nakada and Urban (2020) used surface and satellite data, and observed an increase of 30% in O₃ and a decrease of 54.3% in NO₂ over Sao Paulo state in Brazil during the period 25 February – 20 April 2020. Xu et al. (2020) used ground-based measurements and observed -52.8 and +3.6% differences in NO₂ and O₃, respectively, over Central China between 2020 and the average for the period 2017–2019. Berman and Ebisu (2020) reported a decrease of 25.5% of NO₂ during 08 January – 21 April 2020 with respect to the average of 2017–2019 in the USA. Similar results were also found for ozone and NO₂ by Kerimray et al. (2020) for Almaty and Baldasano (2020) for Barcelona. A model study by Menut et al. (2020) reported 30–50% reduction in NO₂ during March 2020 in Europe when simulating conditions with and without the lockdown restrictions. Sicard et al. (2020) reported an increase in O₃ (17% in Europe and 36% in Wuhan) and reduction (56%) of NO₂ (European cities and Wuhan) during lockdown. Adams (2020) used the Ministry of Environment air pollution data and found a significant reduction in NOₓ and a small slump of ground level O₃ in Ontario, Canada, from 3 January to 6 February 2020. Otmani et al. (2020) used ground-based measurements at two sites in Morocco and found reduction (96%) in NO₂ during the lockdown period (11 March – 02 April 2020). Tobías et al. (2020) analyzed ground-based observations and found 45–51% reduction in NO₂ and 33–57% increase in O₃ in Barcelona.
during the lockdown (16 February – 30 March 2020). Our analysis with satellite and ground-based measurements show comparable results, as most regions show a reduction of about 40–50% in NO$_2$ and an increase of 5–10% in tropospheric O$_3$ during lockdown. However, it should be noted that the changes in tropospheric O$_3$ and total column ozone will be different in these conditions and are not directly comparable.

### 3.6 Limitation of the Study

There is a significant number of studies on lockdown related air quality changes, but we have selected only O$_3$ and NO$_2$ for analysis here for comparison. In addition, since satellite and ground-based measurements are not directly comparable, a separate discussion is presented for the two analyses. However, qualitative comparison is possible in such instances to mutually cross-check the validity and accuracy of the measurements (e.g., both data show increase in O$_3$ and decrease in NO$_2$ during the lockdown). Therefore, caution must be practiced during the comparison studies on these trace gases for lockdown and unlock periods.

### 4 Conclusions

As an impact of COVID-19 pandemic, most outdoor human activities were restricted in India from 25 March to 31 May 2020. As a result, the anthropogenic pollution was substantially reduced during the lockdown. In order to quantify this reduction in pollution levels, we have analyzed the NO$_2$ and O$_3$ concentrations over India during the lockdown. Since the beginning of March, most Indian cities show a reduction in NO$_2$ with up to 15% in Kolkata, Lucknow and Chennai compared to respective concentrations in the previous year. An increase in tropospheric O$_3$ (5–10%) is also observed in most cities and regions together with the reduction in NO$_2$. A similar range of difference for these trace gases has also been observed in other parts of the world. The lockdown restrictions were subsequently lifted off in four phases, from 1 June to 31 September. Consequently, the air pollution again reached comparable levels to those during the same period of the previous years or in the pre-lockdown period. This study, therefore, reports the variability in tropospheric concentrations of O$_3$ and NO$_2$ with respect to graded contributions of anthropogenic sources during various phases of lockdown and unlock periods. Our analyses provide ideas to curb pollution in India and adopt appropriate measures. The reciprocal change in O$_3$ and NO$_2$ during lockdown further cautions that the regulations in particular sectors would not help to control pollution, and careful planning is needed for any pollution control measure and policy-level decision.

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**Author Contribution** GK: Methodology, Software, Validation, Formal analysis, Investigation, Data Curation, Visualization, Writing – Original Draft. JK: Conceptualization, Methodology, Validation, Formal
Data Availability  The data used in the article are available on https://www.temis.nl/index.php, https://developers.google.com/earthengine/datasets/catalog/COPERNICUS_S5P_OFFL_L3_NO2?hl=en, https://app.cpebcr.com/ccc/#/caaqm-dashboard-all/caaqm-landing and https://acd-ext.gsfc.nasa.gov/Data_services/cloud_slice/new_data.html

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