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Spatiotemporal changes in tropospheric nitrogen dioxide hotspot due to emission switch-off condition in the view of lockdown emergency in India

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Abstract
The COVID-19 outbreak has elicited forced lockdown conditions for all anthropogenic emissions across the globe. It has brought an opportunity for the researchers to sort out the relative contribution of the environmental pollutants which are emerged from the coal-based thermal power plants and other industrial sectors. In countries like India, some industrial sectors and thermal power plants coexist; henceforth, they mutually produce NO_2 concentration canopy in the upper atmosphere in raised form. Focusing on this issue, the present work intends to explore the NO_2 emission hot-spots' foci using switch-off conditions in consequence of emergency lockdown. Our results indicate that stable (CV_{low} and NO2 $_{max}$) and large NO_2 concentration canopy is noticeable in the inter-state border areas among Chhattisgarh, Bihar, Madhya Pradesh, and Jharkhand (around "Govind Ballabh Part Sagar" reservoir) where a cluster of thermal power plant is located. The "OFF" situation also proposes a close correspondence between the NO_2 richness column and installed capacity (R^2 value > 0.7 with 0.0002 p value). States that are situated in the eastern part of the country and megacities like Delhi and Kolkata represent a crucial role in NO_2 emission while in certain regions of south India are more or less safe from NO_2 emission. As a consequence, the lockdown has created a temporary pollution baseline for tropospheric NO_2 that offers research prospects to think of alternate sources of energy that can maintain environmental health as well as human well-being.

Keywords Sentinel 5P · NO_2 emission hotspot · Thermal power plants · Switch-off conditions · Pollution baseline

Introduction

In the contemporary era, the rising air pollution has created foremost concern across the globe, especially in developing countries (Fang et al. 2009; Pathakoti et al. 2020). According to the world's urbanization prospects (2018), the urban population of Asia and Africa will rapidly increase about 90% by 2050. Presently, air quality monitoring and prediction are the key challenges especially in the megacities that are deteriorating the environment, ecosystem, ambient air quality, and human health (Shams et al. 2020, 2021a). In India, air pollution is one of the leading health risk factors (Cohen et al. 2017) that is getting worsen day by day due to rapid urbanization, population growth, industrialization, economic development, extensive use of fossil fuels, and uncontrolled burning of residuals from numerous materials (Maiti and Agrawal, 2005). The NO_2 along with some other trace gases form one of the significant families of air-polluting chemical compounds (Shams et al. 2021b). Recently, those gases and their various sources are point of attention for the researchers which need to be examined thoroughly such as their concentration level in the troposphere. Nitric oxide (NO) and nitrogen dioxide (NO_2), generalized as nitrogen oxides (NO_x), play a crucial role in the composition of the Earth's atmosphere (Crutzen, 1979), and this trace gas deteriorated the stratospheric ozone layer by photochemical reactions (Noxon, 1978). Nitrogen dioxide can have a deleterious impact on human health also, specifically the induction of respiratory diseases like lung infections, wheezing, coughing, colds, flu, bronchitis, asthma,

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and many other heart diseases (Dominici et al., 2006; Hansel et al., 2016; Xie and Zhu 2020). A higher concentration of nitrogen dioxide leads to acid rain, photochemical smog, and nitrate aerosol which adversely affect the formation of ozone (Ghude et al., 2008; Liu et al., 2021). Most of the leading NO_2 emission point and non-point sources are ground-based while lightning and aircrafts are the sources in the upper atmosphere (Beck et al., 1992). Global emissions of NO_x are predominantly due to human interference (e.g., fossil fuel combustion and biomass burning), while a slight amount of NO_2 gases enter the atmosphere by natural ways like lightning, microbiological process in soils (soil nitrification and de-nitrification) and wildfires (Fu et al., 2020; Pathakoti et al., 2020). The NO_2 emitted from the ground-based point or non-point sources cannot persist longer time in the lower atmosphere due to air turbulence, lower air convergence, and finally NO_2 rises in the upper atmosphere and forms canopy or tropospheric column.

The inventory made by Garg et al. (2001) shows that several emission point sources of NO_2 in India belong to the industrial sectors (50%), various non-point sources, especially the transportation sector (32%) and several biomass burning sectors (10–20%). The power plants are the major sources of NO_2 in India, and it is estimated that almost 0.5 Gg of NO_2 is added per day to meet the demand for 100 GW energy (Ramachandran et al., 2013). Coal-burning in thermal power plants and for domestic purposes are the key sources of air pollution in India (Gao et al. 2018; GBD MAPS Working Group n.d, 2018). Not only in India, but in other developing countries as well, coal is the foremost priority to generate energy because of its easy availability and relatively cheaper than other energy sources (Guttikunda and Jawahar, 2014). India is the third largest electricity producing country (Bedi and Toshniwal, 2021), wherein the primary sources are the coal-based thermal plants, renewable energy sources, and nuclear power plants contributing 2,03,190 MW (51.7%), 1,51,391 MW (38.5%), and 6780 MW (1.7%) of electricity respectively (Ministry of Power, Govt. of India, 2021). Most of the thermal power plants (TPPs) use second standard bituminous coal, while other TPPs use lignite and soft brown coal; all these kinds of coal contain high moisture (Man et al. 2015). After burning such kinds of coal, TPPs release large amount of particulate matter, trace gases (SO_2, NO_2, CO_2, CO), and volatile organic compounds, which degrade the atmospheric quality and lead to global warming (Saw et al. 2021). Recent studies (Li et al. 2017; Qu et al. 2019) envisages that ambient air pollutants in India have drastically increased by 50% since 2007, a large portion of which was released by the TPPs. In this context, the Indian government imposed National Clean Air Programme (NCAP, 2019), 5-year action strategy in 2019 to reduce the nationwide concentration of particulate matter by 30%.

In India, the first case of COVID-19 was confirmed on January 30, 2020, in Kerala (PIB, 2020), and on May 3 in India, the affected cases of COVID-19 reached 39,980 with the number death of 1301 (Das and Dutta, 2021). To break the chain and make an end to the propagation of the virus, most of the countries imposed lockdown. In India, nationwide lockdown started from March 24, 2020, to April 14, 2020, and extended twice from May 3, 2020, to May 17, 2020, and from May 31, 2020 (Mahato et al. 2020; Kumar et al. 2020). The COVID-19 lockdown enforced the entire world to entail self-isolation reducing personal movement, outdoor activities, and forcefully shutting down most of the economic sectors. Such kind of global actions mitigate the COVID-19 pandemic situation helped to heal the environmental pollution ailments temporarily. Kumar et al. (2020) and Gautam et al. (2021) refer to this situation as "switch off condition" in their research. Considering the argument, the current research intends to appraise the relative contribution of the coal-based thermal plants on NO_2 concentration due to pre- and amid-lockdown situation, that created "ON/OFF" conditions for the emissions, that aim to (i) reveal a holistic picture of spatio-temporal NO_2 richness concentration both the "ON–OFF" situations over the India, (ii) to identify the stable NO_2 hot spot zone, and finally (iii) to explore potential reasons for the concentration changes in different phases of the selected megacities within the various concentric zones. To quantify relative role in NO_2 emission for different sources are difficult as well as impossible in a normal situation. But nature fortunately (in the perspective of the researchers) offered a chance (in COVID-19 lockdown situation) to measure single role in NO_2 emission.

Materials and methods

The installed monitoring stations (ground-based) are insufficient to represent entire nation for the proper observations of the air quality and pollution dispersion. Disparities exist in the geographical distribution of ground-based monitoring stations (Ramachandran et al. 2013); hence, the available station data are unable to provide the scenario for the entire country. To overcome this problem, we have used satellite images (sentinel-5) instead of ground-based data. Satellite data provides the best coverage across the continent uniformly and simultaneously in a recurring temporal frequency. Due to the short lifetime of NO_2 in the troposphere from hours to days (Lange et al. 2021) and the inhomogeneous distribution of the emission sources, the spatial and temporal distributions of NO_2 vary strongly. For the daily monitoring of atmospheric potentially harmful trace gases such as NO_2, O_3, formaldehyde, SO_2, methane, CO, and aerosol, Sentinel-5 Precursor (Sentinel-5 P) satellite has been launched on October 13, 2017. The on-board spectrometer called TOPOMI (TROPOspheric Monitoring Instrument) measures ultraviolet earthshine radiance at high spectral range with finer spatial resolution in comparison to Ozone Monitoring Instrument (Shikwambana et al. 2020). Due to fluctuating behavior of NO_2 existence in the upper atmosphere, a single image is not enough to adequately represent the proper status. Rather, the level of NO_2 concentration within a certain period can be measured using time series sentinel-5P data.

In this study, we have used TROPOMI NO_2 vertical column product offline data (version 1.03.02) that provides daily global coverage with spatial resolution of 7×3.5 km^2 (Vigouroux et al. 2020). The entire Sentinel 5P product archive is now freely accessible via the Copernicus Open Access Data Hub, which provides calibrated data from its nadir-viewing spectrometer measuring reflected sunlight in the ultraviolet and visible band from 270 to 500 nm, in the NIR from 675 to 775 nm and in the SWIR band from 2305 to 2385 nm (Veefkind et al. 2012).

The TROPOMI NO_2 vertical column data have been processed using the Scientific Exploitation of Operational Missions (SEOM) open-source toolbox and then transferred into ArcGIS environment. Afterward, weekly means of NO_2 abundances have been calculated for each pixel within the study domain. We have selected only four fresh images instead of daily data due to inherent instrumental error and weather disturbances such as lightning and cloud cover for the few weeks. Accordingly, for the better comparison and standardization, we have obliged to consider the same number of images in 9-week periods that are selected from February 25 to April 27 of 2020 (Table 1).

To identify the larger stable emission patches, we have used daily data of tropospheric NO_2 column density instead of weekly average. For each pixel, richness of NO_2 and coefficient of variation (CV) values (Eq. 1) are calculated by converting all the daily raster images into point vectors. The point CV values have been equally classified into two classes, i.e., maximum and minimum for respective points which have been used to prepare logic-based segmentation (Table 2).

$$CV = \frac{sd}{\text{mean NO2}} \times 100 \quad (1)$$

To identify the most polluted megacity in terms of fossil fuel combustion due to power generation, we have also prepared a composite box plot that demonstrates NO_2 variability from the arbitrary city center to the fringe zone. For that purpose, five concentric circles with 10 km spacing have been drawn for the four large urban agglomerations viz. Delhi, Mumbai, Chennai, and Kolkata.

Results and discussion

Spatio-temporal change of NO_2 concentration

Spatio-temporal concentration of NO_2 (weakly mean tropospheric column) during pre- and amid-lockdown situation for the different phases are shown in Fig. 1. Here, we have considered the pre-lockdown situation as a reference period

Table 1 List of the Sentinel-5P images used in this study

Sl. no		Date of capture			Date of capture	
1	Pre- lockdown	25–02-2020	25–02-20 to 02–03-20	Amid-lockdown	24–03-2020	24–03-20 to 30–03-20 (1st week)
2		28–02-2020			25–03-2020	
3		29–02-2020			26–03-2020	
4		01–03-2020			28–03-2020	
5		03–03-2020	03–03-20 to 09–03-20		31–03-2020	31–03-20 to 06–04-20 (2nd week)
6		08–03-2020			01–04-2020	
7		06–03-2020			03–04-2020	
8		09–03-2020			04–04-2020	
9		11–03-2020	10–03-20 to 16–03-20		07–04-2020	07–04-20 to 13–04-20 (3rd week)
10		12–03-2020			09–04-2020	
11		13–03-2020			11–04-2020	
12		14–03-2020			13–04-2020	
13		17–03-2020	17–03-20 to 23–03-20		14–04-2020	14–04-20 to 20–04-20 (4th week)
14		18–03-2020			17–04-2020	
15		21–03-2020			18–04-2020	
16		23–03-2020			19–04-2020	
17					21–04-2020	21–04-20 to 27–04-20 (5th week)
18					23–04-2020	
19					24–04-2020	
20					25–04-2020	

Table 2 Point segmentation has been performed by applying the following expressions

Sl. no	Degree of consistency	Logical expression	Decision
1	Stable patch	CV_{low} and $NO2_{max}$	Consistent emission sources: especially thermal power plants, and various industries
2	Stable patch	CV_{low} and $NO2_{min}$	Rural areas
3	Zone of variability	CV_{high} and $NO2_{max}$	Large urban area, lightning, agricultural burning, fire destroys, and brick-kiln industry
4	Zone of variability	CV_{high} and $NO2_{min}$	Small-town, small-scale industry etc

instead of the corresponding time of previous year owing to the fact that during the interval some units of a thermal power plants may have been re-opened and closed according to the demand of electricity.

During the pre-lockdown phases, most of the rich NO_2 concentration foci were observed in the north-eastern coal mining region, eastern part of India, national capital region, upper parts of Chhattisgarh and Odisha states, around the "Govind Ballav Sagar" reservoir, and Mumbai-Gujarat industrial region. On an account, the aforementioned areas have plummeted the levels of NO_2 by 35–45% as per analysis in "OFF" situation. In north-eastern region, relatively high NO_2 concentration was observed during lockdown situation due to regional atmospheric conditions (Ramachandran et al. 2013) as well as some seasonal factors (Pathakoti et al. 2020) which prolonged the persistency of NO_2 in the upper atmosphere. In an attempt to comprehend the reason behind varying NO_2 concentration across the nation, we have explored the regional distribution of coal-based TPPs and other NO_2 emission point sources.

With the help of NO_2 richness maps (Fig. 1) and distribution of the emission point sources (Fig. 2), we have attempted to examine which nitrogen concentrations foci are associated with what kind of nitrogen producing cradles. It is quite noticeable that NO_2-rich foci are spatially well associated with the location of point source emission center of all kinds while association merely persist with the location of TPPs during lockdown phases. The most notable correlation exists (during "OFF" situation) over the vast zones of Indo-Gangetic plain, where the coal-based TPPs are relatively of greater capacity and densely clustered compared to the other regions of the India. On the other hand, Mumbai and Gujarat industrial region witnessed relatively poor association. Ghude et al. (2008) ascertained that transport sector plays a key role in NO_2 emission in comparison to industrial sectors in the western part of the country. Similarly, in the coastal-humid area of Mumbai and Gujarat, photolysis reaction is highly active and it reduces the prolonged existence of NO_2 in the atmosphere. Our findings are also in consentient with the aforementioned explanation. In some places, thermal power plants and other NO_2 producing point sources work concurrently to make nitrogen richness canopies and, in some cases, work individually. All industries and transportation sectors (except: ambulances, medicine, and essential goods carrying vehicles) were closed during the amid lockdown period, but only thermal power plants were functioning to meet the minimum demand of electricity required for the household and other daily needs. As a result, three different scenarios emerged:

i. During pre- and amid-change assessment, substantial changes in NO_2 concentration patches (in terms of areal expansion and richness) have been observed in those places where other NO_2 producing point sources are playing the crucial role. In "OFF" situation, the areal expansion of the NO_2 richness patches became smaller or in some cases disappeared due to the shutdown of leading emission point sources except thermal plants. In the national capital region, various industries are located but coal-based TPPs do not exist in the centre and middle parts of the megacity. Hence, in "OFF" situation, all types of NO_2 emission point sources were closed in Delhi as a consequence NO_2 concentration level is highly plummeted (49%) compared to reference period.

ii. We could not observe the mark changes in canopies expansion in those places where the thermal power plants are playing sole role in the production of NO_2. Instead, in some cases, radii of the patches are somewhat reduced due to lowest ever demand of electricity in lockdown situation.

iii. It is worth mentioning that in some of the places where thermal power plants and other point sources are situated concurrently, they mutually produce nitrogen canopy. In those places, aerial extension of the canopies got reduced at the lockdown period from what existed in reference period since other point sources were close and some units of few thermal power plants were remained inactive during lockdown phases.

Figure 3 represents the distribution of emission hotspots with varying consistency level (see the Table 2) during both "ON" and "OFF" situations. In the pre-lockdown map, high concentrations of NO_2 were observed in the various patches

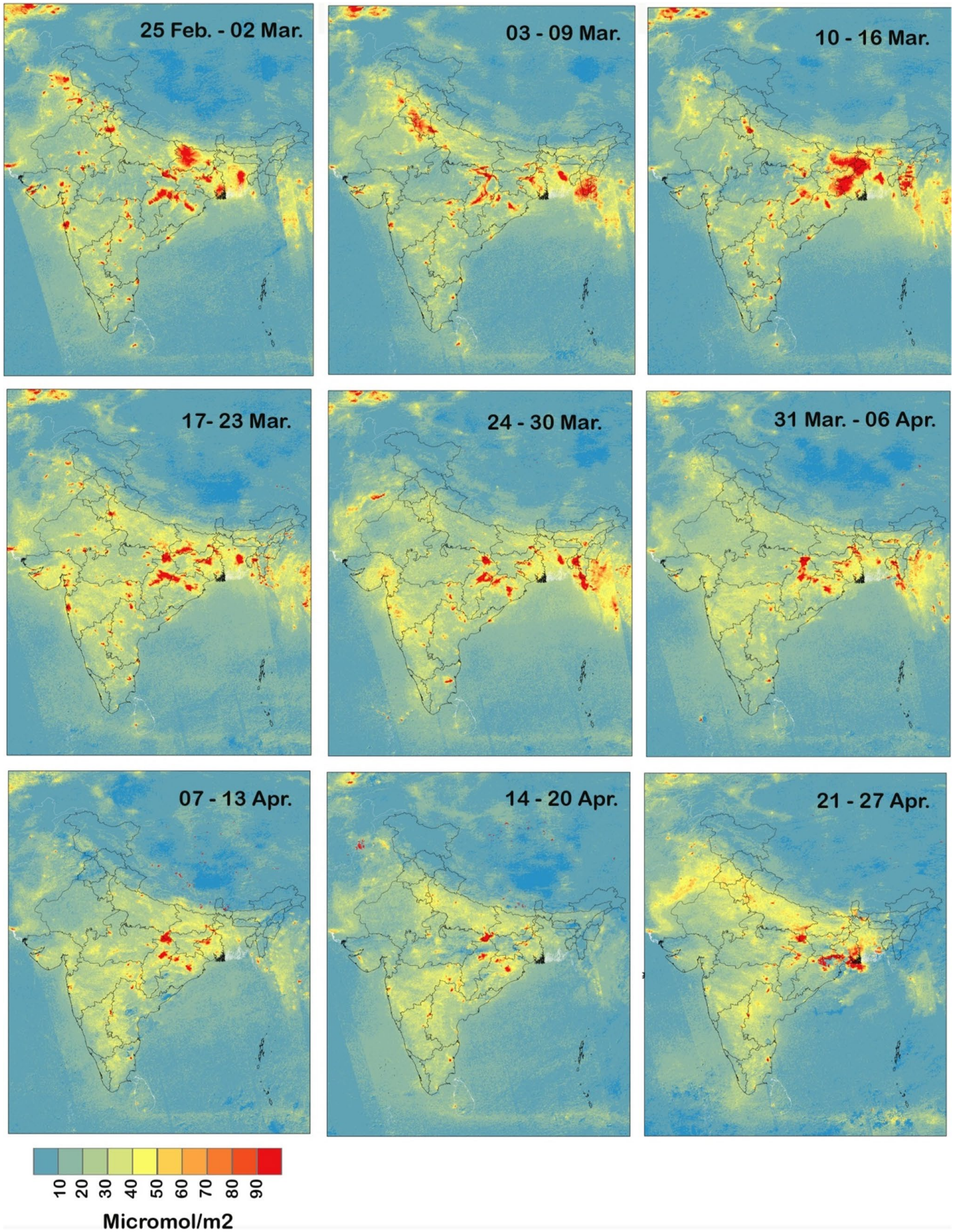


Fig. 1 Spatio-temporal NO_2 concentration variation (7-day interval mean)

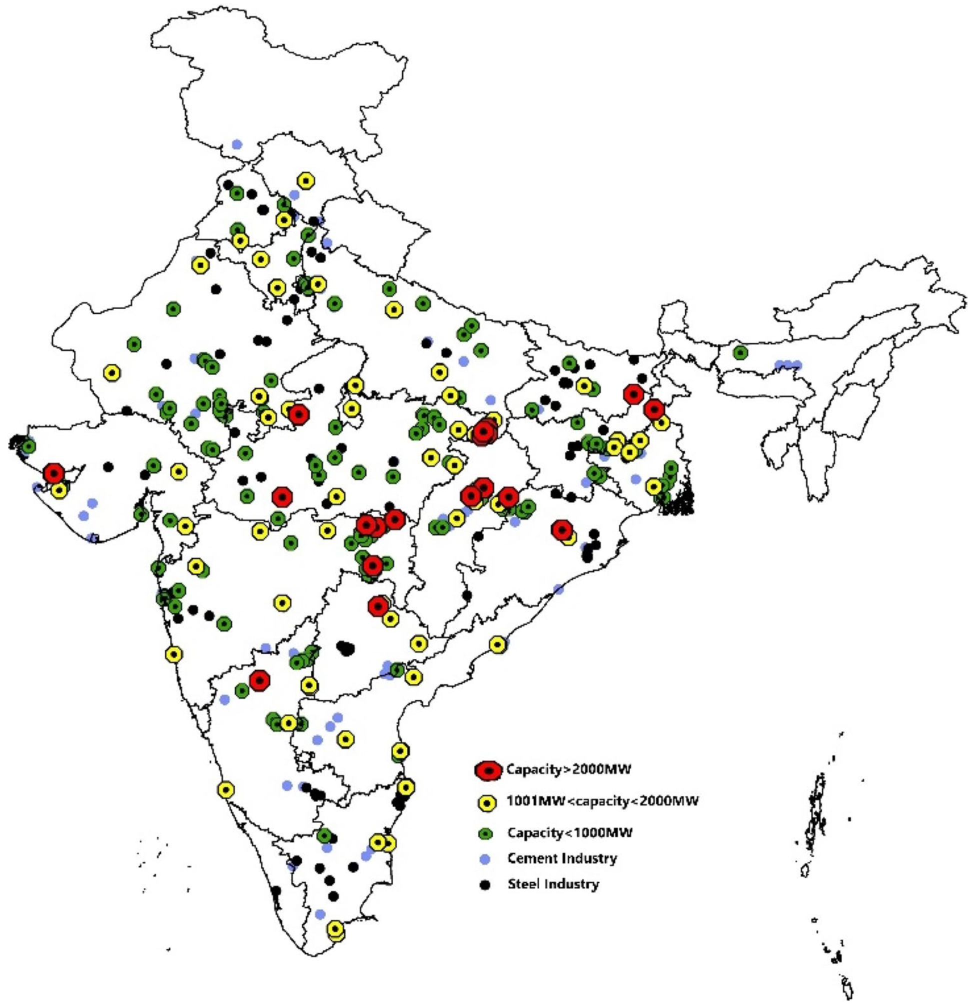


Fig. 2 The distribution of NO_2 emission point sources. The red, yellow, and green circles are showing the thermal power plants and their installed capacity (data accessed from global power plant database (2021)), while the purple and black dots represent the cement and steel industry, respectively (data accessed from Google Earth, 2021)

while amid-lockdown map shows their substantial reduction. Pre-lockdown hotspot map reveals that the most notable NO_2 stable patches (CV_{low} and $NO2_{max}$) are detected in the long stretches of Indo-Gangetic plain, Delhi; eastern coal mining region; Govind Ballav Sagar plant region; upper part of Chhattisgarh-Odisha region; and middle part of the Odisha state and Mumbai-Gujarat industrial region. All the patches witnessed the fact that consistent emission cradles may be TPPs or/and other industries. The stable patches formed just above any types of chimney of industrial plants as a canopy and variability zones are encompassed with it. These zones of variability (CV_{high} and $NO2_{min}$) are either formed by normal diffusion process from stable NO_2 patches or comes from urban areas, small-scale industries, etc. On the other hand, intense anthropogenic activities are the auxiliary factors for greater expansion of variable zone of NO_2 consistency (CV_{high} and $NO2_{max}$) in densely populated Indo-Gangetic plain. In this province, brick-kiln industry is the real culprit behind the rich emission during the months of March, April, and May. Here, agricultural activities are intense throughout the year especially from the January to May where malpractice of agricultural residue burning (Galanter et al. 2000) leads to sudden increase of NO_2 in the atmosphere. In addition, coal and wood burning for domestic cooking are common and regular practice across this zone that are identified being another minor source of NO_2 (Beig and Ali, 2006). During lockdown period, only three distinguishable stable hotspot zones were observed in Govind Ballav Sagar plant region, upper part of Chhattisgarh, and middle part of the Odisha. In the mentioned time frame, all kinds of commercial emission sources were shutdown except TPPs and that is why few patches are left behind as constant source, while other stable patches (viz. Delhi, Mumbai) were vanished totally.

To further analyze, Fig. 4 has been prepared, here we have tried to identify the most consistency and significant cluster zones of NO_2 richness where TPPs play primary role in NO_2 emission. Subsequently, we have created some clusters of TPPs and summed-up the potential electric generation capacity underneath all the significant NO_2 emission foci. To conduct this task, four noticeable NO_2 emission hotspot windows are drawn in the central and eastern parts

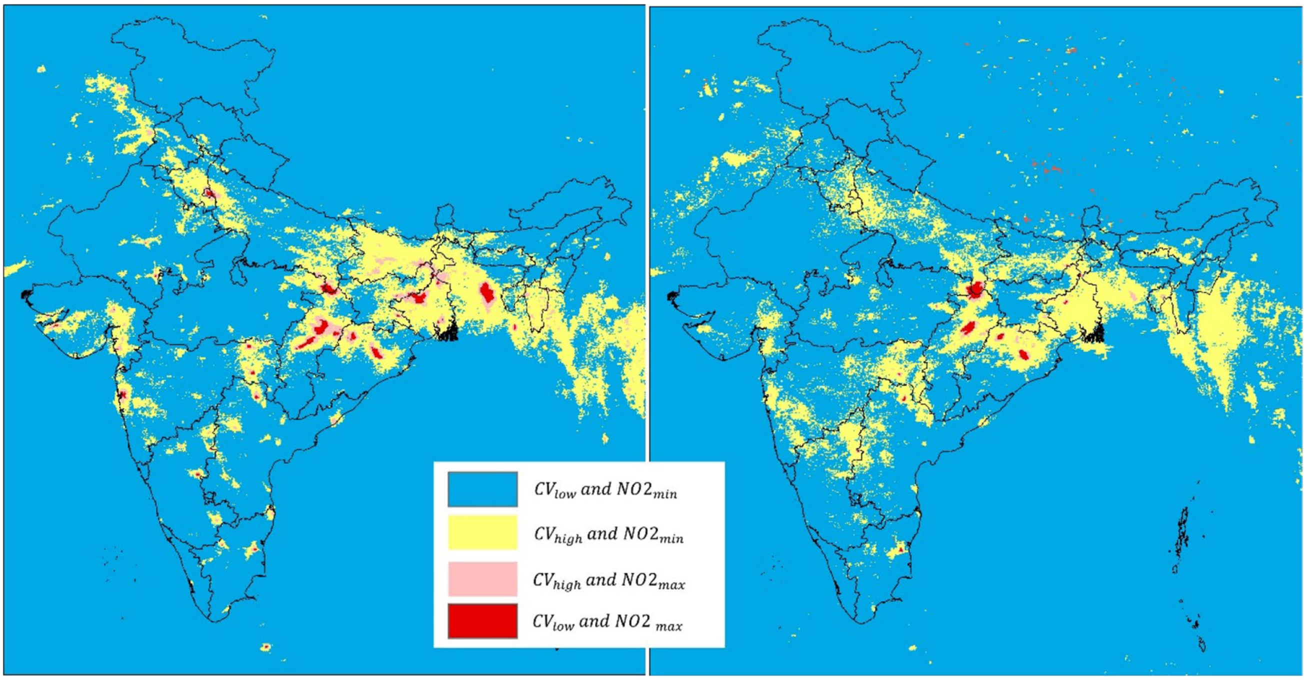


Fig. 3 NO_2 hotspot maps in "ON" and "OFF" situations

of India. The high NO_2 concentration with low CV connotes the consistency in NO_2 emission throughout pre- and amid-lockdown situations. That means thermal power plants were active before and after lockdown with minute vagaries. It is also observed that stable hotspot zones are located in the center part of each of the foci with reddish tone. The stables patches are formed as canopies that have been detected just above chimney of the plants and zones of variability are encircled with it where density of NO_2 decreases with increasing distance.

Window-a covered a part of West Bengal, Bihar, and the states of Jharkhand where the major plants are Crescent Power Limited (40 MW), Chinakuri Power Plant (47.8 MW), Durgapur Thermal Power Station (350 MW), etc. Window-b has been drawn in the inter-state border areas among the Chhattisgarh, Bihar, Madhya Pradesh, and Jharkhand. A thermal power plant cluster has been formed in this place around Govind Ballabh Part Sagar reservoir, where an elevated and consistent NO_2 concentration canopy is detected throughout the study period. Major thermal power plants viz. Uprvunl Anpara Thermal Power Plant (2630 MW), Obra Sonebhadra (1094 MW), Renusagar Thermal Power Plant (801.57 MW), Singrauli Super Thermal Station (2000 MW), Vindhyachal Super Thermal Power Station (4760 MW), and NTPC Rihand (3000 MW) coexist in this area. Window-c has been drawn between Odisha and Chhattisgarh state, where significant thermal power plants are placed viz. Vandana Thermal Power Plant (540 MW), Hasdeo Thermal Power Station (840 MW), Korba Thermal Power Plant (2600 MW), Dr. Shyama Prasad Mukherjee Thermal Power Station (500 MW), Hirakud Captive Power Plant (347.5 MW), Odisha Power Generation Corporation (1740 MW), and IB Thermal Power Station Central Park (1740 MW). In this window, middle portion is with relatively high NO_2 concentration. Window-d has been drawn in the central part of India; in this zone, NO_2 concentration is relatively low and comparatively safe.

Low NO_2 concentration with low CV means those places where emission always remains low. These zones are significantly safe in comparison with other zones. On the other hand, high NO_2 concentration corresponding to high CV value reveals that there was great variability in NO_2 concentration due to sudden industrial energy shutdown during "OFF" situation. The reason behind the scenario is the fact that NO_2 concentration was high in pre-lockdown but the substantial reduction happened in amid-lockdown. As a consequence, the radii of tropospheric NO_2 concentration foci have been reduced significantly. All the point and non-point sources have more or less remained closed, while thermal power plants were active during off situations, but some units were shut down owing to reduction of electric consumption during amid-lockdown. In India, leading NO_2 emission clusters are found in Window b and c. These two zones are gigantic NO_2 emission hotspot zones with the capacity of more than 2000 MW.

In order to comprehend the contribution of TPPs' to produce NO_2 concentration canopies in a more quantitative way, Table 3 has been prepared. To conduct this task, we

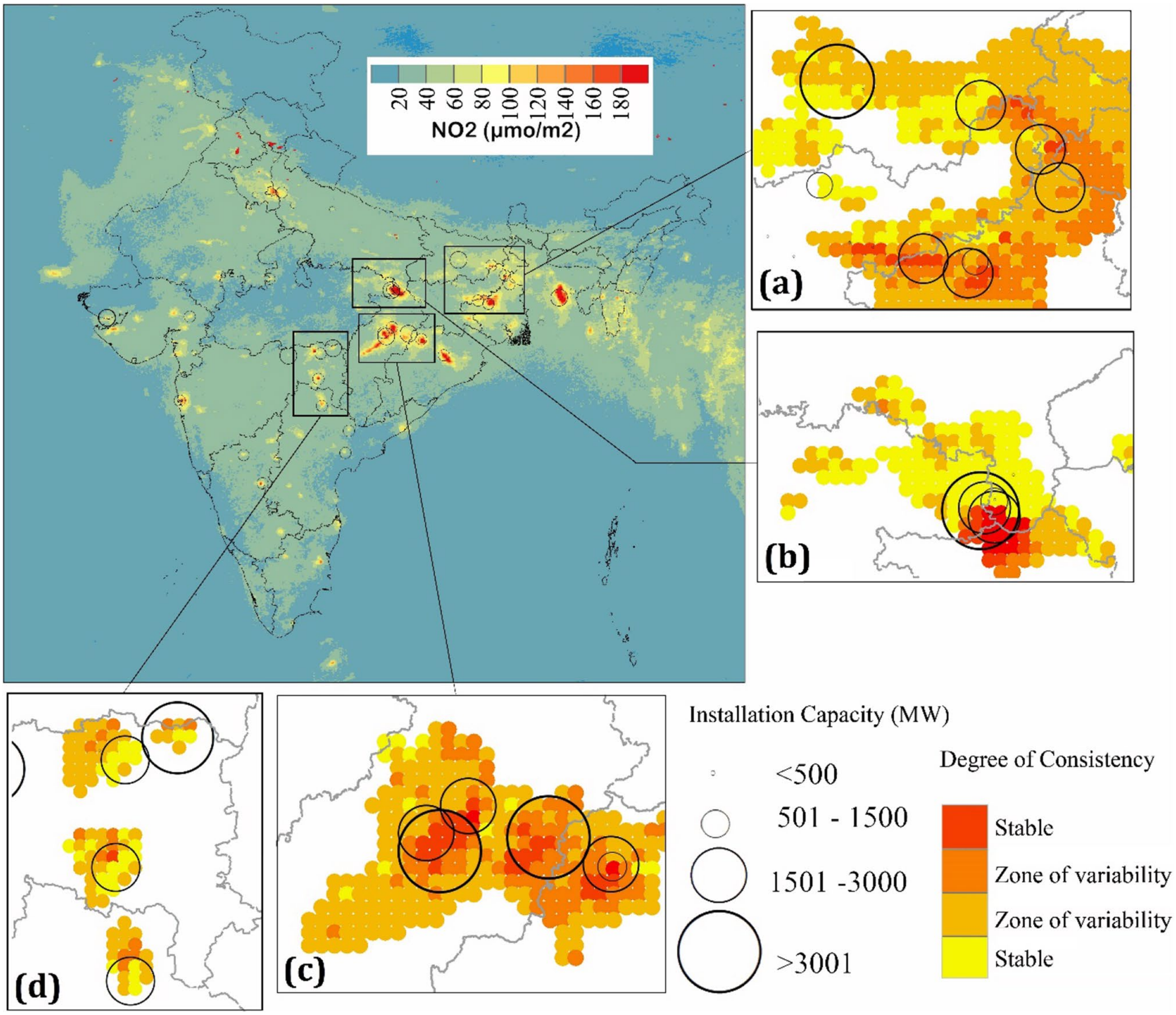


Fig. 4 Spatial association between stable NO_2 richness zone with thermal plant installation capacity in four different windows. (TPPs and their MW collected from Global Energy Observatory, 2018). Window-**a**, represent a part of West Bengal, Bihar, and Jharkhand; Window-**b**, has been drawn in the inter-state border among the Chhattisgarh, Bihar, Madhya Pradesh, and few part of Jharkhand; Window-**c**, has been drawn between Odisha and Chhattisgarh state and Window-**d** represent the central part of India

consider the stable zone (CV_{low} and $NO2_{max}$) of NO_2 consistency and potential electric generation capacity of the TPPs and executed the simple regression analysis. It is worthwhile to mention that in some areas where thermal plants were installed in a proximal location, are treated as TPP cluster, in that cases their total capacity has been considered. From the above table, two different scenarios have been emerged:

i) In "ON" situation, spatial correlation is high with greater *p*-value in comparison to "OFF" situation. This enlightens the fact that in this concerned time span, all kinds of emission point and non-point sources emitted NO_2. The sources other than TPPs amplified the NO_2 amount, and consequently, degree of relation is quite high and level of significance is poor.

ii) During "OFF" situation, spatial association is comparatively higher with better significance level. It is due to the factor that only TPPs played role in NO_2 emission in the concerned time span (see the Table 3).

In the eastern part of country, the greater value of co-efficient of determination (R^2) with higher level of significance reveals the good association between NO_2 emission levels with energy production capacity.

In Fig. 5, we have attempted to portray a holistic picture of NO_2 concentrations in 36 states of India during "ON–OFF" situation with the help of comparative stack bar. In this diagram, NO_2 concentration is divided into

Table 3 Temporal association between NO_2 concentrations level and potential electric generation capacity in some significant NO_2 richness patches observed in five provinces of India

	Regression	Eastern India	North India	South India	West India	Delhi
Pre-lockdown (ON) situation						
25 February to 02 March	Slope (b)	0.0265	0.0538	−0.0049	−0.0428	0.0014
	R^2	0.407	0.3818	0.2058	0.0943	0.0013
	p	0.061	0.0748	0.8874	0.9703	0.1238
03 March to 09 March	b	0.012	0.0348	−0.0517	−0.0028	−0.0125
	R^2	0.241	0.411	0.2005	0.0378	0.0519
	p	0.05	0.0843	0.1707	0.8012	0.5406
10 March to 16 March	b	0.0165	0.0324	−0.0558	0.0147	−0.0058
	R^2	0.3322	0.3738	0.2257	0.0843	0.0323
	p	0.0296	0.0259	0.1598	0.1990	0.5989
17 March to 23 March	b	0.0178	0.032	−0.1221	0.0239	0.0138
	R^2	0.3836	0.3284	0.1077	0.0645	0.0222
	p	0.0490	0.1239	0.0702	0.1274	0.1137
Amid-lockdown (OFF) situation						
1st week	Slope (b)	0.0436	0.0297	−0.065	−0.0028	0.0056
	R^2	0.7065	0.41	0.3218	0.0678	0.0751
	p	0.0004	0.04098	0.2112	0.4790	0.3663
2nd week	b	0.0398	0.0175	−0.0892	0.0012	0.0006
	R^2	0.5155	0.4509	0.3264	0.0832	0.0950
	p	0.0011	0.0256	0.2234	0.9158	0.4232
3rd week	b	0.0402	0.031	−0.0661	0.005	0.0022
	R^2	0.6232	0.5173	0.4951	0.1221	0.1002
	p	0.0002	0.0063	0.1111	0.5090	0.8902
4th week	b	0.0233	0.0248	−0.0706	−0.0059	0.0062
	R^2	0.482	0.3606	0.5062	0.1572	0.0373
	p	0.0032	0.0940	0.1127	0.2711	0.2407
5th week	b	0.0353	0.0345	−0.0485	−0.0077	−0.0049
	R^2	0.7188	0.5462	0.2647	0.1398	0.0908
	p	0.0006	0.0408	0.2551	0.3919	0.4066

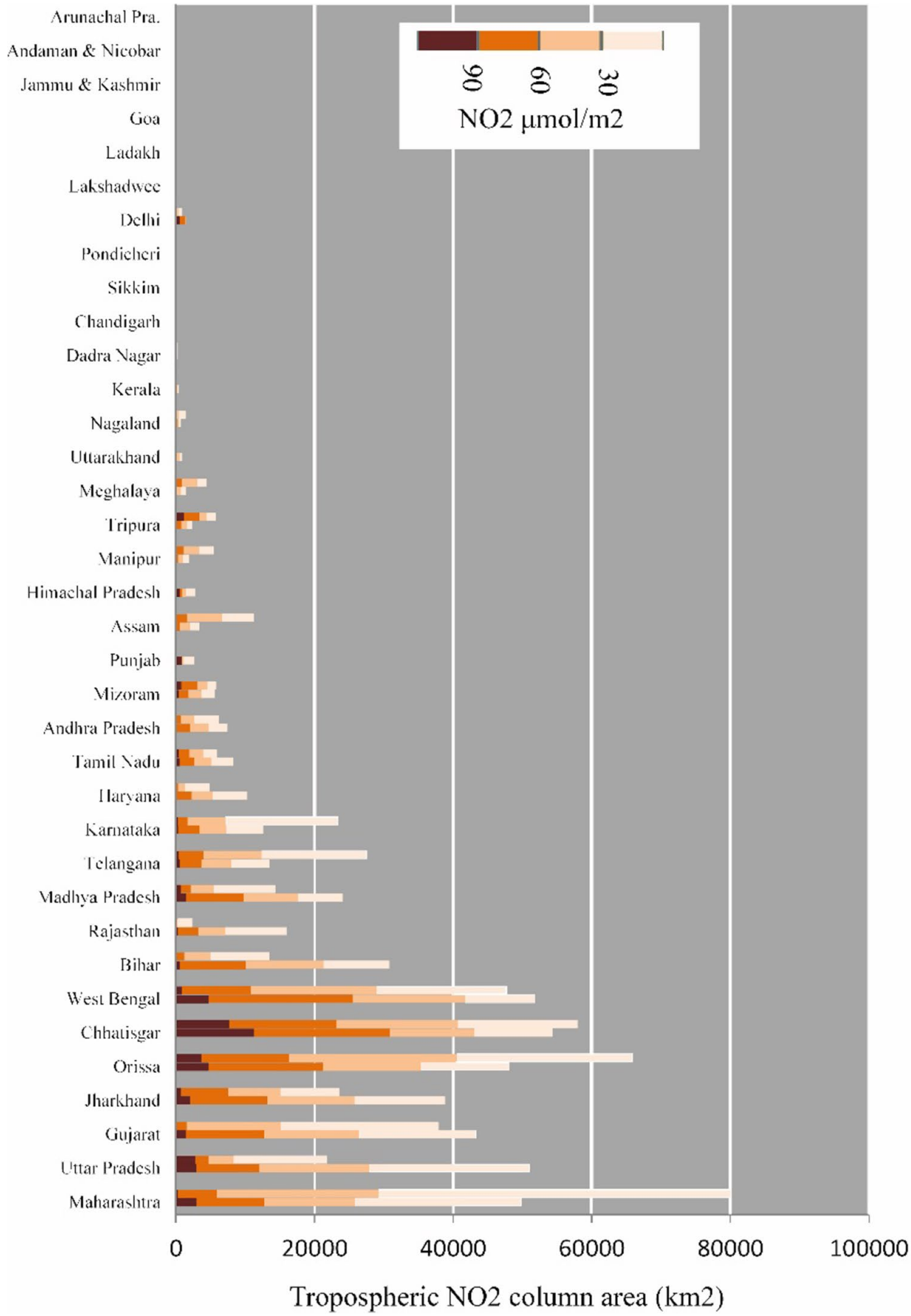
four consecutive classes or zones rendering their difference in richness, of which the first two consecutive zones (0–30 μmol/m^2 and 30–60 μmol/m^2) are ignorable. The rich zone of NO_2 (≥ 60 μmol /m^2) is decreased in each state during lockdown situation owing to reduced emission from the point and non-point sources except thermal power plants. The states situated in the eastern part of the country represent a crucial role in NO_2 emissions especially in West Bengal, Chhattisgarh, and Odisha, while the larger states at the northern and southern part of the territory are playing relatively insignificant roles.

In Fig. 6, we have tried to measure the difference of NO_2 richness in distinct concentric zones of the four major megacities of India during pre- and amid-lockdown situations with the help of box-plots. The global lockdown creates an “OFF” situation for anthropogenic pollution emission around the globe, and with this situation, the industrial and transportation sector went with the flow, whereas thermal power plants did not retain parity (Mahato et al. 2020; Pathakoti et al. 2020). Keeping the said fact in mind, we made a comparative assessment among the four megacities in which coal based thermal plants are located.

Delhi

In the case of most polluted city in India, Delhi (Krishan et al. 2019) has been identified as elevated NO_2 concentrations in each concentric zones during pre-lockdown situation than that in the amid-lockdown. An abrupt fall of NO_2 emission is observed in the zones up to 30 km after implementation of lockdown emergency. The reason behind this scenario is that all types of industries in those zones are completely closed and there are no TPPs located that could have contributed to the NO_2 emission. If we look outside (> 30 km), it is evident that the emission drops slightly owing to the complete shutdown of industrial sectors except the TPPs. Accordingly, from the above analysis, we may hypothesize that the other industrial sectors play a crucial role in pollution in comparison to TPPs in central part of Delhi.

Fig. 5 Statewise changes in various tropospheric NO_2 column intensity zones



Chennai

Chennai is comparatively one of the safe megacities in India in terms of pollution. Here, negligible emission is observed compared to that of the other megacities with minute variability between 10 and 30 km concentric circles. Correspondingly, weekly fluctuation in emission is negligible in the CBD relative to the outskirts. Therefore, it is obvious to conclude that TPP is located neither in the city heart nor in the periphery.

Kolkata

According to Rawat et al. (2019), Kolkata is the 2nd most polluted metropolis in India. In Kolkata, NO_2 emission abruptly falls within 0–20 km during "OFF" situation. Here, it is implicit that there are different types of industries located at the center of Kolkata, wherein we found one leading TPP, Titagarh Coal Power Station within 20 km periphery.

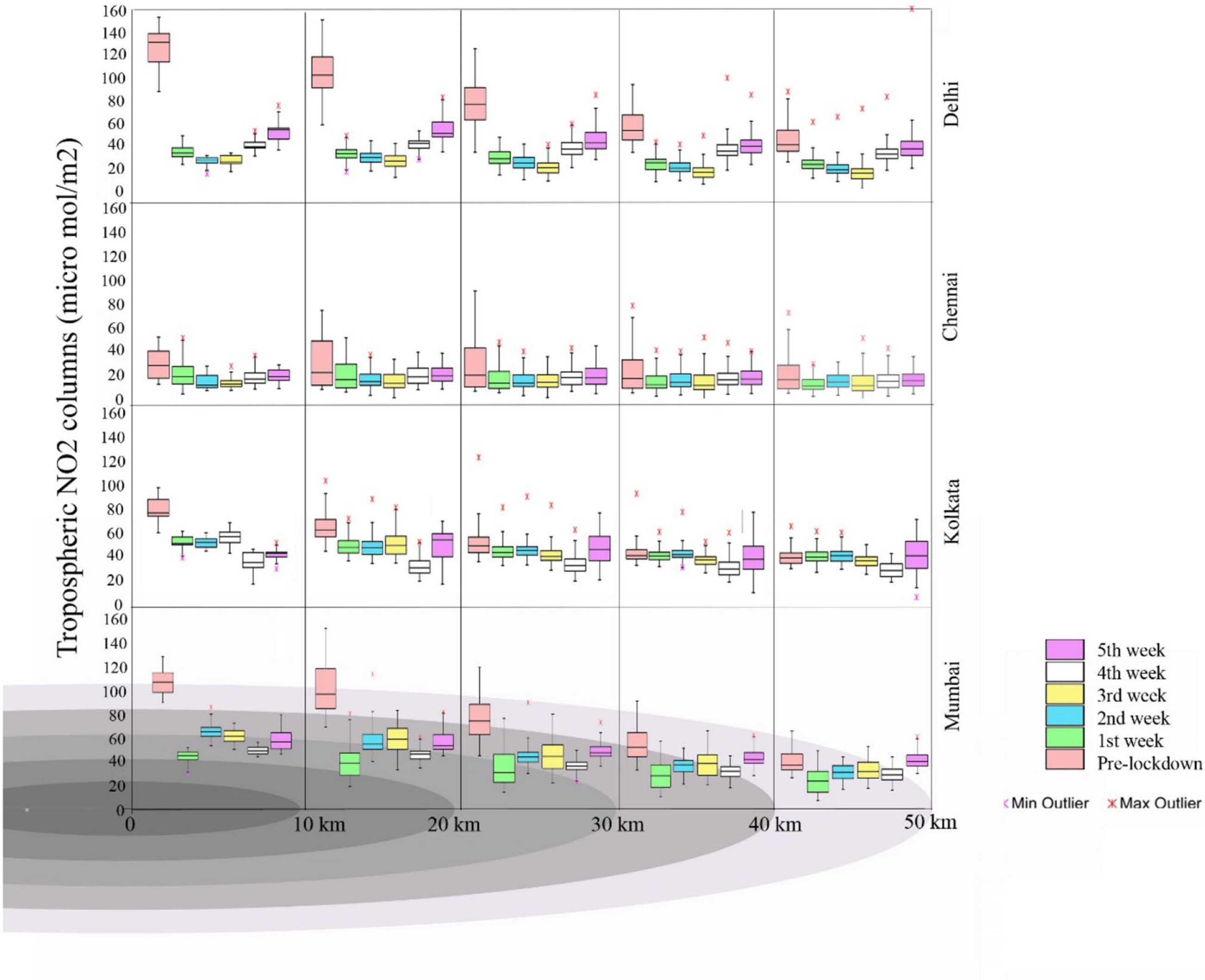


Fig. 6 Comparative box plot of NO_2 richness among four megacities in various concentric zones within 6 consecutive weeks

Mumbai

The high variability in NO_2 emissions is noticeable over all concentric circles with varying radii, in Mumbai. An abrupt change in emission has been observed during "OFF" situation within 30 km from the city center, while NO_2 emission has not decreased significantly in the outskirts of the city (> 30 km). From this scenario, it can be ascertained that few power plants are located at the city periphery.

Conclusion

In recent time, the prime minister of India had committed to achieve "net-zero emission" by 2070 at the COP26 summit in Glasgow, Scotland (BBC NEWS, 2021). The Indian government ensured that 50% energy would be generated from renewable energy sources by 2030 (The Economics Times, 2021). To achieve the "net-zero emission" goal, this study may accomplish the idea to recognize how much the role each sector plays in pollution emission. This paper may also help to distinguish the relative role of coal-based thermal plants in comparison to that of other NO_2 producing sectors. When other industrial sectors and TPPs are developed as coexistence, they mutually produce elevated NO_2 canopy at the upper atmosphere. In this circumstance, it is difficult to find which industrial sector plays major role. The switch "OFF" condition is rare in human history and yielded an experimental opportunity for the researchers to create a pollution baseline. The "OFF" condition is a temporary or may be periodic solution for combating air pollution that provides imperative research opportunities regarding potential control measures and regulations for improved air quality in future.

In our current study, we have identified the eastern region as high nitrogen dioxide concentrated zone and West Bengal, Odisha, and Chhattisgarh are the most NO_2 producing states across the nation. We also have explored that Delhi is the most polluted city, while Chennai is comparatively safer than others. The stable and consistence NO_2 hotspot zones are observed in the Govind Ballav Sagar plant region, upper part of Chhattisgarh and Odisha states, and middle part of the Odisha where maximum NO_2 emission point sources are located in clustered form with greater installed capacity. In the ecological point of view, all the critical zones are highly vulnerable compared to others hotspots where possibility of acid rain along with deterioration of ambient air quality are likely to occur. Therefore, urgent emission reduction oriented action plans are necessary to control the uncurbed NO_2 pollution as well as to protect the environment and ecology.

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Author contribution Dr. Debabrata Mondal conceptualized the work and provided overall guidance and continuous examinations of the work. Mr. Suvojit Sarkar prepared datasets and carried out analysis as well as wrote the manuscript. Both the authors discussed the results and contributed to the final manuscript.

Data availability All the data and materials related to the manuscript are published with the paper, and available from the corresponding author upon request (mandal23dev@gmail.com).

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

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