



Changing air pollution scenario during COVID-19: Redefining the hotspot regions over India[☆]



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ABSTRACT

The present study investigates the air pollution pattern over India during the COVID-19 lockdown period (24 March–31 May 2020), pre-lockdown (1–23 March 2020) and the same periods from 2019 using Moderate Resolution Imaging Spectroradiometer (MODIS) Terra aerosol optical depth (AOD) with level 2 (10 km × 10 km) and level 3 (1° × 1° gridded) collection 6.1 Dark Target Deep Blue (DT-DB) aerosol product the Tropospheric Monitoring Instrument (TROPOMI) NO₂ and SO₂ data with a spatial resolution of 7 km × 3.5 km. We also use long-term average (2000–2017) of AOD for March–May to identify existing hotspot regions and to compare the variations observed in 2019 and 2020. The aim of the present work is to identify the pollution hotspot regions in India that existed during the lockdown and understanding the future projection scenarios reported by previous studies in light of the present findings. We have incorporated Menn-Kendall trend analysis to understand the AOD trends over India and percentage change in AOD, NO₂ and SO₂ to identify air pollution pattern changes during the lockdown. The results indicate higher air pollution levels over eastern India over the coal-fired power plants clusters. By considering the earlier projected studies, our results suggest that eastern India will have higher levels of air pollution, making it a new hotspot region for air pollution with highest magnitudes.

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1. Introduction

Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), the virus that causes coronavirus disease 2019 (COVID-19) has threatened the humanity recently (Sarmadi et al., 2020). COVID-19 was declared a pandemic by the World Health Organisation on March 11, 2020 due to its rapid spread and associated mortality (WHO, 2020). As of July 28, 2020, the disease has spread to 213 countries, making it the most massive pandemic in modern history (WHO, 2020). India too is severely affected by COVID-19 with a total of 9.88 million cases and 1.62 million fatalities as of December 14, 2020 (covid19india.org; <https://www.mygov.in/covid-19>).

The Government of India announced a nationwide lockdown on March 24, 2020. The lockdown was aimed to force people to stay at home and marked an unprecedented situation with an absence of

industrial production or the operation of public and private transportation (Bherwani et al., 2020) – apart from essential services. Various lockdown phases continued until May 31, 2020, after which the Government of India started to ease the restrictions and allowed a return to routine operations for traffic and the industries (<https://www.mygov.in/covid-19>).

Though the lockdown affected negatively personal lives manifold, it showed a positive effect on the environment with improved air quality globally (Dutheil et al., 2020). Many studies have been published after COVID-19 lockdown observing the reduction in pollutants globally. Studied which reported air pollution reductions across the continents found that the reductions varied over different cities with the highest decrease of 57% over Colombia, South America, followed by 42% decrease over Kuwait, and 40% decrease over India (Rodriguez-Urrego and Rodriguez-Urrego, 2020; Chauhan and Singh, 2020; Bherwani et al., 2020). A decrease of 20–30% in NO₂ concentrations over China, Europe, Italy, France, Spain and the US using Aura and Senitel-5P datasets was also reported (Muhammed et al., 2020a,b).

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Analysis of PM_{2.5} and NO₂ over the US during the COVID-19 and pre-COVID-19 outbreak period shows a 25.5% reduction in NO₂ and significant reductions in PM_{2.5} values over urban areas during COVID-19 periods, indicating reduced emissions from traffic and industries (Berman and Ebisu, 2020). However, PM_{2.5} concentrations did not show any such reduction over Ontario, Canada, though there were reductions in NO_x and also slight reductions in O₃ levels (Adams, 2020). Nakada and Urban (2020) reported 64.8% decrease in CO, 77.3% decrease in NO and 54.3% decrease in NO₂, with ~30% increase in O₃ concentrations over São Paulo, Brazil, during partial lockdown due to COVID-19. Krecl et al. (2020) and Dantas et al. (2020) also reported reductions in pollutant concentrations over different sites of São Paulo and Rio de Janeiro, Brazil, during COVID-19 lockdown. Reduction of pollutants over Europe during COVID-19 lockdown was reported by Collivignarelli et al. (2020) and Menut et al. (2020). The results proposed ~30–50% reductions in NO₂ and a significant reduction in PM_{2.5} over western European countries.

Over Asia, the air pollution levels significantly reduced over various countries during COVID-19 lockdown/restrictions. Ju et al. (2020) reported reductions in PM_{2.5}, PM₁₀, NO₂ and CO over Korea during the preventive measure periods. Analysis of PM and trace gases over China suggested that the reductions were significant during COVID-19 lockdown for all regions (e.g., He et al., 2020; Wang and Su, 2020; Bao and Zhang, 2020). Significant reductions in pollutants was also observed over most of the megacities of India during COVID-19 lockdown (e.g., Shehzad et al., 2020; Jain and Sharma, 2020; Kumar et al., 2020; Sharma et al., 2020; Navinya et al., 2020). On an average, there was ~40% reduction in PM and ~30–70% reduction in NO₂ over major cities in India according to most of the studies (Singh et al., 2020; Metya et al., 2020). However, Ranjan et al. (2020) identified no substantial reduction in aerosol optical depth (AOD) over central and eastern regions of India which are associated with coal mining even during the COVID-19 lockdown.

Air pollution shows a significant spatio-temporal variation in India as a combined result of industrial production, power generation, traffic and road-dust emissions, cooking, agricultural waste burning, and construction activity (Guttikunda and Calori, 2013). Future projection studies found an unprecedented increase in the emission of CO₂, PM, SO₂, and other pollutants for India (Upadhyay et al., 2018). The reduction in air pollution during COVID-19 lockdown provides an opportunity to re-draw maps of natural and reduced emissions to understand the baseline air pollution over different regions.

The present work investigates the spatial variation in AOD, NO₂, and SO₂ from satellite measurements over the Indian region during the COVID-19 lockdown (24 March – 31 May 2020). The lockdown period is compared to the same period of 2019 to identify changes in the air pollution patterns over India. The objective of the present work is (a) to quantify the reduction variation over the country and (b) to identify the regions where emission reductions were less significant during the lockdown and the baseline values were high. The results will also allow us to relate and validate the findings with earlier projected model results of hotspot air pollution regions in India for the future. Though there are a few studies on India stating the reduction in pollutants over megacities, the novelty of the present work lies in understanding the higher emission baseline regions and the existing hotspot regions even during the COVID-19 lockdown period.

2. Data and methodology

The area of the study is India. Dark Target Deep Blue (DT-DB) aerosol product of the Moderate Resolution Imaging Spectro-

radiometer (MODIS) level 2 (10 km × 10 km) and level 3 (1° × 1° gridded) collection 6.1 data are used to derive AOD at 550 nm as a proxy for aerosol load (PM pollution). The product combines retrievals using the dark target algorithm (Levy et al., 2007, 2013) over water and the deep blue (Hsu et al., 2013) algorithm over land, and provides improved data coverage over both dark and bright surfaces (Bilal et al., 2018; Wei et al., 2019). The datasets are downloaded from LAADS DAAC (<https://ladsweb.modaps.eosdis.nasa.gov/>). For each day, the level 2 product includes a number of files which covers different parts of the satellite swath, combined over the Indian region to get a daily picture of AOD.

For information on NO₂ and SO₂ concentration, we use high-resolution daily data from the TROPOspheric Monitoring Instrument (TROPOMI) aboard Sentinel-5 Precursor provided by the European Space Agency (Pedernana et al., 2018; Eskes et al., 2019; Hedelt et al., 2019). The spatial resolution is 0.01 arc degrees (7 × 3.5 km²) for both NO₂ and SO₂. The TROPOMI datasets are obtained from the Google Earth Engine (GEE) (Gorelick et al., 2017), an open source online platform for analysis and visualization of scientific datasets, which provides Level 3 data from the original Level 2 TROPOMI datasets. The location details, power generation capacity, annual coal consumption, and annual emissions related to coal-fired power plants are taken from Guttikunda and Jawahar (2014), Sahu et al. (2017) and Guttikunda and Jawahar (2018). Information related to COVID-19 is taken from WHO (2020), covid19india.org and the COVID-19 page of the official Government of India website: <https://www.mygov.in/covid-19>.

To study the variations of a particular parameter, we first averaged the data for the days before and after lockdown for the year 2020, and then compared them with that of 2019. The Menn-Kendall test (MKT) was employed to find a long-term trend in AOD over India. MKT is a non-parametric test widely used for analyzing trends in various research fields in time series or spatial variation of parameters (e.g., Asoka et al., 2017; Vissa et al., 2019). MKT takes the null hypothesis as no monotonic trend is present in a time series, and the trend values may be positive or negative. For MKT, the statistical significance is at the 95% confidence level ($p < 0.05$) in the present study. The mathematical details of the function can be obtained from Sen (1968), and Sen's slope is a clear indication for the trend values. The percentage change of any particular parameter has been calculated for 2020 in the present study by taking values of 2019 as base.

3. Results

3.1. Variation and trend in columnar AOD

AOD variations during the COVID-19 lockdown can be better understood by knowing the average trends in AOD during the pre-monsoon season (March–May). We have calculated average columnar AOD variations for pre-monsoon using MODIS TERRA Level 3 (1° × 1° gridded) data (Fig. 1 (a)) for the period 2000–2017. The Indo-Gangetic plain (IGP) shows high levels of particulate pollution (with AOD values greater than 0.5), as reported in the literature for all the seasons throughout the year; however, the concentrations are highest during monsoon followed by winter, pre- and post-monsoon seasons (e.g., Dey et al., 2012; Dey and Di Girolamo, 2010; Gogikar and Tyagi, 2016). The high values of columnar AOD during the monsoon over IGP are due to presence of sea-salt aerosols and hygroscopic growth of fine particulates other than urban areas' contribution (Kumar et al., 2018). Though, the monsoon AOD climatology could be biased toward observations due to difficulty in satellite data retrievals during active monsoon phases. The chance of successful retrievals of aerosol optical properties from satellite is higher during the break monsoon

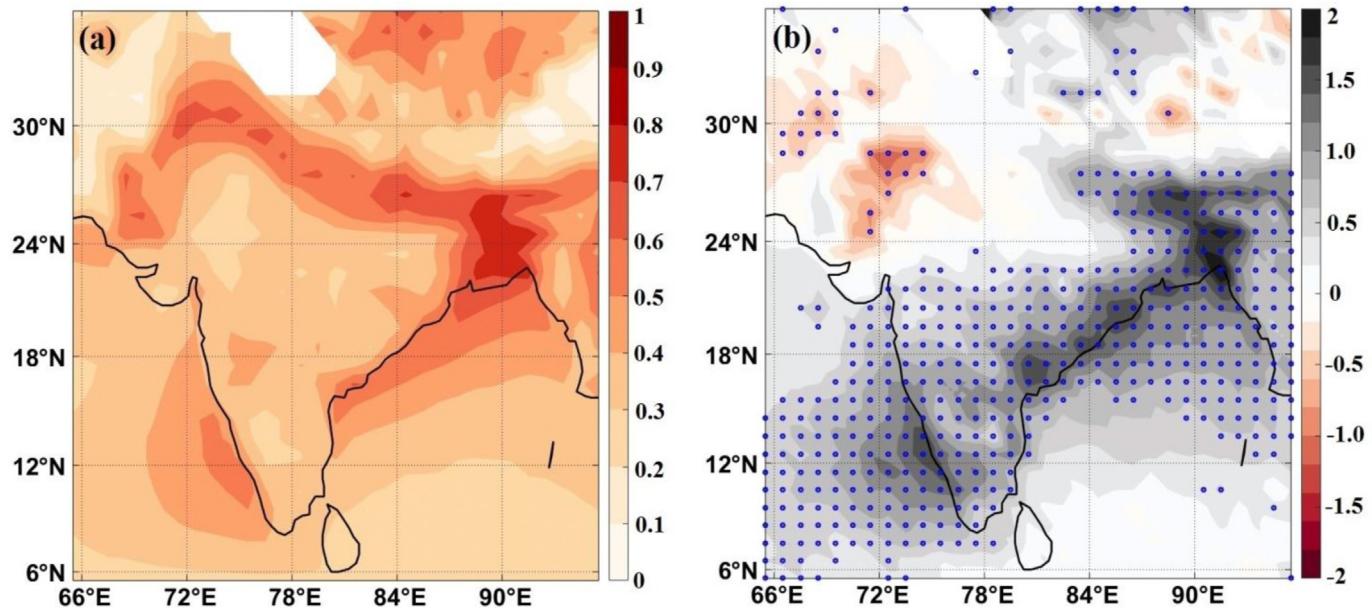


Fig. 1. Mean Terra-MODIS AOD (L3, $1^\circ \times 1^\circ$ gridded) over India between March and May from 2000 to 2017 (a) and Sen's slope values for AOD during that time period. Blue dots mark significant trends. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

phases than in active monsoon phases because of higher cloud coverage in the active phases. The presence of elevated aerosol layers over India is frequent during pre-monsoon as compared to monsoon. Even higher values of around 0.8 are found over north-eastern India and the adjoining parts of Bangladesh for pre-monsoon season. These higher AOD values are primarily associated with frequent thunderstorms over the region (Tyagi and Satyanarayana, 2015), allowing the polluted air masses to uplift vertically and increasing the overall AOD values (Ramachandran and Rupakheti, 2021). IGP is the region of high concentration of other pollutants (NO_x , CO and O_3) as well for both annual and seasonal variations (Ghude et al., 2008; Kar et al., 2010; Yang et al., 2017; Rupakheti et al., 2018).

Applying the Menn-Kendall statistical test, the trends in AOD (Fig. 1 (b)) shows positive trend values over eastern, southern, and northeastern India, and negative trend values over parts of western India (Gujarat and Rajasthan). Significant regions are marked with blue dots over the figure; it is evident that the trend in both western and eastern-southern sector of India is significant. It is interesting to note that even though IGP has been an air pollution hotspot for decades, positive trends in AOD are mostly absent. In contrast, eastern states Odisha and West Bengal show large positive trends for AOD.

3.2. Columnar AOD variation during COVID-19

Fig. 2 presents MODIS Terra AOD (using $10 \text{ km} \times 10 \text{ km}$, Level 2 data) for the entire pre-monsoon season, the pre-lockdown, and lockdown phases to show the associated changes in particulate pollution. The figure also shows AOD maps for the same time periods of 2019 and the calculated percentage change between 2019 and 2020. It is interesting to note that by utilizing the data from 2019 to 2020, IGP and eastern India (Odisha and West Bengal) are regions with higher AOD values compared to the rest of India, as seen in Fig. 1. The same calculations were also made using Level 3 data, which shows similar variations and hotspot regions (Fig. S1).

The pattern of increased AOD is very similar when considering the entire pre-monsoon season in both 2019 and 2020 (Fig. 2a and

b, upper row). During the pre-lockdown period from 1 to March 23, 2020 (middle row), high values of AOD were uniformly distributed over IGP and eastern India (Odisha and West Bengal). During the lockdown (Fig. 2b), AOD decreased over most parts of India, except western India (Maharashtra) and eastern India (Odisha, West Bengal, and Jharkhand) with some parts of IGP (Bihar and eastern Uttar Pradesh), where higher AOD values still persisted. The percentage change in AOD between 2019 and 2020 in the right column of Fig. 2 shows about ~25% reduction in AOD for parts of northern and southern India and some locations in IGP for the whole pre-monsoon period (Fig. 2c). This agrees with the findings of Kumar et al. (2020) and Jain and Sharma (2020). During pre-lockdown, the percentage change shows higher AOD values during 2020 (Fig. 2f), except over the coastal districts of eastern India and Gujarat in the west, highlighting significant increase of AOD over whole India in 2020. For the percentage change in AOD during lockdown, most of India show a decrease in AOD (~25%); however, the western (Maharashtra), central (Chhattisgarh and Madhya Pradesh) and eastern regions (Odisha, West Bengal, and Jharkhand) show increased values (between 25 and 50%). Similar findings of no reduction in $\text{PM}_{2.5}$ and PM_{10} values during COVID-19 over an eastern India station Bhubaneswar have been reported by Sahu et al. (2020).

Though the lockdown was implemented countrywide uniformly and vehicular and industrial emissions ceased to almost zero, the increase in AOD over the western, central, and eastern part of the country is unexpected. These persistently high values can be attributed to the operational coal-fired power plants in the regions (Guttikunda and Jawahar, 2014) and continuous coal mines operation during the lockdown (Ranjan et al., 2020). Emissions from coal-fired power plants may spread widely and cover areas in the order of 150–200 km in radius (Guttikunda and Jawahar, 2018), with an expected aerosol lifetime of 1–2 weeks (Seinfeld and Pandis, 2016).

3.3. Tropospheric columnar NO_2 variation during COVID-19

Tropospheric NO_2 plays a significant role in determining air

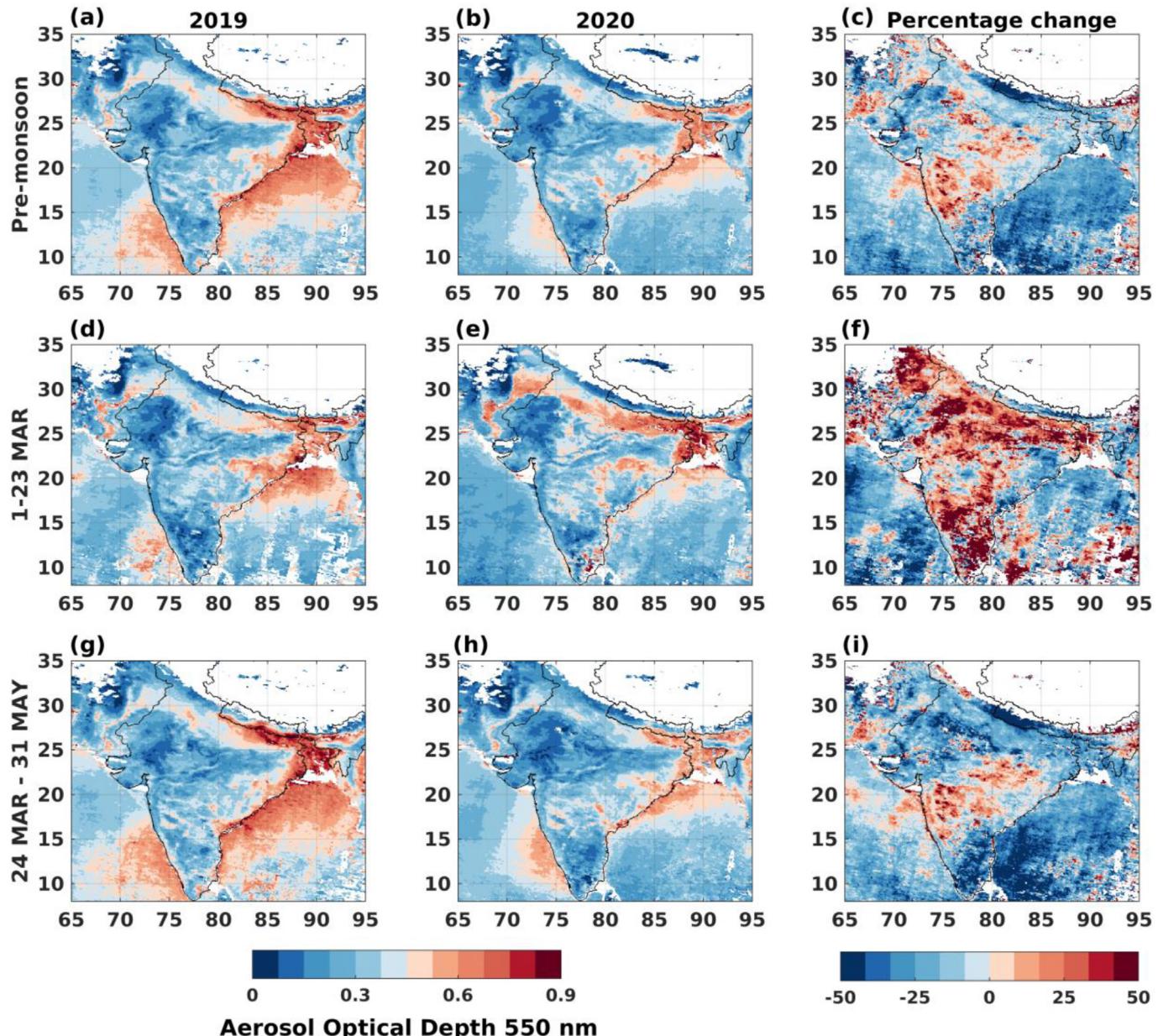


Fig. 2. Total columnar MODIS Terra AOD (L2, 10×10 km) for 2019 (left column) and 2020 (middle column), and associated percentage change (right column) for the time periods from 1 March to 31 May (pre monsoon, first row), 1 March to 23 March (pre lockdown, middle row) and 24 March to 31 May (lockdown period, bottom row).

quality by acting as a precursor for O_3 formation and secondary organic aerosols (Atkinson et al., 2018). Ghude et al. (2008) found that tropospheric NO_2 concentrations were highest in the summer/pre-monsoon season over the Indian region, followed by winter, post-monsoon and monsoon seasons. However, in all seasons, the highest concentration region was IGP, for an average of 2003–2006 in the study by Ghude et al. (2008), with visible hotspots over other parts of India. Columnar NO_2 measurements from TROPOMI provide reasonable estimates of NO_2 with a high spatial resolution (Eskes et al., 2019). Due to COVID-19 related lockdowns and reduction in vehicular and industrial emissions, the concentration of tropospheric NO_2 has decreased globally (Bauwens et al., 2020).

Fig. 3 shows the change in NO_2 concentration over India between pre-monsoon, pre-lockdown and lockdown periods of 2019 and 2020. The data of 2019 reveals various hotspot regions of tropospheric NO_2 emissions over eastern India (West Bengal,

Odisha, and Jharkhand), the northeastern region (Assam and Mizoram), the northern region (Delhi and nearby regions) as well as a few smaller hotspots in south (Telangana, Andhra Pradesh, Karnataka, and Tamil Nadu) and west (Maharashtra and Gujarat) of the country (Fig. 3a).

The overall pre-monsoon picture in 2020 (Fig. 3b) reveals the eastern region as a dominant emission hotspot in India. During the pre-lockdown period, there was a significant decrease in NO_2 concentrations for 2020 over the Indian region (Fig. 3d and e), which can be ~15–30% except in northern India (Rajasthan, Haryana, and Punjab) and hotspot regions in Odisha, West Bengal, and Jharkhand, where values increased ~20–30% in 2020 (Fig. 3f). The data taken during the lockdown period (Fig. 3g and h) show only the eastern India hotspot while other sources disappear. This difference is not observed for the week leading to the lockdown (Fig. 3e). The percentage change (Fig. 3i) quantifies the decrease in

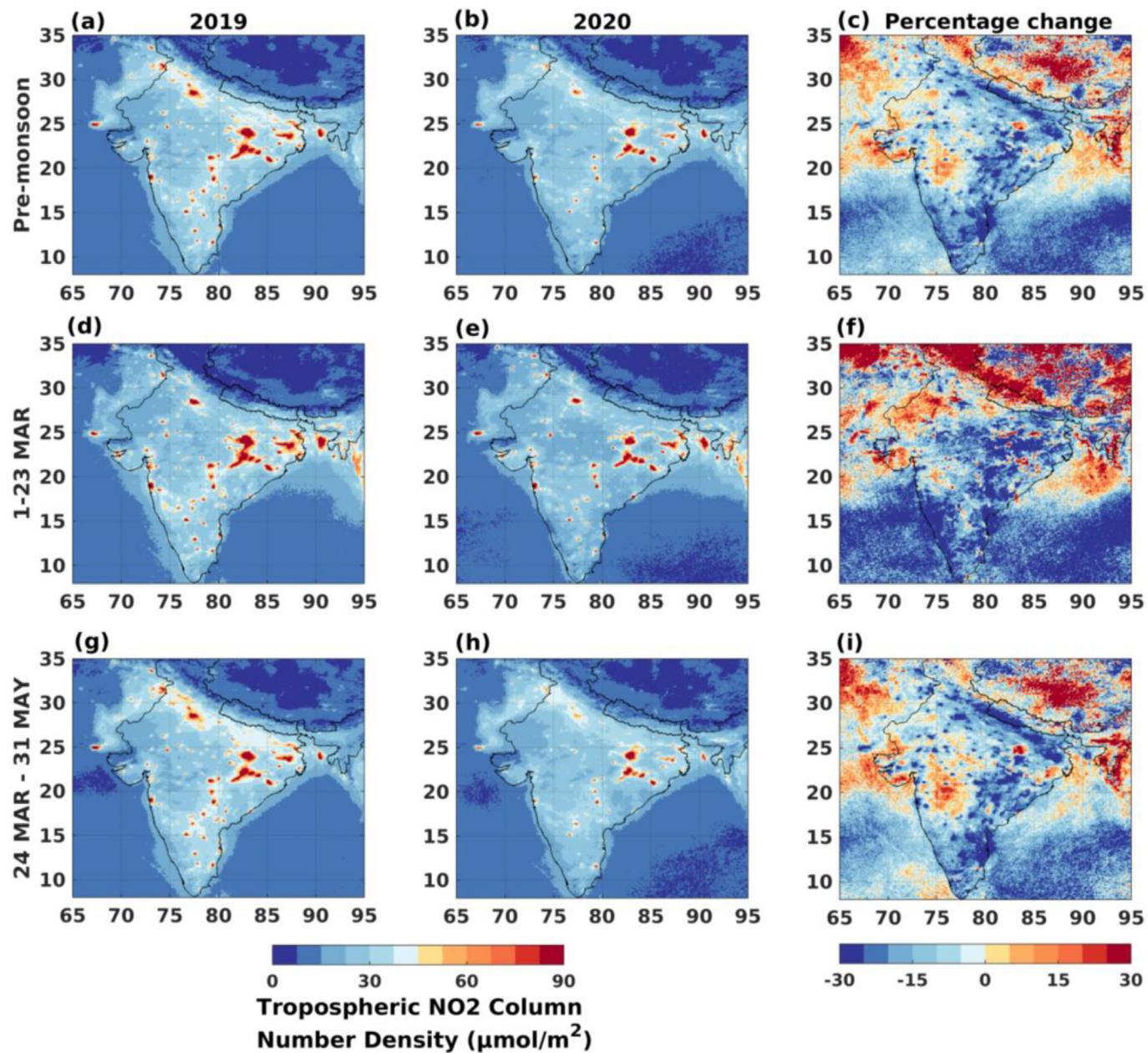


Fig. 3. TROPOMI columnar NO₂ concentrations and percentage change over India for 2019 (left column) and 2020 (middle column), and associated percentage change (right column) for the time periods from 1 March to 31 May (pre monsoon, first row), 1 March to 23 March (pre lockdown, middle row) and 24 March to 31 May (lockdown period, bottom row).

NO₂ concentrations as ~30% for most of the regions except over parts of Gujarat and Maharashtra and hotspot regions of Odisha and West Bengal. In these areas, NO₂ concentration has increased despite the lockdown (~15–30%).

Previously, Ghude et al. (2008) used monthly data from GOME (March 1996 to December 2002) and SCIAMACHY (January 2003 to December 2006) to identify hotspots of tropospheric NO₂ concentrations over India. While their findings are in general agreement with our results for 2019, we find that the hotspot regions have changed their intensity since Ghude et al. (2008) as a result of increase in the number of power plants over Odisha, West Bengal, and Jharkhand (Sahu et al., 2017; Guttikunda and Jawahar, 2018). Similar to the case of particulate pollution (AOD), the highest NO₂ concentrations are found over eastern India (Odisha, West Bengal,

and Jharkhand), even during the lockdown.

Because of the short lifetime of NO₂ (about one day) compared to aerosols (Seinfeld and Pandis, 2016), it is less likely that NO₂ emissions are dispersed in the same way as might happen in the case of AOD. Percentage change results (right column in Fig. 3) indicate that before the lockdown, northern states of Haryana, Punjab, and Himachal Pradesh mark a positive percentage change, indicating higher emissions in 2020. Another important observation is the strong emission of NO₂ in the states of Maharashtra and Madhya Pradesh (central to western India) during lockdown (Fig. 3 (i)) that occurred over a large area without easily distinguishable hotspots, particularly near Mumbai. These results identify eastern (Odisha, West Bengal, and Jharkhand) and western (Maharashtra and parts of Gujarat) regions as producing higher emissions in

2020, even during the lockdown. The reduction in NO₂ despite higher AOD values in certain regions may be attributed to the continuous biomass burning, thus maintaining higher AOD values, but the restricted vehicular and industrial emission reduced the NO₂ concentrations (Ramachandran and Rupakheti, 2021).

3.4. Tropospheric columnar SO₂ variation during COVID-19

Tropospheric SO₂ seasonal variation over India shows the highest concentrations during winter followed by post-monsoon, pre-monsoon, and monsoon seasons. The highest concentration regions are IGP and eastern India (regions of Odisha, West Bengal, and Jharkhand; Chutia et al., 2020). The primary source of SO₂ emission is the combustion of fossil fuel, mainly from the coal-fired

power plants. The quantity of SO₂ emissions in India is further related to the quality of the burnt fuel (Chakraborty et al., 2008). In Fig. 4, eastern India (Odisha, West Bengal, and Jharkhand) and parts of central India (mainly Chhattisgarh) emerge as significant hotspot area in the analysis of SO₂ over India for the pre-monsoon season of 2019 and 2020. For 2019, there are also increased values in northern and central India (particularly near Delhi and Mumbai), but the highest concentrations are found over eastern India.

The plots for the pre-lockdown period of 2020 (Fig. 4e) clearly show dominance of the hotspot region in eastern India (Odisha, West Bengal, and Jharkhand), similar to 2019 (Fig. 4d). Overall, pre-lockdown analysis for 2020 shows several new locations with increased values of SO₂ concentration compared to 2019, which suggests a growth in industrialization and other emissions. During

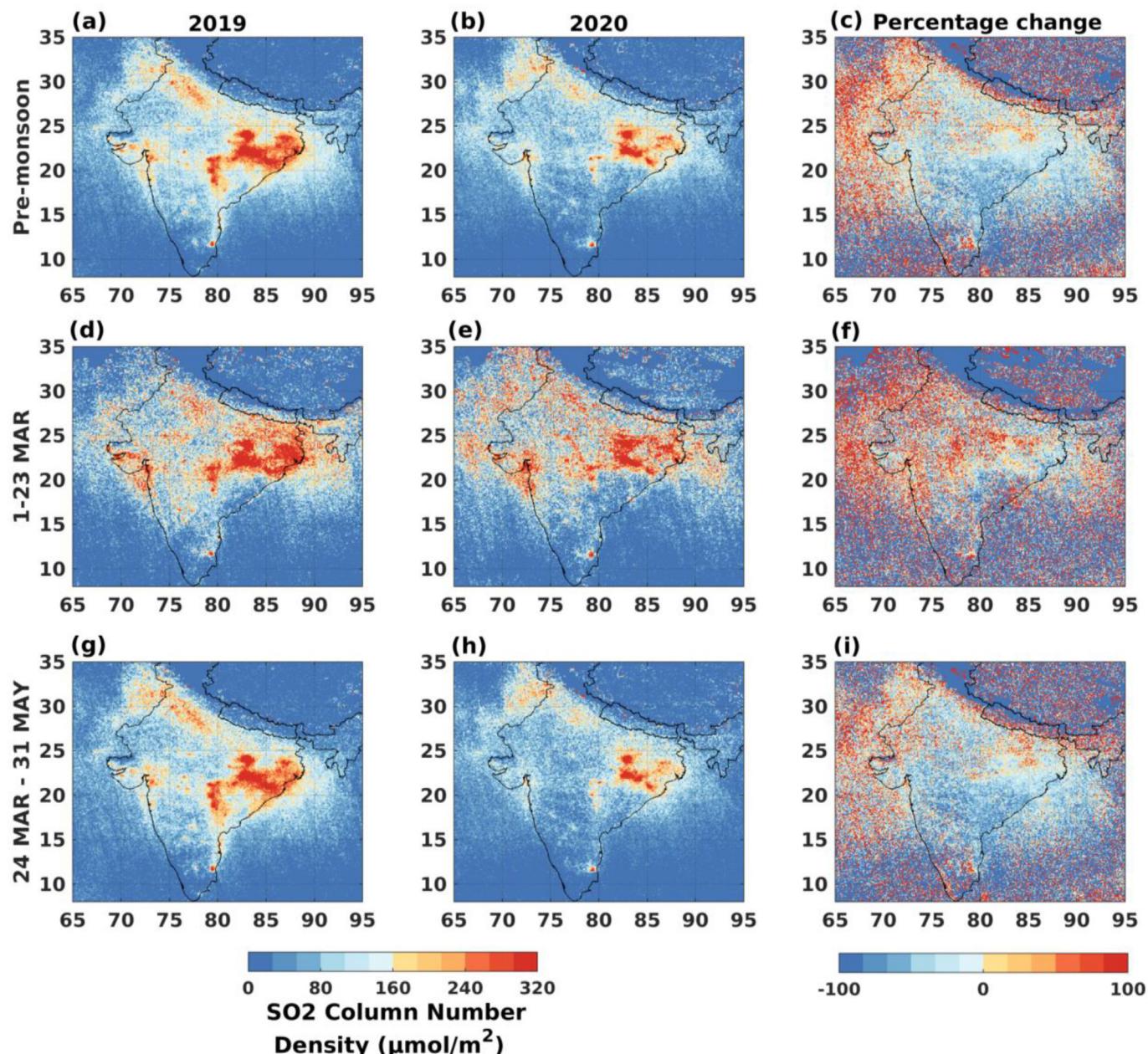


Fig. 4. TROPOMI columnar SO₂ concentrations and percentage change over India for 2019 (left column) and 2020 (middle column), and associated percentage change (right column) for the time periods from 1 March to 31 May (pre monsoon, first row), 1 March to 23 March (pre lockdown, middle row) and 24 March to 31 May (lockdown period, bottom row).

the lockdown (the bottom row of Fig. 4), while other emission spots decreased in SO₂ concentration (Fig. 4h), dominant emission region was again identified over eastern India. This lack of sources in other parts of the country is not found for 2019 (Fig. 4g).

The percentage change variation from 2019 to 2020 shows a substantial decrease in SO₂ (~60–70%) for the most parts of India as indicated by Sharma et al. (2020). However, over the eastern region, there is only a slight decrease over a few pockets in SO₂ concentration. The hotspot regions of Odisha and West Bengal show positive percentage change (~45–50% during the lockdown), indicating that even during the lockdown, emissions were higher in 2020.

The reason can be attributed to the dense network of high capacity coal-fired power plants, with new plants operational in 2020 (Guttikunda and Jawahar, 2018). Additionally, higher SO₂ emissions over eastern India may be related to coal mining, which is widespread in this part of the country (<https://coal.nic.in>), for cheap fuel for domestic heating and cooking (Li et al., 2018). The similarities of the spatial extent in the concentration of SO₂ and NO₂ indicate that they both originate from the same sources, i.e., coal-fired power plants and coal mining regions of the country.

4. Discussion

Understanding the changing air pollution scenario is important for developing countries in decreasing the disease burden and to prevent the environmental degradation. One common proxy for understanding the changed emission scenario over developing countries like India and China is to analyze CO₂ emissions (Luo et al., 2020). Several studies suggested that various factors indirectly play an important role in changing the air pollution scenario over lower-middle income countries like India, including endogenous and foreign innovation, imports and exports, and several other institutional factors including political stability, foreign direct investment, and income level (Muhammad and Long, 2021; Salman

et al., 2019). Urbanization and international trade is also one important reason for changed CO₂ emissions across India (Muhammad et al., 2020b).

Though the present study deals with the analysis of NO₂, SO₂ and AOD, it is focused on possible emissions over regions which were operative even during the lockdown. Emissions from coal-fired power plants can deteriorate the environment to a high extent (Crandall, 1983). Their role in poor air quality over India has been a focus of extensive research (Guttikunda and Jawahar, 2014, 2018; Sahu et al., 2017). For AOD, whereas most of the country recorded a decrease of ~25% in AOD values, Odisha, West Bengal, Jharkhand, Madhya Pradesh, Chhattisgarh, and Maharashtra recorded an increase (25–50%) during the lockdown. Except parts of Odisha, West Bengal, and Maharashtra, which emerge as hotspot regions of NO₂ during the lockdown (with an increase of ~15–30%), rest of the country marked a decrease of ~30% in NO₂ concentrations while SO₂ decreased substantially (~60–70%) over the whole country, except in hotspot regions of West Bengal, Odisha, and Rajasthan, where the increase was ~45% during the lockdown.

The reason to focus on hotspot regions in India is to prepare for the associated health complications over densely populated areas of eastern India (~270–1029/km², according to the census of 2011) and to understand the relative change in their location with changing energy production statistics (from IGP to eastern India). Another reason is to make lawmakers aware of these transformations for possible changes in policies over different regions to tackle the increased/changing patterns of the pollutants. Fig. 5 shows the location of major power plants together with major metallic and non-metallic mineral distribution across India. It is interesting to note that the hotspot region of NO₂, SO₂ and AOD during the countrywide lockdown coincided with the dense cluster of coal-fired power plants, several mines, and the central coal reserve of the country, located mostly in the states of Odisha, West Bengal, Jharkhand, and Chhattisgarh.

Though identifying these areas as a hotspot air pollution zone is

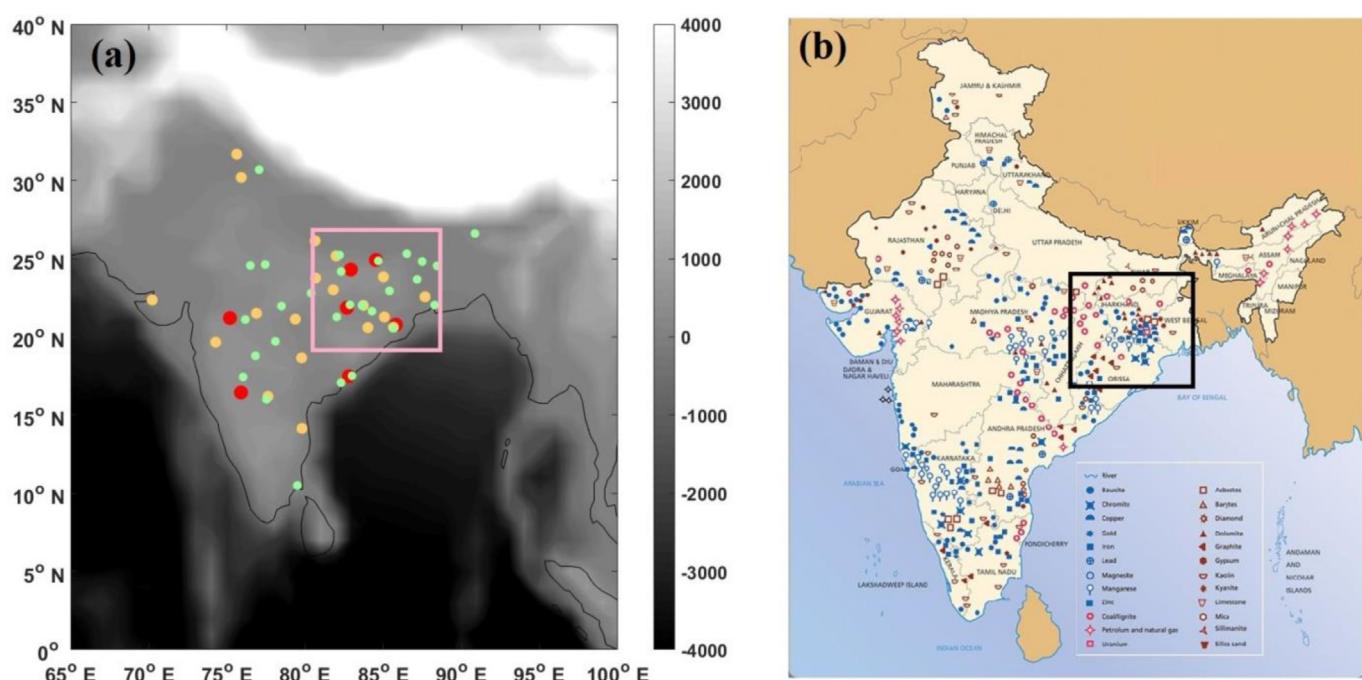


Fig. 5. (a) Location of major coal fired thermal power plants after Guttikunda and Jawahar (2018) with capacities > 2000 MW (red), of 1000–2000 MW (yellow), and <1000 MW (green); (b) location of metallic and non-metallic mineral distribution in India (adopted from <http://ismenvis.nic.in/>). The region with observed NO₂ and SO₂ hotspots is marked by the box in (a) and (b). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

not new (e.g., Ghude et al., 2008; Sahu et al., 2017), the critical observation is that despite the strict lockdown in the country, when all other hotspots diminished, these particular regions showed no decrease in emissions. Even though vehicular emissions ceased practically to zero and industries were not operational during the lockdown, the hotspot zones of NO₂ and SO₂ over eastern India maintained because of the continuous operation of coal-fired power plants, which could not be shut down due to power requirements. Residential burning of coal for household cooking is another factor for the increased values. Since the industrial coal-consuming may have been reduced, the residential burning might have increased during the study period, which cannot be separated based on the columnar data from the satellite. The exact data of coal-burning by industries is required during the study period to quantify different contributors.

These high SO₂ values match with regions with reported higher fossil fuel consumption and SO₂ emissions in eastern India for 1996–1997 (Reddy and Venkataraman, 2002a; 2002b). Projection studies suggest that Odisha, West Bengal, and Jharkhand will have the highest PM_{2.5} pollution load (with maximum values of 11.5, 14.1 and 11.5 µg/m³ in 2020) due to planned expansion of coal-fired power plants (Guttikunda and Jawahar, 2018) and high CO₂ production with a value of 25–35 kt/year (Sahu et al., 2017).

Regions with increased AOD in eastern (West Bengal, Odisha, and Jharkhand), central (Chhattisgarh and Madhya Pradesh) and western India (Maharashtra) before and during lockdown in 2020 are another observation from the results, which partly can be attributed to coal-fired power plants. Considering the plans for upcoming power plants in the country (Guttikunda and Jawahar, 2018), the regions of low air quality identified here are going to include even denser clusters of coal-fired power plants in next decade. Given the current developments, the eastern, central, and western parts of India are going to become the new hotspot regions for environmental pollution in the next decade. The analysis of the air quality during the lockdown gives a clear indication of things to come. Even if emissions are cut to a minimum, eastern India will be still affected by high loads of pollutants emitted by coal-fired power plants.

The country is developing fast and electricity is needed to support this change. While it is not feasible to stop this development, a shift towards better policies for emission controls are needed to protect the population and to improve environmental conditions. A good example to such practical changes in the policy related to air quality comes from China, where after enforcing strict regulations on the energy sector, emissions from power plants were reduced by more than 13% (van der A et al., 2017; Ni et al., 2018; Karplus et al., 2018). Ultralow emission techniques such as fuel gas desulfurization, retrofitted electrostatic precipitation, and wet electrostatic precipitation have been found to be helpful in reducing the coal-fired power plants emission over China in the last decade (Ni et al., 2018; Sui et al., 2016). For eastern India, adoption of these techniques by the power plant industry may result in a reduced amount of air pollution load over the region.

5. Conclusions

The present results shows a shift of air pollution hotspot to eastern India. The findings can be summarized as follows:

- The columnar AOD values over western (Maharashtra), central (Chhattisgarh and Madhya Pradesh) and eastern India (West Bengal, Odisha, and Jharkhand) are higher in 2020 than in 2019, even during the lockdown.
- Eastern India (West Bengal, Odisha, and Jharkhand) was identified as a hotspot emission region for columnar NO₂ and SO₂

during the lockdown. This air pollution hotspot region was still active even when other air pollution hotspot regions over India showed a substantial decrease during the lockdown.

- The primary emissions can be attributed to a dense cluster of coal-fired power plants in eastern India. These plants were continuously operational during the lockdown as was the residential burning of coal as fuel and no shutdown of coal mining in the region.
- Considering the upcoming power plant establishment plans in eastern India, the present study identifies eastern India as a peculiar hotspot region of air pollution in the country.

The limitations of the work include correlating the coal consumption data by different power plants and residential burning areas with amount of air pollutants during the study period. The results advocate an immediate need for improved emission regulations in eastern India.

CRediT author statement

Bhishma Tyagi: Conceptualization, Methodology, Writing – original draft, Software, Goutam Choudhury: Software, Writing – review & editing, Naresh Krishna Vissa: Software, Writing – review & editing, Jyotsna Singh: Writing – review & editing, Matthias Tesche: Writing – review & editing

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.envpol.2020.116354>.

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