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COVID-19 lockdown and its impact on tropospheric NO_2 concentrations over India using satellite-based data

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ABSTRACT

The World Health Organization has declared the COVID-19 pandemic a global public health emergency. Many countries of the world, including India, closed their borders and imposed a nationwide lockdown. In India, the lockdown was declared on March 24 for 21 days (March 25–April 14, 2020) and was later extended until May 3, 2020. During the lockdown, all major anthropogenic activities, which contribute to atmospheric pollution (such as industries, vehicles, and businesses), were restricted. The current study examines the impact of the lockdown on tropospheric NO_2 concentrations. Satellite-based ozone monitoring instrument sensor data were analyzed in order to investigate the variations in tropospheric NO_2 concentrations. The results showed that from March 1 to 21, 2020, the average tropospheric NO_2 concentration was 214.4 $\times 10^{13}$ molecule cm^{-2} over India, and it subsequently decreased by 12.1% over the next four weeks. An increase of 0.8% in tropospheric NO_2 concentrations was observed for the same period in 2019 and hence, the reduced tropospheric NO_2 concentrations can be attributed to restricted anthropogenic activities during the lockdown. In the absence of significant activities, the contribution of various sources was estimated, and the emissions from biomass burning were identified as a major source of tropospheric NO_2 during the lockdown. The findings of this study provide an opportunity to understand the mechanism of tropospheric NO_2 emissions over India, in order to improve air quality modeling and management strategies.

1. Introduction

Coronavirus disease 2019 (COVID-19) is a declared pandemic of the 21st century (WHO, 2020). It was initially identified in Wuhan in December 2019 as a pneumonia of unknown origin (Chen et al., 2020). The peculiarity of COVID-19 is that it is spread through droplets, and has spread rapidly across the community (Wang et al., 2020a; Malik et al., 2020). The outbreak of COVID-19 has led many countries to shut their borders and impose a nationwide lockdown. In India, the lockdown was declared on March 24 for 21 days (March 25–April 14, 2020), but as the numbers of newly confirmed infections and deaths due to COVID-19 continued to escalate, the lockdown was extended for 19 days (April 15–May 3, 2020).

Due to the COVID-19 lockdown, anthropogenic industrial, vehicular, and other commercial energy-consuming activities were restricted (Jain and Sharma, 2020). Recent studies using ground-based monitoring data have reported significant changes in pollutants during India's lockdown. The concentrations of particulate matter with aerodynamic diameters of less than 10 and 2.5 μm (PM_{10} and $PM_{2.5}$, respectively), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and carbon monoxide (CO) declined significantly, whereas the trend of ozone (O_3) varied in different regions of the country (Sharma et al., 2020; Jain and Sharma, 2020; Mahato et al., 2020; Chauhan and Singh, 2020). Various studies have reported that vehicular, industrial, and thermal power plant emissions contribute significantly to atmospheric pollution loads, including gaseous pollutants (Van Vuuren et al., 2017; Ravindra et al., 2016; Fan et al., 2020; Zhang et al., 2019; Zhao et al., 2019, Singh et al., 2020a). Furthermore, as highlighted by Zhao et al. (2018), the secondary formation and fast growth of fine aerosols also contribute to the atmospheric pollution load at urban locations. In addition, solid biomass burning, crop residue burning, and forest fires also contribute significantly to atmospheric emissions in India (Ravindra et al., 2020; Singh et al., 2020b, c; Beig et al., 2020; Badarinath et al., 2007).

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Oxides of nitrogen (NOx) such as nitric oxide (NO) and NO_2, play a crucial role in tropospheric pollution chemistry and climate change. The primary source of NOx is the combustion process, which significantly contributes to anthropogenic NOx emissions. Simultaneously, emissions from the biosphere, lightning, and biomass burning contribute lower amount of NOx (Solomon et al., 2007; Venkataraman et al., 2006). The severe threat of lung infection at high exposure to NO_2 (World Health Organization, 2003; Schraufnagel et al., 2019) means that NO_2 is listed by the Central Pollution Control Board as a criteria pollutant (which cause environmental and health impacts) under the Indian National Ambient Air Quality Standards (Gurjar et al., 2016). Garg et al. (2001) identified the transportation sector in India as one of the primary contributors of NOx emissions (32%), followed by the power generation sector (28%), industry (21%), and biomass burning (19%).

In addition to ground-based point observations, satellite-based remote sensing provides spatial vertical tropospheric column density (VCD), which is the vertical integral of the tropospheric NO_2 concentrations measured in molecule cm^{-2} (Krotkov et al., 2017; Hilboll et al., 2017; Ghude et al., 2013a, 2013b). Zheng et al. (2018) used the observations of the Ozone Monitoring Instrument (OMI) to study the spatial-temporal distribution of NO_2 and highlighted the impact of anthropogenic activities on varying NO_2 trends. The NO_2 VCD has a strong and characteristically structured electronic, vibrational rotational, ultraviolet, and visible spectra, which is easily observed in polluted areas (Hilboll et al., 2017). Therefore, during the COVID-19 lockdown, the change in NO_2 concentrations can be studied using satellite-based measurement datasets because of spatio-temporal coverage.

The impact of the lockdown on tropospheric NO_2 concentrations has been reported by some studies across some regions of the world. A study conducted by Xu et al. (2020) showed that NO_2 concentrations were 35.6% lower in three cities (Wuhan, Jingmen, and Enshi) in China during February and March 2020 compared to the same period in 2017–2019, and similar findings were also reported by Zheng et al. (2018). During the lockdown period, a 25.5% decline in surface NO_2 concentrations was reported by Berman and Ebisu (2020) in the United States, and the two large cities Madrid and Barcelona in Spain showed reductions of 62% and 50%, respectively (Baldasano, 2020). Similar results are reported by Krecl et al. (2020) for the megacity of São Paulo, Brazil, where NO_2 concentrations declined by 34–68%. In India, several studies reported that restricted human activities during lockdown resulted in a significant reduction in surface NO_2 emissions in Indian cities and megacities (Mor et al., 2020; Jain and Sharma, 2020; Singh et al., 2020d). NO_2 measured by the Tropospheric Monitoring Instrument on the Sentinel-5 satellite of the ESA showed a 30% reduction in tropospheric NO_2 concentrations across Chinese cities (NASA, 2020; Dutheil et al., 2020). The OMI on NASA's Aura satellite data also showed similar observations (NASA, 2020). The reduction was attributed to reduced industrial and commercial activities, and restricted vehicular movements. However, there was no linear correlation observed by Wang et al. (2020b) between emissions reduction and a decline in pollution concentrations.

In this study, open-source, satellite-based NO_2 VCD data were used to understand the impact of the COVID-19 lockdown on the behavior of tropospheric NO_2 concentrations over India. In the absence of major anthropogenic activities, the contribution of biomass burning was also examined to apportion its contribution to NO_2 emissions. The tropospheric NO_2 concentrations observed during the lockdown were also compared with datasets of the previous year to validate scientific interpretation and support air pollution management, including inputs for air quality modeling.

2. Methodology

For comparison, a seven week period was selected, from March 1 to April 18, 2020, and the matching period in 2019. The weeks were counted from March 1 to March 7, 2020, and so on. For the entire study duration, weeks 4–7 were the lockdown weeks, and weeks 1–3 were the pre-lockdown weeks. The tropospheric VCDs of weekly averaged NO_2 measured by the NASA Aura satellite OMI sensor at 0.25° spatial resolution over India were obtained from an open-access data portal (GIOVANNI). The data were processed by masking for the Indian administrative boundary, and the concentration differences for the lockdown weeks (4–7) were computed. For fire counts, VIIRS (Visible Infrared Imaging Radiometer Suite) data were downloaded from FIRMS (Fire Information for Resource Management System) open access data sources for the durations described (FIRMS, 2020). The administrative level (called states in India) tropospheric NO_2, and VIIRS fire data were computed by summing the spatially collocated grids within an administrative boundary using geographical information system software.

3. Results and discussion

3.1. Spatial distribution of tropospheric NO_2 concentrations over India

The tropospheric NO_2 concentrations were studied over India before, and during, the lockdown period. The average tropospheric NO_2 level during the three weeks before the lockdown (March 1–21, 2020), was 214.4 $\times 10^{13}$ molecule cm^{-2}, and decreased by 12.7%, 13.7%, 15.9%, and 6.1% during the subsequent weeks. The maximum reduction was observed during the third week after the lockdown. Table 1 shows the spatially averaged tropospheric NO_2 concentrations over India, and Figure 1 indicates the spatial distribution of tropospheric NO_2 concentrations over India before, and during, the lockdown period. The decline in tropospheric NO_2 concentrations was also compared for the same duration in 2019 (Table 2).

The average tropospheric NO_2 concentrations during lockdown reveal a 12.1% reduction. However, in 2019, there was a 0.8% increase in tropospheric NO_2 concentrations over India during the same period. The results indicate that restrictions on major anthropogenic activities resulted in the reduction of NO_2 levels. The mean tropospheric NO_2 concentration over all of 2019 in India was 206 .87$\times 10^{13}$ molecule cm^{-2}. During the lockdown, the recorded tropospheric NO_2 concentration was 189.52 $\times 10^{13}$ molecule cm^{-2}, whereas for the same period in 2019, the concentration was 225.64 $\times 10^{13}$ molecule cm^{-2}. However, Ul-Haq et al. (2015) reported that in South Asia, including India, there was a significant decadal increase of 14% in NO_2, and an estimated average tropospheric NO_2 concentration of 100.0 $\pm$ 0.05 $\times$ 10^{13} molecule/cm^2, over the region. Using satellite data over India, an increasing annual trend of tropospheric NO_2 concentrations was also reported by Ramachandran et al. (2013). The authors explained tropospheric NO_2 distribution over India and identified NO_2 hotpots, which mainly lie over urban areas, and thermal power plants.

Hilboll et al. (2017) also noted that in India, NO_2 pollution is strongly influenced by the type of economic activities and development, and reported an annual NO_2 increase of 4.4%. Similarly, Ghude et al. (2013a, b) estimated 1.9 TgN/yr of NOx emissions from India. During the lockdown, although transportation and industrial activities were restricted, power generation and biomass burning remained active, adding to the atmospheric NO_2 emissions.

Ghude et al. (2008) also identified thermal power plants and industrial zones as major NO_2 emissions hotspots over India. The current study observed a decrease in tropospheric NO_2 concentrations, but it was not as high as that of atmospheric particulate matter (PM_{10} and $PM_{2.5}$). For example, approximately 43% and 18% declines in $PM_{2.5}$, and NO_2 concentrations, respectively, were reported by Sharma et al. (2020). In South Asia, Rana et al. (2018) reported that the variability of tropospheric NO_2 was found to be significantly associated with aerosol optical depth (AOD), and meteorological parameters such as temperature. A positive correlation between tropospheric vertical columnar NO_2 and AOD over many megacities of India, and its association with an increase in urbanization and industrialization, were reported by Ul-Haq et al. (2017).

In comparison to atmospheric particles, the relatively lower NO_2 reduction could be due to household emissions, including biomass

Table 1. Columnar NO_2 concentration over India before and during lockdown period.

Time period (1 March 2020–18 April 2020)	Columnar NO_2 concentration $\times 10^{13}$ (molecule cm^{-2})	Percentage reduction during the lockdown period from average columnar NO_2 concentration before lockdown
Before Lockdown		
Before Lockdown Week-1	215.7 ± 128.5	
Before Lockdown Week-2	194.9 ± 136.2	
Before Lockdown Week-3	236.2 ± 178.9	
During lockdown		
During lockdown Week-1	188.2 ± 119.5	12.7 %
During lockdown Week-2	186.0 ± 118.4	13.7 %
During lockdown Week-3	181.4 ± 108.5	15.9 %
During lockdown Week-4	202.5 ± 119.8	6.1 %

be significant. This was observed for the National Capital Territory (NCT) of Delhi (-66%).

3.1.1. Distribution of tropospheric NO_2 concentrations at administrative levels

The columnar NO_2 concentrations over India at administrative levels during the lockdown period in 2020, and the corresponding period in 2019, are depicted in Table 3. In 2019, the highest average columnar NO_2 concentrations were observed over the NCT of Delhi (653.3×10^{13} molecule cm^{-2}), followed by Chhattisgarh, West Bengal, Jharkhand, and Mizoram, with 438.5, 388.6, 385.3, and 364.5 $\times10^{13}$ molecule cm^{-2}, respectively. During the lockdown period, tropospheric NO_2 concentrations in these states declined by 65.9%, 23.5%, 15.4%, 20.9%, and 33.3%, respectively. The highest reduction in the NCT of Delhi may be due to a reduction in vehicular emissions, which is the major pollutant source in this region, whereas other regions have thermal power plants that burn coal as raw material. In the north-eastern states of India,

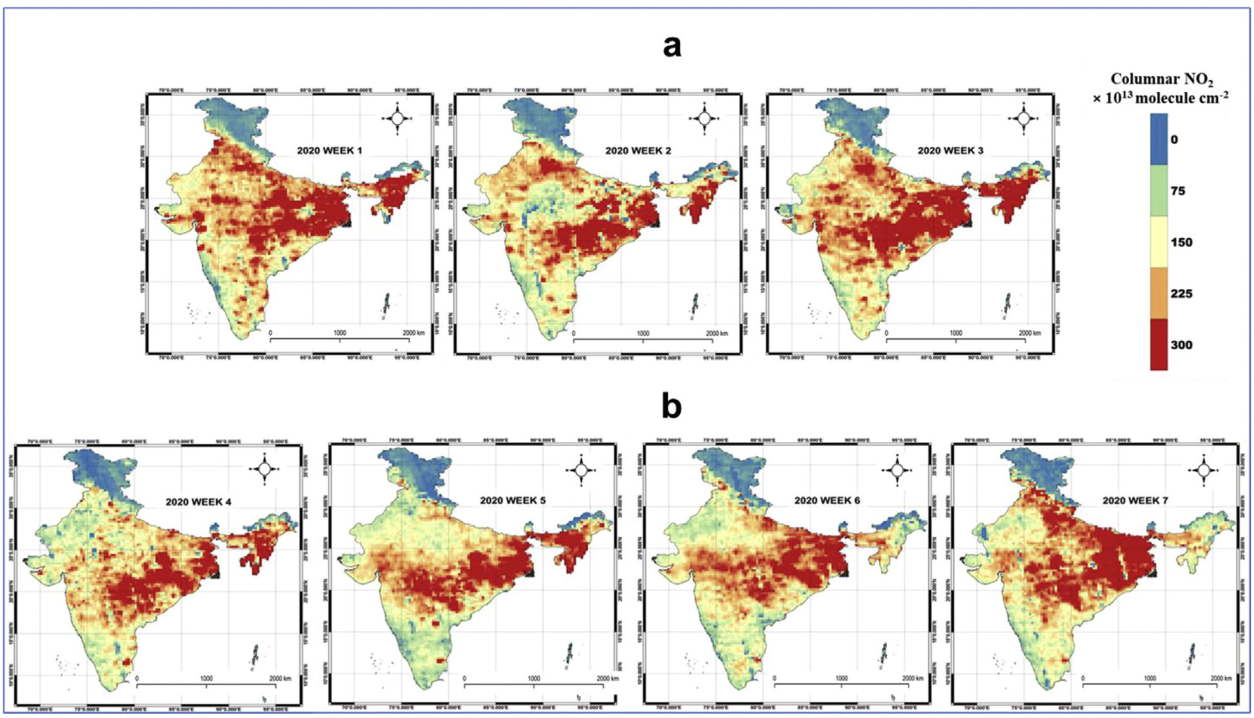

Figure 1. Spatial distribution of columnar NO_2 concentration over India before (a) and during (b) the COVID-19 lockdown period.

Table 2. Comparison of NO_2 concentrations over India before and during lockdown with previous year concentrations.

Time period (1 March 2020–18 April 2020)	Columnar NO_2 concentration $\times10^{13}$ (molecule cm^{-2})		Columnar NO_2 compared to 2019 (increase/decrease) %
	2020	2019	
Week-1	215.7 ± 128.5	198.4 ± 141.9	+8.8
Week-2	194.9 ± 136.2	224.9 ± 151.5	-13.4
Week-3	236.2 ± 178.9	247.8 ± 168.7	-4.7
Week-4	188.2 ± 119.5	228.6 ± 161.9	-17.6
Week-5	186.0 ± 118.4	245.3 ± 163.5	-24.2
Week-6	181.4 ± 108.5	209.5 ± 121.2	-13.4
Week-7	202.5 ± 119.8	219.0 ± 125.2	-7.5

burning (Targino et al., 2013, 2019; Sidhu et al., 2017; Chowdhury et al., 2018), because this remained active in India during the lockdown. Correspondingly, NO_2 has a short lifetime and a high dispersion rate in the atmosphere during the summer (Val Martin et al., 2008). Furthermore, it should be noted that reductions are lower because they are spatially averaged over India and therefore, city-specific reductions could

including Mizoram, forest fires often occur in this season, and can be the source of higher NO_2 emissions. Other states that show major reductions are situated in the Indo-Gangetic Plain region with Haryana (39.2%), Himachal Pradesh (37.6%), Punjab (36.9%), Uttarakhand (22%), and Uttar Pradesh (20%). In contrast to the effect of the lockdown on air pollution reduction in many regions, the columnar NO_2 concentrations

Table 3. Columnar NO_2 concentration over India during the lockdown period in 2020 and the matching period in 2019 along with percentage change.

State	Columnar NO_2 concentration$\times10^{13}$ (molecule cm^{-2}) 2019	Columnar NO_2 concentration$\times10^{13}$ (molecule cm^{-2}) 2020	Percentage change (%)
NCT of Delhi	653.3	222.9	-65.9
Puducherry	290.5	176.6	-39.2
Haryana	243.5	148.1	-39.2
Himachal Pradesh	112.5	70.3	-37.6
Punjab	247.3	156.0	-36.9
Mizoram	364.5	243.1	-33.3
Andhra Pradesh	201.1	139.2	-30.8
Karnataka	176.7	129.3	-26.8
Chhattisgarh	438.5	335.3	-23.5
Uttarakhand	153.6	119.9	-22.0
Telangana	284.0	223.3	-21.4
Jharkhand	385.3	304.7	-20.9
Uttar Pradesh	275.3	220.1	-20.0
Dadara & Nagar Havelli	181.7	148.7	-18.1
Goa	100.3	83.0	-17.3
Nagaland	227.3	189.7	-16.5
Odisha	334.9	282.0	-15.8
Maharashtra	259.1	218.8	-15.5
West Bengal	388.6	328.6	-15.4
Kerala	110.7	95.5	-13.7
Bihar	331.8	286.4	-13.7
Tamil Nadu	155.4	134.8	-13.3
Daman & Diu	148.7	132.4	-11.0
Arunachal Pradesh	109.2	98.1	-10.2
Tripura	302.6	273.1	-9.7
Manipur	324.3	292.8	-9.7
Madhya Pradesh	242.4	220.8	-8.9
Rajasthan	150.9	140.6	-6.9
Sikkim	44.7	46.3	+3.7
Gujarat	164.3	172.1	+4.7
Jammu & Kashmir	76.3	80.6	+5.6
Assam	228.2	243.4	+6.6
Meghalaya	218.6	234.9	+7.5
Andamans and Nicobars	30.7	37.5	+22.0
Ladakh	15.3	21.3	+39.1

over Gujarat, Jammu and Kashmir, Ladakh, Sikkim, Assam, Meghalaya, and the Andaman and Nicobar Islands showed a net percentage increase. The increase in tropospheric NO_2 concentrations over Gujarat may be due to large petroleum refineries, whereas in the northeast states, it may be due to forest fires. In contrast, the increase in tropospheric NO_2 concentrations in the Jammu and Kashmir region could be due to detection anomalies over the snow covered region. Despite decline in 2020, the elevated columnar NO_2 concentrations of $>300\ \times10^{13}$ molecule cm^{-2} over Chhattisgarh, Jharkhand, and West Bengal may be due to the continuous operation of thermal power plants in these regions.

3.2. Biomass burning over India and its association with NO_2 concentrations

Massive biomass burning events that mainly included forest fires, were observed during the study period across India. These biomass burning events were primarily identified over central and southeastern India. Figure 2 shows the spatial distribution of fire counts over India before, and during, the lockdown period to demonstrate the impact of emissions from these biomass burning events. Tables 4 and 5 show the fire counts and fire radiative power (FRP) over India during the study period, compared with the same period in 2019. Week 2 of the lockdown shows maximum fire counts (37051), followed by week 4. The estimated fire counts in 2019 during the study period were higher than those in 2020, but the FRP was observed to be relatively higher in 2020.

This study found that due to biomass burning, the net reduction in tropospheric NO_2 emissions was compromised during the lockdown period. Ghude et al. (2008) also reported great variations in tropospheric NO_2 concentrations in India during the summer and winters, because significant biomass and crop residue burning activities take place during these seasons (Ravindra et al., 2019a,b). Their study reported that during the summer season, increased tropospheric NO_2 concentrations are mainly due to biomass burning, and partially due to soil emissions.

Figure 3 depicts the percentage reduction in tropospheric NO_2 concentrations over India before, and during, the lockdown period. It can be inferred that in locations where biomass burning was more frequent, no significant reduction in tropospheric NO_2 concentrations was observed. When comparing satellite-based NO_2 with ground data for northeast India, Ghude et al. (2013a, b) estimated that the peak biomass burning period accounted for an average NO_2 flux of 1.55×10^{11} molecules cm^{-2} s^{-1}. Figure 4 shows the correlation between fire count and FRP with columnar NO_2 over India in the lockdown period, and the corresponding period in 2019. In 2019, the Pearson's correlation coefficient between fire count and columnar NO_2 concentrations was $r = 0.32$, whereas that

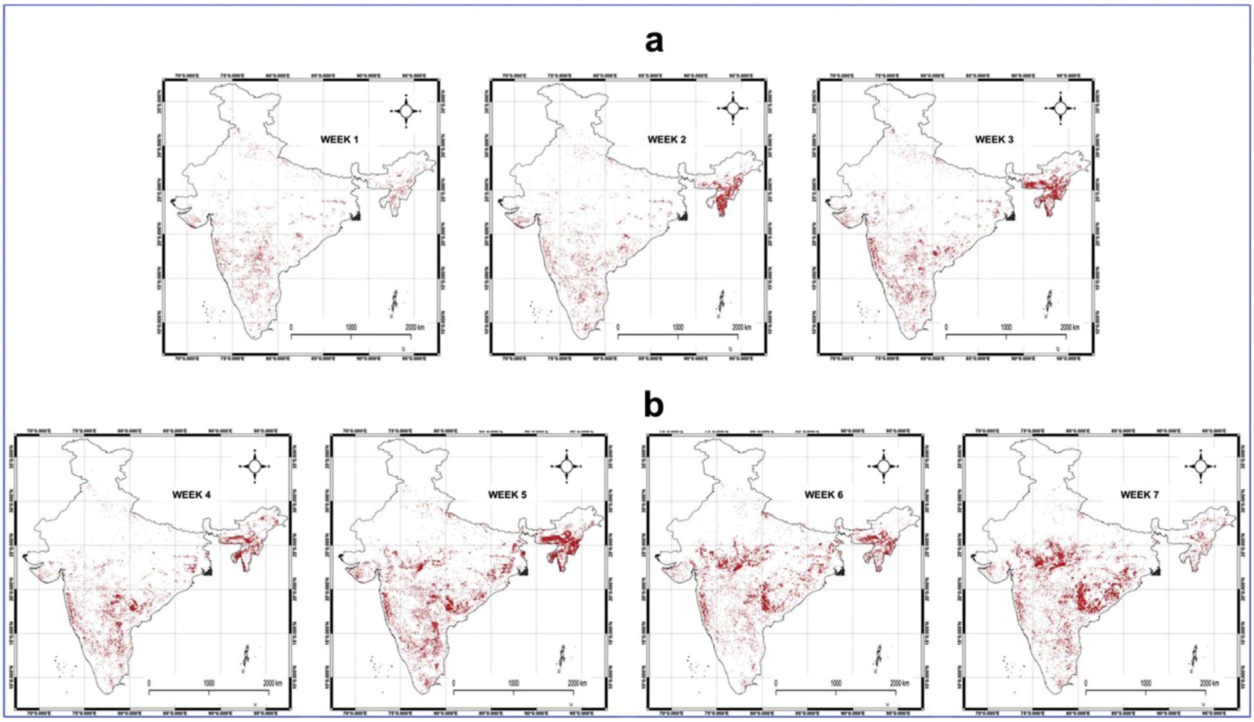

Figure 2. Spatial distribution of Fire counts over India before (a) and during (b) the COVID-19 lockdown period.

Table 4. Fire counts and fire radiative power (FRP) over India during the study period.

Study Period (1st March – 18th April 2020)	Fire counts	FRP (MW)
Before Lockdown		
Before Lockdown Week-1	6661	39904.7
Before Lockdown Week-2	13360	346149.5
Before Lockdown Week-3	19405	269819.4
During lockdown		
During lockdown Week-1	19003	200400.8
During lockdown Week-2	37051	305118.5
During lockdown Week-3	26020	155986.9
During lockdown Week-4	32887	207487.9

Table 5. Comparison of Fire counts and fire radiative power (FRP) over India with the previous year.

	2020		2019	
	Fire counts	FRP (MW)	Fire counts	FRP (MW)
Before Lockdown Week-1	6661	39904.7	10473	44581.7
Before Lockdown Week-2	13360	346149.5	19845	178936
Before Lockdown Week-3	19405	269819.4	27334	293068.2
During lockdown Week-1	19003	200400.8	35415	390719.6
During lockdown Week-2	37051	305118.5	38122	252788.5
During lockdown Week-3	26020	155986.9	26029	153087.8
During lockdown Week-4	32887	207487.9	28028	198128.4
Total	**154387**	**1524867.7**	**185246**	**1511310**

between FRP and columnar NO_2 concentrations was $r = 0.31$. In contrast, during the lockdown period in 2020, a strong correlation between columnar NO_2 concentrations with fire count ($r = 0.50$) and FRP ($r = 0.45$) was observed. The strong correlation indicates that during the lockdown period, biomass burning played a significant role in elevating NO_2 levels over certain regions in India.

3.3. Reduction in NO_2 concentrations during the lockdown and implications for better air quality strategies

As highlighted in several studies, fossil fuel and biomass burning, including crop residue burning, are the primary sources of NO_2 emissions in India (Ghude et al., 2008, 2013a,b; Ravindra et al., 2019a,b, 2020; Gurjar et al., 2016; Rana et al., 2019; Sembhi et al., 2020). NO_2 plays a significant role in atmospheric chemistry and reactivity, and the chemical budget of tropospheric ozone largely depends on NOx concentrations (Van der et al., 2008). A reduction in the NO_2 concentration during the lockdown period provides an opportunity to understand the contribution of various sources in the absence of primary anthropogenic emission sources.

Livestock activities are prominent in India (Aneja et al., 2012), and the lockdown also provides an opportunity to explore the role of NO_2 in ammonia neutralization. Furthermore, the role of NO_2 in the formation of secondary aerosols could be examined during this season (Zhao et al., 2018). Atmospheric photochemistry also plays a significant role in the development of secondary pollutants (Li et al., 2018). An average 12.1% decrease in tropospheric NO_2 concentrations was observed during the lockdown. In contrast, during the same period in 2019, an increase of 0.8% was observed in tropospheric NO_2 concentrations. However, emissions from natural (forest fire) and additional anthropogenic activities such as crop residue burning and household solid biomass fuel uses, were common during the same period.

By restricting the precursors of secondary aerosols through proper planning, and following specific measures such as short lockdowns, it may be possible to achieve the goals of the National Clean Air Programme, which aims to reduce the pollution concentrations over India by 20–30%. Integrated countrywide policy and the implementation of strategies are required to reduce air pollution and improve human health and the environment.

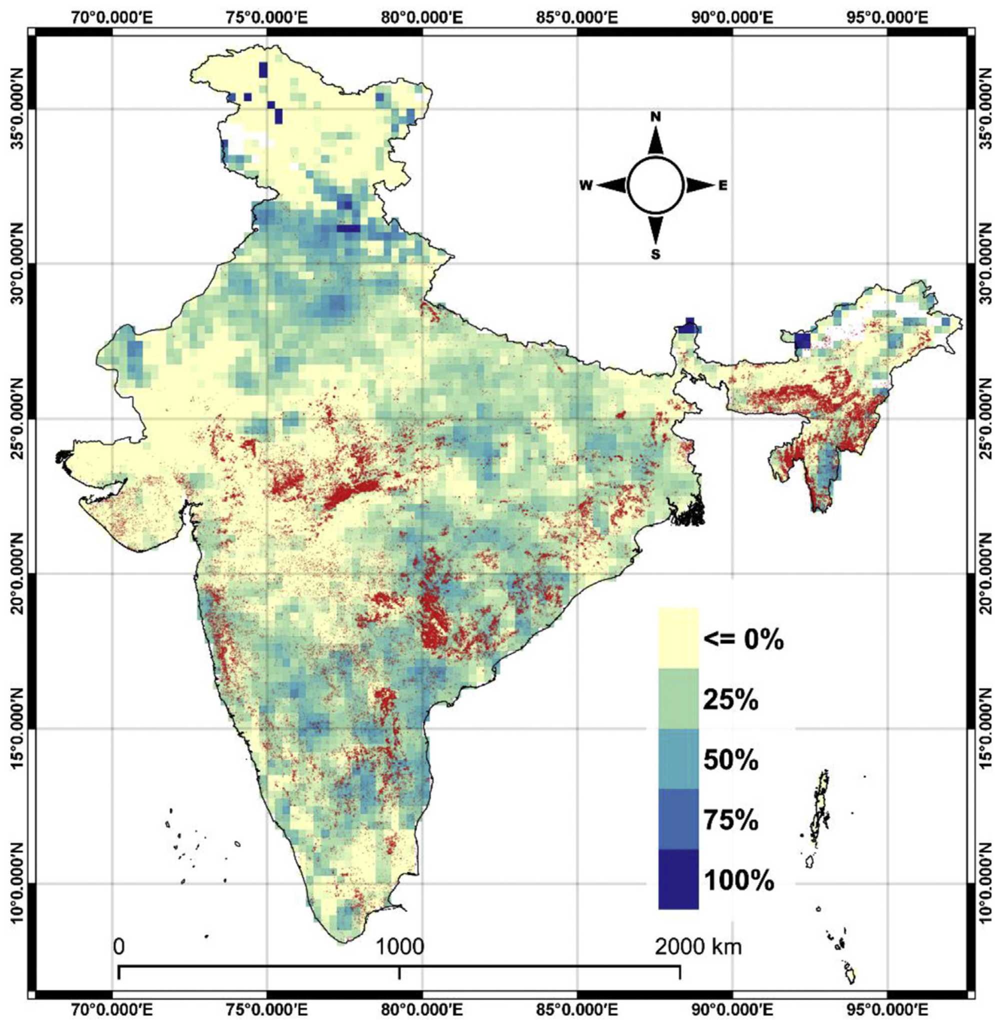

Figure 3. Percentage reduction in columnar NO_2 during 2020 lockdown period over India.

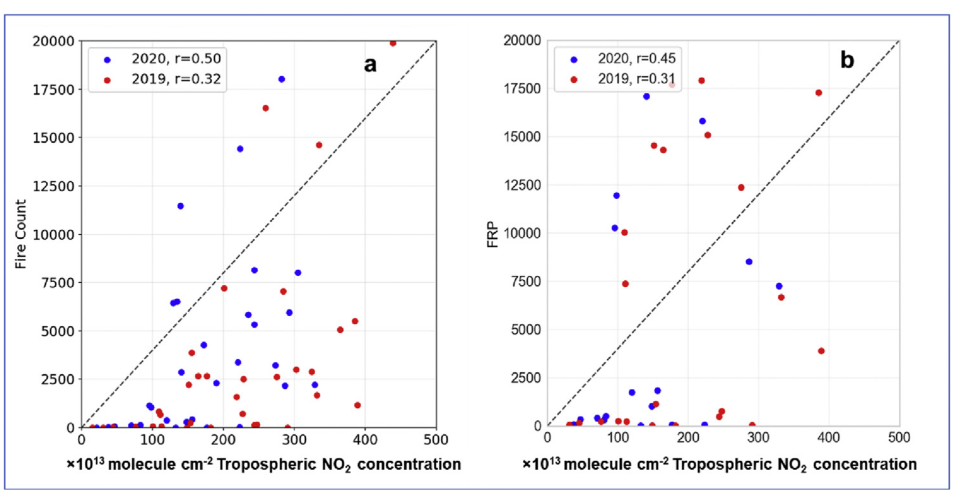

Figure 4. Spatial correlation between fire count (a) and fire radiative power (b) with columnar NO_2 concentration$\times 10^{13}$ molecule cm^{-2} for lockdown period in the year 2020 and the matching period in the year 2019 over India.

4. Conclusions

This study examined the impact of the COVID-19 lockdown on the concentration of tropospheric NO_2 over India. The results showed that before lockdown, the average tropospheric NO_2 concentration over India was 214.4 molecule cm^{-2} $\times 10^{13}$, which decreased by 12.7%, 13.7%, 15.9%, and 6.1% during consecutive weeks after lockdown commenced. The average tropospheric NO_2 concentration after lockdown showed a

12.1% reduction over India, whereas there was an increase of 0.8% in the previous year during the same period. In the absence of major emission activities, the effect of biomass burning was examined, which revealed that it was a significant source of NO_2 emissions during the lockdown. The net reduction in tropospheric NO_2 emissions could be observed during the lockdown period. The study demonstrated how the tropospheric NO_2 emissions varied across India owing to the restriction of major anthropogenic activities. The findings of the current study could help in planning better air pollution reduction strategies and improving air quality modeling and forecasting for the betterment of health and the environment.

Declarations

Author contribution statement

Akash Biswal, Tanbir Singh, Vikas Singh: Analyzed and interpreted the data; Wrote the paper.

Khaiwal Ravindra, Suman Mor: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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