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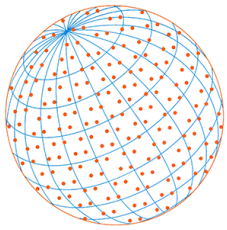

Aerosol and Air Quality Research

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Impacts of COVID-19 on Air Quality in India

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ABSTRACT

The COVID-19 pandemic spread all over the world in early 2020. India imposed a nationwide lockdown on March 25, 2020, for more than a month to contain the COVID-19 infection. During the nationwide lockdown, transport, industries, and commercial activities were suspended, except for essential services. We made a detailed analysis of the impacts of COVID-19 on air quality in India by using the data from more than 200 Continuous Ambient Air Quality Monitoring Stations (CAAQMS) and reported a change in the National Air Quality Index (NAQI), spatial distribution and concentration levels of PM_{10}, $PM_{2.5}$, CO, NO_2, SO_2, and O_3 from January to April 2020 nationwide and in five major cities, namely, Delhi, Mumbai, Kolkata, Chennai, and Hyderabad. We defined the period between February 25 to March 24, 2020, as 'before lockdown' and March 25 to April 30, 2020, as 'during lockdown'. The NAQI and satellite visual maps of AOD, NO_2, CO, and SO_2 from January to April 2020 showed a significant decrease in air pollution levels in India. The average concentration levels of PM_{10}, $PM_{2.5}$, CO, NO_2, and SO_2 have decreased nationwide by 33, 34, 21, 47, and 21%, respectively, during the nationwide lockdown compared to their concentration levels before the lockdown. While comparing their concentration levels of the nationwide lockdown period with those observed in April 2019 at the same CAAQMS, it was found that the nationwide average concentration levels of PM_{10}, $PM_{2.5}$, CO, NO_2, and SO_2 were decreased by 53, 45, 27, 54, and 35%, respectively. The trends of decreasing air pollutants during the lockdown in five major cities were almost the same as nationwide. The concentration levels of O_3 have shown an increasing trend from January–April 2020 including during the nationwide lockdown. The COVID-19 has provided a rare opportunity for India for the collection of air pollution baseline data which could be useful in the formulation of air pollution reduction policies in the future.

Keywords: Air quality, Lockdown, COVID-19, Air quality index, Particulate matters

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1 INTRODUCTION

India is facing serious air pollution problems. The air quality in most Indian cities has been deteriorating over the past many years (WHO, 2016; Bernard and Kazmin, 2018; Chowdhury *et al*, 2019; HEI, 2019; Mishra, 2019). The emissions of air pollutants from anthropogenic sources, such as transport, industry, power generation, construction, residential, and commercial activities have been increasing significantly during the past many years (Guttikunda *et al*., 2014; Kurokawa and Ohara, 2020). Open burning of municipal waste and agricultural residuals are adding extra emission burden of air pollutants in the region which significantly deteriorates air pollution problems, especially during winter when stagnant meteorology promotes accumulation of air pollutants in the atmosphere (Badarinath *et al*., 2009; Rastogi *et al*., 2016; Kumari *et al*., 2017; Liu *et al*., 2018; Bray *et al*., 2019; Sawlani *et al*., 2019). Increasing air pollution in India is significantly impacting air quality, increasing disease burdens, and incurring economic loss (Bhome, 2012; Rizwan *et al*., 2013; Bunett *et al*., 2018; Gordon *et al*., 2019; Reddy and Roberts, 2019).

The Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) or commonly known as coronavirus disease 2019 (COVID-19) pandemic, emerged from the city of Wuhan, China, in December 2019, spread around the world in early 2020. Many countries imposed the lockdown

in the cities, as well as, nationwide to minimize transmission of the COVID-19 infection. In the lockdown, commercial activities including transport, industries, and public gathering places were closed. As a result, the emissions of air pollutants were significantly decreased in many parts of the world (He *et al.*, 2020; Patel and Stevens, 2020; Sulaman *et al.*, 2020). For example, the total nitrogen dioxide (NO_2) column was reduced by about 40 percent (%) over the Chinese cities and 20-38% over Western Europe (Bauwens *et al.*, 2020). Sicard *et al.* (2020) reported a reduction in oxides of nitrogen (NO_x) and particulate matters (PM) by about 56% and 42%, respectively, in Chinese cities. In the United States and Spain, a decrease in NO_2 concentrations by 25.5% and 50–62% were observed, respectively, (Berman and Ebisu, 2020; Baldasano, 2020).

India imposed a nationwide lockdown from March 25, 2020, onward for a few months to minimize the spread of the COVID-19 infection. During the lockdown, all transport services (road, airplane, and railway), schools, colleges, industrial operations, hotels, restaurants, shopping malls, markets were suspended, except for essential services (CPCB, 2020). The real-time National Air Quality Index (NAQI) published by the Central Pollution Control Board (CPCB, https://app.cpcbccr.com/AQI_India/) and CPCB's preliminary report on the NAQI suggested that the air pollution in India has been substantially decreased during the nationwide lockdown. This encouraged us to study in detail the impacts of the COVID-19 on air quality in India.

Several studies have been published on the impacts of the COVID-19 on air pollution level in India (Jain and Sharma, 2020; Kumar, 2020; Kumari and Toshniwal, 2020; Majumdar, 2020; Mahato *et al.*, 2020; Sharma *et al.*, 2020; Shehzad *et al.*, 2020; Singh and Chauhan, 2020). However, most of the studies have reported measurements of air pollution in metro cities and urban regions. In this article, we reported the nationwide air pollution measurements, using the data from more than 200 Continuous Ambient Air Quality Monitoring Stations (CAAQMS) located all over the country, from January to April 2020, the trends in the change in NAQI in Indian states, the spatial distribution of concentrations of Aerosol Optical Depth (AOD) and Carbon Monoxide (CO), NO_2, Sulfur Dioxide (SO_2), and Ozone (O_3) using the satellite visual maps, and made a comprehensive statistical analysis of the change in the concentrations of PM (both PM_{10}, $PM_{2.5}$), CO, NO_2, SO_2, and O_3 at nationwide and in major Indian cities, namely, Delhi, Mumbai, Kolkata, Chennai, and Hyderabad. For a better understanding of the impacts of the nationwide lockdown on the air pollution level, we defined, the period from February 25, 2020, to March 24, 2020, as "before lockdown" and from March 25, 2020, to April 30, 2020, as "during lockdown". We compared time-series and average concentrations of key air pollutants observed from January to April 2020 with those observed from January to April 2019.

2 DATA COLLECTION

2.1 Air Pollutants

India operates a network of 231 CAAQMS located in various parts of the country. Fig. 1 shows a spatial distribution of the CAAQMS network in India, blue dots are the location of each CAAQMS. These CAAQMS are operated by CPCB, State Pollution Control Boards (SPCBs), Delhi Pollution Control Committee (DPCC), and Indian Meteorological Department (IMD). Air pollution data from these CAAQMS acquired at CPCB. For the present study, we downloaded 24-hr averaged data from the CPCB website (https://app.cpcbccr.com/ccr/#/caaqm-dashboard-all/caaqm-landing/data) for PM_{10}, $PM_{2.5}$, CO, NO_2, SO_2, and O_3 for January to April 2019 and January to April 2020. The data from January to April 2019 has been used only for comparison of temporal variations in the concentration levels of air pollutants for 2019 and 2020, while data observed in April 2019 included in statistical analysis for comparison of concentration levels of air pollutants that observed during the nationwide lockdown. We would like to clarify that quality control of data was beyond our reach since these CAAQMS are operated by different organizations and there is no information available on data quality control. However, we assumed that data quality control has been performed by the respective CAAQMS operators.

2.2 National Air Quality Index

CPCB published a real-time NAQI of 231 CAAQMS (https://app.cpcbccr.com/AQI_India/). NAQI is calculated by a weighted average of 8 criteria pollutants, namely, PM_{10}, $PM_{2.5}$, SO_2, NO_2, CO,

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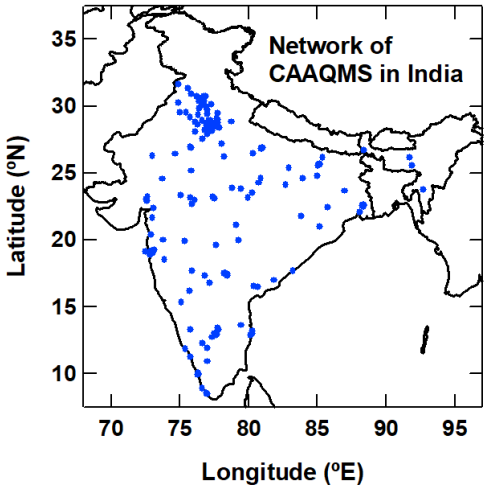

Fig. 1. A network of Continuous Ambient Air Quality Monitoring Stations (CAAQMS) in India. Blue dots are the geographic location (latitude and longitude) of each CAAQMS.

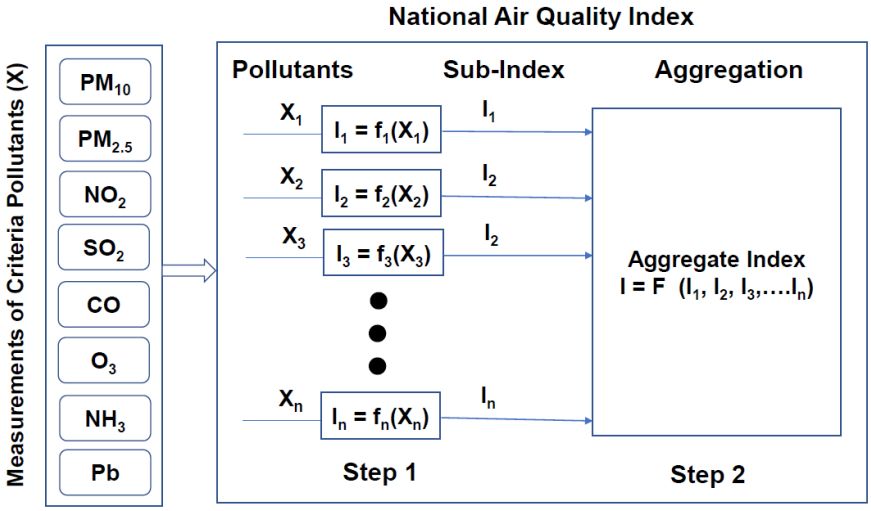

Fig. 2. A flow chart of the systematic scheme used by CPCB for the calculation of National Air Quality Index (NAQI) from measurements of 8 criteria pollutants (CPCB, 2014).

O_3, NH_3, and Lead (Pb) into a single value matrix. The basic scheme used by CPCB for the calculation of NAQI is summarized in Fig. 2. Briefly, NAQI has been calculated in 2 steps. In step 1, the sub-index of each criteria pollutant was calculated, and then in step 2, all sub-indexes were aggregated to a single index. Details of equations used for the calculation of NAQI have been discussed in the Report on National Air Quality Index (CPCB, 2014). For the present study, 24-hour averaged NAQI data was downloaded from the CPCB website from January to April 2020 from the CAAQMS, shown in Fig. 1. If the number of CAAQMS in a city is more than one, one 24-hour averaged NAQI value from all CAAQMS has been published for that city. Also, not all CAAQMS are operated all the time.

2.3 Satellite Visual Maps

Time-averaged visual maps of AOD (AOD at 550 nm, daily 1 degree, MODIS-Aqua MYDO8_D3 v6.1), NO_2 total column (1/cm^2, 30% cloud screened, daily 0.25 degree, OMI OMNO2d v003), CO surface concentration (ppbv, monthly 0.5 × 0.625 degree, MERRA-2 Model M2TMNXCHM v5.12.4), SO_2 surface mass concentration (kg m^{-3}, monthly 0.5 × 0.625 degree, MERRA-2 Model M2TMNXAER v5.12.4), O_3 (Mole Fraction in Air, AIRS-only, daily 1 degree, @700 hPa, AIRS3STD v006), and Incoming Shortwave Flux (W m^{-2}, MERRA-2 Model M2T1NXRAD v5.12.4, 0.5 × 0.625 deg.) were

plotted online on NASA's GIOVANNI website (https://giovanni.gsfc.nasa.gov/giovanni/) from January to April 2020. The geographical domain chosen for satellite visual maps of India was 8N°–35.5N° and 68E°–97E°.

3 RESULT AND DISCUSSION

3.1 NAQI

Air Quality Index is an effective tool to communicate the status of air quality to the public in a single value matrix with its possible impacts on human health and the environment. Fig. 3(a) shows the visual maps of the state-wise spatial distribution of monthly averaged NAQI from January to April 2020. The value of NAQI for each state was calculated by averaging the daily NAQI values of all the CAAQMS located in the state and then it was further averaged to a single value for the state for each month. The average values of NAQI used in Fig. 3(a) for each state have been plotted separately in Fig. 3(b). In Fig. 3(a), the color filled in the states indicates the status of the air quality of the respective states on the NAQI color scale. CPCB categorized the NAQI color scale into six categories with value range and status, as follows: Green (0–50) - Good; Light green (51–100) - Satisfactory; Yellow (101–200) - Moderate; Orange (201–300) - Poor; Red (301–400) - Very poor, and Dark red (401–500) - Severe (https://cpcb.nic.in/national-air-quality-index/). In Fig. 3(a), some states have been shown with grey color because no NAQI data was available for these states.

The state-wise spatial distribution (Fig. 3(a)) and state-wise NAQI (Fig. 3(b)) shows a visible trend in the improvement in air quality status (from bad to good) in each state from January to April 2020. In January and February 2020, the observed air quality status with NAQI range between 201–300 in the states of Bihar, Delhi, Uttar Pradesh, Odisha (not in February), and Assam was categorized as poor. Whereas, during the same months, the air quality status with NAQI range between 101–200 in the states of Odisha, Haryana, Jharkhand, West Bengal, Madhya Pradesh, Rajasthan, Maharashtra, Gujrat, Kerala, and Punjab was categorized as moderate (Fig. 3(b)). While in the rest of the states, namely, Telangana, Chandigarh, Andhra Pradesh, Tamil Nadu, Meghalaya, and Mizoram, the NAQI range was between 50–100, and the air quality status was categorized as satisfactory in January and February 2020 (Fig. 3(b)). In India, the meteorological conditions improved from March onward with increasing surface temperature and vertical mixing which disperse the polluted air. In March 2020, the air quality status in the states of Bihar, Delhi, Uttar Pradesh, Assam, Odisha, Jharkhand, West Bengal, Rajasthan, Maharashtra, and Gujrat was moderate with NAQI ranging between 101 to 200, while in the states of Kerala, Punjab, Karnataka, Telangana, Chandigarh, Andhra Pradesh, Tamil Nadu, Madhya Pradesh, Haryana, Meghalaya, and Mizoram, the air quality status was good or satisfactory, with NAQI ranging in between 0 to 100 (Fig. 3(b)). In April 2020, which was also the nationwide lockdown period, the air quality status in all the states was good or satisfactory, except Uttar Pradesh, Jharkhand, and Odisha where air quality status was still moderate. The reason for this disparity has been discussed later.

Fig. 4 shows the time series for temporal variations in the NAQI observed in 115 Indian cities. The NAQI of Delhi, Mumbai, Kolkata, Chennai, and Hyderabad are highlighted separately to assess the impact of the nationwide lockdown on the air quality status in these cities. The temporal variations in the NAQI in 115 Indian cities including nationwide average and nationwide median show higher NAQI in January, February, until mid-March 2020. The NAQI nationwide average and nationwide median showed a decreasing trend during the observation period. The NAQI values in Indian cities were quite scattered, covering a range from satisfactory to very poor or even severe (Fig. 4). From mid-March to the end of April 2020, the nationwide average and nationwide median of NAQI decreased and maintained below 100 NAQI with satisfactory air quality status. This could be cumulative effects of improvement in air quality due to meteorological conditions and simultaneously reduction of emissions of air pollutants due to the nationwide lockdown. The NAQI in Delhi was higher from January to mid-March 2020 as compared to Mumbai and Kolkata. The NAQI in Delhi, Mumbai, and Kolkata were higher than the nationwide NAQI average, whereas, in Chennai and Hyderabad the NAQI was lower than the nationwide NAQI average (Fig. 4).

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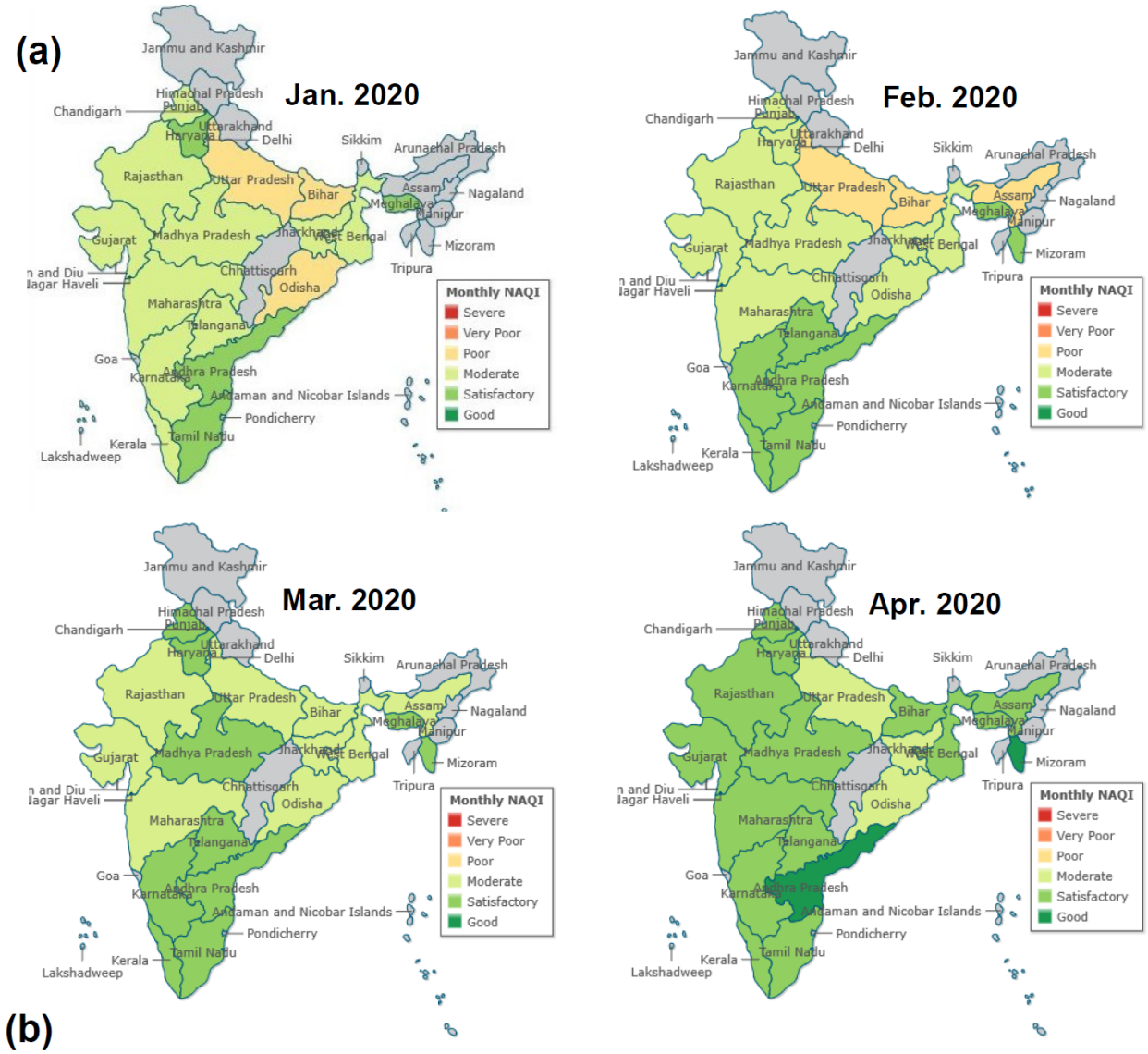

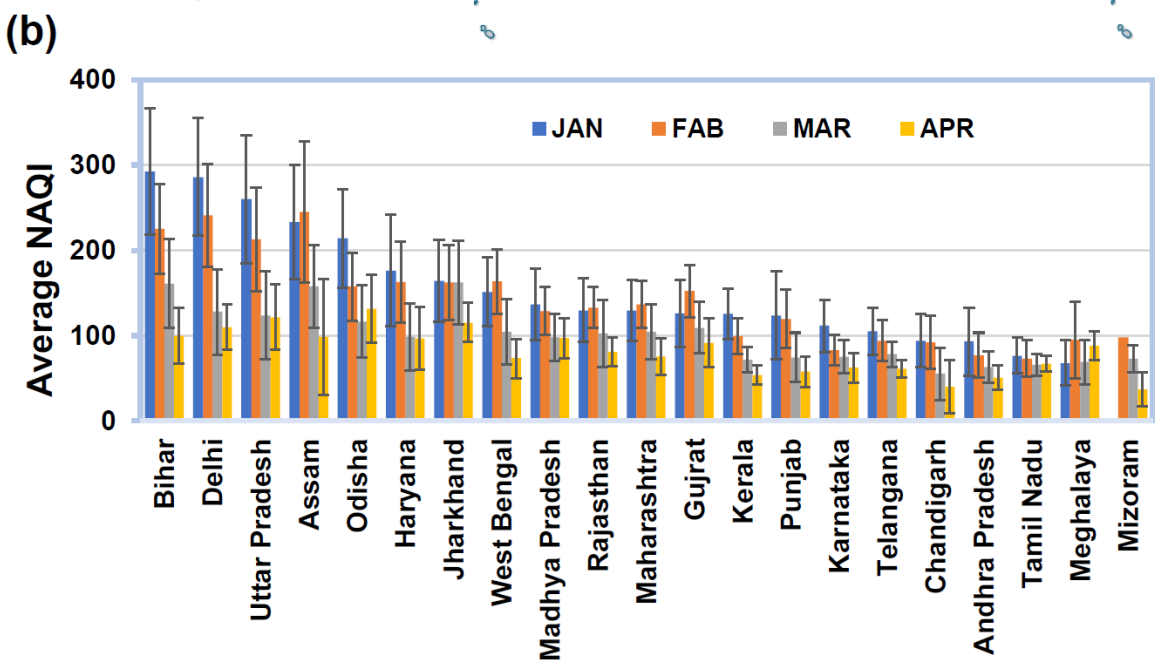

Fig. 3. National Air Quality Index (NAQI) in India from January to April 2020 (a) visual maps of the state-wise spatial distribution of monthly averaged NAQI and (b) monthly average ±1 standard deviation (SD) for each state.

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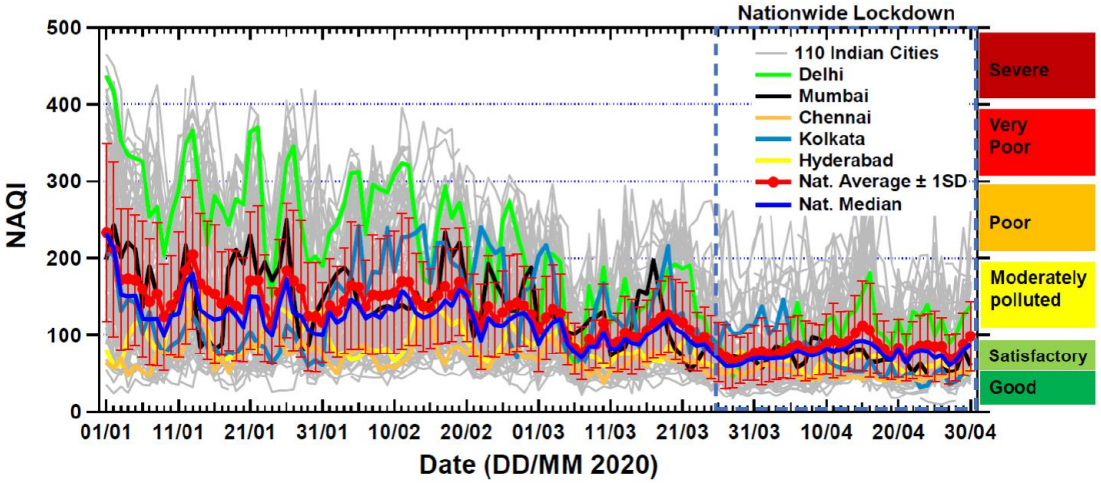

Fig. 4. Time-series of NAQI observed in 115 in Indian cities. Time-series of NAQI of Delhi, Mumbai, Kolkata, Chennai, and Hyderabad are highlighted separately. The nationwide average ± 1 SD and nationwide median of NAQI is shown in Figure. The gridlines are labeled with color codes showing the categories of NAQI, as indicated in the NAQI guideline. The Figure is marked with a blue dash line to show the nationwide lockdown period.

3.2 Satellite Visual Maps

Fig. 5 shows the satellite visual maps of (a) AOD, (b) NO_2, (c) CO, and (d) SO_2. AOD is an excellent quantitative indicator for PM pollution and useful for estimation of $PM_{2.5}$ surface concentration (Zhang *et al.*, 2018; Krishna *et al.*, 2019; Wang *et al.*, 2019). The level of AOD over the Indo-Gangetic Plain (IGP) was large during January and February 2020, as similar patterns have been seen in the case of NAQI (Fig. 3(a)). The AOD was small in March 2020 and it was much smaller in April 2020 over central and north India, except in the eastern part of India.

Combustion is the main source of NO_2, generally emitted from the transport, industrial, commercial, and residential sectors. In Fig. 5(b), the NO_2 hotspots were seen in the urban regions of India. The NO_2 hotspots were largely seen in north India including Delhi, Haryana, Punjab, Western Uttar Pradesh, and in the eastern part of India including Bihar, Jharkhand, West Bengal, and Odisha. Although the sources of NO_2 emissions exist all over India, however, in the states of Delhi, Haryana, Punjab, Uttar Pradesh, Bihar, Jharkhand, West Bengal, and Odisha, they were predominantly more due to the dense population and industries. Also, these states are part of the IGP corridor where frequent stagnant meteorological conditions favor the accumulation of pollutants in the atmosphere (Dekker *et al.*, 2019; Sawlani *et al.*, 2019; Kanawade *et al.*, 2020; Ojha *et al.*, 2020).

In January 2020, there were many NO_2 hotspots in the north and eastern part of India, which slightly decreased in February 2020. In March 2020, the NO_2 hotspots almost disappeared from north India, while in April 2020 they disappeared from entire India, except few hot spots in the eastern part of India (Fig. 5(b)). The disappearance of NO_2 hotspots in March and April 2020 could be attributed to the decreasing NO_2 emissions from transport and industries, as both emission sources were suspended during the nationwide lockdown. The emissions of CO link with the combustion sources, hence the pattern of the CO in the satellite visual maps were the same as those of NO_2 (Figs. 5(b) and 5(c)).

The hotspots of SO_2 emissions were visible along the IGP corridor (Delhi, Uttar Pradesh, Bihar, Jharkhand) and in the eastern states of Odisha and West Bengal and south-western industrial regions in the states of Maharashtra and Gujrat (Fig. 5(d)). The main source of SO_2 is coal-fired power plants and industries that use coal in the boilers. The intensity of SO_2 emission hotspots in India was almost the same in January and February 2020. They decreased slightly in March 2020, however, still visible during April 2020 (Fig. 5(d)) despite the nationwide lockdown. As mentioned, power supply was classified as emergency service during the nationwide lockdown, so power generation was continued in the coal-fired power plants. Interestingly, high AOD and emission hotspots of NO_2, CO, and SO_2 did not disappear in the states Odisha and Jharkhand in April 2020 (Fig. 5(a)–5(d)). Also, the NAQI was moderate in these states (Fig. 3(a) and 3(b)). This

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might be because in the states of Jharkhand and Odisha, large-scale coal mining is done, and these mines were likely operating during the nationwide lockdown to meet the demand for coal for power generation. Recently published regional emission inventory in Asia (REAS, version 3.1) by Kurokawa and Ohara (2020) has shown that the emissions of NO_2, CO, and SO_2 were large in the eastern part of India where the states of Jharkhand and Odisha are located.

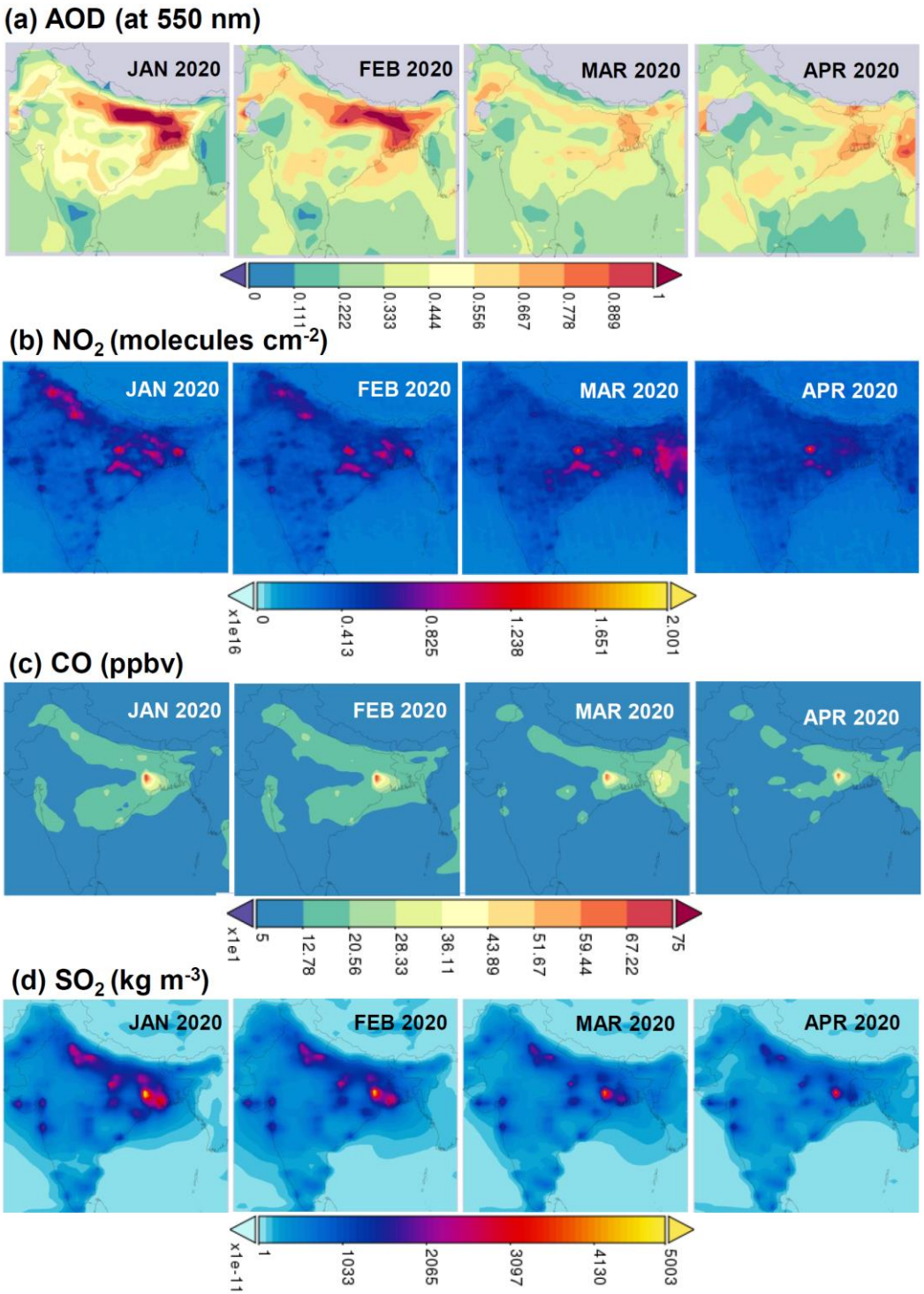

Fig. 5. Time-averaged visual maps of (a) Aerosol Optical Depth (AOD at 550 nm), (b) NO_2 total column (molecules cm^{-2}) (c) CO surface concentration (ppbv), and (d) SO_2 surface mass concentration (kg m^{-3}) plotted online for each month on NASA's GIOVANNI website (https://giovanni.gsfc.nasa.gov/giovanni/) from January to April 2020. The geographical domain selected for India was 8N°–35.5N° and 68E°–97E°.

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3.3 Temporal Variations

Figs. 6(a)–6(f) shows the time-series for temporal variations in the concentrations of PM_{10}, $PM_{2.5}$, CO, NO_2, SO_2, and O_3 from January to April 2020. Figs. 6(a)–6(f) included data available from CAAQMS (shown in Fig. 1), nationwide average ± 1 SD, nationwide median, and 24-hour National Ambient Air Quality Standard (NAAQS) (except CO). There is no 24-hour NAAQS for CO.

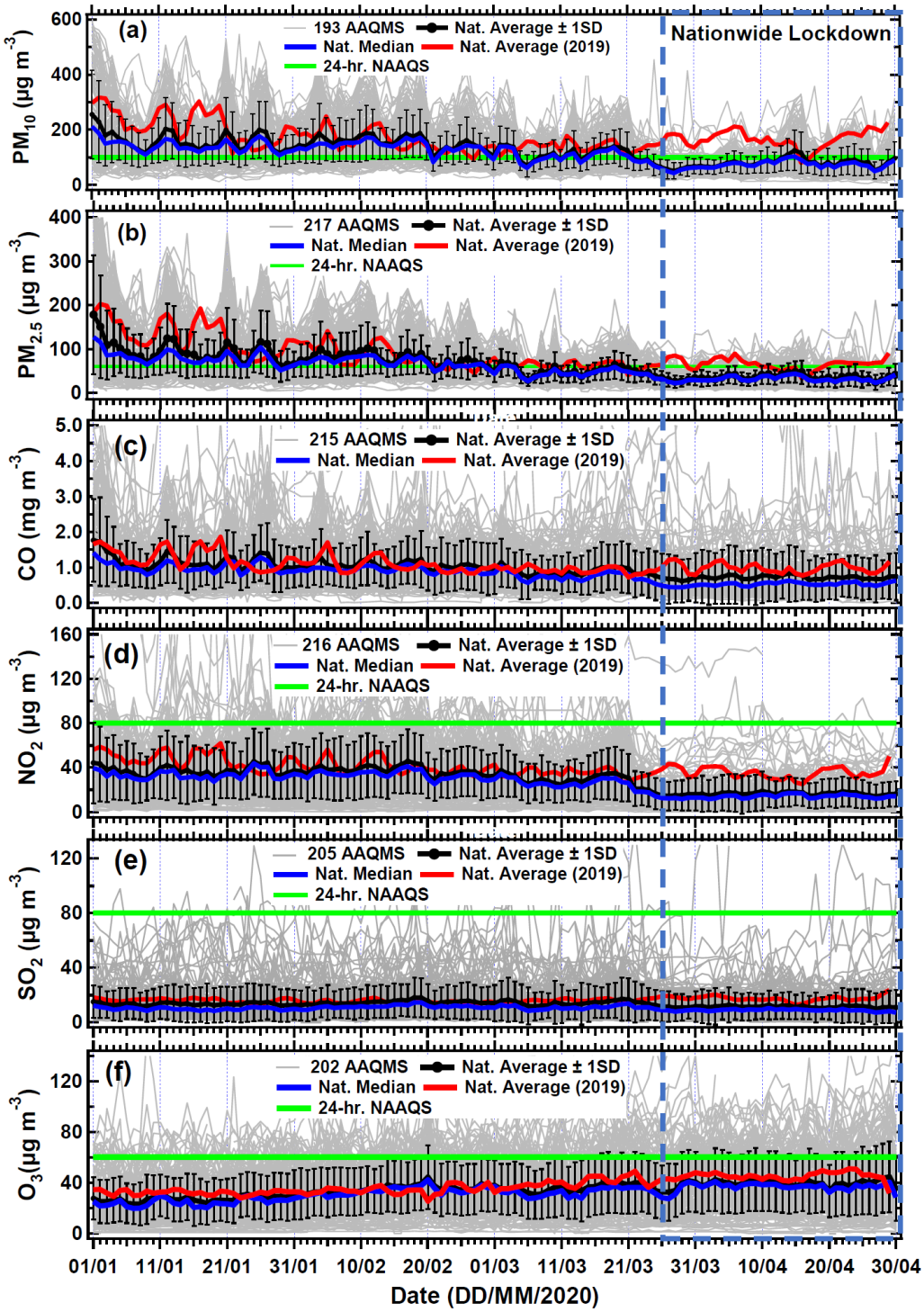

Fig. 6. Time-series of (a) PM_{10}, (b) $PM_{2.5}$, (c) CO, (d) NO_2, (e) SO_2, and (f) O_3 from January to April 2020. Figs. 6(a)–6(f) included data available from a number of CAAQMS for each parameter, nationwide average ±1 SD, nationwide median, the nationwide average of 2019, and 24-hour national ambient air quality standard (except CO). The nationwide lockdown period (25 March–30 April 2020) is also indicated as a blue dashed line.

The nationwide lockdown period (25 March–30 April 2020) was also indicated as a blue dashed line in Fig. 6. In Figs. 6(a)–6(f) the nationwide average concentrations of PM_{10}, $PM_{2.5}$, CO, NO_2, SO_2, and O_3 observed from January to April 2019 at the same CAAQMS were also included for showing a better comparison of the concentration levels of air pollutants, especially during the nationwide lockdown period.

The temporal variations in the concentrations of PM_{10}, $PM_{2.5}$, CO, and NO_2 show a similar trend which shows proximity in the emission sources of these pollutants, such as fossil fuels combustion in transport, industries, residential and commercial activities (Figs. 6(a)–6(d)). The PM_{10} and $PM_{2.5}$ concentrations were quite high at a few CAAQMS during January and February 2020 (Figs. 6(a) and 6(b)), however, their concentrations systematically decreased with time. The nationwide average and nationwide median concentrations of PM_{10} and $PM_{2.5}$ continuously shown a decreasing trend from January to mid-March 2020. The nationwide average concentrations of PM_{10} and $PM_{2.5}$ observed from January to April 2019 have also shown a similar decreasing trend, but their levels were higher in January and February 2019 compared to those in January and February 2020. From February to mid-March, the nationwide average concentration of PM_{10} and $PM_{2.5}$ both in 2019 and 2020 were almost the same. Afterward, the nationwide average concentrations of PM_{10} and $PM_{2.5}$ of 2019 have remained almost steady, whereas the nationwide average concentrations of PM_{10} and $PM_{2.5}$ of 2020 decreased significantly, which could be attributed to the impacts of the nationwide lockdown (Figs. 6(a) and 6(b)).

The nationwide average and nationwide median concentrations of PM_{10} and $PM_{2.5}$ in 2020 and the nationwide average concentrations PM_{10} and $PM_{2.5}$ in 2019 were higher than the 24-hour NAAQS for PM_{10} and $PM_{2.5}$ from January to mid of March. Afterward, from March 21, 2020, both the nationwide average and nationwide median concentrations of PM_{10} and $PM_{2.5}$ were lower than the 24-hour NAAQS (Figs. 6(a) and 6(b)). The lower nationwide average and nationwide median concentrations of PM_{10} and $PM_{2.5}$ during the nationwide lockdown as compared to their 24-hour NAAQS provided a new nationwide baseline data for the PM_{10} and $PM_{2.5}$.

Like PM_{10} and $PM_{2.5}$, the nationwide average and nationwide median concentrations of CO and NO_2 were higher during January 2020 which subsequently decreased with time. The nationwide average of CO and NO_2 in January 2019 was higher as compared to those observed in January 2020. However, during February and March in both 2019 and 2020, the nationwide average and nationwide median concentrations of CO and NO_2 were almost similar (Figs. 6(c) and 6(d)), which implied that the magnitude of CO and NO_2 emissions were not changed significantly during both years. After mid-March, the nationwide average concentrations of CO and NO_2 has remained steady in 2019, while the nationwide average and nationwide median concentrations of CO and NO_2 in 2020 has been decreased significantly during the nationwide lockdown (Figs. 6(c) and 6(d)). The 24-hour NAAQS of NO_2 was always higher than the nationwide average and nationwide median concentrations (Fig. 6(d)).

The temporal variations in the concentrations of SO_2 were quite different than those of PM_{10}, $PM_{2.5}$, CO, and NO_2 (Figs. 6(a)–6(e)The nationwide average and nationwide median concentrations of SO_2 observed from January to March 2020 had remained steady. During the nationwide lockdown, a slight decrease in the concentrations of nationwide average and nationwide median of SO_2 was observed compared to those observed in April 2019. The 24-hour NAAQS of SO_2 was always higher than the nationwide average and nationwide median of SO_2 (Fig. 6(d)).

O_3 is a secondary pollutant. Ground-level O_3 is formed during photochemical chain reactions between oxides of nitrogen (NO_x), volatile organic compounds (VOCs), and CO. The temporal variations in the nationwide average and the nationwide median concentrations of O_3 showed a consistently increasing trend from January to April 2020 including during the nationwide lockdown (Fig. 6(f)). Almost the same trend has been shown by the nationwide average concentrations of O_3 observed from January to April 2019. However, the nationwide average and nationwide median concentrations of O_3 observed during the nationwide lockdown were slightly lower than those in April 2019. The increasing trend in the temporal variations in the O_3 concentrations was quite opposite to that shown by primary key pollutants including during the nationwide lockdown (Figs. 6(a)–6(d)). It was expected that during the nationwide lockdown, since the precursors of O_3, (e.g., NO_2 and CO) have shown a decreasing trend (Figs. 6(c) and 6(d)), the O_3 concentrations were also expected to show a decreasing trend.

To investigate the increasing trend in the concentration of O_3, time-averaged satellite visual

maps of O_3 and Incoming Shortwave Flux were plotted from January-April 2020 for each month, shown in Figs. 7(a) and 7(b), respectively. As can be seen in Figs. 7(a) and 7(b), the spatial distribution of concentrations of O_3 were kept increasing from January–April 2020, in particular over north India, along with incoming shortwave flux. This implied that despite the decreasing trend in the concentrations of O_3 precursors (e.g., NO_2 and CO) at ground level observations (Figs. 6(c) and 4(d)), there were enough emissions of NO_2, CO, and probably VOCs which causes the formation of O_3 in northern India. The emissions of NO_2, CO, and VOCs might be from the burning of biofuels in domestic cooking in remote or rural regions of India since the burning of biofuels are a big source of O_3 precursors in north India (Pallavi *et al.*, 2019; Jat *et al.*, 2020). It may be noted that the observation sites, shown in Fig. 1, are mostly located in urban regions of India which failed to capture the emissions of O_3 precursors from rural or remote areas. The 24-hour NAAQS of O_3 was always higher than the nationwide average concentration of O_3 during both 2019 and 2020 (Fig. 6(f)).

3.4 Statistical Analysis

Tables 1(a)–1(f) shows statistical analysis of change in the average concentrations (±1 SD) of PM_{10}, $PM_{2.5}$, CO, NO_2, SO_2, and O_3 nationwide and in Delhi, Mumbai, Kolkata, Chennai, and Hyderabad during January and April 2020 including before the lockdown and during the lockdown and those observed in April 2019. Figs. 8(a1)–8(f1) and 8(a2)–8(f2) graphically represents the change in the average (±1 SD) concentrations of PM_{10}, $PM_{2.5}$, CO, NO_2, SO_2, and O_3 during the lockdown with the period before the lockdown (left panels: a1–f1) and the change in average (±1 SD) concentrations of PM_{10}, $PM_{2.5}$, CO, NO_2, SO_2, and O_3 with average concentrations of these parameters observed in April 2019 (right panels: a2–f2) at nationwide and in Delhi, Mumbai, Kolkata, Chennai, and Hyderabad. Among these cities, Mumbai, Kolkata, and Chennai are the

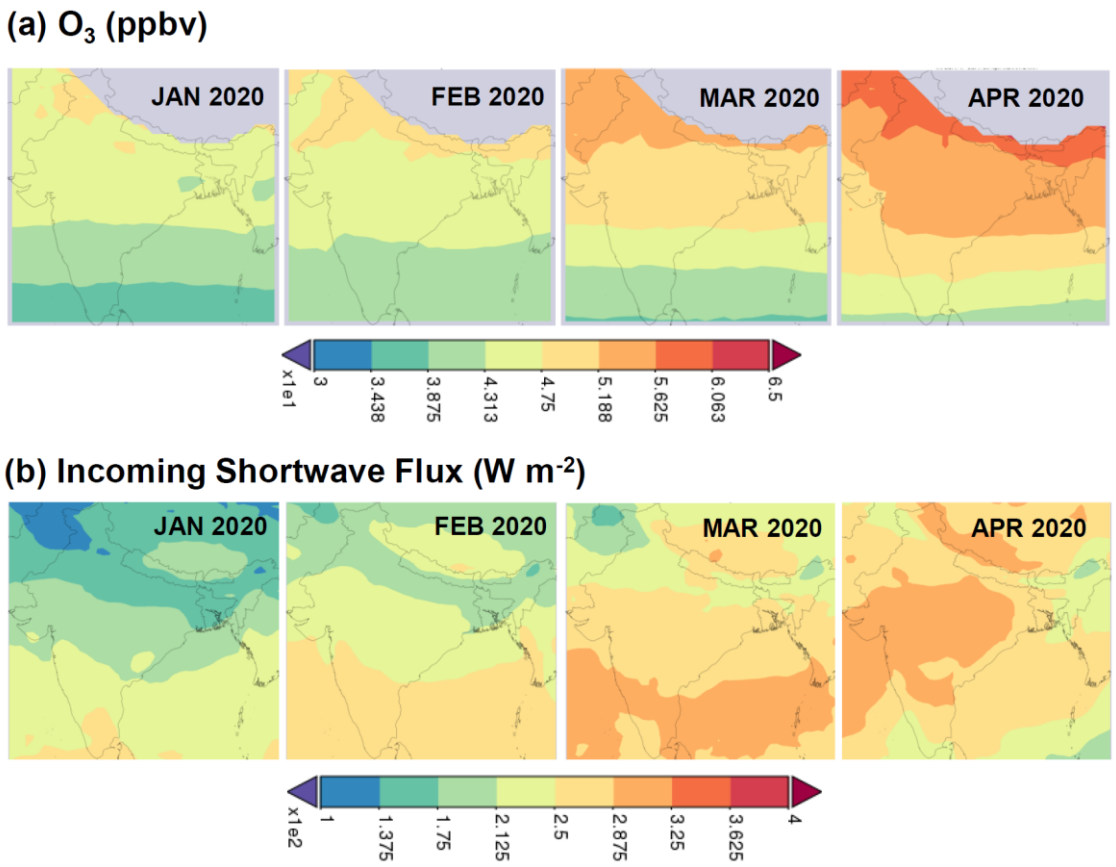

Fig. 7. Time-averaged satellite visual maps of (a) Ozone (O_3) (mole fraction air (ppbv), nighttime/descending, AIRS3STD v006, 1 deg., @700 hPa) and (b) Incoming Shortwave Flux (W m^{-2}, MERRA-2 Model M2T1NXRAD v5.12.4, 0.5 × 0.625 deg.) for each month from January to April 2020, plotted online on NASA's GIOVANNI website (https://giovanni.gsfc.nasa.gov/giovanni/).

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Table 1. Statistical analysis of change in the average concentration levels (±1 standard deviation (SD)) of key air pollutants nationwide and in major cities of India, namely, Delhi, Mumbai, Kolkata, Chennai, and Hyderabad during January and February 2020, before the lockdown (25 February–24 March 2020) (BLD), and during the lockdown (25 March–30 April 2020) (DLD) and a comparison with those observed in April 2019.

Region	2020					2019			Change in concentrations of air pollutants in DLD with respect to BLD		Change in concentrations of air pollutants in DLD with respect to April 2019	
	Data from no. of CAAQMS	January	February	BLD (25 Feb.–24 Mar.)	DLD (25 Mar.–30 Apr.)	April 2019	Data from no. of CAAQMS					
		Ave ± 1SD	Ave ± 1SD	Ave ± 1SD	Ave ± 1SD	Ave ± 1SD		Δ Ave	% Change	Δ Ave	% Change
(a) PM_{10} (μg m^{-3})											
Nationwide	193	160 ± 83	155 ± 70	117 ± 52	78 ± 40	167 ± 87	137	−39	−33	−89	−53
Delhi	33	240 ± 50	222 ± 50	153 ± 37	98 ± 24	235 ± 66	33	−55	−36	−137	−58
Mumbai	15	144 ± 53	161 ± 58	146 ± 39	65 ± 16	101 ± 32	3	− 81	−55	−36	−36
Kolkata	10	201 ± 67	181 ± 54	110 ± 28	54 ± 12	80 ± 20	4	− 56	−51	−26	−33
Chennai	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Hyderabad	4	100 ± 9	96 ± 9	86 ± 7	60 ± 5	92 ± 8	4	−26	−30	−32	−35
(b) $PM_{2.5}$ (μg m^{-3})											
Nationwide	217	94 ± 57	78 ± 40	53 ± 26	35 ± 20	64 ± 33	156	−18	−34	−29	−45
Delhi	36	157 ± 33	121± 27	71 ± 16	44 ± 17	83 ± 23	37	−27	−38	−39	−47
Mumbai	13	74 ± 14	72 ± 16	43 ± 13	25 ± 6	26 ± 4	2	−18	−42	−1	−4
Kolkata	10	103 ± 28	87 ± 23	56 ± 13	28 ± 6	41 ± 2	4	−28	−50	−13	−32
Chennai	4	45 ± 13	37 ± 11	32 ± 13	17 ± 7	31 ± 16	4	−15	−47	−14	−45
Hyderabad	6	53 ± 10	44 ± 9	37 ± 8	31 ± 6	37 ± 8	6	−6	−16	−6	−16
(c) CO (mg m^{-3})											
Nationwide	215	1.18 ± 0.71	1.06 ± 0.64	0.91 ± 0.62	0.72 ± 0.68	0.98 ± 0.59	161	−0.19	−21	−0.26	−27
Delhi	36	1.57 ± 0.62	1.30 ± 0.53	1.01 ± 0.56	0.77 ± 0.52	1.36 ± 0.67	37	−0.24	−24	−0.59	−43
Mumbai	15	1.13 ± 0.63	1.20 ± 0.64	0.92 ± 0.51	0.65 ± 0.57	1.68 ± 0.61	3	−0.27	−29	−1.03	−61
Kolkata	10	1.19 ± 0.39	0.89 ± 0.24	0.70 ± 0.31	0.40 ± 0.17	0.53 ± 0.15	4	−0.30	−43	−0.13	−25
Chennai	4	0.84 ± 0.36	0.82 ± 0.36	0.73 ± 0.40	0.60 ± 0.19	0.91 ± 0.22	4	−0.13	−18	−0.31	−34
Hyderabad	6	0.65 ± 0.17	0.61 ± 0.15	0.57 ± 0.16	0.46 ± 0.14	0.61 ± 0.13	6	−0.11	−19	−0.15	−25
(d) NO_2 (μg m^{-3})											
Nationwide	216	37 ± 26	38 ± 25	30 ± 19	16 ± 14	35 ± 24	164	−14	−47	−19	−54
Delhi	37	48 ± 28	49± 25	39 ± 17	20 ± 13	49 ± 25	38	−19	−49	−29	−59
Mumbai	14	40 ± 21	48± 26	34 ± 18	9 ± 5	21 ± 5	2	−25	−74	−12	−57
Kolkata	10	59 ± 16	61± 17	39 ± 15	12 ± 5	29 ± 12	4	−27	−69	−17	−59
Chennai	4	16 ± 11	14 ± 9	10 ± 5	8 ± 6	11 ± 7	4	−2	−20	−3	−27
Hyderabad	6	34 ± 11	36 ± 12	27 ± 10	21 ± 15	36 ± 13	6	−6	−22	−15	−42
(e) SO_2 (μg m^{-3})											
Nationwide	205	14 ± 12	15 ± 12	14 ± 12	11 ± 10	17 ± 14	149	−3	−21	−6	−35
Delhi	27	11 ± 5	15 ± 7	16 ± 10	14 ± 10	23 ± 10	25	−2	−12	−9	−39
Mumbai	15	14 ± 12	17 ± 14	18 ± 16	11 ± 14	31 ± 12	3	−7	−39	−20	−65
Kolkata	10	17 ± 12	17 ± 9	15 ± 8	9 ± 3	10 ± 7	4	−6	−40	−1	−10

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Table 1. Statistical analysis of change in the average concentration levels (±1 standard deviation (SD)) of key air pollutants nationwide and in major cities of India, namely, Delhi, Mumbai, Kolkata, Chennai, and Hyderabad during January and February 2020, before the lockdown (25 February–24 March 2020) (BLD), and during the lockdown (25 March–30 April 2020) (DLD) and a comparison with those observed in April 2019.

Region	2020					2019			Change in concentrations of air pollutants in DLD with respect to BLD		Change in concentrations of air pollutants in DLD with respect to April 2019	
	Data from no. of CAAQMS	January	February	BLD (25 Feb.–24 Mar.)	DLD (25 Mar.–30 Apr.)	April 2019	Data from no. of CAAQMS					
		Ave ± 1SD	Ave ± 1SD	Ave ± 1SD	Ave ± 1SD	Ave ± 1SD		Δ Ave	% Change	Δ Ave	% Change
Chennai	4	15 ± 13	13 ± 10	9 ± 4	6 ± 3	7 ± 2	4	–3	–33	–1	–14
Hyderabad	6	8 ± 5	7 ± 4	6 ± 3	6 ± 4	6 ± 4	6	–0	–0	–0	–0
(f) O_3 (μg m^{-3})											
Nationwide	202	27 ± 17	35 ± 20	36 ± 22	39 ± 24	45 ± 23	149	+3	+8	–6	–13
Delhi	36	19 ± 13	31 ± 19	35 ± 21	43 ± 23	36 ± 18	36	+8	+23	+7	+19
Mumbai	14	37 ± 13	45 ± 21	34 ± 16	29 ± 23	19 ± 5	2	–5	–15	+10	+53
Kolkata	10	33 ± 12	39 ± 14	42 ± 15	47 ± 23	30 ± 7	4	+5	+12	+17	+57
Chennai	2	31 ± 6	25 ± 5	39 ± 18	47 ± 34	26 ± 11	2	+8	+21	+21	+81
Hyderabad	6	29 ± 6	28 ± 5	27 ± 5	29 ± 9	42 ± 14	6	+2	+7	– 13	–31

coastal cities while Delhi and Hyderabad have located hinterland quite far from the coastal environment. These cities are located in different parts of the country. For example, Delhi is situated in the north, Mumbai in the west, Kolkata in the east, Chennai in the south, and Hyderabad in the south but far from the coastal environment. These five cities represented the major urban conglomerates of India.

The nationwide average concentrations of PM_{10} were 160 and 155 μg m^{-3} in January and February of 2020, respectively. The nationwide PM_{10} average concentrations before the lockdown and during the lockdown were 117 and 78 μg m^{-3}, respectively. On comparing, the nationwide PM_{10} average concentration observed during the lockdown with that before the lockdown, it was found that PM_{10} nationwide average concentration decreased by 33% (Fig. 8(a1) and Table 1(a)). The nationwide PM_{10} average concentration observed in April 2019 at the same CAAQMS was 167 μg m^{-3}. The nationwide PM_{10} average concentration observed during the lockdown decreased by 53% when compared with PM_{10} nationwide average concentrations of April 2019 (Fig. 8(a2) and Table 1(a)). In Delhi, Mumbai, Kolkata, and Hyderabad, the average PM_{10} concentrations observed in January 2020 were 240, 144, 201, and 100 μg m^{-3}, respectively. The PM_{10} average concentrations in these four cities in February 2020 were 222, 161, 181, and 96 μg m^{-3}, respectively. Before the lockdown, the average PM_{10} concentrations in Delhi, Mumbai, Kolkata, and Hyderabad were 153, 146, 110, and 86 μg m^{-3}, respectively, while during the lockdown, PM_{10} concentrations have decreased to 98, 65, 54, and 60 μg m^{-3} in Delhi, Mumbai, Kolkata, and Hyderabad, respectively. It was found that average PM_{10} concentrations decreased by 36, 55, 51, and 30% in Delhi, Mumbai, Kolkata, and Hyderabad, respectively, during the lockdown as compared to those before the lockdown in these cities (Fig. 8(a1) and Table 1(a)). In Mumbai and Kolkata, the percentage decrease in PM_{10} average concentrations during the lockdown was nearly 50%, higher than Delhi and Hyderabad. This could be an additional impact of the coastal environment where the land-sea breeze circulation brought clean air from the ocean to the land which helps in diluting the polluted air. During April 2019, the average PM_{10} concentrations in Delhi, Mumbai, Kolkata, and Hyderabad were 235, 101, 80, and 92 μg m^{-3}, when compared these average PM_{10} concentrations with those observed during the lockdown in these cities, it was found that PM_{10} concentrations decreased by 58, 36, 33, and 35% in Delhi, Mumbai, Kolkata, and Hyderabad, respectively (Fig. 8(a2) and Table 1(a)).

The nationwide average concentrations of $PM_{2.5}$ in January and February 2020 were 94 and 78 μg m^{-3}, respectively. While, the nationwide $PM_{2.5}$ average concentrations before the lockdown and during the lockdown were 53 and 35 μg m^{-3}, respectively. Comparing the nationwide $PM_{2.5}$ average concentration of the lockdown with that before the lockdown, the $PM_{2.5}$ concentration decreased by 34% during the lockdown with that before the lockdown (Fig. 8(b1) and Table 1(b)). The nationwide $PM_{2.5}$ average concentration observed in April 2019 was 64 μg m^{-3}. On comparing the nationwide $PM_{2.5}$ average concentrations of the lockdown with that observed in April 2019, it was found to have decreased by 45% (Fig. 8(b2) and Table 1(b)). In Delhi, Mumbai, Kolkata, Chennai, and Hyderabad, the average $PM_{2.5}$ concentrations were 157, 74, 103, 45, and 53 μg m^{-3}, respectively, in January 2020. Whereas, in February 2020, the average of $PM_{2.5}$ concentrations in Delhi, Mumbai, Kolkata, Chennai, and Hyderabad were 121, 72, 87, 37, and 44 μg m^{-3}, respectively. Before the lockdown, the average of $PM_{2.5}$ concentrations in Delhi, Mumbai, Kolkata, Chennai, and Hyderabad was 71, 43, 56, 32, and 37 μg m^{-3}, respectively, which reduced to 44, 25, 28, 17, and 31 μg m^{-3}, respectively, in these cities during the lockdown, and showing a reduction of 38, 42, 50, 47, and 16%, respectively (Fig. 8(b1) and Table 1(b)). Like PM_{10}, the percentage decrease in $PM_{2.5}$ average concentrations in the coastal cities of Mumbai, Kolkata, and Chennai during the lockdown was higher than in land-locked cities of Delhi and Hyderabad, which could be cumulative effects of the lockdown and coastal environment that promote dilution of air through land-sea breeze circulation. During April 2019, the average $PM_{2.5}$ concentrations in Delhi, Mumbai, Kolkata, Chennai, and Hyderabad were 83, 26, 41, 31, and 37 μg m^{-3}, respectively. When compared, the average $PM_{2.5}$ concentrations of April 2019 with the average $PM_{2.5}$ concentrations observed during the lockdown in Delhi, Mumbai, Kolkata, Chennai, and Hyderabad, it was found that average $PM_{2.5}$ concentrations were decreased by 47, 4, 32, 45, and 16%, respectively, during the lockdown (Fig. 8(b2) and Table 1(b)).

The nationwide CO average concentrations during January and February 2020 were 1.18 and 1.06 mg m^{-3}, respectively. Whereas, the nationwide CO average concentration before the

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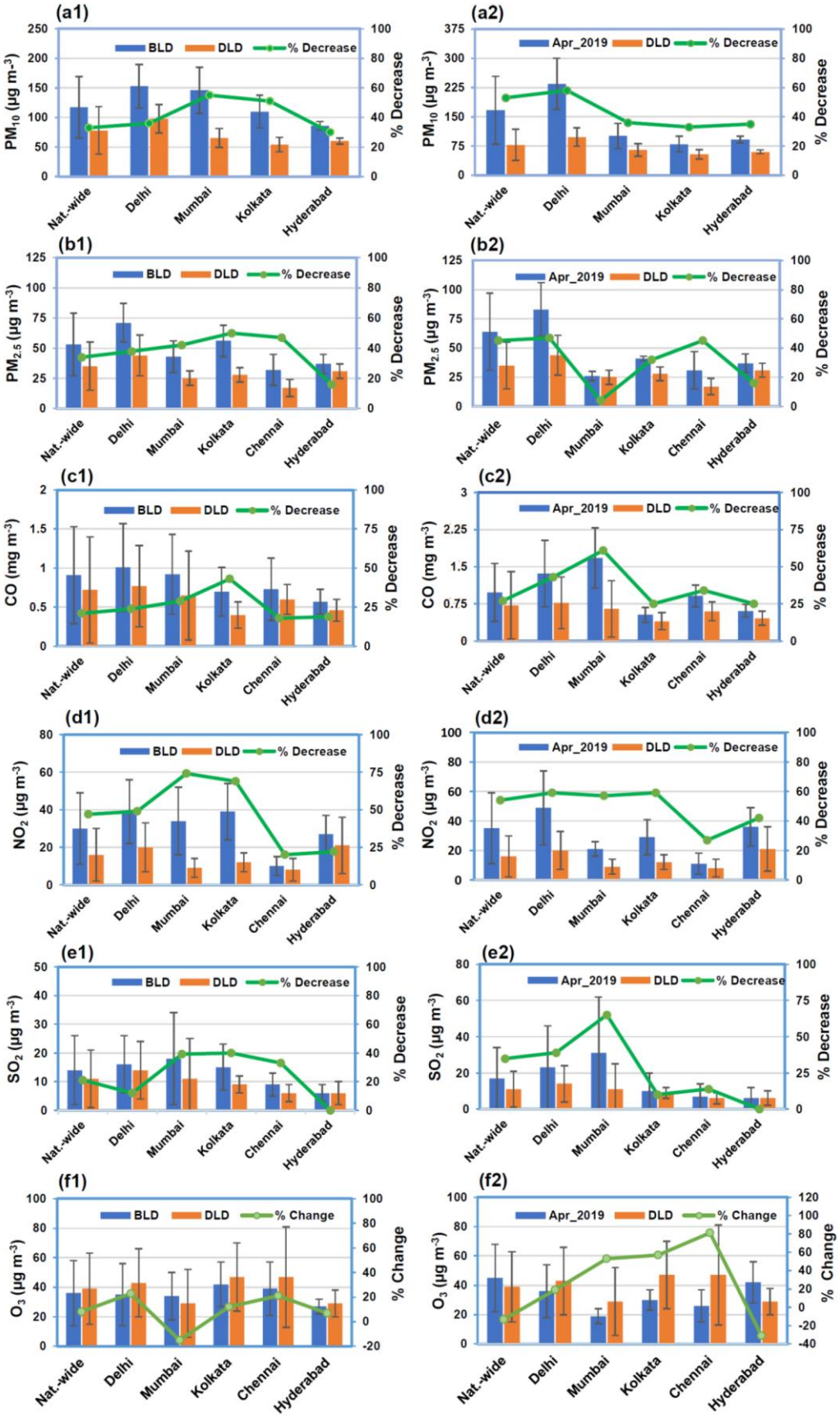

Fig. 8. Change in average concentration (±1 SD) levels of PM_{10}, $PM_{2.5}$, CO, NO_2, SO_2, and O_3 during the lockdown (DLD) with respect to before the lockdown (BLD) (left panels: a1–f1) and with respect to average concentration (±1 SD) levels of those observed in April 2019 (right panels: a2–f2) nationwide and in Delhi, Mumbai, Kolkata, Chennai, and Hyderabad.

lockdown and during the lockdown were 0.91 and 0.72 mg m^{-3}, respectively. The nationwide average CO concentration decreased by 21% during the lockdown compared to that before the lockdown (Fig. 8(c1) and Table 1(c)). The nationwide average CO concentration during April 2019 was 0.98 in mg m^{-3}. The nationwide average CO concentration decreased by 27% during the lockdown with that observed in April 2019 (Fig. 8(c2) and Table 1(c)). In Delhi, Mumbai, Kolkata, Chennai, and Hyderabad, the average CO concentrations were 1.57, 1.13, 1.19, 0.84, and 0.65 mg m^{-3}, respectively, in January 2020 and 1.30, 1.20, 0.89, 0.82, and 0.61 mg m^{-3}, respectively, in February 2020. Before the lockdown, the average CO concentrations were 1.01, 0.92, 0.70, 0.73, and 0.57 mg m^{-3} in Delhi, Mumbai, Kolkata, Chennai, and Hyderabad, respectively. While during the lockdown, the average CO concentrations were 0.77, 0.65, 0.40, 0.60, and 0.46 mg m^{-3} in Delhi, Mumbai, Kolkata, Chennai, and Hyderabad, respectively. It was found that during the lockdown, the average CO concentrations decreased by 24, 29, 43, 18, and 19% in Delhi, Mumbai, Kolkata, Chennai, and Hyderabad, respectively, with those observed before the lockdown (Fig. 8(c1) and Table 1(c)). The average CO concentrations observed in April 2019 in Delhi, Mumbai, Kolkata, Chennai, and Hyderabad were 1.36, 1.68, 0.53, 0.91, and 0.61 mg m^{-3}, respectively. When compared the average CO concentrations of these cities during the lockdown period with those during April 2019, the average CO concentrations have decreased by 43, 61, 25, 34, and 25% during the lockdown in Delhi, Mumbai, Kolkata, Chennai, and Hyderabad, respectively (Fig. 8(c2) and Table 1(c)).

The nationwide average NO_2 concentrations during January and February 2020 were 37 and 38 μg m^{-3}, respectively. Whereas, before the lockdown and during the lockdown, the nationwide average NO_2 concentrations were 30 and 16 μg m^{-3}, respectively. The nationwide average NO_2 concentration was decreased by 47% during the lockdown with respect to what it was before the lockdown (Fig. 8(d1) and Table 1(d)). The nationwide average NO_2 concentration in April 2019 was 35 μg m^{-3}. The nationwide average NO_2 concentration has reduced by 54% during the lockdown when compared with that of April 2019 (Fig. (8d2) and Table 1(d)). In Delhi, Mumbai, Kolkata, Chennai, and Hyderabad, the average NO_2 concentrations were 48, 40, 59, 16, and 34 μg m^{-3}, respectively, in January 2020 and 49, 48, 61, 14, and 36 μg m^{-3}, respectively, in February 2020. Before the lockdown, the average NO_2 concentrations were 39, 34, 39, 10, and 27 μg m^{-3} in Delhi, Mumbai, Kolkata, Chennai, and Hyderabad, respectively. While during the lockdown, the average NO_2 concentrations were 20, 9, 12, 8, and 21 μg m^{-3} in Delhi, Mumbai, Kolkata, Chennai, and Hyderabad, respectively. It was observed that during the lockdown, the average NO_2 concentrations decreased by 49, 74, 69, 20, and 22% in Delhi, Mumbai, Kolkata, Chennai, and Hyderabad, respectively, when compared with average NO_2 concentrations before the lockdown in these cities (Fig. 8(d1) and Table 1(d)). The observation suggests that the average NO_2 concentration decrease was the highest in Mumbai and lowest in Chennai. The average NO_2 concentrations observed in April 2019 in Delhi, Mumbai, Kolkata, Chennai, and Hyderabad were 49, 21, 29, 11, and 36 μg m^{-3}, respectively. When compared with the average NO_2 concentrations of the lockdown period with those observed in April 2019, it appeared that average NO_2 concentrations decreased by 59, 57, 59, 27, and 42% in Delhi, Mumbai, Kolkata, Chennai, and Hyderabad, respectively (Fig. 8(d1) and Table 1(d)).

The nationwide average SO_2 concentrations during January and February 2020 were 14 and 15 μg m^{-3}, respectively, and the nationwide average SO_2 concentrations before the lockdown and during the lockdown were 14 and 11 μg m^{-3}, respectively. The nationwide average SO_2 concentration was decreased by 21% with that observed before the lockdown (Fig. 8(e1) and Table 1(e)). The nationwide average SO_2 concentration during April 2019 was 17 μg m^{-3}. The nationwide SO_2 average concentration was decreased by 35% during the lockdown period with that observed in April 2019 (Fig. 8(e1) and Table 1(e)). In Delhi, Mumbai, Kolkata, Chennai, and Hyderabad, the average SO_2 concentrations were 11, 14, 17, 15, and 8 μg m^{-3}, respectively, in January 2020. While in February 2020, average SO_2 concentrations in Delhi, Mumbai, Kolkata, Chennai, and Hyderabad were 15, 17, 17, 13, and 7 μg m^{-3}, respectively. Before the lockdown, average SO_2 concentrations in Delhi, Mumbai, Kolkata, Chennai, and Hyderabad were 16, 18, 15, 9, and 6 μg m^{-3}, respectively. During the lockdown, average SO_2 concentrations in Delhi, Mumbai, Kolkata, Chennai, and Hyderabad have reduced to 14, 11, 9, 6, and 6 μg m^{-3}, respectively. The average SO_2 concentrations were decreased by 12, 39, 40, 33%, and nil during the lockdown, in Delhi, Mumbai, Kolkata, Chennai, and Hyderabad, respectively, with those before the lockdown

(Fig. 8(e1) and Table 1(e)). The average SO_2 concentrations observed in April 2019 in Delhi, Mumbai, Kolkata, Chennai, and Hyderabad were 23, 31, 10, 7, and 6 μg m^{-3}, respectively. When compared with average SO_2 concentrations of the lockdown period in these cities with those observed in April 2019, it was found that average SO_2 concentrations have decreased by 39, 65, 10, 14%, and nil in Delhi, Mumbai, Kolkata, Chennai, and Hyderabad, respectively (Fig. 8(e2) and Table 1(e)).

The nationwide average O_3 concentrations during January and February 2020 were 27 and 35 μg m^{-3}, respectively. Whereas, the nationwide average O_3 concentrations before the lockdown and during the lockdown were 36 and 39 μg m^{-3}, respectively. The nationwide average O_3 concentration was increased by 8% when compared with that before the lockdown period (Fig. 8(f1) and Table 1(f)). The nationwide average O_3 concentration in April 2019 was 45 μg m^{-3}. By comparing, the nationwide average O_3 concentration of the lockdown period with that observed in April 2019, it has found decreased by 13% ((Fig. 8(f2) and Table 1(f)). In Delhi, Mumbai, Kolkata, Chennai, and Hyderabad, the average O_3 concentrations were 19, 37, 33, 31, and 29 μg m^{-3}, respectively, in January 2020, and 31, 45, 39, 25, and 28 μg m^{-3}, respectively, in February 2020. Before the lockdown, the average O_3 concentrations in Delhi, Mumbai, Kolkata, Chennai, and Hyderabad were 35, 34, 42, 39, and 27 μg m^{-3}, respectively. While during the lockdown, the average O_3 concentrations in Delhi, Mumbai, Kolkata, Chennai, and Hyderabad were 43, 29, 47, 47, and 29 μg m^{-3}, respectively. During the lockdown, the average O_3 concentrations have increased by 23, 12, 21, and 7% in Delhi, Kolkata, Chennai, and Hyderabad, respectively, with those before the lockdown (Fig. 8(f1) and Table 1(f)). Only in Mumbai, the average O_3 concentration has decreased by 15% during the lockdown with that before the lockdown (Fig. 8(f1) and Table 1(f)). This may be due to a large decrease in NO_2 concentration (74%) in Mumbai during the lockdown (Fig. 8(d1) and Table 1(d)). The average O_3 concentrations observed in April 2019 in Delhi, Mumbai, Kolkata, Chennai, and Hyderabad were 36, 19, 30, 26, and 42 μg m^{-3}, respectively. When compared with the average O_3 concentrations of the lockdown with those observed in April 2019 in Delhi, Mumbai, Kolkata, and Chennai, it was found that the average O_3 concentrations of the lockdown were increased by 19, 53, 57, and 81%, respectively (Fig. 8(f2) and Table 1(f)). It was observed that the formation of O_3 in Mumbai, Kolkata, and Chennai was higher as compared to Delhi. This may be due to that Mumbai, Kolkata, and Chennai are coastal cities with a relatively clean environment and receives enough solar radiation, and probably have enough O_3 precursors. However, a deeper investigation is needed to understand the reason for O_3 formation in Mumbai, Kolkata, and Chennai and is beyond the scope of this study.

3.5 Policy Relevance

The COVID-19 has provided a rare opportunity to countries for the collection of air pollution baseline data since during the nationwide lockdown the emissions of air pollutants from transport, industries, and commercial activities were reduced significantly and have relevance to air pollution reduction policies. India imposed a nationwide lockdown from March 25, 2020, onward for a few months. As a result, the concentrations of air pollutants decreased significantly (Figs. 6 and 8). The observed nationwide average concentrations of PM_{10} and $PM_{2.5}$ were well below the NAAQS of PM_{10} and $PM_{2.5}$ during the nationwide lockdown (Figs. 6(a) and 6(b)). Also, the observed nationwide average concentrations of NO_2, SO_2, and O_3 were always below the respective NAAQS of NO_2, SO_2, and O_3 (Figs. 6(d), 6(e), and 6(f)). As per the WHO (2005) guidelines, the ambient air quality standards for PM_{10} and $PM_{2.5}$ must be close to 50 μg m^{-3} and 25 μg m^{-3}, respectively, considering their impacts on human health. The NAAQS of India for PM_{10} and $PM_{2.5}$ is 100 μg m^{-3} and 60 μg m^{-3}, respectively, which is about 2 times higher than the WHO (2005) prescribed guidelines. Considering the high pollution levels in India (WHO, 2016; Bernard and Kazmin, 2018; Chowdhury *et al.*, 2019; HEI, 2019; Mishra, 2019), there is sufficient ground to review the current NAAQS of air pollutants for mitigation of air pollution. The air pollution measurement data summarized in this study showed that during the nationwide lockdown, emissions of air pollutants from transport, industries, and commercial activities were reduced significantly. As a result, the concentrations of PM_{10} and $PM_{2.5}$ attained the NAAQS or even observed lower than the NAAQS. This suggests that if the emissions of air pollutants, particularly PM_{10} and $PM_{2.5}$, reduced from transport, industries, commercial activities, including from biomass burning in

domestic cooking as well open biomass burning, the current NAAQS, as well as the lower level of PM_{10} and $PM_{2.5}$, can be achieved. This can be done by providing clean fuels and implementing 25 mitigations measures proposed by the Science-Based Solutions Report (UNEP, 2019).

4 CONCLUSION

This study made a detailed analysis of the impacts of the COVID-19 on air quality in India by using the observation data from more than 200 CAAQMS. India imposed a nationwide lockdown on March 25, 2020, for a few months and suspended transport, industries, and commercial activities, except for essential services. We defined the period from February 25 to March 24, 2020, as 'before lockdown' and March 25 to April 30, 2020, as 'during lockdown'. The study found that from January to April 2020, which included the nationwide lockdown period, the monthly NAQI was improved from poor to satisfactory or good; AOD and emission hotspots of CO, NO_2, and SO_2 were gradually disappeared; and temporal variations in the concentrations PM_{10}, $PM_{2.5}$, CO, NO_2, and SO_2 showed a gradually decreasing trend. The nationwide average concentrations of PM_{10}, $PM_{2.5}$, CO, NO_2, and SO_2 decreased during the lockdown by 33, 34, 21, 47, and 21%, respectively, compared to their levels before the lockdown. The average concentration levels of PM_{10}, $PM_{2.5}$, CO, NO_2, and SO_2 of the lockdown period when compared with those observed in April 2019, it was found that their average concentration levels were decreased by 53, 45, 27, 54, and 35%. The O_3 level was slightly increased during the lockdown. The COVID-19 has provided a rare opportunity for India for the collection of air pollution baseline data which could be useful in the formulation of pollution reduction policies.

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