Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
Effect of lockdown due to SARS COVID-19 on aerosol optical depth (AOD) over urban and mining regions in India

Avinash Kumar Ranjan a, A.K. Patra b, A.K. Gorai a,⁎

a Department of Mining Engineering, National Institute of Technology (NIT), Rourkela 769008, India
b Department of Mining Engineering, Indian Institute of Technology (IIT), Kharagpur 721302, India

HIGHLIGHTS

• COVID-19 pandemic triggered lockdown events in India greatly reduced the AOD level.
• Nearly 45% AOD level dropped over Indian Territory during lockdown periods.
• A significant negative anomaly in mean AOD level was observed in most of the states.
• Metropolitan cities showed negative mean AOD anomaly for entire lockdown period.
• No significant reduction in mean AOD level over coal mining regions was observed.

GRAPHICAL ABSTRACT

Abstract

The Severe Acute Respiratory Syndrome-COronaVirus Diseases 2019 (SARS-COVID-19) pandemic has posed a serious threat to human health (death) and substantial economic losses across the globe. It was however presumed that extreme preventive measures of entire lockdown in India might have reduced the air pollution level and therefore decreased the aerosol optical depth (AOD). The Moderate Resolution Imaging Spectroradiometer (MODIS)-based Multi-angle Implementation of Atmospheric Correction (MAIAC) daily AOD product was deployed to investigate the change in AOD level during lockdown phases across the Indian Territory as compared to the long-term mean AOD level (2000–2019) of the same periods. The key findings of the study revealed that 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). Furthermore, a noteworthy negative AOD anomaly (−6 to 37%) was observed across the four metropolitan cities in India during the entire lockdown period (25th March to 15th May 2020). However, coal mining regions of the various coalfields in India showed a positive anomaly (−11 to 40%) during the lockdown periods due to ongoing mining operations. In a nutshell, the study results indicated a huge drop in the AOD level over Indian Territory during lockdown periods. It is expected that the pandemic can influence some policy decisions to propose air pollution control methods. Lockdown events possibly may play a crucial role as a potential solution for air pollution abatement in the future. It may not be uncommon in future when the governments may implement deliberately selective lockdowns at pollution hotspots to control the pollution level.

© 2020 Published by Elsevier B.V.
1. Introduction

The Severe Acute Respiratory Syndrome-COronaVirus Diseases 2019 (SARS-CoV-2), also recognized as SARS-CoV-2, has severely hit the world through extensive human to human transmission and triggered the human death rate and substantial economic losses across the globe (Buhkari and Jameel, 2020). World Health Organization (WHO) has avowed the SARS-COV-2 (COVID-19) as the sixth public health emergency on a global scale on 30th January 2020 (https://www.who.int/emergencies/news/highlights/en/). The COVID-19 pandemic is making global impacts like the Spanish Flu (1918), Mexican Smallpox (1967), AIDS (1980s), SARS (2002), Bird Flu (2005), H1N1 Swine Flu (2009), Ebola in West Africa (2014), Zika (2016), and Ebola in the Democratic Republic of Congo (2019) (https://www.who.int/emergencies/diseases/en/). The first COVID-19 case was found in the Wuhan region of Central Hubei Province of China on 31st December 2019 (Shi et al., 2020). It has rapidly been spreading since then across the globe (Li et al., 2020a) with 4,761,559 confirmed cases, including 317,529 deaths, from 216 countries as of 7:10 pm CEST, 20th May 2020 (https://covid19.who.int/). The world’s top five affected countries with confirmed cases are the United States of America (1,477,459), Russia Federation (299,941), Brazil (254,220), The United Kingdom (246,410), and Spain (2,316,060) as on 20th May 2020 (https://covid19.who.int/). The details of worldwide COVID-19 cases can be found by following the WHO COVID-19 dashboard (https://covid19.who.int/).

In India, the first COVID-19 infection was detected on a student (returned from Wuhan, China) in the Kerala state on 30th January 2020. Since then, there has been an exponential rise in the active cases and death cases due to COVID-19. The Ministry of Health and Family Welfare, Government of India, reported 61,149 active cases, 3303 deaths, and 42,297 cured/discharged cases as of 20th May 2020 (https://www.mohfw.gov.in/). Maharashtra is the most affected state of India, with 37,136 confirmed cases followed by Tamil Nadu (12,448), Gujarat (12,140), Delhi (10,554), and Rajasthan (5845) as on 20th May 2020. The details of COVID-19 cases in India can be found by following the Ministry of Health and Family Welfare, Govt. of India (https://www.mohfw.gov.in/), or myGOV portal of Govt. of India (https://www.mygov.in/covid-19). India potentially carries a significant risk due to higher population density, limited infrastructure, and partial health care capability for medical treatment of a considerable number of patients over a specific period.

To avert the COVID-19 pandemic risk, various reduction measures like social-distancing, cluster and entire lockdowns, extensive travel bans, mass quarantines, etc. have been implemented across the world. These risk reduction measures have led to a direct impact on the local and global socio-political relations and economic growth (Long and Feng, 2020). However, such preemptive measures to control the COVID-19 transmission have dramatically improved the air quality owing to the reduction of anthropogenic-based emissions. The deterioration of air quality across the globe due to various kind of anthropogenic interventions is the most serious issue in 21st century (Mehdiopour and Memarianfard, 2017; Motesaddi et al., 2017). In such a time, COVID-19 pandemic-imposed lockdown events have compelled to stop the anti-environmental deeds. Consequently, air quality level across the different continent of the globe is greatly improved during pandemic situation. In this context, Lal et al. (2020) have reported a substantial reduction in the level of NO\textsubscript{2}, CO, and AOD across the globe during COVID-19 pandemic (Jan.–Apr., 2020). Muhammad et al. (2020) have reported ~20–30% reduction in NO\textsubscript{2} level during lockdown periods across various countries, namely, China, Europe, Italy, France, Spain, and USA. Tobias et al. (2020) have also reported ~45, 51, 31, and 19% reduction in the level of PM\textsubscript{10}, SO\textsubscript{2}, and black carbon respectively, over Barcelona (Spain) during one-month lockdown period. Similarly, many other recent studies have demonstrated the significant reduction in the level of air pollutants (e.g. PM\textsubscript{2.5}, PM\textsubscript{10}, CO, SO\textsubscript{2}, NO\textsubscript{2}, etc.) across the world during COVID-19 pandemic (Collivignarelli et al., 2020; Dantas et al., 2020; Kerimray et al., 2020; Nakada and Urban, 2020; Otmani et al., 2020; Wang and Su, 2020). In India, a few recent studies have also reported a huge drop in the level of air pollutants (i.e. PM\textsubscript{2.5}, PM\textsubscript{10}, CO, SO\textsubscript{2}, NO\textsubscript{2}) across the different cities of India during lockdown periods (Mahato et al., 2020; Sharma et al., 2020; Srivastava et al., 2020). The above-mentioned studies were mainly focused on the investigation of PM\textsubscript{2.5}, PM\textsubscript{10}, CO, SO\textsubscript{2}, NO\textsubscript{2} level during COVID-19 pandemic situation. Although long-term AOD data are available in various temporal resolution (daily to monthly), only a few researchers (Lal et al., 2020; Kannahia et al., 2020) over the globe have paid attention to investigate the AOD level variation during this pandemic situation. As aforementioned studies have accounted a substantial drop in the level of various air pollutants, it is presumed that there must be a declining trend in the AOD level during different phases of the lockdown in India due to complete or partial shutdown of the major aerosol sources, like, biomass burning, industrial emissions, motor vehicle emissions, heavy transportation emissions, heavy machines emissions, etc.

Countless studies have already unveiled the importance of aerosol research, and also demonstrated the direct and indirect contributions of aerosols on the climate change at regional to global scales (Qian and Giorgi, 1999; Menon, 2002; Huang et al., 2014). The aerosol optical depth (AOD) affects the atmospheric stability and precipitation as aerosols disturb the scattering and absorption of solar radiation (Jiang et al., 2016; Shaw and Gorai, 2018), the hydrological cycle (Prasad et al., 2004), and vegetation cover and its growth (Lal et al., 2019; Sarkar and Kafatos, 2004). Apart from climatic effects, aerosols cause many serious health-related issues (i.e., asthma, premature death, lung cancer, cardiopulmonary mortality, and pulmonary inflammation) (Prasad et al., 2005; Huang et al., 2012; Mulenga and Siziya, 2019). Furthermore, numerous past studies have shown that AOD can be used as a metric to estimate air pollution level, whereas AOD is typically used as a proxy of PM\textsubscript{2.5} and PM\textsubscript{10} concentration estimation (Kumar et al., 2007; Lin et al., 2015). Thus, study on AOD during lockdown periods can help in understanding the influence anthropogenic activities on the tropospheric aerosol level. An approximate concentration of particulate matter can also be anticipated. The current study therefore investigated the impacts of COVID-19 imposed lockdown events on AOD level over the Indian Territory. The overarching objectives of this investigation are (1) to analyze the effect of lockdown due to COVID-19 on the AOD level over the Indian Territory with special emphasis on four metropolitan cities and ten coal mining regions in India; and (2) to estimate the AOD anomaly during the lockdown periods (2020) as compared to the long-term (2000–2019) mean AOD during the same periods. Retrieval and processing of long-term daily AOD data using Google Earth Engine (GEE) cloud platform is the crucial aspect of the present study. Till date, it is the maiden study where long-term (2000–2020) daily AOD were retrieved for the entire Indian Territory with special emphasis on four metropolitan cities and ten coal mining locations during the lockdown periods.

Nomenclature

| Acronym | Description |
|---------|-------------|
| AOD     | Aerosol Optical Depth |
| CO      | Carbon Monoxide |
| GEE     | Google Earth Engine |
| MAIAC   | Multi-angle Implementation of Atmospheric Correction |
| MODIS   | Moderate Resolution Imaging Spectroradiometer |
| NCR     | National Capital Region |
| NO\textsubscript{x} | Nitrogen Oxides |
| PM      | Particulate Matter |
| SARS-COVID-19 | Severe Acute Respiratory Syndrome-COronaVirus Diseases 2019 |
| UT      | Union Territory |
| WHO     | World Health Organization |
This paper is structured as follows: Section 1 is the Introduction section, where emergence of COVID-19 pandemic, status of affected countries from COVID-19 pandemic, status of COVID-19 cases in India, literature review on positive impacts of COVID-19 enforced lockdown on environment, importance of AOD study, motivation and objectives of the present investigation have been summarized. Section 2 describes the materials and method that include details of satellite data, details of the study regions, phase-wise data processing, and the data analysis sequence. The key findings of the study, like, phase-wise AOD concentration over the Indian Territory (including four metropolitan cities and ten coal mine locations), AOD anomaly as compared to last 20 year mean AOD for the same periods, comparison with earlier studies have been discussed in the Section 3 (Results and discussion). Section 4 contains the conclusion of the study, wherein, we have highlighted the important outcomes of the present investigation with some future resolutions.

2. Materials and method

2.1. Data used

The AOD product of Moderate Resolution Imaging Spectroradiometer (MODIS) satellite sensor (MCD19A2-v6) is used in the present study to retrieve the daily basis AOD over the Indian Territory. MCD19A2 is a MODIS Terra and Aqua combined Multi-angle Implementation of Atmospheric Correction (MAIAC) Land Aerosol Optical Depth (AOD) Level-2 gridded product having a spatial resolution of 1 km. MCD19A2 offers daily-basis AOD for land at two different wavelength bands, i.e., 470 nm (blue band) and 550 nm (green band). AOD at 550 nm (green band) was used in the present study due to its better consistency (Lyapustin and Wang, 2018a). The MCD19A2 product was typically available in sinusoidal grid projection, which was re-projected on the WGS 1984 geographic coordinate system. The daily AOD datasets were acquired and processed for the phase-wise national lockdown periods implemented in India as a preventive measure of COVID-19. The datasets were processed for first lockdown period (Phase – 01: 25th March to 14th April 2020), second lockdown period (Phase – 02: 15th April to 3rd May 2020), third lockdown period (Phase – 03: 4th May to 15th May 2020), and for the entire lockdown period (25th March to 15th May 2020). Third lockdown period was implemented till 17th May 2020, but our study has considered till 15th May 2020. Conversely, the mean AOD was retrieved from 2000 to 2019 for the same time periods as that of the lockdown periods for comparative analysis. The daily AOD datasets were pooled from Land Processes Distributed Active Archive Center (LPDAAC) geoportal (a component of NASA’s Earth Observing System Data and Information System (EOSDIS)) (https://lpdaac.usgs.gov/products/mcd19a2v006/). The details of the AOD product used in the present study are given in Table 1. Basic processing of daily AOD datasets (i.e. re-projection into WGS 1984, conversion in a standard format (using scaling factor), long-term mean value composite data preparation for the lockdown periods, etc.) was performed in google earth engine (GEE) cloud platform (https://code.earthengine.google.com/). Thereafter, phase-wise mean AOD datasets were exported, and further processing, map preparation, assessment, etc. were completed in ArcGIS (v10.5) software.

2.2. Methods

The present study is focused to analyze the impact of phase-wise nationwide lockdown on the spatio-temporal pattern of AOD level over the Indian Territory as compared to last 20 years mean AOD level. Furthermore, attention is paid to investigate the variation in AOD level within the 5 km buffer zone (from mid point) of the four metropolitan cities of India, namely, National Capital Region (NCR), Kolkata, Bengaluru, and Mumbai. Ten coal mine locations of different coalfields in India were also selected for analyzing the AOD change pattern during the lockdown periods (as coal mining activities are one of the key sources of AOD and particulate matter emission, and the mining activities during lockdown periods was not suspended). The mean AOD level within the 5 km buffer zone (from mid point) of coal mine was considered to represent the region. The details of the study region including four metropolitan cities and ten coal mine locations are presented in Fig. 1.

The spatio-temporal pattern of mean AOD level is portrayed in four schemes viz. (1) during first lockdown period (Phase – 01: 25th March to 14th April 2020), (2) during second lockdown period (Phase – 02: 15th April to 3rd May 2020), (3) during third lockdown period (Phase – 03: 4th May to 15th May 2020), and (4) for the entire lockdown period (25th March to 15th May 2020). Simultaneously, the long-term mean AOD (2000–2019) for the same time periods are estimated to understand the alteration in the AOD level pattern during lockdown periods. Furthermore, phase-wise anomaly maps are derived using Eq. (1) to portray the percent changes in AOD level at a particular spatial location during lockdown period as compared to the long-term mean (2000–2019) AOD for the same time-periods. The self-explanatory flowchart for the methodological workflow is given in Fig. 2, wherein the sequence of data acquisition, pre-processing, AOD extraction, phase-wise AOD estimation, and AOD anomaly assessment are presented.

\[
\text{Anomaly(\%)} = \frac{(X) - (\bar{X})}{(\bar{X})} \times 100
\]

where, \(X\) is the phase-wise mean AOD for the year 2020; and \(\bar{X}\) is the phase-wise long-term (2000–2019) mean AOD.

3. Results and discussion

3.1. Phase-wise AOD concentration over the Indian Territory

The phase-wise AOD distribution map of Indian Territory is prepared and presented in Fig. 3. Fig. 3(a)–(d) represents the long-term (2000–2019) mean AOD for (a) Phase – 01 (25th March to 14th April), (b) Phase – 02 (15th April to 3rd May), (c) Phase – 03 (4th May to 15th May), and (d) during 25th March to 15th May. On the other hand, the mean AOD during first lockdown period (Phase – 01) (25th March to 14th April 2020), during second lockdown period (Phase – 02) (15th April to 3rd May 2020), during third lockdown period (Phase – 03) (4th May to 15th May 2020), and during entire lockdown period (25th March to 15th May 2020) are presented in Fig. 3 (a′) – (d′), respectively. Visually, it can be interpreted that most of the Indian states except Jammu and Kashmir (JK), Ladakh (LK), Himachal Pradesh (HP), Arunachal Pradesh (AR), and major part of the Uttarakhand (UK), have a higher long-term (2000–2019) mean AOD than in 2020 during the study time periods (Fig. 3(a)–(d)). During Phase 1 (2000–2019), Gujrat (GJ), Maharashtra (MH), Uttar Pradesh (UP), and Punjab (PB) had slightly lower long-term mean AOD as compared to AOD in other states. A drastic reduction of AOD was noted across the Indian states during lockdown periods (Fig. 3(a)′–(d)′). However, in some areas of a few states like Odisha (OD), Chhattisgarh (CG),

Table 1: Details of AOD product used in the present study.

| Datasets          | Time period                | Band used          | Spatial resolution | Temporal resolution | Citation               |
|-------------------|----------------------------|--------------------|--------------------|---------------------|-----------------------|
| MCD19A2 (Aerosol Optical Depth) | 25th March to 15th May (2000–2020) | 550 nm (green band) | 1 km               | Daily               | Lyapustin and Wang (2018b) |
Telangana (TS), east and western part of Maharashtra (MH), and north-east part of Andhra Pradesh (AP), the AOD was still higher as compared to other states during the first lockdown period (Phase – 01; 25th March to 14th April 2020). (Fig. 3(a)). Notably, during second lockdown period (Phase – 02; 15th April to 3rd May 2020), a substantial reduction in AOD was observed across all the Indian states, although a few states like, UP, Bihar (BR), Assam (AS), Jharkhand (JH), and some parts West Bengal (WB), OD, AP, and TS have showed slightly higher AOD as compared to the other states (Fig. 3(b)). During third lockdown period (Phase – 03; 4th May to 15th May 2020), all states have showed very less AOD as compared to the long-term mean AOD for the same time period except a few regions namely, the western part of Rajasthan (RJ), central parts of UP, some parts of BR and WB, north-east part of JH, south and east parts of TS, some parts of AP and Karnataka (KA), where AOD was little higher as compared to the other states (Fig. 3(c)). Cumulatively, during the entire lockdown period in the India (25th March to 15th May 2020), a significant reduction in AOD value across the Indian states, suggesting corresponding reduction in air pollution (especially PM$_{2.5}$ and PM$_{10}$) level over the Indian Territory.

3.2. Phase-wise AOD anomaly over Indian Territory

Phase-wise AOD anomaly was estimated using Eq. (1) and map was prepared to understand the spatial variation in AOD during the lockdown period in India as compared to the long-term mean AOD (2000–2019). The prepared AOD anomaly map is presented in Fig. 4, wherein negative range (green - yellow) shows the decrement and positive range (light blue — dark blue) shows the increment in the AOD during different phases of the lockdown as compared to the long-term mean AOD during the same periods.

The prepared AOD anomaly map shows a significant reduction in AOD during lockdown periods as compared to long-term mean AOD. During Phase 1, a significant reduction in the AOD as compared to the long-term mean AOD were observed in most of the states, except a few patches in MH, some portion of RJ, MP, CG, OD, TS, and AP states that reported higher AOD value (Fig. 4(a)). During Phase 2, almost all states had negative AOD anomaly percent; only a few small unevenly distributed patches of positive AOD anomaly percent were detected across the north-east to south-eastern states of India (Fig. 4(b)). However, slightly higher positive AOD anomaly patches were observed during Phase 3. Almost every state was detected with few small spatial patches of positive AOD anomaly percent; particularly, RJ, UP, BR, all north-east states, JH, WB, MH, TS, AP, and KA were found with relatively higher positive anomaly patches (Fig. 4(c)). Furthermore, AOD anomaly map during the entire lockdown period (25th March to 15th May 2020) is shown in Fig. 4(d). The map indicated that during the lockdown period, the AOD level reduced drastically across the Indian Territory (as AOD anomaly percent was found negative across most of the area).
Nevertheless, few spatial patches were observed across MP, MH, TS, AP, OD, WB, and AS states where the positive anomaly was detected. The quantitative analysis of AOD anomaly (state-wise mean AOD anomaly is presented in Fig. 5. The bar diagram showed that maximum AOD anomaly as +13.7 and −42.5% for MH and UK state, respectively. A few states namely, Andaman & Nicobar (AN), AS, CC, Dadra & Nagar Haveli (DN), Lakshadweep (LD), MH, OD, WB, and TS states have showed a little positive AOD anomaly (∼14%). The rest of the states have shown substantial negative AOD anomaly with UK, HR and DL having negative anomaly >30%. For a particular pixel, the minimum and maximum AOD anomaly percent varied from +40 to −70%, although it cannot be overlooked that still there was some inconsistency in terms of missing pixel values. The higher positive AOD anomaly over the few regions or states is quite unacceptable and unlikely during the entire lockdown periods, wherein all the major sources of AOD were almost completely closed. The prime reason behind this unreasonable outcome was the inconsistency in the number of AOD pixels within the state’s administrative boundary during the corresponding phases of 2000–2019 and 2020. The total count of AOD pixels within states administrative boundaries were not same in all the cases, so there may be slight variation in the AOD anomaly across the Indian Territory. However, major findings of the present study will remain valid.

3.3. AOD anomaly over four Indian metropolitan cities

Phase-wise AOD anomaly (mean) within the 5 km buffer zone (from mid point) of the four metropolitan cities of India (i.e. National Capital Region (NCR), Kolkata, Mumbai, and Bengaluru (also known as Bangalore)) were computed using Eq. (1) for analyzing the lockdown effects on the AOD level variation (Fig. 6). As expected, negative anomaly (mean) within 5 km buffer zone of all the metropolitan cities (except Kolkata) was noted during lockdown phases. A huge decrement in the AOD was observed within the 5 km buffer zone of NCR. The anomalies detected were (∼) 37, 25, 44, and 37% during Phase 1, 2, 3, and during the entire lockdown (entire LD) period, respectively. Similarly, a substantial reduction in AOD within 5 km buffer zone of Mumbai metropolitan city was noted throughout various phases of lockdown. The anomaly percent (mean) was (∼) 17, 20, 15, and 15% during Phase 1, 2, 3, and entire LD period, respectively. In Bengaluru metropolitan city, AOD anomaly was roughly (∼) 5, 28, and 6% anomaly was found during Phase 1, 2, and entire LD period, respectively. Due to the missing pixel inconsistency, anomaly for the Phase 3 could not be estimated within the 5 km buffer zone of the Bengaluru.

Surprisingly, ~27 and 40% positive AOD anomalies were found for Kolkata during second and third lockdown period, respectively. This positive anomaly is very unlikely situation in a lockdown period when predominant aerosol sources in the city such as traffic and industry operations were severely curtailed. The reason for higher AOD value during these phases in Kolkata is attributed to inconsistency in total number of AOD pixels within the boundary (as discussed in Section 3.2). The number of AOD pixels within the 5 km buffer zone of Kolkata was not same for the years 2000–2019 and 2020, hence the AOD anomaly may be less than the estimated during Phase 2 and 3. However, when mean AOD anomaly during the entire lockdown period (25th March to 15th May 2020) is considered, a negative anomaly of (∼) 17% was detected. It indicated that AOD significantly reduced during the entire LD period within the 5 km buffer zone of the Kolkata region. The mean AOD anomaly, all negative, during the entire lockdown period was highest in NCR (36.5%) and the lowest in Bengaluru (5.6%), which suggests that in terms of reduction of air pollution, the lockdown had the highest impact in NCR and the lowest in Bengaluru. During the third lockdown, a few relaxations such as transport on road was given,
trains ferried migrant workers across the country and specified national and international flights evacuated the stranded people. This resulted in aerosol emissions gradually increasing and therefore for all four cities, the anomaly was the highest during a particular lockdown phase ((−) 44.2% during Phase 1 at NCR, (−) 19.6% during Phase 2 at Mumbai, (−) 19.95% during Phase 1 in Kolkata and (−) 27.5% in Phase 2 in Bengaluru) than the AOD anomaly for entire LD period. Overall, our analysis showed that these metropolitan cities which are highly polluted regions (Delhi followed by Mumbai, Kolkata, Bengaluru) in the term of air quality during the normal days (Sikarwar and Rani, 2020), experienced a noteworthy reduction in air pollution level (as high as (−) 44.2% in NCR) during the lockdown periods. Few recent studies (Gautam, 2020; Kumari and Toshniwal, 2020; Sikarwar and Rani, 2020) have also reported a significant reduction in air pollution or pollutants concentration (> 50%) over Delhi, Mumbai, Lucknow, and other megacities of India during entire lockdown period as compared to same period of last 2–3 years. These studies were mainly focused to analyze the air pollutants (i.e., PM10, PM2.5, NO2, SO2, CO) concentration prior to and during lockdown periods. However, the current one is the maiden study which reports a significant reduction in the AOD level over the Indian Territory along with four metropolitan cities and 10 coal mine locations during lockdown periods as compared to same periods of last 20 year mean AOD level. Overall, these studies revealed that COVID-19 pandemic enforced lockdown events resulted in significant improvement of the air quality in highly polluted Indian cities.

3.4. AOD anomaly over coal mine locations of India

Phase-wise AOD anomaly (mean) within the 3 km buffer zone (from mid point) of the 10 coal mines of different coalfields in India (i.e. Talcher, Singrauli, Godavari Valley, Namchik Namphuk, Raniganj, Jharia, Ramgarh, Ib Valley, Sohagpur, and Jhilimili) were extracted for analyzing the AOD variation during lockdown periods. The bar diagram for phase-wise mean AOD anomaly over the coal mine locations is presented in Fig. 7.

Higher (positive) AOD anomalies (up to +70% approximately) were observed at most of the mine locations throughout the lockdown periods, because most of the coal mines (except a few) across the country were not closed during the lockdown periods (as coal-based electricity accounts for nearly 80% of the power generation in India). Further, the production capacity of these mines increased in recent decades with corresponding higher emission of pollutants, especially dust. As a result, the mean AOD over these coal mine locations during the lockdown phases were higher than 2000–2019 mean AOD. During Phase 1, most of the mine locations showed positive AOD anomaly (up to +31% roughly), except three mine locations namely, Singrauli, Raniganj, and Ramgarh which showed a slightly negative anomaly, approximately (−) 7, 4, and 2%, respectively. Notably, during Phase 2, not a single mine location was found with the negative anomaly. The minimum and maximum AOD anomaly was noted over mines of Talcher and Ramgarh coalfield with (−) 37 and (+) 70% respectively. Three mining regions (Godavari valley, Jharia, and Ib valley coalfield) showed positive AOD anomaly of around 52%, 11%, and 8%, respectively. Overall, during the entire lockdown period (25th March to 15th May 2020), almost all the mine locations of different coalfield have shown positive anomaly except a mine each in Singrauli and Raniganj coalfield. Thus, it can be inferred that most of the coalmines...
of the different coalfields were active during the lockdown periods, whereas, some of the mine locations seems to be closed or working with very less capacity during Phase 3 lockdown. However, unusually high positive anomaly over the few mine locations can be due to the spatio-temporal variation in areal coverage of coal mine locations along with the amount of coal extraction. One more possibility is that some of the mines were may not be functional since 2000 and coal production from these mines started after 2010, which resulted in very less...
AOD during that time period as compared to recent years. Moreover, inconsistency in the total number of AOD pixels within the 3 km buffer zone of the coal mine locations cannot be overlooked. This may be the one of the possible reasons for slightly higher positive AOD anomaly, as we have discussed in Sections 3.2 and 3.3. No such study was available to compare the AOD level over the mine locations.

In a nutshell, our investigation reports a huge reduction in AOD level across the Indian Territory during lockdown periods as compared to the last 20 year mean AOD level (2000–2019). The COVID-19 pandemic has made a serious threat to human health along with huge economic loss across the globe. However, there is growing evidence that COVID-19 triggered preventive measures (e.g. partial or full lockdowns events in terms of transportation ban, restriction in mass gathering, non-functioning of industries, etc.) have greatly reduced the air pollution levels across different continents. Kanniah et al. (2020) have reported a significant drop in AOD and other air pollutants (i.e. PM2.5, PM10, NOx, SO2, and CO) over the Southeast Asia region due to lockdown events. They reported ~40 and ~70 % (in industrial and urban sites, respectively) reduction in AOD level in Malaysia during March–April 2020 as compared to the same period in 2019 and 2018. Similarly, few more studies have been conducted across the different countries for PM10, PM2.5, NOx, SO2, and CO measurement during COVID-19 enforced lockdown periods. However, very fewer studies have paid attention for AOD assessment during lockdown periods. Otmani et al. (2020) assessed the impacts of COVID-19 lockdown on air pollutants (i.e. PM10, SO2, and NOx) in Salé City, Morocco. They observed ~75, 49, and 96% decrement in the concentration of PM10, SO2 and NOx, respectively, during and before lockdown. Li et al. (2020b) observed a reduction in SO2, NOx, PM2.5 and VOCs emissions by ~16–26%, 29–47%, 27–46% and 37–57% over Yangtze River Delta Region, China during the Level I and Level II lockdown periods, respectively as compared to same period of 2019. Kerimray et al. (2020) estimated a reduction in PM2.5, CO, and NO2 concentration by ~21, 49, and 35%, respectively over Almaty, Kazakhstan during lockdown period as compared to same period during 2018–2019. A study on two megacities, Rio de Janeiro and São Paulo in Brazil, revealed a substantial reduction in the air pollutants (i.e. PM10, NO2, and CO) during the partial lockdown (Dantas et al., 2020; Siciliano et al., 2020). Both studies have estimated a huge drop in CO level as compared to same period of 2019. Therefore, the pandemic enforced lockdown events have played a crucial role in reducing the concentration of air pollutants across the globe, suggesting our environment and nature got an extremely rare window to recover itself in the term of air pollution.

4. Conclusions

The COVID-19 pandemic has turned out a serious threat to human health along with huge economic loss across the globe. However, the pandemic triggered lockdown demonstrates that nature can heal itself if an opportunity is given by mankind. The
current investigation exhibited that AOD level across the Indian Territory is dramatically reduced due to pandemic triggered lockdown events. Furthermore, it is anticipated that proportionate reduction in air pollution parameters (especially PM$_{2.5}$ and PM$_{10}$) over the country would have resulted during the entire lockdown period. The state-wise analysis revealed that UK state had the highest positive impact of lockdown, where AOD level reduced up to $-43\%$ during the lockdown period. All the four metropolitan cities showed negative AOD anomaly with the NCR having the highest negative AOD anomaly ($-36.5\%$) during the entire lockdown period (25th March to 15th May 2020). On the other hand, positive AOD anomaly (up to $+70\%$) for the coal mine locations (within 3 km of buffer zone) of different coalfields were observed throughout the lockdown periods due to on-going coal mining operations. Only a few mines working in reduced capacity during Phase 3 of the lockdown were noted with less AOD anomaly. The analysis presented in this paper has the limitations that it could not extract some AOD pixel values for a few locations, and therefore the results may slightly change when all pixel values are considered. Although, we believe that the major findings of the study will still remain valid. Therefore, the lockdown events may play a crucial role as a potential solution for air pollution abatement in the future. It may not be uncommon in future when the governments may implement strategically selective lockdowns at local levels to control the pollution levels over pollution hotspots. We believe the governments, policy-makers and environmentalist will formulate new innovative programs and methods for imposition of these lockdowns with minimal impact on economy.

**CRediT authorship contribution statement**

Avinash Kumar Ranjan: Conceptualization, Methodology, Software, Validation, Formal analysis, Data curation, Writing - original draft, Writing - review & editing, Visualization. A.K. Patra: Formal analysis, Writing - review & editing. A.K. Gorai: Conceptualization, Formal analysis, Writing - review & editing, Visualization, Supervision, Project administration. All authors have read and approved the final version of the manuscript for publication.

**Declaration of competing interest**

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

---

### Acknowledgment

Authors sincerely thanks and acknowledge the Google Earth Group for Google Earth Engine (GEE) cloud platform and freely available MODIS MAIAC AOD product (MCD19A2) form Land Processes Distributed Active Archive Center (LPDAAC) geoportal (NASA EOSDIS).

### Funding

The financial support of the Council of Scientific & Industrial Research (CSIR), Govt. of India, New Delhi [Grant no. 24(0352)/18/EMR-II] on AOD study over the mining region is acknowledged.

### Ethical approval

Not required.

### References

Bukhari, Q., Jameel, Y., 2020. Will coronavirus pandemic diminish by summer? SSRN Electronic J. [https://doi.org/10.2139/ssrn.3556998].

Collivignarelli, M.C., Abbà, A., Bertanza, G., Pedrazzani, R., Ricciardi, P., Carnevalse Miino, M., 2020. Lockdown for Covid-2019 in Milan: what are the effects on air quality? Sci. Total Environ. 732, 139085. [https://doi.org/10.1016/j.scitotenv.2020.139085].

Dantas, G., Siciliano, B., França, R.R., da Silva, C.M., Arbilla, C., 2020. The impact of COVID-19 partial lockdown on the air quality of the city of Rio de Janeiro, Brazil. Sci. Total Environ. 729, 139085. [https://doi.org/10.1016/j.scitotenv.2020.139085].

Gautam, S., 2020. The influence of COVID-19 on air quality in India: a boon or inutile. Bull. Environ. Contam. Toxicol. 104 (6), 724–726. [https://doi.org/10.1007/s00128-020-02877-y].

Huang, W., Cao, J., Tao, Y., Dai, L., Lu, S.-E., Hou, B., Wang, Z., Zhu, T., 2012. Seasonal variation of chemical species associated with short-term mortality effects of PM$_{2.5}$ in Xi’an, a central city in China. Am. J. Epidemiol. 175 (6), 556–566. [https://doi.org/10.1093/aje/kws342].

Huang, J., Wang, T., Wang, W., Li, Z., Yan, H., 2014. Climate effects of dust aerosols over East Asian arid and semi-arid regions: climate effects of East Asian dust. J. Geophys. Res.-Atmos. 119 (19), 11,398–11,416. [https://doi.org/10.1002/2014JD021796].

Jiang, M., Li, Z., Wan, B., Cribb, M., 2016. Impact of aerosols on precipitation from deep convective clouds in eastern China: impact of aerosols on precipitation. J. Geophys. Res.-Atmos. 121 (16), 9607–9620. [https://doi.org/10.1002/2015JD024246].

Kanniah, K.D., Kamarul Zaman, N.A.F., Kaskaoutis, D.G., Latif, M.T., 2020. COVID-19’s impact on the atmospheric environment in the Southeast Asia region. Sci. Total Environ. 736, 139658. [https://doi.org/10.1016/j.scitotenv.2020.139658].

Kerimray, A., Baimatova, N., Ibragimova, O.P., Bukenov, B., Kenessov, B., Plotitsyn, P., Karaca, F., 2020. Assessing air quality changes in large cities during COVID-19 lockdowns: the impacts of traffic-free urban conditions in Almaty, Kazakhstan. Sci. Total Environ. 730, 139179. [https://doi.org/10.1016/j.scitotenv.2020.139179].

Kumar, N., Chu, A., Foster, A., 2007. An empirical relationship between PM$_{2.5}$ and aerosol opticaldepth in Delhi metropolitan. Atmos. Environ. 41, 4492–4503. [https://doi.org/10.1016/j.atmosenv.2007.01.046].

Kumari, P., Toshniwal, D., 2020. Impact of lockdown measures during COVID-19 on air quality– a case study of India. Int. J. Environ. Health Res., 1–8 [https://doi.org/10.1080/09603123.2020.1778646].

### Table: Phase-wise mean AOD anomaly over various coalmines of different coalfields of India.

| Coalfield Name | Phase 1 | Phase 2 | Phase 3 | Entire LD |
|----------------|---------|---------|---------|-----------|
| Talcher        | 3.35    | 2.39    | -1.19   | -2.61     |
| Singrauli      | 2.39    | 2.36    | 0.12    | 0.24      |
| Godavari Valley| 1.73    | 5.05    | 2.92    | 8.5       |
| Namchik        | 2.5     | 4.02    | -4.3    | -2.08     |
| Jharia         | 8.0     | 21.1    | 12.0    | 10.8      |
| Ramgarh        | -2.2    | -2.7    | -2.7    | -2.2      |
| Ib Valley      | -2.7    | -1.6    | 2.3     | 2.3       |
| Sohagpur       | 12.5    | 21.3    | 12.5    | 21.3      |
| Jhillimili     | 23.3    | 26.5    | 26.5    | 26.5      |
| Kumari         | 23.9    | 50.5    | 50.5    | 50.5      |
| Toshniwal      | 26.5    | 69.5    | 69.5    | 69.5      |

**Fig. 7.** Phase-wise mean AOD anomaly over various coalmines of different coalfields of India.
