Spatial distribution of aerosol optical depth over India during COVID-19 lockdown phase-1

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Abstract The present study analysed the spatial distribution of Aerosol Optical Depth (AOD) over India during the COVID-19 lockdown phase-1 (March 25 to April 15, 2020) using MODIS Terra (MOD04) AOD data (550 nm) during 2001–2020. Air temperature, rainfall, forest fire incidents, and wind patterns were analysed to understand their effect on the distribution of aerosols over India during the lockdown phase-1. Moderate absorption fine aerosol type is predominant but sparsely distributed over India during the study period compared to the reference period indicating the positive influence of the lockdown. Mean AOD has reduced by 9% over India during the lockdown phase-1 compared to the corresponding mean of the past 19 years (2001–2019). About 70% of the states/UTs of India showed a reduction in mean AOD due to restrictions on non-essential economic activities and rainfall occurrence. However, some states showed an increase in aerosol loading over specific pockets despite the restrictions on economic activities (Arunachal Pradesh, Assam, Gujarat, Orissa, Andhra Pradesh, Madhya Pradesh, Chhattisgarh, Maharashtra, Assam, Nagaland, Manipur and Karnataka) because of active forest fire cases. This study would be helpful for planners and policymakers to adopt suitable measures to control the rising concentrations of aerosols over hotspot regions of India.

Keywords MODIS · Aerosol optical depth · COVID-19 · Air quality

1 Introduction

Coronavirus disease (COVID-19) is an infectious disease that is caused by the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). It spreads from China to other countries around the world and the World Health Organization (WHO) declared this a global pandemic on 12 March 2020 [1]. Consequently, many countries of the world announced a lockdown (restrictions on economic activities and movement of people) to control the spread of the virus. To prevent the spread of COVID-19, the Indian government announced a complete lockdown (complete restrictions on all non-essential economic activities and movement of people) on 25 March 2020. This lockdown has been renewed four times in continuity with the first (ending on 14 April), second (till 03 May), third (till 17 May), and fourth (31 May 2020) phases. Many studies in different parts of the world including India reported an improvement in the air quality at varying scales and levels due to the lockdown or restriction of anthropogenic activities (release of aerosols) [2–7].

The amount of atmospheric aerosols is one of the key indicators of air quality. In climate science, aerosols are considered as key components which absorb and scatter the insolation and alter cloud microphysical properties [8, 9]. Eventually, the warming or cooling of the atmosphere is also closely related to the presence/absence of aerosols.
Hence, aerosols influence the radiation budget of the atmosphere and air quality. Distribution of aerosols and their refractive indices are highly variable in the atmosphere over space and time, influencing global or regional climate suggesting the need to manage it properly [9]. The source of atmospheric aerosol is natural (sea salt and mineral dust) as well as anthropogenic (water-soluble aerosols and black carbon) but physical and chemical processes in the atmosphere also generate aerosols [11, 12]. Moreover, particles produced by anthropogenic activities are smaller in size than those formed by natural processes [13].

Aerosol optical depth (AOD) is a measure of the extinction of solar radiation due to scattering and absorption by aerosols [9]. In recent times, space-borne earth observation satellites have been used to understand aerosol properties on a global scale such as Scanning Imaging Absorption Spectrometer for Atmospheric Cartography (SCIAMACHY), Ozone Monitoring Instrument (OMI), Along Track Scanning Radiometer (ATSR), Multiangle Imaging Spectroradiometer (MISR) [14], Polarization and Directionality of Earth Reflectance (POLDER), Sea-viewing Wide Field-of-view Sensor (SeaWiFS), Total Ozone Mapping Spectrometer (TOMS), Advanced Very High-Resolution Radiometer (AVHRR), Moderate Resolution Imaging Spectro-radiometer (MODIS), UVN (UV–VIS-NIR) Spectrometer [15] and Visible Infrared Imaging Radiometer Suite (VIIRS) [16]. The optical properties of aerosols obtained by these sensors are frequently validated by ground-based instruments to find out uncertainties in the data [17, 18]. MODIS has been widely used for the AOD estimation over land and ocean since early 2000 [16, 17, 19–22]. Variation of AOD over India has also been extensively studied using MODIS aerosol data [18, 23–25]. Moreover, all the above-mentioned research works have been conducted under the usual natural conditions without any restrictions on anthropogenic activities. Studies conducted in India during the lockdown have attributed the air quality improvement to the complete travel lockdown and suspension of all the non-essential travel activities in the country [26–28]. There has been a lack of studies that considered the effects of air temperature, rainfall, and forest fire on changes in aerosols over India during the lockdown phase-1. Therefore, the present study aims to understand the impact of COVID-19-imposed nation-wide lockdown phase-1 (March 25- April 15, 2020, when the majority of the human activities were legally restricted) on the distribution of AOD over India by analysing its spatial variability. The study has been carried out at the India level using the states and union territories (UTs) wise aerosol data and examined the effect of air temperature, rainfall, and forest fire incidents on aerosols.

2 Materials and methods

India is a tropical country and has bestowed diverse physiographical regions. The spatial variation of average temperature conditions in India varies from 12.5 °C to 30 °C. India receives an average annual rainfall of approximately 1000 mm. The present study period lies between the late winter and early summer or pre-monsoon season; when rainfall is lowest in the country and temperature conditions are moderate to high. Pre-monsoon season (March to May) is the driest and warmest among all seasons with low humidity content. The present study has followed political divisions (twenty-eight states and seven UTs) as per the Census of India, 2011 [29] (Fig. 1).

Aerosol data have been obtained from the MODIS AOD level-2 (Terra MOD04) product (Collection 006) at the spatial resolution of 3 km (at nadir) array from the Level-1 and Atmosphere Archive and Distribution System (LAADS) (https://ladsweb.modaps.eosdis.nasa.gov/) [30]. MODIS has two aerosols data products, namely MOD04_L2, obtained from the Terra sensor; and MYD04_L2, acquired from the Aqua sensor. The MODIS aerosol products examine the ambient AOD over the

Fig. 1 Location and extent of the study area (including names of State and Union Territories) (Census of India 2011) 1: Jammu & Kashmir 2: Himachal Pradesh 3: Punjab 4: Chandigarh 5: Uttar Pradesh 6: Haryana 7: Delhi 8: Rajasthan 9: Uttar Pradesh 10: Bihar 11: Sikkim 12: Arunachal Pradesh 13: Nagaland 14: Manipur 15: Mizoram 16: Tripura 17: Meghalaya 18: Assam 19: West Bengal 20: Jharkhand 21: Orissa 22: Chhattisgarh 23: Madhya Pradesh 24: Gujarat 25: Daman & Diu 26: Dadra & Nagar Haveli 27: Maharashtra 28: Andhra Pradesh 29: Karnataka 30: Goa 31: Lakshadweep 32: Kerala 33: Tamil Nadu 34: Puducherry 35: Andaman & Nicobar
oceans and continents globally. Tian and Gao [31] have used Aerosol Robotic Network (AERONET) data of Gandhi college (25.871 N & 84.128 E) and Kanpur (26.513 N & 80.232 E) for the validation of Terra-MODIS collection (6.1) dark target (DT) and deep blue (DB) aerosol products during 2001–2016. They reported that the correlation between AERONET and MOD04 DT AOD at Gandhi College and Kanpur city (located in the state of Uttar Pradesh, India) is 0.821 and 0.809, respectively, which reflects a very strong association. Hence, DT and aerosol type layers of MOD04 have been used to understand the variations in aerosols during the lockdown phase-1. It includes optical depth at 470, 550, 659, and 2130 nm. The 550 nm channel has been selected to analyse the spatial distribution of AOD over India during the lockdown phase-1.

Air temperature, rainfall, forest fire incidents and wind patterns data of India have been used to understand the effects of these factors on the aerosols conditions in the country during the lockdown phase-1. The ERA 5 air temperature (2 m above the land surface) (0.25° × 0.25°) of India was obtained for the period 1980–2020 (March and April months of the lockdown phase-1) (more than 30 years period is chosen to compute the normal air temperature over India) (http://climate.copernicus.eu/climate-reanalysis) to understand the temperature conditions of the country during the lockdown phase-1 [32, 33]. The daily gridded rainfall (0.25° × 0.25°) and forest fire incidents data (lockdown phase-1) of India has been obtained from the India Meteorological Department (IMD) [34] and the Forest Survey of India (FSI) [35], respectively. Wind patterns at 1000 and 950 hPa over the Indian subcontinent have also been examined during the lockdown phase-1 [33]. The surface lifted index data of India have been obtained from the Physical Sciences Laboratory [36]. The lifted index represents the difference between the temperature at 500 hPa and the temperature of an air parcel lifted to 500 hPa from the Earth’s surface [37]. Wind pattern and lifted index help to find out the possible movement and direction of aerosols over an area.

AOD data of India are averaged over the lockdown phase-1 (2020) and the corresponding reference period (2001–2019). The change in mean AOD and its percentage change have been calculated for all the states and UTs by taking the reference period using Eqs. 1 & 2.

\[
\text{Change in mean Aerosol} = T_2 - T_1
\]

\[
\text{Change in mean Aerosol}(\%) = \left[ \frac{T_2 - T_1}{T_1} \right] \times 100
\]

Where \( T_1 \) is representing aerosol level or concentrations of the reference period (2001–2019) while \( T_2 \) is denoting the lockdown phase-1 (2020).

The change in mean air temperature and its percentage change of the lockdown months (March and April) have been calculated for all the states and UTs by taking the reference period (1980–2019) using Eqs. 3 & 4.

\[
\text{Change in mean air temperature} = T_2 - T_1
\]

\[
\text{Change in mean air temperature}(\%) = \left[ \frac{T_2 - T_1}{T_1} \right] \times 100
\]

Where \( T_1 \) is representing the mean air temperature of the reference period (1980–2019) while \( T_2 \) is denoting the lockdown period (2020).

Then, state and UTs-wise cumulative average rainfall have been calculated using a method of Kumar et al. [38]. The non-parametric Theil Sen slope estimator test [39, 40] has been carried out for reporting trends in air temperature and its significance has been tested by the Mann Kendall significance test on pixel level (sig is tested at 0.10 level) [41, 42]. The Pearson product-moment correlation method has been computed to determine the association of mean AOD values with air temperature and cumulative average rainfall during the lockdown phase-1.

3 Results and discussion

3.1 Aerosol types and mean AOD across India

Types of aerosols prevailing in the corresponding reference period from 2001 to 2019 are continental, moderate absorption fine, and strong absorption fine over India (Fig. 2). During 2001–2019, continental aerosols are found in abundance over Rajasthan, the south-western part of Andhra Pradesh and the south-eastern part of Karnataka. However, continental aerosol type shows the scattered distribution over Uttar Pradesh, Bihar, Gujaratt, Madhya Pradesh, Chhattisgarh, Jharkhand, Orissa, Andhra Pradesh, Karnataka, and Tamil Nadu during the lockdown phase-1 period (Fig. 2). In both the periods (reference as well as lockdown phase-1), moderate absorption fine aerosol type is predominant in India. Compared to the period 2001–2019, moderate absorption fine aerosols show reduction over Manipur, Arunachal Pradesh, Sikkim, the northern part of West Bengal, the southern part of Sikkim, Bihar, the northern part of Chhattisgarh, east Madhya Pradesh, Himachal Pradesh and southern part of Jammu and Kashmir, Kerala and Tamil Nadu during the lockdown phase-1 (2020) indicating the effect of controlling travel and suspension of all the non-economic activities in the country. The distribution of strong absorption fine aerosols is negligible over India in both the periods.
3.2 Comparison of state-wise mean AOD of the lockdown period of 2020 with 2001–2019

Mean AOD for the corresponding lockdown period during 2001–2019 is 0.204 while it reduces to 0.185 in 2020, indicating an overall reduction of 9% over India (Fig. 3a, b). Due to lockdown, about 70% of the Indian states/UTs show a reduction in mean AOD. The stringent measures taken during the lockdown led to a reduction in mean AOD over Tripura, Sikkim, Jammu & Kashmir, Mizoram, West Bengal, Kerala, Madhya Pradesh, Meghalaya, Uttarakhand, Jharkhand, Himachal Pradesh, Uttar Pradesh, Gujarat, Delhi, Daman & Diu, Goa, Dadra & Nagar Haveli, Punjab, Bihar, Haryana, Chandigarh, Rajasthan, Pondicherry and Tamil Nadu (Fig. 3a,b,c). In these states, the reduction in mean AOD ranges between 6 and 77%. The highest reduction is observed over Tamil Nadu (77%) while the lowest is found over Tripura (6%) (Fig. 3c). However, an increase in mean AOD has also been found in Arunachal Pradesh, Orissa, Andhra Pradesh, Chhattisgarh, Maharashtra, Assam, Andaman & Nicobar Islands, Nagaland, Manipur, and Karnataka (Fig. 3c). The percentage increase of mean AOD in these states is varying between 7 and 77%. The highest increase in mean AOD has been observed over Arunachal Pradesh (77%) while the lowest over Karnataka (7%). Earlier, Sarkar et al. [10] reported high AOD over northern India compared to southern India. Contrary to this study, the present study found low AOD over northern India compared to southern India. The findings of the present study are consistent with the previous studies conducted particularly in the urban areas [2, 6, 26, 28]. Kumar et al. [2] found showed a general decrease (up to 54%) in AOD loading in different cities of India such as 29% (Chennai), 11% (Delhi), 4% (Kolkata), and 1% (Mumbai) against 2019 data. Jain and Sharma [26] also found a similar reduction of around 30–80% in pollutants concentrations in all the megacities (Mumbai, Chennai, Kolkata, and Bangalore) in India. Sharma et al. [28] found improvement in air quality especially in northern and eastern regions in 2020 compared to previous years based on the study of 22 cities of India. Muhammad et al. [6] found a reduction of up to 30% in the environmental pollution in countries of China, Italy, Spain, and the USA during the lockdown period.

During the lockdown, reduction in aerosols could be favorable both for weather and human beings [2, 26, 28]. The WHO [43] called air pollution one of the greatest environmental risks to health and mentioned that countries can reduce the burden of diseases (stroke, heart disease, lung cancer, and acute respiratory diseases, including asthma) by reducing air pollution levels. Hence, such reduction in the aerosols lowers air pollution which could improve the human’s cardiovascular and respiratory health in short term. However, there is a need to think about whether such initiative can be taken for a longer period to improve the aerosols loading in the atmosphere. This lockdown improves the air quality but leads to an economic slowdown in almost every nation of the world.
3.3 Factors affecting aerosol distribution during the lockdown phase-1

Studies attributed to the reduction in aerosols due to closure of industries, construction and demolition activities, commercial transportation and reduction in electricity demand from thermal power plants [2, 26, 28]. However, besides lockdown, the role of air temperature, rainfall, and forest fire is ignored in the improvement of aerosol concentrations in the atmosphere. Table 1 shows the relation of AOD with mean air temperature and rainfall during the lockdown phase-1. It shows significant positive relation with air temperature suggesting the positive influence of air temperature over AOD (Fig. 4). It is consistent with the previous study that also found a positive relationship of temperature with reported AODs across much of northern India during the winter months due to receiving a substantial amount of precipitation while the remaining parts (particular Deccan Plateau and north-eastern India) had a strong negative association [44]. Air temperature shows a significant decline over India compared to the reference period (1980–2019) (Fig. 4). Percentage change in air temperature varies from -4.9% to more than -10% over central India during the lockdown phase-1 compared to the reference period 2001–2019.

Table 1 Correlation of mean AOD with mean air temperature, and rainfall (2020)

| Variables                | Mean AOD (550 nm) |
|--------------------------|-------------------|
| Mean Air Temperature     | 0.195**           |
| Cumulative Average Rainfall | – 0.143**       |

**significant at 0.01** level
to the corresponding period (1980–2020). However, a statistically significant negative correlation is found between mean AOD and average rainfall during the lockdown phase-1. Unlike air temperature, rainfall plays an important role in reducing the aerosol density in the atmosphere during the lockdown phase-1 (Fig. 5).

Furthermore, dust over Punjab, Haryana, Chandigarh, Delhi, and western parts of Uttar Pradesh are transported from the major dust source regions like the Middle East countries, East Pakistan, the Thar Desert and semi-arid part of Rajasthan by the westerly and south-westerly [45]. The lifted index values are positive across the Middle East countries, East Pakistan, the Thar Desert and the semi-arid part of Rajasthan, which indicate a relatively stable atmospheric condition during the lockdown phase-1 (Fig. 6). This restricts the release of crustal dust to the atmosphere, which resulted in low aerosol concentrations in some parts of India during the lockdown phase-1. In this context, Bhattacharjee et al. [46] have studied a dust storm that originated from the Thar Desert during April 01–11, 2005, and reported negative lifted index values associated with that dust storm event over Delhi. Further, Rajasthan,
Gujarat, Madhya Pradesh, Punjab, Haryana, Chandigarh, and Delhi have received more than 60% of normal rainfall during the lockdown phase-1 period (March 26-April 01, 2020) due to strong western disturbances [47]. This favoured the wet deposition of the aerosol particles over these states. Therefore, a decline in the concentrations of atmospheric aerosols during the lockdown phase-1 period is also attributed to the stable atmospheric condition (restrict the release of the dust from the source regions), the above-normal rainfall (favours wet deposition of aerosol particles) and the strict measures taken by the Government of India (limits the emission of anthropogenic aerosols from non-essential sectors).

However, pixel-wise difference between mean AOD of the lockdown phase-1 (2020) and the corresponding period (2001–2019) shows a marked increase in mean AOD over these states. Therefore, a decline in the concentrations of atmospheric aerosols during the lockdown phase-1 period is also attributed to the stable atmospheric condition (restrict the release of the dust from the source regions), the above-normal rainfall (favours wet deposition of aerosol particles) and the strict measures taken by the Government of India (limits the emission of anthropogenic aerosols from non-essential sectors).

However, pixel-wise difference between mean AOD of the lockdown phase-1 (2020) and the corresponding period (2001–2019) shows a marked increase in mean AOD over southern Arunachal Pradesh, Orissa, central and southern Chhattisgarh, south and south-east parts of Maharashtra, central and north-eastern parts of Assam, central, northern and north-eastern part of Andhra Pradesh, south-western part of West Bengal, southern and central parts of Madhya Pradesh, south-western part of Gujarat, Nagaland, Manipur and northern part of Karnataka due to active forest fire incidents, biomass burning for domestic uses [48] and emission from the thermal plants (gas and fly ash) (Fig. 7).

As per the record of the FSI, there were 22,658 forest fire incidents that occurred in different parts of the Indian states and UTs during the lockdown phase 1 (Fig. 7). Out of these, 2268 forest fire incidents occurred on 25 March 2020 (Fig. 7). The corresponding values of the remaining days were 8856 on 30 March 2020, 4175 on 5 April 2020, 2865 on 10 April 2020 and 4494 on 15 April 2020. Jain and Sharma [26] also pointed that stubble burning at various places of the Central and Southern plains of India is responsible for high air pollutant concentrations in Southern India compared to Northern India.

Further, the wind patterns at 1000 hPa (near-surface) and 950 hPa show well-marked anti-cyclonic conditions over the Indian sub-continent during the lockdown phase-1 (Fig. 8). Generally, winds cause the dispersal of forest fire smoke from the source regions. For instance, winds have transported forest fire smoke from the south Madhya Pradesh, Andhra Pradesh, west Maharashtra, and north Tamil Nadu to north Karnataka, south, and south-east parts of Maharashtra (Fig. 8). Also, the north-eastern part of Assam shows high AOD due to wind-induced dispersal of forest fire smoke from the western and southern parts of Assam, Arunachal Pradesh, and Nagaland. The dispersal of smoke from the central part of Orissa towards the east has also been observed through northwest winds. Jain and Sharma [26] found that along with the lockdown, meteorological parameters also played a significant role in the reduction in air pollution levels in most places. Sharma et al. [28] found high air pollutants in some cities of India despite lockdown and attributed to unfavourable meteorological conditions in the country. However, the study also mentioned that strict control measures can reduce air pollutants despite unfavourable meteorological conditions [26]. Overall, a considerable reduction in mean AOD during the lockdown phase-1 is due to the occurrence of western disturbance-induced precipitation (rainfall and snowfall mostly over north Indian states), localized rainfall (other states) and restricted anthropogenic activities in the present study. There is a need to think in this direction in terms of economic burden and the possibility of taking such strict measures in a highly populated country like India. The present study revealed the significant role of both rainfall and anthropogenic factors in reducing the aerosol concentrations in the atmosphere. However, the present study suggests that it is necessary to investigate the influence of lockdown on aerosols at the micro geographic scale in order to adopt area-specific initiatives to reduce air pollution.

4 Conclusions

The findings of the present study found a significant reduction in mean AOD (about 9% at the India level) in the majority of parts of India during the lockdown phase-1. About 70% of the states/UTs have experienced a reduction in mean AOD that is between 6 and 77% during the lockdown phase-1 compared to the reference period. However, some states have shown an increase in AOD in...
the specific pockets of Arunachal Pradesh, Assam, Gujarat, Orissa, Andhra Pradesh, Madhya Pradesh, Chhattisgarh, Maharashtra, Assam, Nagaland, Manipur, and Karnataka which is attributed to some forest fire incidents and wind-induced dispersal of smoke. The relationship between AOD and rainfall suggests that it plays a contribution in lowering AOD loading in the atmosphere during the lockdown phase-1. The study found the reduction in mean AOD over the majority parts of India due to restrictions on non-essential economic activities and favorable meteorological conditions (rainfall). The study realized the need to further investigate the role of natural and anthropogenic factors in the reduction of aerosols and their relative role in the reduction of aerosols. According to the findings of this study, it is vital to explore the impact of lockdown on aerosols at the micro geographic scale in order to implement area-specific strategies to minimize air pollution. This study would be helpful for planners and policymakers to adopt suitable measures to control the anthropogenic factors that determine the density of aerosols in the atmosphere.

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