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Nationwide CoViD-19 lockdown impact on air quality in India

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सार — यह पेपर चरण 1 **(**25 **मार्च से** 14 **अप्रैल), चरण** 2 **(**15 **अप्रैल से** 3 **मई) और चरण** 3 **(**3 **मई से** 17 **मई) के दौरान किए गए सतह और उपग्रह माप के तुलनात्मक परिणाम प्रस्तुत करता है, जो कि** 2020 **की लॉकडाउन अवधि को लागू करता है और उन भारत में** 2019 **के दौरान समान स्थानों और अवधियों का। ये तुलनात्मक विश्लेषण भारतीय राज्यों और टियर** 1 **मेगासिटी के लिए किए गए हैं जहां देशव्यापी तालाबंदी से आर्थिक गतिविधियां बुरी तरह प्रभावित हुई हैं। सल्फर डाइऑक्साइड** (SO_2), **कार्बन मोनोऑक्साइड** (CO), $PM_{2.5}$ **और** PM_{10}, **ओजोन** (O_3), **नाइट्रोजन डाइऑक्साइड** (NO_2) **की सतह सांद्रता में परिवर्तन पर ध्यान केंद्रित किया गया है और** TROPOMI **से पुनर्प्राप्त स्तंभ** NO_2 **और एयरोसोल ऑप्टिकल गहराई** (AOD) **से प्राप्त किया गया है।** MODIS **उपग्रह।** $PM_{2.5}$ **की सतह सांद्रता में** 30.59%, 31.64% **और** 37.06%, PM_{10} **में** 40.64%, 44.95% **और** 46.58%, SO2 **में** 16.73%, 12.13% **और** 6.71%, **स्तंभ** NO_2 **में** 46.34%, 45.82% **की कमी हुई और** 39.58% **और** CO **में** 45.08%, 41.51% **और** 60.45% **क्रमशः चरण** 1, **चरण** 2 **और चरण** 3 **की लॉकडाउन अवधि के दौरान भारत में** 2019 **की अवधि की तुलना में। लॉकडाउन के पहले चरण के दौरान, मॉडल सिम्युलेटेड** $PM_{2.5}$ **मनाया गया** $PM_{2.5}$ **द्रव्यमान सांद्रता की तुलना में अधिक अनुमान दिखाता है। मॉडल** $PM_{2.5}$ **को लॉकडाउन से पहले और लॉकडाउन अवधि के पहले चरण में कमी किए बिना कम करके आंका गया है। अध्ययन अवधि के दौरान सतह परिवहन गतिशीलता मानचित्रों के साथ** $PM_{2.5}$, PM_{10}, CO **और स्तंभ** NO_2 **के उत्सर्जन में कमी पर चर्चा की गई है। सतह गतिशीलता डेटा में देखी गई कमी के आधार पर उत्सर्जन में कमी, मॉडल ने मनाए गए पीएम** 2.5 **सांद्रता को पकड़ने में उत्कृष्ट कौशल दिखाया। फिर भी, लॉकडाउन अवधि के पहले और तीसरे चरण के दौरान** AOD 5 **से** 40% **तक कम हो गया। सरफेस** O_3 **में लॉकडाउन अवधि के पहले और तीसरे चरण के दौरान क्रमशः** 1.52% **और** 5.91% **की वृद्धि हुई, जबकि लॉकडाउन अवधि के दूसरे चरण के दौरान** -8.29% **की कमी आई।**

ABSTRACT. This paper presents the comparative results of surface and satellite measurements made during the Phase 1 (25 March to 14 April), Phase 2 (15 April to 3 May) and Phase 3 (3 May to 17 May) of Covid-19 imposed lockdown periods of 2020 and those of the same locations and periods during 2019 over India. These comparative analyses are performed for Indian states and Tier 1 megacities where economic activities have been severely affected with the nationwide lockdown. The focus is on changes in the surface concentration of sulfur dioxide (SO_2), carbon monoxide (CO), $PM_{2.5}$ and PM_{10}, Ozone (O_3), Nitrogen dioxide (NO_2) and retrieved columnar NO_2 from TROPOMI and Aerosol Optical Depth (AOD) from MODIS satellite. Surface concentrations of $PM_{2.5}$ were reduced by 30.59%, 31.64% and 37.06%, PM_{10} by 40.64%, 44.95% and 46.58%, SO_2 by 16.73%, 12.13% and 6.71%, columnar NO_2 by 46.34%, 45.82% and 39.58% and CO by 45.08%, 41.51% and 60.45% during lockdown periods of Phase 1, Phase 2 and Phase 3 respectively as compared to those of 2019 periods over India. During 1st phase of lockdown, model simulated $PM_{2.5}$ shows overestimations to those of observed $PM_{2.5}$ mass concentrations. The model underestimates the $PM_{2.5}$ to those of without reduction before lockdown and 1st phase of lockdown periods. The reduction in emissions of $PM_{2.5}$, PM_{10}, CO and columnar NO_2 are discussed with the surface transportation mobility maps during the study periods. Reduction in the emissions based on the observed reduction in the surface mobility data, the model showed excellent skills in capturing the

observed $PM_{2.5}$ concentrations. Nevertheless, during the 1st & 3rd phases of lockdown periods AOD reduced by 5 to 40%. Surface O_3 was increased by 1.52% and 5.91% during 1st and 3rd Phases of lockdown periods respectively, while decreased by -8.29% during 2nd Phase of lockdown period.

Key words – Covid19, Nationwide lockdown, Air quality, Emissions, WRF-Chem.

1. Introduction

The current and ongoing pandemic caused by the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) and the resulting disease termed as CoronaVIrus Disease 2019 (COVID-19) has forced nearly all the governments around the world for imposing restrictions of varying magnitude on human activities to limits the spread of new disease and protect their citizens. These restrictions have dramatically reduced the direct anthropogenic emissions of air pollutants to the atmosphere as seen in many ground-based (Ogen, 2020; Zhang *et al*., 2021) and space-borne observations (Bauwens *et al*., 2020). However, the secondary pollutants such as ground level ozone and secondary organic aerosols have either remained like previous year levels (Dantas *et al*., 2020; Sharma *et al*., 2020) or increased by a factor of 2 (Shi and Brasseur, 2020). Past studies have highlighted the impact of exposure to near-surface $PM_{2.5}$ and O_3 concentrations(Jain *et al*., 2007; Kumar, 2004; Pattnaik, 2019; Peshin *et al*., 2017; Singh and Kant, 2006) on premature mortalities associated in India (Ghude *et al*., 2016). However under the health emergency nationwide lockdown in India, surface and aviation transport services, educational institutions, industrial establishments and hospitality services were suspended for the smooth operations of essential services. As a result, significant air quality improvement has been observed in major megacities across the India (CPCB, 2020; Dhaka *et al*., 2020). The improved air quality due to reduction in anthropogenic emissions, during lockdown period stands the motivation for investigating the levels of tropospheric ozone and secondary organic aerosols in a comparative scenario with respect to the emissions scenario before lockdown period.

In this study, we analyze surface and satellite measurements made during the Phase 1 (25 March to 14 April), Phase 2 (15 April to 3 May) and Phase 3 (3 May to 17 May) of lockdown periods of 2020 and compare these results with the observations available for the same locations and periods during 2019 over India. The comparative analyses are performed for Indian states and Tier 1 megacities (or megacity Delhi) in which the economic activity has been severely affected over the lockdown periods. To that aim, paper reports the changes in the surface concentration of nitrogen oxides (NOx), carbon monoxide (CO), sulfur dioxide (SO_2), particulate matter ($PM_{2.5}$ and PM_{10}) and ozone (O_3).

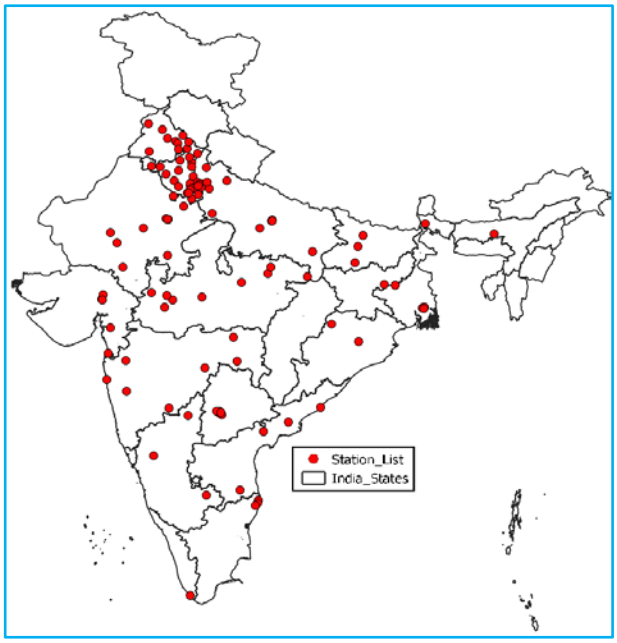


Fig. 1. Geographical locations of air quality monitoring stations across India

One of the largest source of reactive nitrogen (N_r) emission to the atmosphere is NOx which is primarily emitted by industrial activity and transportation (Ghude *et al*., 2009, 2012, 2013, 2020; Ghude *et al*. 2008; Jena *et al*., 2015) together with ammonia (NH3) which is significantly emitted by agricultural source (Pawar *et al*., 2021), whereas CO is a product of residential combustion and power generation (Fadnavis *et al*., 2011; Ghude *et al*., 2011; Palve *et al*., 2018). Similarly, analyses are carried out for the change of NO_2 column data from high-resolution nadir-viewing satellite sensors, the Tropospheric Monitoring Instrument (TROPOMI), single payload of the Sentinel-5 Precursor launched in October 2017 (Veefkind *et al*., 2012).

2. Data and modeling

2.1. *Surface observation*

This study uses $PM_{2.5}$, PM_{10}, NO_2, CO, SO_2 and O_3 measurements conducted by the Central Pollution Control Board (CPCB) at 146 sites over India. The details of the geographical locations are shown in Fig. 1. The quality control and assurance method followed by CPCB for these

air quality monitoring stations is given athttps://cpcb.nic.in/quality-assurance-quality-control/. Furthermore, we take the following steps to reassure the quality of observations from the CPCB network stations. First, we rejected all the observations values above 1000 $\mu g/m^3$ at a given site if other sites in the network do not show values outside this range. Second, we removed single peaks that are characterized by a change in just one hour for all the data in CPCB monitoring stations. This step filters random fluctuations in the observations. Third, we removed some very high concentration values that appeared in the time series right after the missing values.

2.2. *Satellite observation*

We use TROPOMI NO_2 tropospheric vertical column densities (VCDs) from the offline level 2 product provided by KNMI on Sentinel-5P Pre-Operations Data Hub. The details pertaining to the TROPOMI instrument and the data product can be found elsewhere(Van Geffen *et al*., 2015, 2018; Veefkind *et al*., 2012). Briefly, the Sentinel 5 Precursor aboard TROPOMI instrument provides daily measurements of NO2 VCDs at ~13:30 local solar time. In Nadir view, the ground footprint of TROPOMI has a spatial resolution of 7.2 × 5.5 km^2 before 6thAugust, 2019 and 5.6 × 5.5 km^2 afterwards. To retain the best quality data, we have only retained measurement for pixels corresponding to effective cloud fraction less than 0.3 and recommended quality assurance (qa) value greater than 0.75. In order to calculate the mean for a lockdown phase, the original level 2 data were oversampled at a 3.0 × 3.0 km^2 spatial grid. Means were calculated only for those grids, for which at least three days of the acceptable quality data was available in a given lockdown phase. We also obtained AOD measurements from the Moderate Resolution Imaging Spectroradiometer (MODIS) on-board the TERRA and AQUA satellites having Equator overpasses at local solar times 1030 and 1330, respectively (Kumar *et al.*, 2020). We have used MODIS Level 3 aerosol gridded data at a spatial resolution of 1° × 1° with daily temporal averaging (Gupta *et al*., 2020).

3. Model setup

In this study, we used the Weather Research and Forecasting model coupled with chemistry WRF-Chem v3.9.1 to simulate surface $PM_{2.5}$ mass concentration during as well as before and after lockdown period (1st phase, 2nd phase and 3rd phase), starting from 8 March to 17 May, 2020. The forecasting system consists in a two-domain set-up with the outer domain covering northern part of the Indian subcontinent at a horizontal resolution of 10 km, the second domain covering the NCR

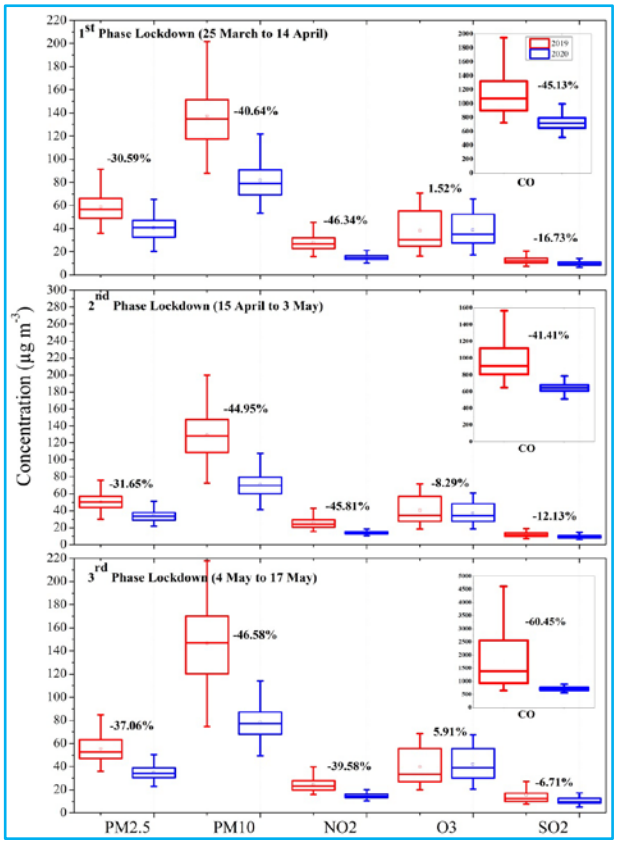
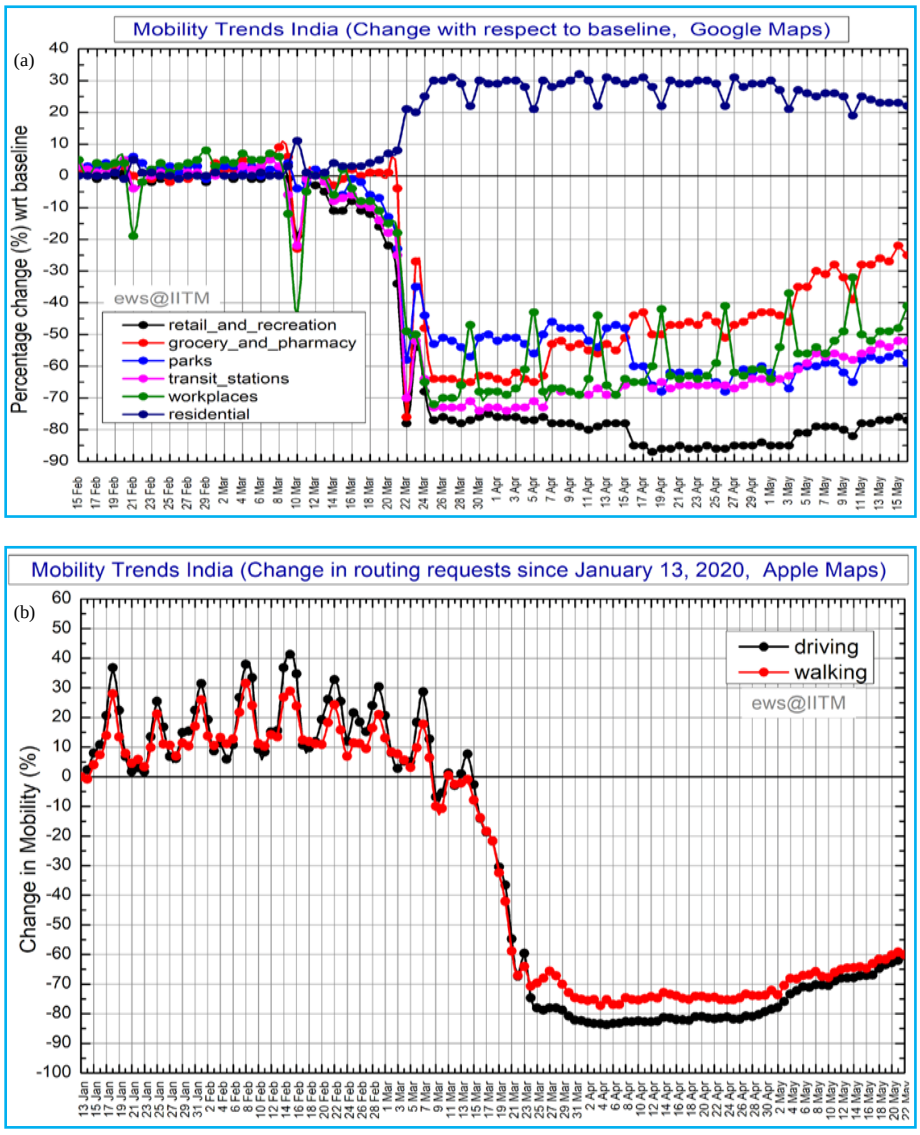


Fig. 2. Box-whisker plots of $PM_{2.5}$, PM_{10}, NO_2, O_3, SO_2 and CO during lockdown periods of Phase 1, Phase 2 and Phase 3 of 2020 (blue color) compare with 2019 (red color) over India

and neighboring state at 2 km resolution (Ghude *et al*., 2020; Jena *et al*., 2021). The meteorological initial and boundary conditions are based on the analysis and forecast product (Ensemble-Kalman filtering) produced by the IITM-Global Forecasting System (IITM-GFS, T1534) spectral model at 12.5 km grid resolution available at every three hours. The outer domain (D1) is provided with the six-hourly chemical boundary conditions from the MOZART-4 10-year climatology. However, chemistry output from the D1 domain every three-hour interval was dynamically used to establish a chemical boundary for the WRF-Chem inner domain (D2). The details on the physical and chemical parameterizations used in the model are given in Jena *et al*. (2021).The forecast was run with MOZART-4 gas-phase chemistry linked to GOCART aerosol scheme (MOZCART). We used anthropogenic, biogenic, fire and dust emissions details described in Jena *et al*., 2021. We used three-dimensional variational method (3D-Var) component of the community Grid point Statistical Interpolation (GSI) system Version 3.5. The 3D-var scheme blends the information from the satellite AOD and surface $PM_{2.5}$ observations details described in Jena *et al*. (2021).



Figs. 3(a&b). Change is community mobility before and during the nationwide COVID-19 lockdown in India (a) recorded by Google maps (https://www.google.com/covid19/mobility/) and (b) Apple maps (https://covid19.apple.com/mobility)

4. Results

4.1. *Surface observation description*

A lockdown was enforced due to spread of the COVID-19 disease with initial phase of 25 March to 14 April (Phase 1), 2nd Phase of 15 April to 3 May (Phase 2) and 3rd phase of 3 May to 17 May (Phase 3) over India. We explore the surface measurements of fine-mode aerosols and trace gas species over entire India. Fig. 2 shows the box plot of surface concentration of $PM_{2.5}$, PM_{10}, NO_2, CO, SO_2 and O_3 during (Phase 1, Phase 2, Phase 3) lockdown periods of 2020 (blue color) compare with 2019 (red color) over India. Surface concentration of mean $PM_{2.5}$ over India was reduced by 30.59%, 31.64% and 37.06% as compared to 2019 and 2020 during lockdown periods of Phase 1, Phase 2 and Phase 3 respectively over India. The surface concentration of PM10 was reduced by 40.64%, 44.95% and 46.58% during Phase 1, Phase 2 and Phase 3 periods respectively over India. The SO2 concentration was reduced by 16.73%, 12.13% and 6.71%, during Phase 1, Phase 2 and Phase 3 periods respectively with respect to those of 2019 during Phase 1, Phase 2 and Phase 3 periods respectively over India. The NO_2 concentration was also reduced by 46.34%, 45.82% and 39.58% during lockdown periods of Phase 1, Phase 2 and Phase 3 respectively as compared to 2019 and 2020 over India. The surface concentration of

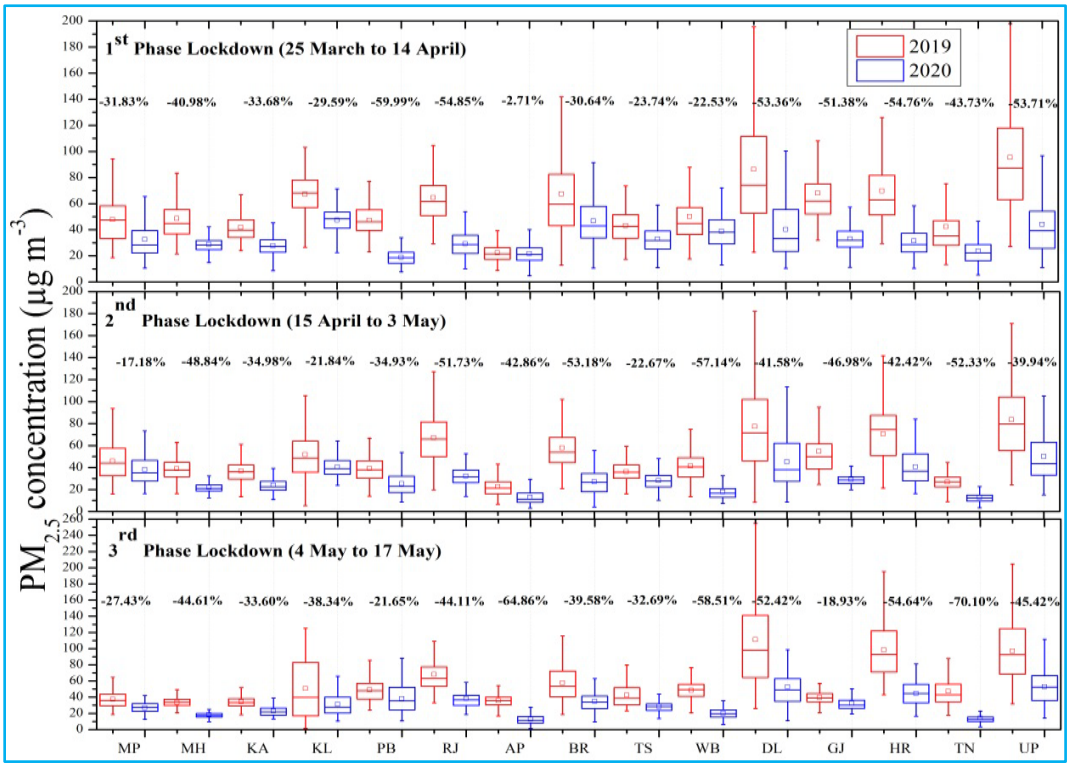


Fig. 4(a). Box-whisker plots of $PM_{2.5}$ for 2019 (red color) and 2020 (blue color) for 1st phase (top), 2nd phase (middle) and 3rd phase (bottom) over different states of India during nationwide COVID-19 lockdown period

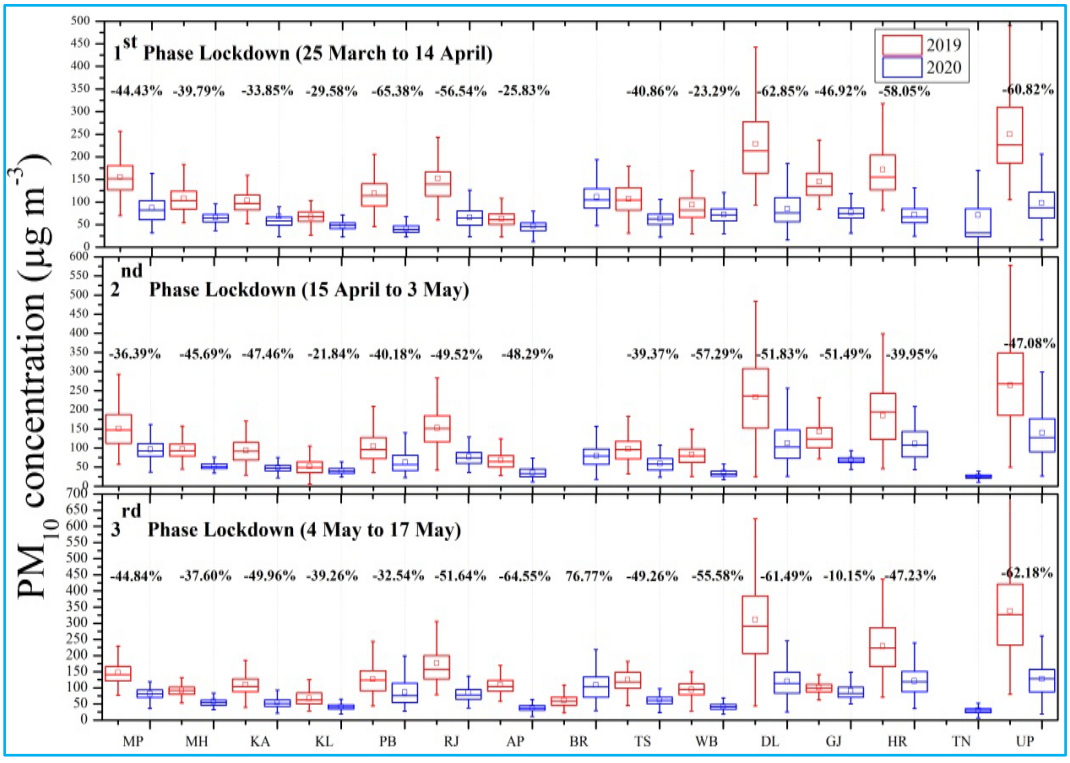


Fig. 4(b). Box-whisker plots of PM_{10} for 2019 (red color) and 2020 (blue color) for 1st phase (top), 2nd phase (middle) and 3rd phase (bottom) over different states of India during nationwide COVID-19 lockdown period

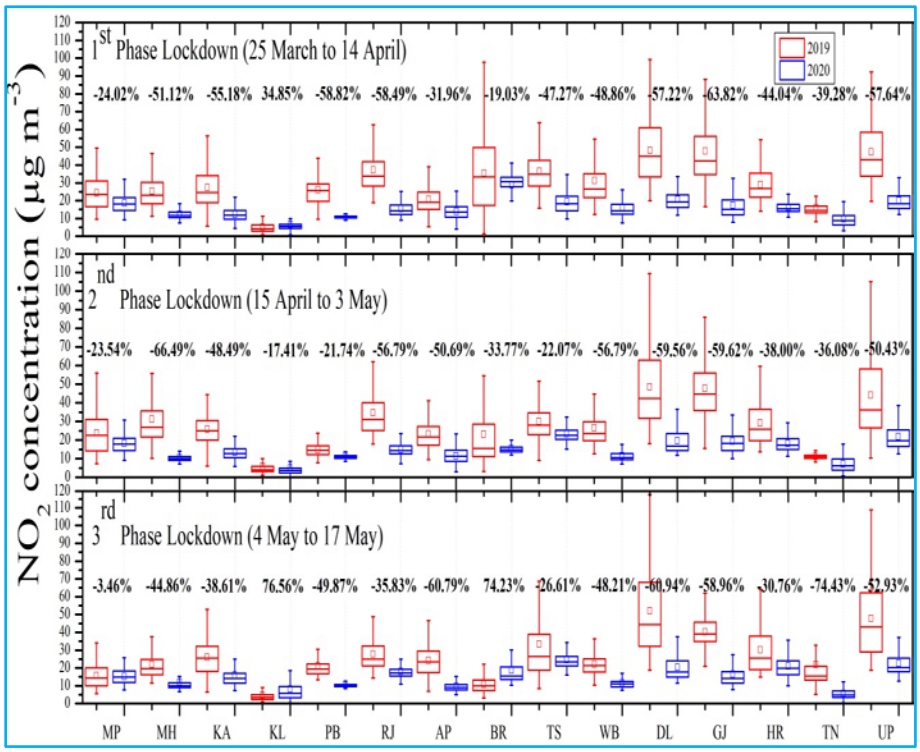


Fig. 4(c). Box-whisker plots of Nitrogen dioxide (NO_2) for 2019 (red color) and 2020 (blue color) for 1st phase (top), 2nd phase (middle) and 3rd phase (bottom) over different states of India during nationwide COVID-19 lockdown period

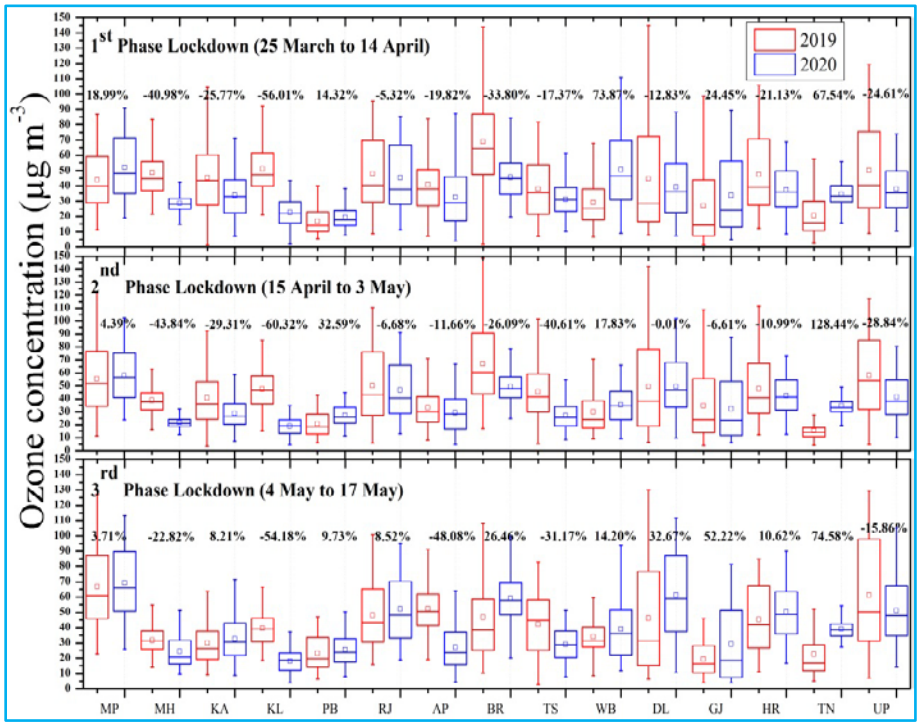


Fig. 4(d). Box-whisker plots of Ozone (O_3) for 2019 (red color) and 2020 (blue color) for 1st phase (top), 2nd phase (middle) and 3rd phase (bottom) over different states of India during nationwide COVID-19 lockdown period

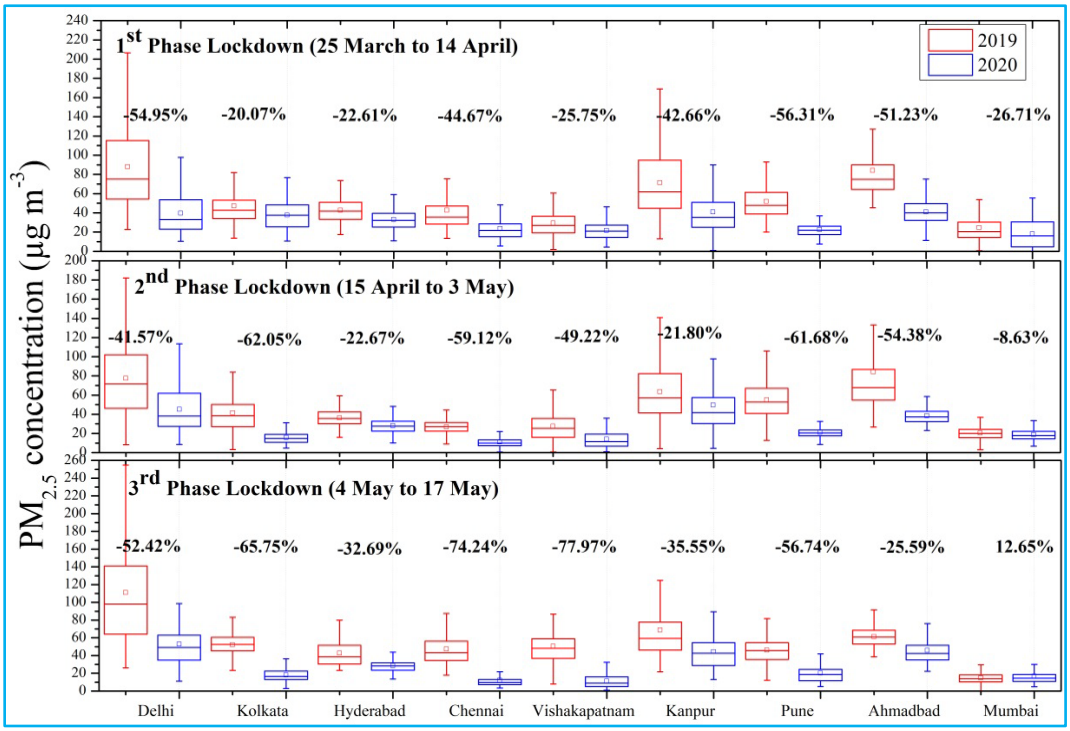


Fig. 5(a). Box-whisker plots of $PM_{2.5}$ 2019 (red color) and 2020 (blue color) for 1st phase (top), 2nd phase (middle) and 3rd phase (bottom) for tire 1 cities of India during nationwide COVID-19 lockdown period

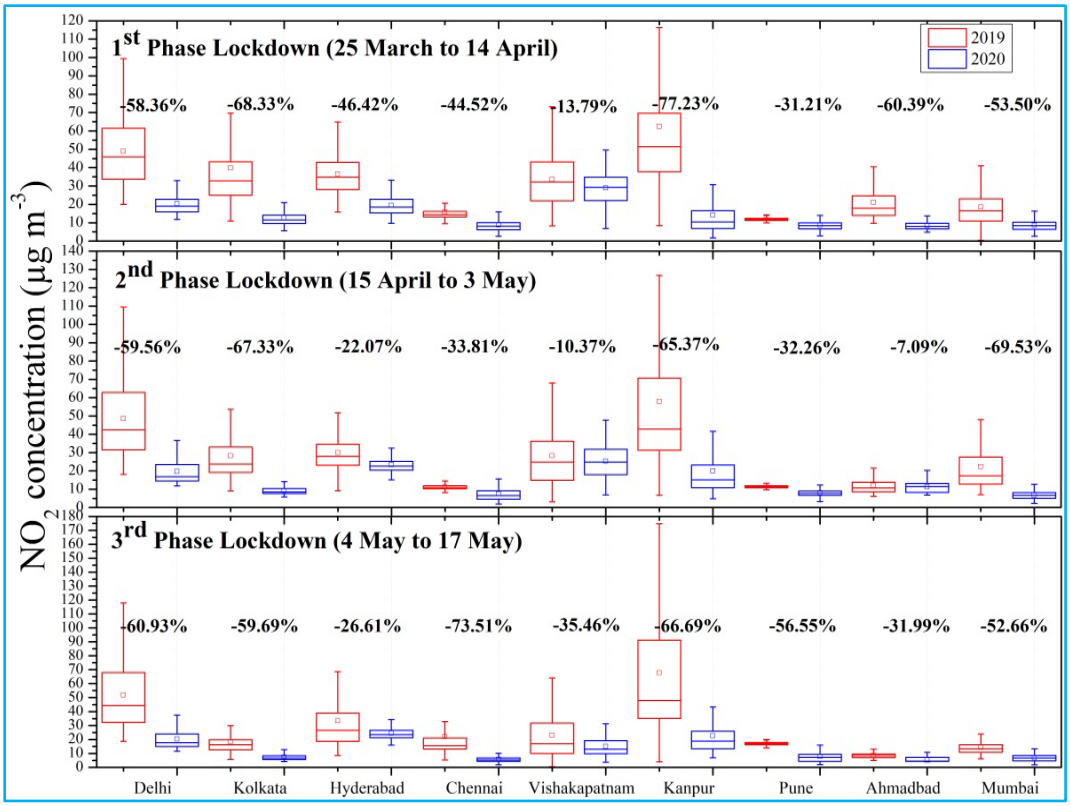


Fig. 5(b). Box-whisker plots of Nitrogen dioxide (NO_2) for 2019 (red color) and 2020 (blue color) for 1st phase (top), 2nd phase (middle) and 3rd phase (bottom) for tire 1 cities of India during nationwide COVID-19 lockdown period

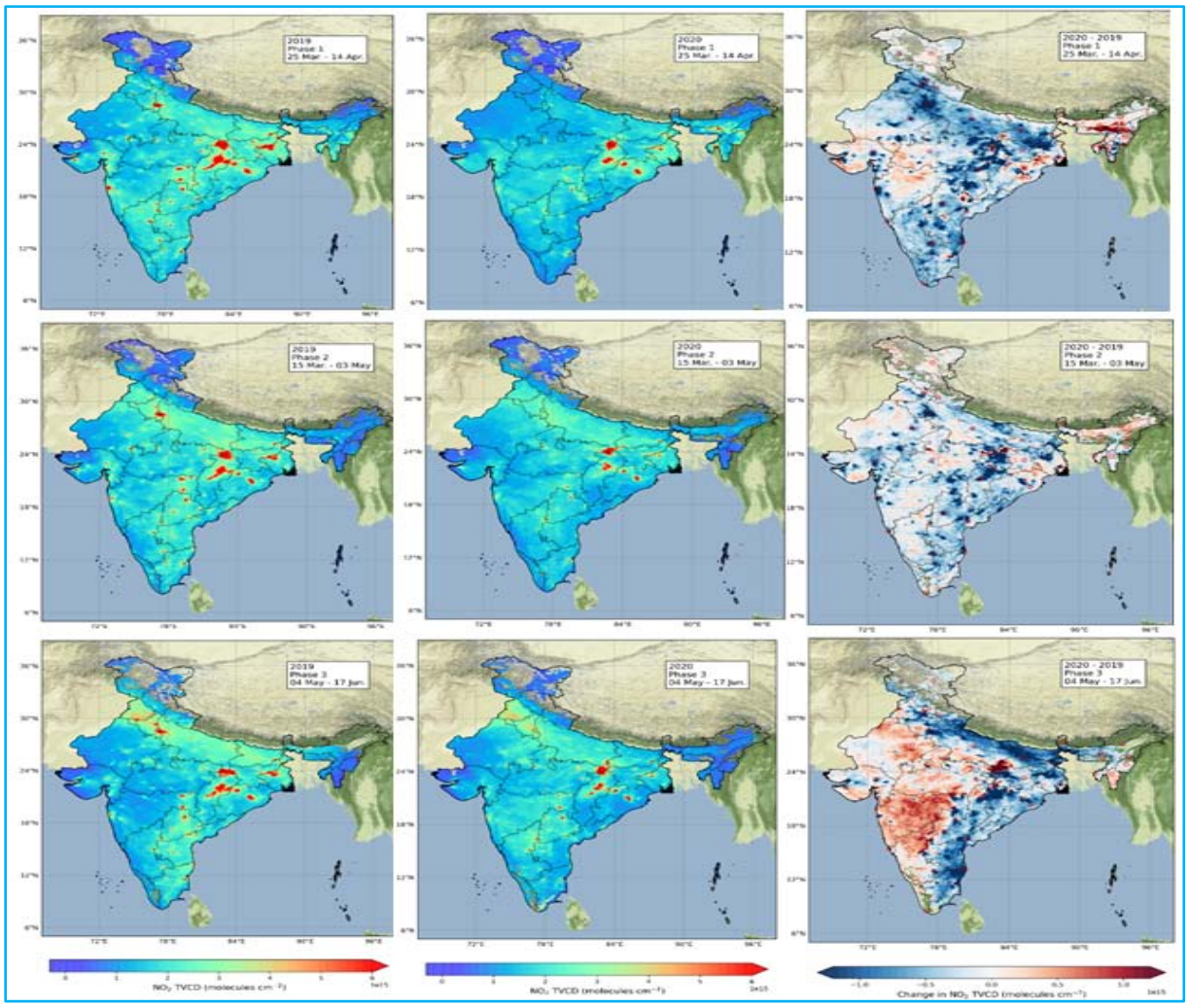


Fig. 6. Terrain map of India showing the NO_2 tropospheric vertical column densities for 2019 (left) and 2020 (center) during phase 1 (top panel), phase 2 (middle panel) and phase 3 (bottom panel). The right panels show the changes in NO_2 TVCD in 2020 with respect to 2019 for the three different phases of lockdown. The open circles in the right panels mark the location of state capitals of India

CO was reduced by 45.08%, 41.51% and 60.45% during lockdown periods of Phase 1, Phase 2 and Phase 3 respectively over India. These atmospheric species have been affected by the reduction in mobility sector shown in Fig. 3 and industrial sector activity during the lockdown periods over entire India. Ozone is increased during Phase 1 (1.52%) and Phase 3 (5.91%) lockdown periods but slightly decreased in Phase 2 (-8.29%) as shown in Fig. 1. The ozone chemistry is highly non-linear in the pre-monsoon time of different states of India, its production is in a NO_X saturated regime due to the relative lack of HO_X radicals (Seinfeld *et al*., 2012). Besides, reduction of fresh NO emissions alleviates ozone titration (Seinfeld *et al*., 2012). Thus, a reduction of NO_X leads to an increase in Ozone (Chate *et al*., 2014; Seinfeld *et al*., 2016).

We further extended our analysis of surface concentration of $PM_{2.5}$, PM_{10}, NO_2 and O_3covering the different states of India. Figs. 4 (a-d) shows the box-whisker plot of surface concentration of $PM_{2.5}$, PM_{10}, NO_2 and O_3 during Phase 1, Phase 2 and Phase 3 of lockdown periods of 2020 (blue color) and those of 2019 (red color) over Madhya Pradesh (MP), Maharashtra (MH), Karnataka (KA), Kerala (KL), Punjab (PB), Rajasthan (RJ), Andhra Pradesh (AP), Bihar (BR), Telangana (TS), West Bengal (WB), Delhi (DL), Gujarat (GJ), Haryana (HR), Tamil Nadu (TN) and Uttar Pradesh (UP) states of India. The surface concentration of $PM_{2.5}$, PM_{10} and NO_2 were reduced by 3 - 60%, 23 - 65 % and 20 - 64 % as compared to 2019 and 2020 of different states of India during Phase 1 respectively except Kerala (KL) which show increase by about 35% of NO_2 concentration.

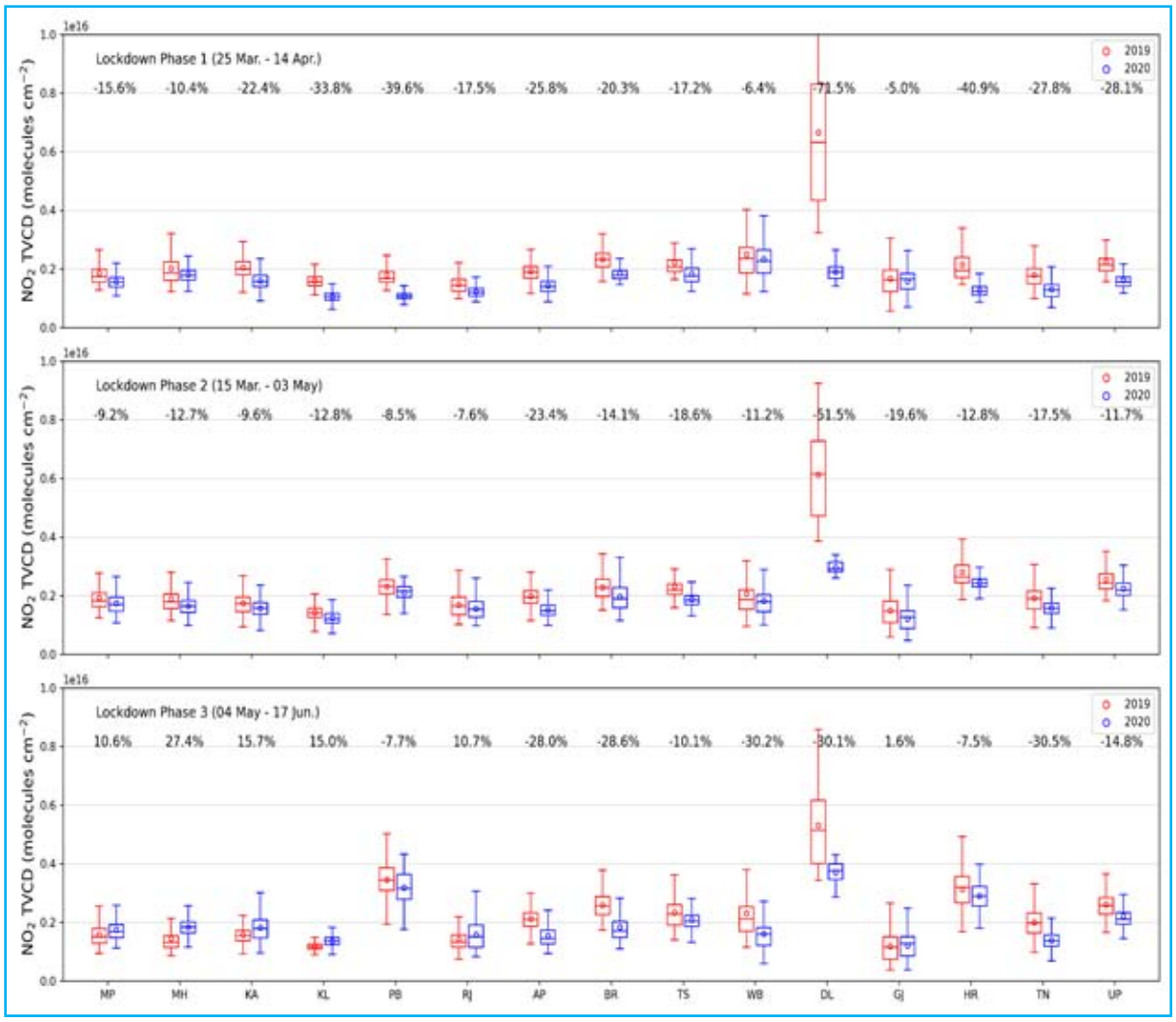


Fig. 7. Box and whiskers plot showing the statistical distribution of the mean NO_2 tropospheric columns over the selected states for the year 2019 (red) and 2020 (blue) for the periods corresponding to lockdown Phase 1 (top panel), Phase 2 (middle panel) and Phase 3 (bottom panel). The numbers above the boxes show the percentage change observed in 2020 relative to the mean in 2019

During Phase 2, the surface concentration of $PM_{2.5}$, PM_{10} and NO_2 were reduced by 17 - 57%, 22 - 57% and 17 - 67% as compared to 2019 and 2020 respectively of different states of India. During Phase 3, as compared to 2019 and 2020 of the surface concentrations of $PM_{2.5}$, PM_{10} and NO_2 were reduced by 19 - 70%, 10 - 64% and 3 - 74% respectively of different states of India except Bihar increase by 74 - 76% of NO_2 and PM_{10} concentration and increase 76% of NO_2 in Kerala. The surface concentration of O_3 was reduce by 5 - 56% as compared to 2019 and 2020 of different states of India during Phase 1 except MP, PB, WB, GJ and TN were increased by 15 - 73%. During Phase 2, the concentration of O_3 was reduced by 1 - 60% of different states of India except MP, PB, WB and TN were increase by 4 - 128%. During Phase 3, the concentration of O_3 was increased by 3 - 74% of different states of India except MH, KL, AP, TS and UP were reduce by 15 - 54%.

Figs. 5(a&b) shows the evolution of surface concentration of $PM_{2.5}$ and NO_2 during Phase 1, Phase 2 and Phase 3 of lockdown periods of 2020 (blue color) and 2019 (red color) over a Tier 1 cities of India (Delhi, Kolkata, Hyderabad, Chennai, Vishakapatnam, Kanpur, Pune, Ahmadabad and Mumbai). It can be seen that the maximum decrease in surface concentration of $PM_{2.5}$ (~55%) and NO_2 (~33%) was observed in Delhi during phase 1 period.

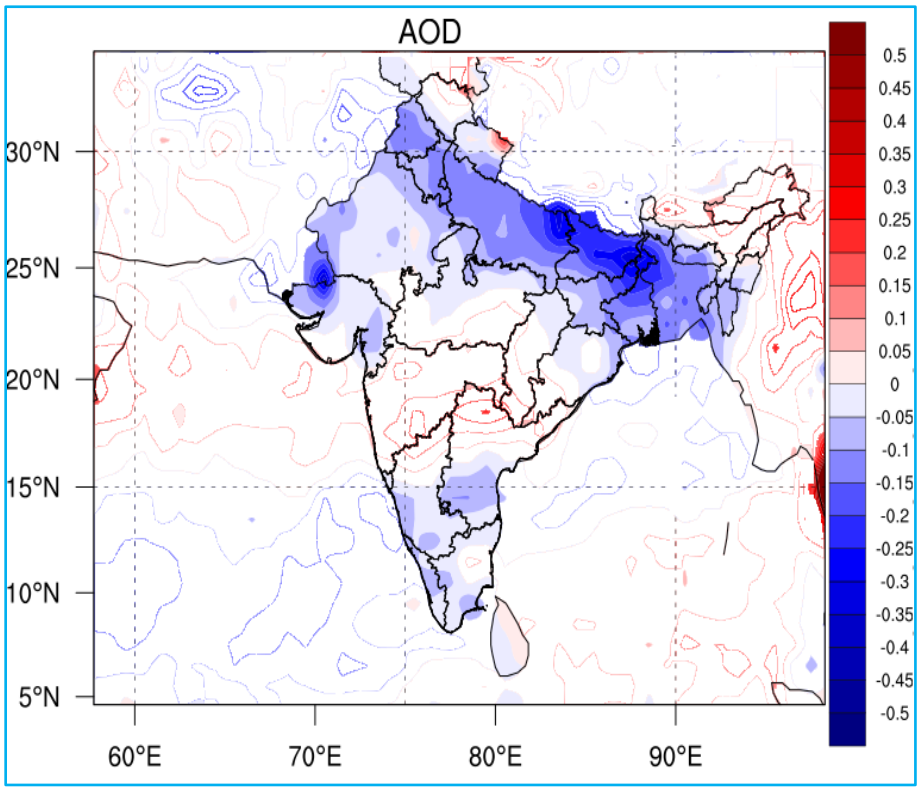


Fig. 8(a). Spatial difference of AOD over India during the lockdown period for Phase 1 of 2020 compared to 2019

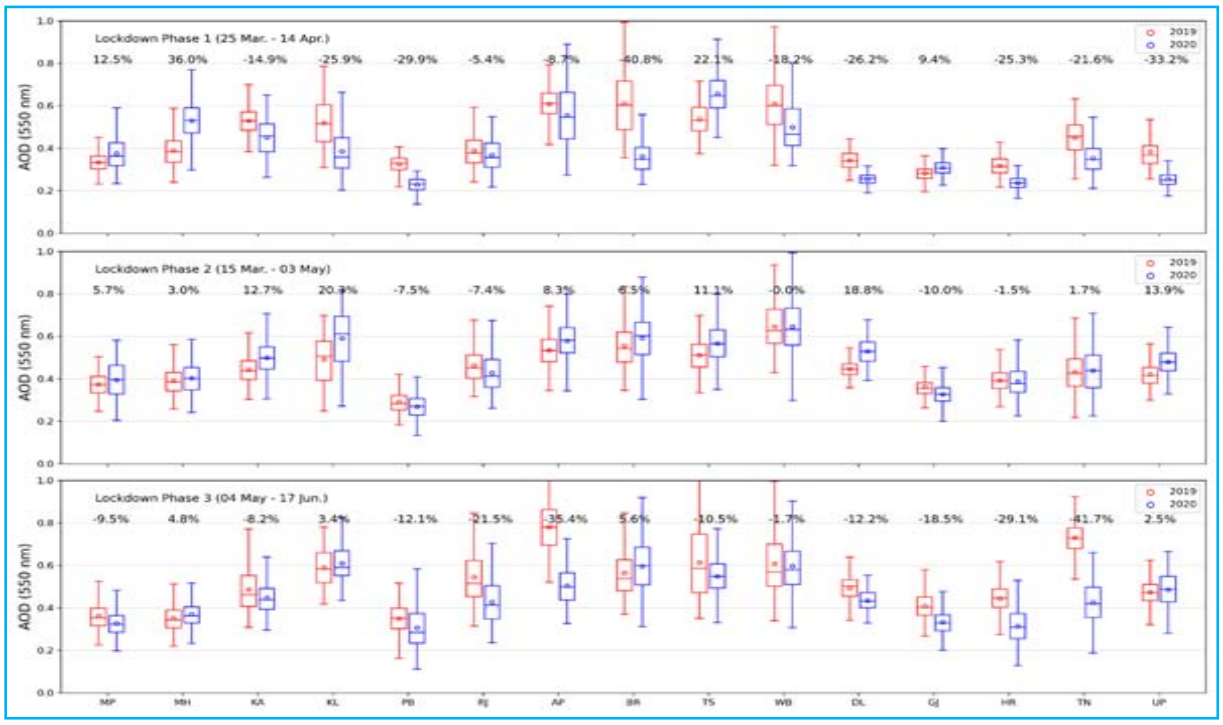


Fig. 8(b). Box and whiskers plot showing the statistical distribution of the mean MAIAC AOD at 550nm over the selected states for the year 2019 (red) and 2020 (blue) for the periods corresponding to lockdown Phase 1 (top panel), Phase 2 (middle panel) and Phase 3 (bottom panel). The numbers above the boxes show the percentage change observed in 2020 relative to the mean in 2019

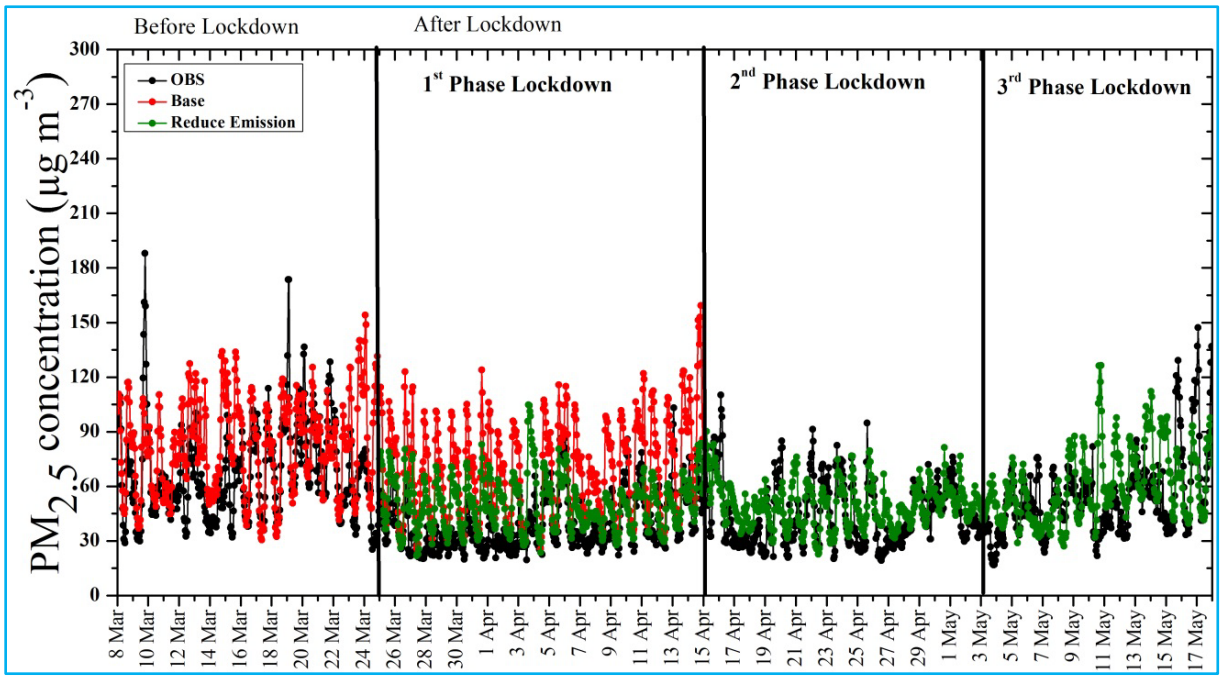


Fig. 9. Comparisons between hourly mean $PM_{2.5}$ forecast without emission reduction (red), hourly mean $PM_{2.5}$ forecast with emission reduction (green) and hourly mean $PM_{2.5}$ observations (black) on day one forecast at 2km horizontal grid spacing over Delhi during 8 March to 17 May, 2020

5. Satellite observation

5.1. *Tropospheric vertical column densities of NO_2*

The tropospheric vertical column densities (TVCD) of NO_2 retrieved by TROPOMI instrument on-board the Sentinel-5P satellite; broadly convey the same message about the impact of COVID-19 related lock-down on the tropospheric air-quality over India, except over Kerala during phase 1. Fig. 6 show the spatial distribution of TVCD of NO_2 averaged for the 3 phases of lock-down for 2019 (left panel) during 2020 lockdown (middle panel) and their difference (right panel). In-general, as compared to 2019, in 2020 TVCD of NO_2 were expectedly lesser, during the lock-down days. The reductions were mainly seen over the Indo-Gangetic plains and also over the other emission pockets (*i.e.*, mainly over the polluted cities) spread across the country. While most of the regions showed a decline in TVCD of NO_2 during 2020, the northeast region of India showed an increase especially during phase 1 of the lock-down. This elevated NO_2 levels especially in northeast region may be associated with increased fire counts due tobiomass burning period (Biswal *et al.*, 2020). During the phase 2, the reduction in TVCD of NO_2, were less spread and were more concentrated mainly over the urban hotspots. The phase 3 of the lock-down depicted a mixed signal. The TVCD of NO_2 was reduced over IGP and eastern parts of India, however that over central-west part of India was seen to have increased with respect to the year 2019. Interestingly, such an increase in columnar NO_2 over the western states (for example MH, MP and KA) is not reflected in the surface measurements of NO_2 [Fig. 4(c)]. The possible reason behind such a contrasting tendency in NO_2 over the western part of India could be explored further in a separate study.

In Fig. 7, we analyze the state-wise averaged TVCD of NO_2 during lockdown period of 2020 and compared with the TVCD of NO_2 during the year 2019 for the same duration. In-general, maximum reductions in TVCD of NO_2 (30-71%) were seen over the national capital, New Delhi. During the 1st phase of the lock-down the state-wise reduction in columnar NO_2 were between 6.4% and 71.5%, while that during the second phase columnar NO2stabilized down between 7.6% and 51.5%. As seen in Fig. 7, the 3rd phase of the lock-down showed a mixed signal with TVCD of NO_2 changing from -30.2% to +15.7%. Interestingly, the states in the central-west part of India (MH, MP, KP, GJ and RJ) showed an increase in TVCD of NO_2 as compared to the previous year.

5.2. *Aerosol Optical Depth (AOD)*

In addition to the columnar NO_2, we also performed analyses of the columnar aerosol optical depth (AOD)

TABLE 1

Performance statistics over Delhi

State	Variables	2 km					
		MB	NMB (%)	NMFB (%)	NMFE (%)	RMSE	R
Delhi	Before Lockdown	15.7	23.6	21.1	30.8	30.4	0.5
	1st Phase Lockdown without reduce emission	31.0	79.2	56.7	57.1	37.8	0.6
	1st Phase Lockdown reduce emission	11.2	28.8	25.2	33.2	19.1	0.5
	2nd Phase Lockdown reduce emission	5.0	11.2	10.6	26.2	15.6	0.6
	3rd Phase Lockdown reduce emission	6.7	12.7	12.0	31.7	24.5	0.4

from MODIS over the Indian region for the same time period. The details of the datasets used in this analysis can be found in section 2. Fig. 8(a) shows the spatial difference of AOD over India during the lockdown period of 2020 compared to 2019. It can be seen that Aerosol loading was significantly reduced over the India region and particularly large reduction is seen over the IGP region. Fig. 8(b) shows the state-wise averaged TVCD of AOD during lockdown period of 2020 and compared with the TVCD of AOD during year 2019. During the 1st phase of the lock-down, most of the states depicted reduced AOD in 2020 compared to 2019, with reduction ranging between 5-40%. In the 2nd phase of the lock-down, barring the states in the western part of India (PB, HR and GJ), the AOD showed increments above the corresponding 2019 levels of around 3-20%. During the 3rd phase of the lock-down, AOD again was seen to be generally lesser than its 2019 values by around 6 to 41%. AOD is an integrated effect of natural and anthropogenic aerosols. The increments in AOD could be associated with the perturbed natural aerosols as well. The possible reasons behind such a response of AOD to the lock-down related restrictions on anthropogenic activities could be investigated further using numerical models.

6. Model results

Fig. 9 illustrates the comparative analyses of hourly mean $PM_{2.5}$ forecast without emission reduction (red) and with emission reduction (green) and observed hourly mean $PM_{2.5}$ observations (black) on day one forecast at 2km horizontal grid spacing over Delhi during 8 March to 17 May, 2020. The observed $PM_{2.5}$ mass concentrations averaged over all the CPCB stations at Delhi shows higher levels before the lockdown period (8th to 24th March, 2020) as compared to those during 1st, 2nd and 3rd phases of lockdown periods. Hourly mean forecasted values of $PM_{2.5}$ mass concentrations with business as usual (without emission reduction-red) before the lockdown (1st phase) periods corroborates the model ability of predictions during the normal days of business as usual (before lockdown or previous year 2019 of same period). Nevertheless, during 1st phase of lockdown, model simulated $PM_{2.5}$ shows over estimation to those of observed $PM_{2.5}$ mass concentrations and over estimation of hourly forecast values of $PM_{2.5}$ to those of without reduction of emissions. Model simulated hourly mean values of $PM_{2.5}$ mass concentrations with emission reduction (green) and hourly mean $PM_{2.5}$ observations (black) over Delhi during 2nd and 3rd phases of lockdown period are by and large in agreement except few peaks either in observed or in simulated results during these lockdown periods. Based on the observed reduction in the surface mobility data (Fig. 3) we reduced the emissions of $PM_{2.5}$, PM_{10}, CO, SO_2, BC, OC and NMVOCs and NO_X by 75% during all the three phases of lockdown. After reducing the emissions, model showed excellent skills in capturing the observed $PM_{2.5}$ concentrations (green line in Fig. 9) over Delhi. The performance statistics for before lockdown, 1st phase lockdown without & with reduced emissions 2nd and 3rd phases of lockdown reduced emissions of the simulated $PM_{2.5}$ mass concentrations over Delhi are evaluated by examining the mean bias (MB), Pearson's correlation coefficient (R), normalized mean fractional bias (NMFB) and normalized mean fractional error (NMFE) (Table 1). Table 1 reveals that $PM_{2.5}$ simulations performed close to excellent criteria for before lockdown, 1st, 2nd and 3rd phases of lockdown reduce emissions as the NMFE is within 33.2%.

7. Conclusions

The paper presents the surface and satellite measurements made during the Phase 1 (25 March to 14 April), Phase 2 (15 April to 3 May) and Phase 3 (3 May to 17May) of lockdown periods of 2020 and compare these results with the observations available for the same locations and periods during 2019 over India. The comparative analysis are performed for Indian states and Tier 1 megacities and reports the changes in the surface

concentration of CO, $PM_{2.5}$ and PM_{10}, O_3 and satellite retrieved columnar NO_2. Surface $PM_{2.5}$ was reduced by 30.59%, 31.64% and 37.06%, PM10 by 40.64%, 44.95% and 46.58% and CO by 45.08%, 41.51% and 60.45% as well as columnar NO_2 by 46.34%, 45.82% and 39.58% as compared to 2019 and 2020 during lockdown periods of Phase 1, Phase 2 and Phase 3 respectively over India. The reduction in $PM_{2.5}$, PM_{10}, CO and columnar NO_2 were on account of restricted transports mobility and industrial activity during the lockdown periods over India.

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References

Bauwens, M., Compernolle, S.,Stavrakou, T., Müller, J. F., van Gent, J., Eskes, H., Levelt, P. F., van der A., R., Veefkind, J. P., Vlietinck, J., Yu, H. and Zehner, C., 2020, "Impact of Coronavirus Outbreak on NO2 Pollution Assessed Using TROPOMI and OMI Observations", *Geophysical Research Letters*,**47**, 11, e2020GL087978. doi : https://doi.org/10.1029/2020GL087978.

Biswal, Akash, Singh, Tanbir, Singh, Vikas, Ravindra, Khaiwal and Mor.Suman, 2020, "COVID-19 Lockdown and Its Impact on Tropospheric NO_2 Concentrations over India Using Satellite-Based Data", *Heliyon*, **6**, 9, e04764. doi : 10.1016/j.heliyon.2020.e04764.

Chate, Dilip, Ghude, Sachin,Beig, G., Mahajan, Anoop, Jena, Chinmay, Reka, Srinivas, Dahiya, Anita and Kumar, Nandini, 2014, "Deviations from the O_3-NO-NO_2 Photo-Stationary State in Delhi, India", *Atmospheric Environment*, **96**, 353-358. doi : 10.1016/j.atmosenv.2014.07.054.

CPCB, 2020, "Annual Report", available at https://cpcb.nic.in/annual-report.php (last access : 12 November 2021).

Dantas, Guilherme, Bruno Siciliano, Bruno Boscaro França, Cleyton M. da Silva and Graciela Arbilla, 2020, "The Impact of COVID-19 Partial Lockdown on the Air Quality of the City of Rio de Janeiro, Brazil", *The Science of the Total Environment*, **729**, 139085. doi : 10.1016/j.scitotenv.2020.139085.

Dhaka, Surendra, Chetna, K., Kumar, Vinay, Panwar, Vivek, Dimri, A. P., Singh, Narendra, Patra, Prabir K., Matsumi, Yutaka, Takigawa, Masayuki, Nakayama, Tomoki, Yamaji, Kazuyo, Kajino, Mizuo, Misra, Prakhar and Hayashida, Sachiko, 2020, "$PM_{2.5}$ Diminution and Haze Events over Delhi during the COVID-19 Lockdown Period : An Interplay between the Baseline Pollution and Meteorology", *Scientific Reports*, **10**, 1, 13442. doi : 10.1038/s41598-020-70179-8.

Fadnavis, S., Buchunde, P., Ghude, Sachin D., Kulkarni, S. H. and Beig, G., 2011, "Evidence of Seasonal Enhancement of CO in the Upper Troposphere over India", *International Journal of Remote Sensing*, **32**, 22, 7441-52. doi : 10.1080/01431161.2010.523733.

Geffen, Van, J. H. G. M, Eskes, H. J. and J. P. Boersma, K. F. Maasakkers, J. D. and Veefkind, 2018, "TROPOMI ATBD of the Total and Tropospheric NO_2 Data Products Jos van Geffen", (1.2.0).

Ghude, Sachin D., Beig, G., Kulkarni, Pavan S., Kanawade, Vijay P., Fadnavis, Suvarna, Remedios, John J. and Kulkarni, S. H., 2011, "Regional Co Pollution over the Indian-Subcontinent and Various Transport Pathways as Observed by Mopitt", *International Journal of Remote Sensing*, **32**, 21, 6133-48. doi : 10.1080/01431161.2010.507796.

Ghude, Sachin D., Chate, D. M., Jena, C.,Beig, G., Kumar, R., Barth, M. C., Pfister, G. G., Fadnavis, S. and Pithani, Prakash, 2016, "Premature Mortality in India Due to PM 2.5 and Ozone Exposure", *Geophysical Research Letters*, **43**, 9, 4650-58. doi : 10.1002/2016GL068949.

Ghude, Sachin D., Fadnavis, S., Beig, G., Polade, S. D. and R. J. van der A., 2008, "Detection of Surface Emission Hot Spots, Trends and Seasonal Cycle from Satellite-Retrieved NO_2 over India", *Journal of Geophysical Research*, 113(D20):D20305. doi : 10.1029/2007JD009615.

Ghude, Sachin D., Jain, S. L., Arya, B. C., Beig, G., Ahammed, Y. N., Kumar, Arun and Tyagi, B., 2008, "Ozone in Ambient Air at a Tropical Megacity, Delhi: Characteristics, Trends and Cumulative Ozone Exposure Indices", *Journal of Atmospheric Chemistry*, **60**, 3, 237-52. doi : 10.1007/s10874-009-9119-4.

Ghude, Sachin D., Kumar, Rajesh, Jena, Chinmay, Debnath, Sreyashi, Kulkarni, Rachana G., Alessandrini, Stefano, Biswas, Mrinal, Kulkrani, Santosh, Pithani, Prakash, Kelkar, Saurab, Sajjan, Veeresh, Chate, D. M., Soni, V. K., Singh, Siddhartha, Ravi S. Nanjundiah and Rajeevan, M., 2020, "Evaluation of $PM_{2.5}$ Forecast Using Chemical Data Assimilation in the WRF-Chem Model : A Novel Initiative under the Ministry of Earth Sciences Air Quality Early Warning System for Delhi, India", *Current Science*, **118**, 11, 1803-1815. doi : 10.18520/cs/v118/i11/1803-1815.

Ghude, Sachin D., Pfister, Gabriele G., Jena, Chinmay Kumar, Emmons, Louisa K., Kumar, Rajesh and Ronald J. van der A., 2012, "Satellite Constraints of Nitrogen Oxide (NOx) Emissions from India Based on OMI Observations and WRF-Chem Simulations", *Geophysical Research Letters*, **40(x)**, 423-428. doi : 10.1029/2012gl053926.

Ghude, Sachin D., Pfister, Gabriele G., Jena, Chinmay, R. J. Van Der A., Emmons, Louisa K. and Kumar, Rajesh, 2013, "Satellite Constraints of Nitrogen Oxide (NOx) Emissions from India

Based on OMI Observations and WRF-Chem Simulations", *Geophysical Research Letters*,**40**, 2, 423-28. doi : 10.1029/ 2012GL053926.

Ghude, Sachin D., R. J. Van der A., Beig, G., Fadnavis, S. and Polade, S. D., 2009, "Satellite Derived Trends in NO2 over the Major Global Hotspot Regions during the Past Decade and Their Inter-Comparison", *Environmental Pollution*, **157**, 6, 1873-78. doi : 10.1016/j.envpol.2009.01.013.

Gupta, Pawan, Lorraine A. Remer, Falguni Patadia, Robert C. Levy and Sundar A. Christopher, 2020, "High-Resolution Gridded Level 3 Aerosol Optical Depth Data from Modis", *Remote Sensing*, **12**, 17, 1-22. doi : 10.3390/rs12172847.

Jain, S. L., Kulkarni, Pavan S., Arya, B. C., Kumar, Arun,Ghude, Sachin D. and Singh, Pankaj, 2007, "Altitudinal Variation of Surface Aerosol with Change in Site : A Comparative Study", *Indian Journal of Radio and Space Physics*, **36**, 6, 571-575.

Jena, Chinmay, Ghude, Sachin D., Beig, G., Chate, D. M., Kumar, Rajesh, Pfister, G. G., Lal, D. M.,Surendran, Divya E., Fadnavis, S. and R. J. van der A. 2015, "Inter-Comparison of Different NOX Emission Inventories and Associated Variation in Simulated Surface Ozone in Indian Region",*Atmospheric Environment*, **117**, 61-73. doi : 10.1016/j.atmosenv.2015. 06.057.

Jena, Chinmay, Ghude, Sachin D., Kumar, Rajesh, Debnath, Sreyashi, Govardhan, Gaurav, Soni, Vijay K., Kulkarni, Santosh H., Beig, G., Nanjundiah, Ravi S. and Rajeevan, M., 2021, "Performance of High Resolution (400 m) $PM_{2.5}$ Forecast over Delhi", *Scientific Reports*, **11**, 1, 1-9. doi : 10.1038/s41598-021-83467-8.

Jena, Chinmay, Ghude, Sachin, Kulkarni, Rachana, Debnath, Sreyashi, Kumar, Rajesh, Soni, Vijay Kumar, Acharja, Prodip, Kulkarni, Santosh, Khare, Manoj, Kaginalkar, Akshara, Chate, Dilip, Ali, Kaushar, Nanjundiah, Ravi and Rajeevan, Madhavan, 2020, "Evaluating the Sensitivity of Fine Particulate Matter (PM_{2.5}) Simulations to Chemical Mechanism in Delhi", *Atmospheric Chemistry and Physics Discussions*, **3**, 1-28. doi : 10.5194/acp-2020-673.

Kumar, Arun and Dash, S. K., 2004, "Study of Air Quality at an Industrial Area in Coastal India", *MAUSAM*, **55**, 4, 611-624.

Kumar, V., Beirle, S., Dörner, S., Mishra, A. K., Donner, S., Wang, Y., Sinha, V. and Wagner, T., 2020, "Long-Term MAX-DOAS Measurements of NO$_{2}$, HCHO and Aerosols and Evaluation of Corresponding Satellite Data Products over Mohali in the Indo-Gangetic Plain", *Atmospheric Chemistry and Physics*, **20**, 22, 14183-235. doi : 10.5194/acp-20-14183-2020.

Ogen, Yaron, 2020, "Assessing Nitrogen Dioxide (NO2) Levels as a Contributing Factor to Coronavirus (COVID-19) Fatality", *Science of The Total Environment*, 726:138605. doi : https:// doi.org/10.1016/j.scitotenv.2020.138605.

Palve, S. N., Nemade, P. D. and Ghude, S. D., 2018, "MOPITT Carbon Monoxide Its Source Distributions, Interannual Variability and Transport Pathways over India during 2005-2015", *International Journal of Remote Sensing*, **39**, 18, 5952-64. doi : 10.1080/01431161.2018.1452076.

Pattnaik, Sandeep, 2019, "Review_Recent Develop", *MAUSAM*, **3**, 453-464.

Pawar, Pooja V., Sachin D. Ghude, Chinmay Jena, Andrea Móring, Mark A. Sutton, Santosh Kulkarni, Deen Mani Lal, Divya Surendran, Martin Van Damme, Lieven Clarisse, Pierre-François Coheur, Xuejun Liu, Gaurav Govardhan, Wen Xu, Jize Jiang and Tapan Kumar Adhya, 2021, "Analysis of Atmospheric Ammonia over South and East Asia Based on the MOZART-4 Model and Its Comparison with Satellite and Surface Observations", *Atmospheric Chemistry and Physics*, **21**, 8, 6389-6409. doi : 10.5194/acp-21-6389-2021.

Peshin, Sunil Kumar, Sinha, Priyanka and Bisht, Amit, 2017, "Impact of Diwali Firework Emissions on Air Quality of New Delhi, India during 2013-2015", *MAUSAM*, **68**, 1, 111-118.

Seinfeld, J. H., Pandis, S. N., 2012, "Atmospheric Chemistry and Physics : From Air Pollution to Climate Change", *Wiley*, available at https://books.google.co.in/books?id=J3s30hwn_ K0C (last access : 12 November 2021).

Sharma, Shubham, Mengyuan Zhang, Anshika, Jingsi Gao, Hongliang Zhang and Sri Harsha Kota, 2020, "Effect of Restricted Emissions during COVID-19 on Air Quality in India", *The Science of the Total Environment*, 728:138878. doi : 10.1016/ j.scitotenv.2020.138878.

Shi, Xiaoqin and Brasseur, Guy P., 2020, "The response in air quality to the reduction of chinese economic activities during the COVID-19 outbreak", *Geophysical Research Letters*, 47(11) : e2020 GL088070. doi : https://doi.org/10.1029/2020GL088070.

Singh, Jagadish and Kant, Surya, 2006, "Radiation fog over North India during winter from 1989-2004", **57**.

van Geffen, J. H. G. M., K. F. Boersma, M. Van Roozendael, F. Hendrick, E. Mahieu, I. De Smedt, M. Sneep and J. P. Veefkind, 2015, "Improved Spectral Fitting of Nitrogen Dioxide from OMI in the 405-465 Nm Window", *Atmospheric Measurement Techniques*, **8**, 4, 1685-99. doi : 10.5194/amt-8-1685-2015.

Veefkind, J. P., Aben, I., McMullan, K., Förster, H., Vries, J. de, Otter, G., Claas, J., Eskes, H. J., Haan, J. F. de, Kleipool, Q.,Weele, M. van, Hasekamp, O., Hoogeveen, R., Landgraf, J., Snel, R., Tol, P., Ingmann, P., Voors, R., Kruizinga, B.,Vink, R., Visser, H. and Levelt, P. F., 2012, "TROPOMI on the ESA Sentinel-5 Precursor: A GMES Mission for Global Observations of the Atmospheric Composition for Climate, Air Quality and Ozone Layer Applications", *Remote Sensing of Environment*, **120**, 70-83. doi : https://doi.org/10.1016/j.rse.2011.09.027.

Zhang, M., Katiyar, A., Zhu, S., Shen, J., Xia, M., Ma, J., Kota, S. H., Wang, P. and Zhang, H., 2021, "Impact of Reduced Anthropogenic Emissions during COVID-19 on Air Quality in India", *Atmospheric Chemistry and Physics*, **21**, 5, 4025-4037. doi : 10.5194/acp-21-4025-2021.