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Effects of COVID-19 lockdown phases in India: an atmospheric perspective

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Abstract

Coronavirus disease 2019 (COVID-19) is an infectious disease caused by severe acute respiratory syndrome coronavirus. It was first identified in December 2019 in Wuhan, Hubei, China, and has resulted in an ongoing pandemic. As of 5 July 2020, more than 11.1 million cases have been reported across 188 countries and territories, resulting in more than 528,000 deaths. More than 6.03 million people have recovered. The entire world population currently faces enormous challenges (i.e., social, environmental, health, and economic) due to the impact of COVID-19. In this regard, the affected countries are now trying to slow down the virus's transmission through social-distancing, lockdowns, increasing the number of tests and treatment facilities. There have been four lockdowns (25 March 2020–31 May 2020), and two unlock periods (1 June–31 July 2020) in India. Aerosol Optical Depth (AOD) has been analyzed using MODIS satellite data during various phases of lockdowns over India. With the implementation of lockdown steps, AOD values dropped significantly over various regions. A significant reduction in AOD over the North-Central regions (up to -50%) compared to the regions in the South or Northeast India. The AOD over these regions was significantly affected by the lock/unlock phases. It was also observed that there was a considerable buildup of AOD during the pre-lockdown period in the year 2020 as compared to the past two years.

Keywords COVID-19 · AOD · India

1 Introduction

The first case of novel coronavirus (COVID-19) was reported in the Wuhan district of China in December 2019 (Gautam and Hens 2020). The virus transmitted rapidly and affected several people within a month (WHO 2020). The first person reported in India was from the State of Kerala in late January 2020 (Gautam 2020b), and according to his travel history, he had returned from China. Since then, there has been a significant rise in the number of COVID-19 patients in India's various states. As of 5 July 2020, a total of 19,289 deaths have been reported with 6,74,313 infected persons over entire India (https://www.

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ndtv.com//:5 July 2020). Maharashtra, Tamil Nadu, and Delhi have nearly 50% of all India cases, whereas northeast states have the least number of cases. Considering the seriousness of the disease, initially, a 21-day nationwide lockdown (25 March 2020 to 14 April 2020: LD1.0) was announced by the prime minister of India, "Shri. Narendra Modi" to control the transmission of COVID-19 and due to which many industries, academic institutes, markets, as well as public gatherings were shut down. After the first lockdown (LD 1.0), there have been three more lowdown phases in succession (LD2.0: 15 April to 3 May 2020, LD3.0: 4 May to 17 May 2020, LD4.0: 18 May to 31 May 2020). After that, to restart the Indian economy, two unlock phases (UL) have also been announced (UL1.0: 1 June 2020 to 30 June 2020, and UL1.0: 1 July 2020 to 31 July 2020).

The direct outcomes of the various lockdown phases were that the mortality rate of COVID-19 and its cases were significantly controlled. However, there have been various indirect effects of these phases as such lockdowns on the mass level have not been implemented in the world for a long time. Apart from medical research, various scientists around the world have also focused on finding the environmental effects of COVID-19 lockdowns (Kanniah et al. 2020; Menut et al. 2020; Suresh et al. 2020; Mitra et al. 2020; Liu et al. 2020a, b; Nakada and Urban 2020; Baldasano 2020). Ghosh and Ghosh (2020) reviewed 15 empirical research articles all around the world and inferred that all the studies had reported a trend of decrease in the level of concentrations of PM10, PM2.5, CO, NO, NO2, NH3, NOx, SO2 during the lockdown period. Srivastava (2020) also reviewed various studies focusing on the impact of weather on the spread and severity of COVID-19. They also found that air quality has immensely improved due to lockdown.

Indian scientists have also explored environmental and atmospheric changes incurred to COVID-19 lockdowns. Gautam (2020a) analyzed NO_2 data, which were collected from the satellite (Sentinel – 5P), and found a significant reduction in its levels for the Asian and European countries due to COVID-19 lockdowns. Gautam (2020b) used secondary results from the National Aeronautics and Space Administration (NASA) and found a significant reduction (50%) in the air quality of the Indian region. Lokhandwala and Gautam (2020) also found an improvement of air quality and environment during pre- and post-lockdown of this pandemic situation. Gupta et al. (2020) analyzed various harmful pollutants present in the environment and observed that over India temperature has been reduced to near about 15 degree Celsius, there is also a reduction in humidity up to 40%, particulate matter (PM2.5) reaches near about normal, i.e., 40 g/m^3, and carbon monoxide levels have also been reduced to 10 ppm. Mahato et al. (2020) also found 40–50% improvement in air quality over Delhi. Jain and Sharma (2020) found around 30–80% reduction in pollutant concentrations in all the megacities in India. Kumari and Toshniwal (2020) found a substantial reduction in the concentration of PM10, PM2.5, NO2, and SO2 in two major cities (Delhi and Mumbai) of India post-lockdown phase. Bera et al. (2020) did a similar analysis with PM2.5 for another major city of India (Kolkata). They found a positive correlation between air pollution in Kolkata and the lethality related to COVID-19. Using Aerosol Optical Depth (AOD) from MODIS, Ranjan et al. (2020) found that the AOD level over the Indian Territory is greatly reduced (45%) during the lockdown periods as compared to the long-term mean AOD level (2000–2019). Aman et al. (2020) analyzed the impact of lockdown on water and air quality using remote sensing data and found a significant reduction in the average suspended particulate matter over Ahmedabad, India.

In India, there have been four lockdown phases, and one unlock phase has passed, and at the time of writing this article (for the first time), the second unlock phase is in progress. All the previous studies have focused on analyzing air quality during pre- and post-lockdown situations, mostly for individual cities. Moreover, these studies have not tried to identify major

regions that contribute most to the anthropogenic air pollution in India. Since there has not been a major shutdown of various Industries/activities throughout the country at such a mass level, these lockdown phases can be taken as an opportunity to identify the hot spots (in terms of anthropogenic air pollution) in India. The present study was carried out with the following objectives:

1. To analyze the impacts of various lockdown phases in India.
2. To identify anthropogenic pollution hot spots of India.

2 Study area and data used

According to the World Air Quality Report (WAQR (2019)), 21 of the world's 30 cities with the worst air pollution are in India, with six in the top ten. Considering the above fact, the present study has been carried out over India. Further, five different regions (covering Delhi, Maharashtra, Uttar Pradesh, Tamil Nadu, and northeast states) were analyzed, as shown in Fig. 1. As of 5 July 2020, Maharashtra, Delhi, and Tamil Nadu have nearly 50% of all India COVID-19 cases.

The analysis has been carried out using the AOD at 550 nm over land regions, obtained from MODIS/Terra level-3 (MOD08_D3) satellite that is publicly available at daily temporal resolution and 1-degree spatial resolution. The MODIS is the most reliable public source of AOD around the globe. Mangla et al. (2020) compared AOD data for the 2010–2017 (8 years) from multiple satellites (MISR, MODIS, and OMI) and ground-based AOD (AERONET) over Indo-Gangetic Plains (Gandhi College, Jaipur, and Kanpur) region. They found that MODIS, as compared to other sensors, has a high correlation with AERONET.

3 Methodology

The AOD of the year 2020 over entire India and various regions marked in Fig. 1 was analyzed and compared with previous years (2018, 2019) AOD data. For comparison, anomalies of AOD of the year 2020 have been calculated by subtracting it from the AODs of the years 2018 and 2019 at each grid point.

The analysis is carried out for different time intervals, as shown in Table 1. The first period, pre-Lockdown, was the period before any lockdown was imposed in India from 1 January 2020 to 24 March 2020. The second period will be called as the lockdown 1.0 (LD1.0) that existed from 25 March 2020 to 14 April 2020. Subsequently, there were three more lockdowns (LD2.0, LD3.0, and LD4.0) between 15 April 2020 and 31 May 2020. After that, the first unlock period (UL1.0) started from 1 June 2020 to 30 June 2020. At present, the second unlock phase (UL2.0) is in progress.

4 Results

4.1 Entire India

Since, for the year 2020, data were available only up to 30 June 2020, the spatial pattern of AOD (averaged over the last three years) is shown for this period in Fig. 2. It can be
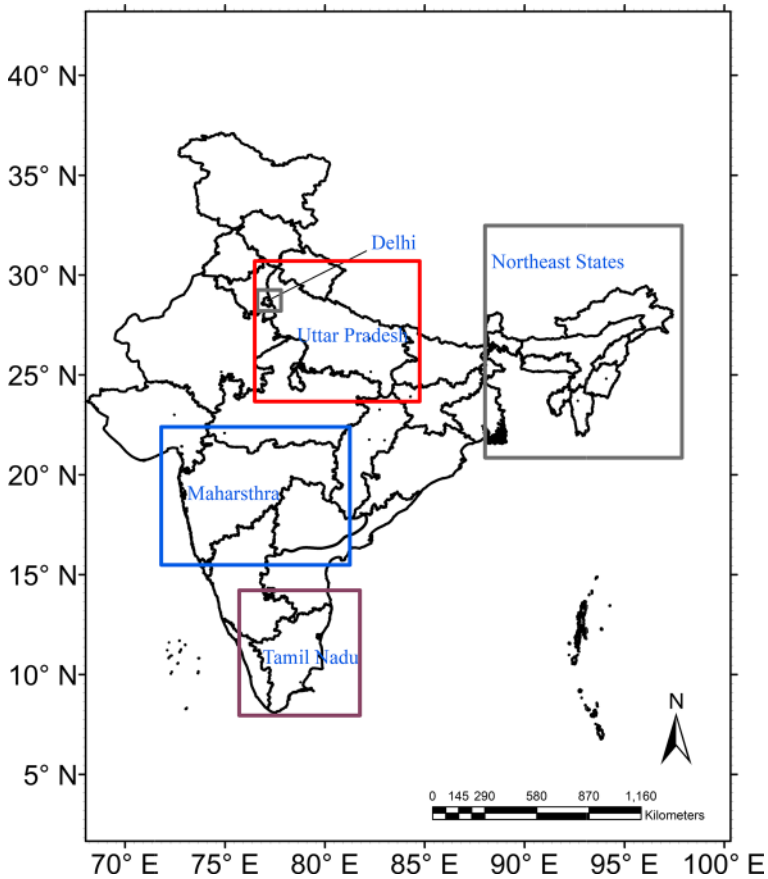
Fig. 1 Study area: The regions have been named based on the state lying in it

Table 1 Various lockdown/unlock phases in India due to COVID-19

S. No.	Phase	Start	End
1	Pre-lockdown (PL)	1 January 20	24 March 20
2	Lockdown 1.0 (LD1.0)	25 March 20	14 April 20
3	Lockdown 2.0 (LD2.0)	15 April 20	3 May 20
4	Lockdown 3.0 (LD3.0)	4 May 20	17 May 20
5	Lockdown 4.0 (LD4.0)	18 May 20	31 May 20
6	Unlock 1.0 (UL1.0)	1 June 20	30 June 20
7	Unlock 2.0 (UL2.0)	1 July 20	31 July 20

seen that compared to the southern parts of India, there is a substantial buildup of aerosols over the north and the eastern regions. The average AOD for the period of January to June reaches up to 0.9.

Figure 3 shows the anomaly for the PL period. There is a considerable increase in AOD during this period in the year 2020 compared to 2018 and 2019 over entire India. Since

there was no imposition of any restriction, due to the rapid growth of Industrial activities, a considerable increase in AOD during this period was observed. On average, there was about 6.24% and 11.87% increase in AOD compared to the corresponding periods of the years 2018 and 2019, respectively.

The AOD anomalies from the years 2018 and 2019 after the PL phase are shown in Fig. 4. During the first phase (LD1.0) only, there is a considerable reduction of AOD over India. This reduction is more prominent over Indo-Gangetic Plains (IGP) as compared to other places.

An anomaly from the year 2018 shows that in the year 2020, AOD is always lower after the PL period, which shows a significant impact of lockdown phases over entire India. Compared to the year 2018, there is an average reduction of about 18.56% over entire India during the lockdown phases (LD1.0 to LD 4.0), whereas, for the same period, it is only 5.76% from the year 2019. From the anomalies of the year 2019, we can see that, as the lockdown phases end, a relative increase in AOD over the central part of India can be observed as various activities slowly start to take place. However, this change is most prominent for the central part of India.

All India averaged 10-day running mean timeservers of AOD are shown in Fig. 5 for all three years. During the PL period, AOD in the year 2020 is much higher than in the past two years. Moreover, just at the beginning of lockdown phases 1.0 and 2.0, there is a considerable decrease in AOD of the year 2020. After the unlock process begins (UL1.0), the AOD of the year 2020 begins to match with the AOD previous year (2018).
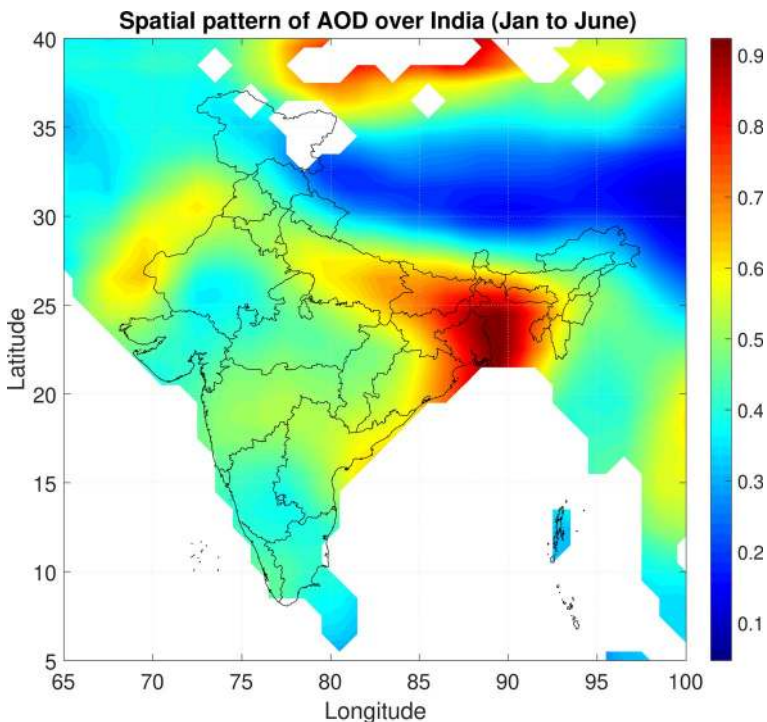

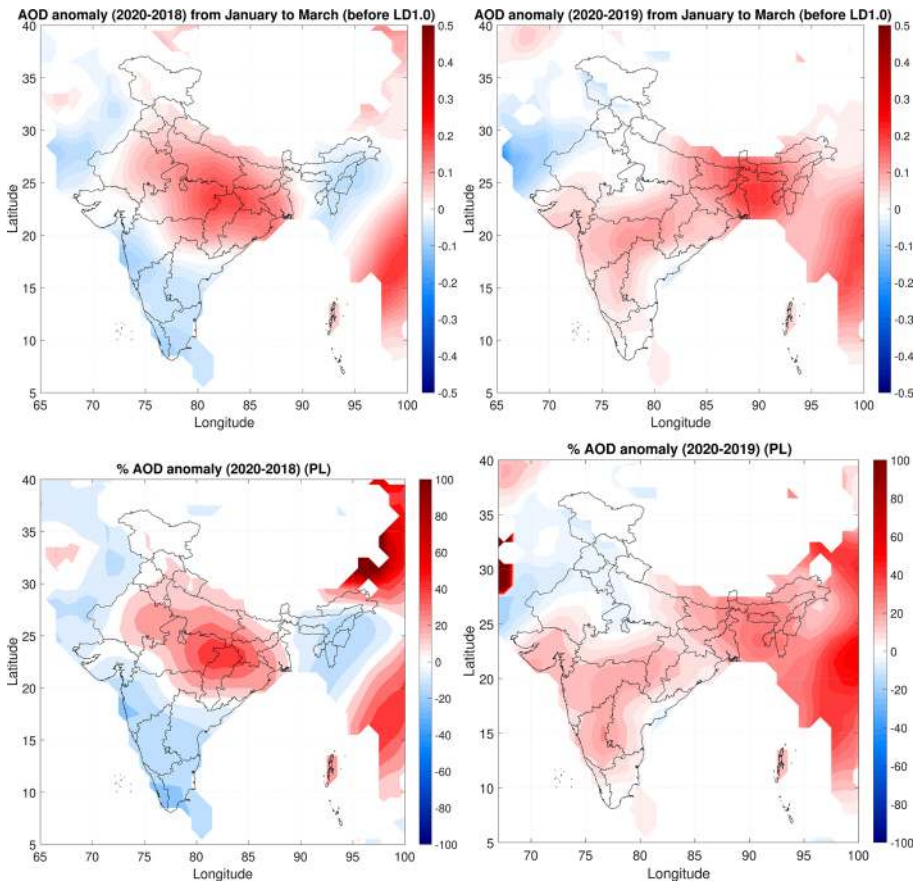**Fig. 2** Spatial pattern of AOD over India from January 2020 to June 2020

**Fig. 3** Spatial pattern of AOD anomaly for the pre-lockdown period

4.2 Regional level analysis

To analyze the effects of lockdown over different regions (as shown in Fig. 1), average AOD over these regions was obtained. The anomalies of AOD of the year 2020 were calculated by subtracting it from the AOD of the years 2018 and 2019 over the same region.

The 10-day running means anomalous time series from the year 2018 is shown in Fig. 6 for all five regions. From the figure, we can see that over Delhi, Maharashtra and UP, a clear distinction can be seen between the PL period and lockdown phases. Over Delhi and UP region, it is even more evident that before the lockdown began, there was a significant rise in the AOD, which declined after the lockdown phases. However, over the Tamil Nadu and northeast states, this behavior was not observed clearly. Although there is a decrease in AOD for the year 2020, still the effect of lockdown phases is not observed.

Similar plots for anomaly from the year 2019 are shown in Fig. 7. Over Delhi and UP regions, just before the lockdown period, there was a rise in AOD, which drops in lockdown phases. The percentage change in the AOD over various periods is shown in Tables 2 and 3, respectively. As compared to the year 2018, Delhi had 23.53% more AOD during the PL period. During all the lockdown periods, it reduced to a minimum of −47.97%

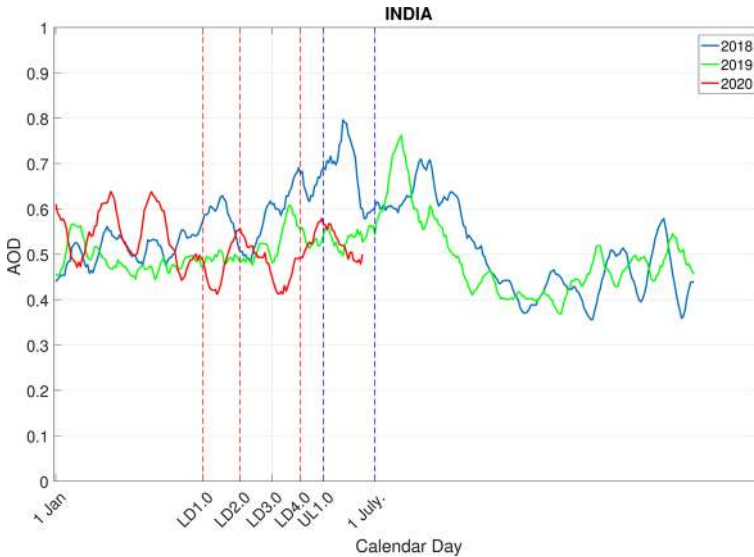**Fig. 4** Spatial pattern of AOD anomaly for different lockdown/unlock phases
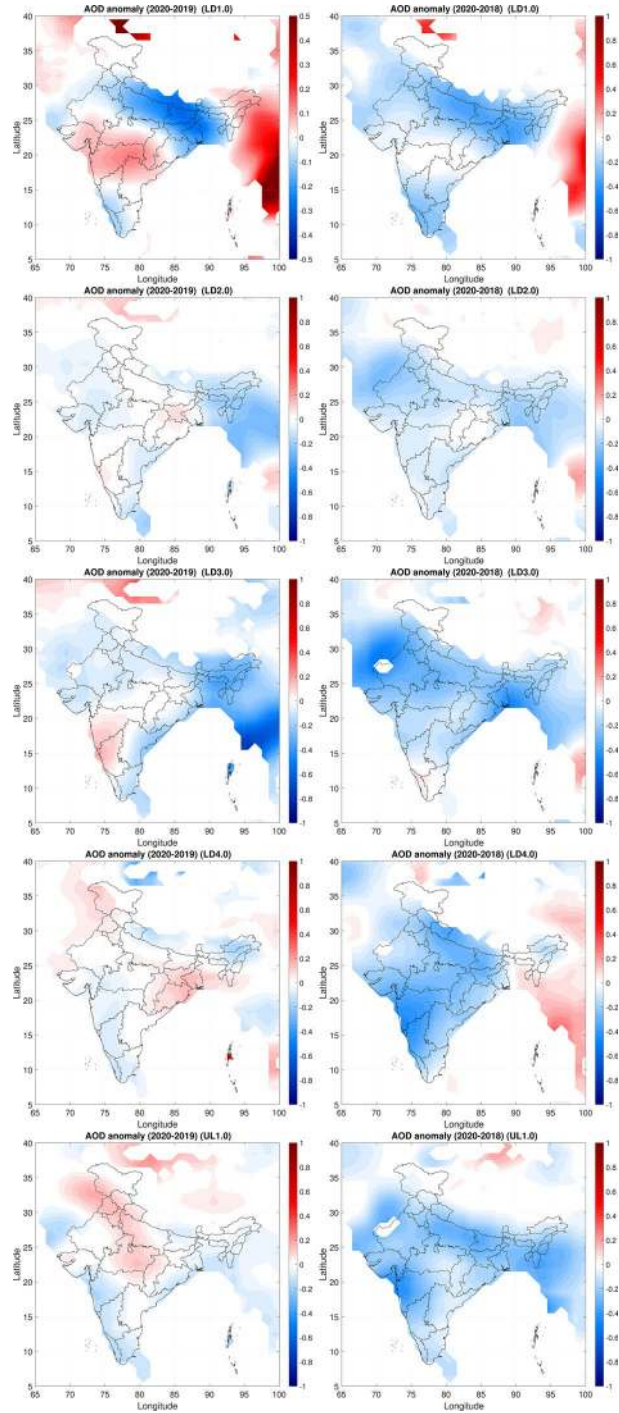
Fig. 5 All India averaged 10-day running mean timeservers of AOD

during the LD3.0 phase. A similar pattern was observed for Uttar Pradesh also. The highest drop in AOD was observed for the Uttar Pradesh region during the LD1.0 phase (−49.67% from 2018 and −33.37% from 2019). However, as shown in Table 3, in contrast to the year 2018, during the PL period, AOD in 2020 increased for all the regions compared to the year 2019. However, the significant reduction during the lockdown phase is visible for Delhi, Maharashtra, and northeast.

5 Summary and conclusions

The AOD data obtained from the MODIS satellite were analyzed over India for various lockdown phases over different regions during the COVID-19 pandemic. Apart from the analyses over India as a whole, a total of five major regions (Delhi, Maharashtra, Uttar Pradesh, Tamil Nadu, and northeast states) were also chosen. The analysis was carried out for six different periods of 2018, 2019, and 2020. The first period was the pre-lockdown period (PL), which was up to 24 March 2020. Four different lockdown periods were then selected (LD 1.0 to LD 4.0), and one UL1.0 period was also selected.

There is a considerable increase in AOD for the PL period in 2020 over India compared to the years 2018 and 2019. On average, there was about 6.24% and 11.87% increase in AOD during this period compared to corresponding periods of the years 2018 and 2019, respectively. During the lockdown phases (LD1.0 to LD 4.0), compared to the year 2018, there is an average reduction of about 18.56% over entire India, whereas, for the same period, there is a reduction of only 5.76% from the year 2019.

Over Delhi, Maharashtra, and Uttar Pradesh, there was a significant rise in the AOD, which declined after the lockdown phases begin. However, over the Tamil Nadu and northeast states, such behavior was not observed clearly. As compared to the year 2018, Delhi had 23.53% more AOD during the PL period. The lowest anomaly −47.97% was observed
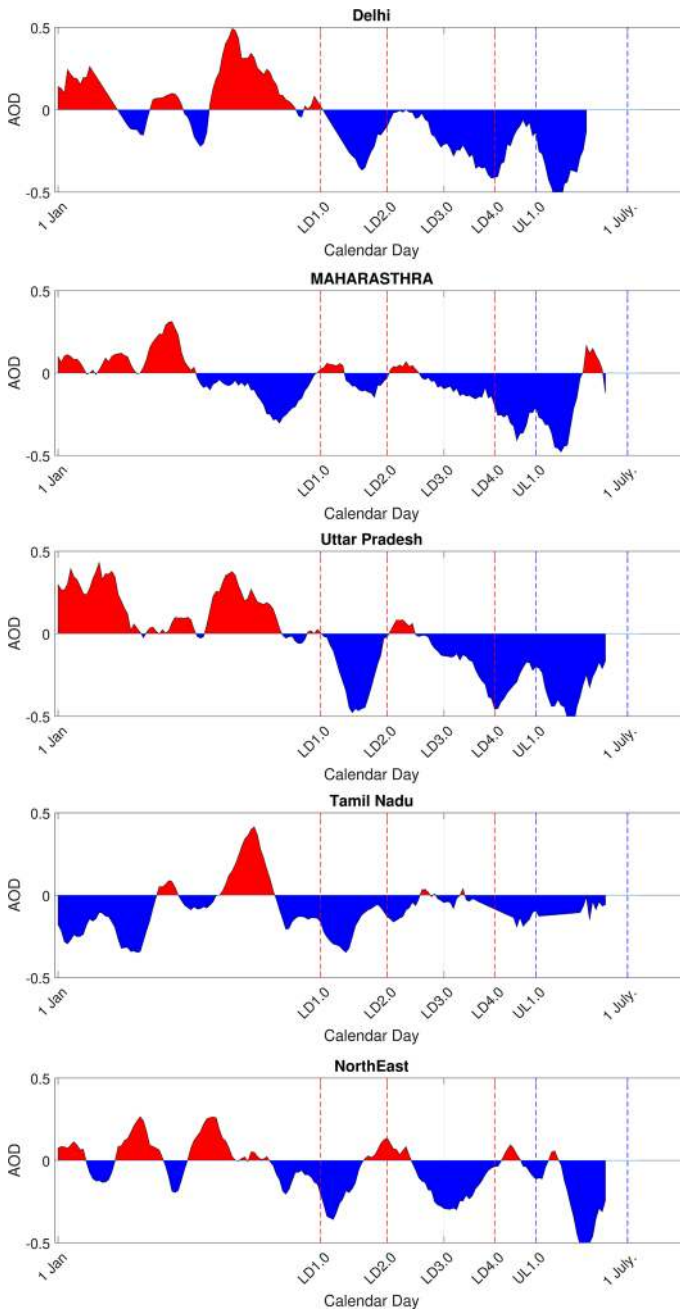
Fig. 6 The 10-day running means anomalous time series from the year 2018

during the LD3.0 phase for Delhi. Similar patterns were observed for Uttar Pradesh also. Overall, the most significant drop in AOD was observed for the Uttar Pradesh region during the LD1.0 phase (−49.67% from 2018 and −33.37% from 2019). In contrast to the year
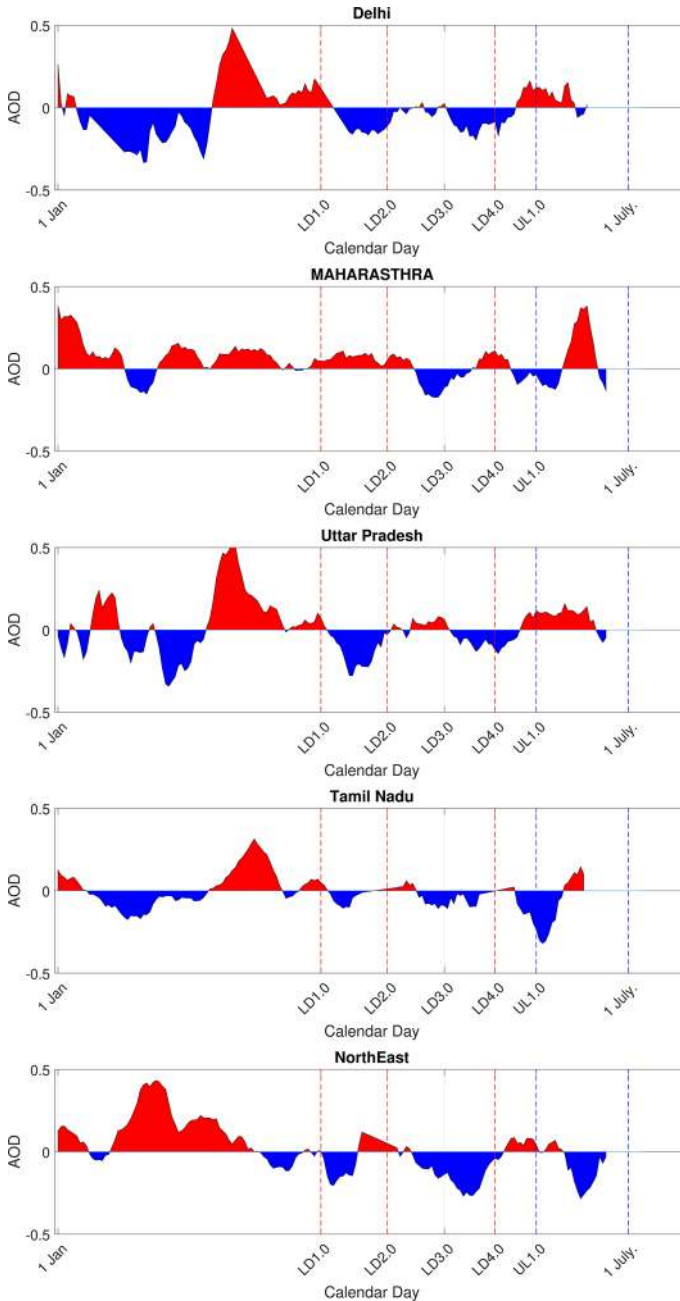
Fig. 7 The 10-day running means anomalous time series from the year 2019

2018, during the PL period, AOD in 2020 increased for all the regions compared to the year 2019.

The major conclusions from the study can be enumerated as

Table 2 % AOD anomaly from year 2018

	PL	LD1.0	LD2.0	LD3.0	LD4.0	UL1.0
Delhi	23.53	−36.49	−21.69	−47.97	−31.80	−36.17
Maharashtra	−1.23	−7.09	−0.75	−27.14	−44.63	−23.57
UP	29.71	−49.67	1.22	−35.79	−36.87	−33.45
Tamil Nadu	−16.56	−39.22	−13.39	−6.53	−17.52	−25.68
Northeast	3.41	−16.86	−12.18	−30.35	1.48	−32.58

Table 3 % AOD anomaly from year 2019

	PL	LD1.0	LD2.0	LD3.0	LD4.0	UL1.0
Delhi	1.75	−16.40	−10.37	−24.14	6.88	−0.99
Maharashtra	16.54	30.38	−14.34	5.04	−7.71	−1.50
UP	6.52	−33.37	5.61	−13.56	−0.88	3.33
Tamil Nadu	5.25	−10.66	−6.86	−5.01	−7.02	−16.43
Northeast	21.98	−4.02	−8.78	−29.64	7.64	−15.75

1. There was a considerable buildup of AOD during the pre-lockdown period in the year 2020
2. As the lockdown phases began, there was a sudden drop in AOD values, especially over the Indo-Gangetic Plains. The drop was as high as -47.97% for Delhi during the LD3.0 phase.
3. As the unlock phase begins, the drop in AOD was flattened for Delhi and Uttar Pradesh regions.
4. The industrialized regions in the north are significantly affected by the lock/unlock phases as compared to regions in the south or northeast.

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