Classification and transformation of aerosols over selected Indian cities during reduced emissions under Covid-19 lockdown

PRADEEP ATTRI1, SIDDHARTHA SARKAR2 and DEVLEENA MANI1,*

1 Centre for Earth, Ocean and Atmospheric Sciences, University of Hyderabad, Hyderabad 500 046, Telangana, India.
2 Physical Research Laboratory, Ahmedabad 380 009, Gujarat, India.
*Corresponding author. e-mail: dtiwarisp@uohyd.ac.in

MS received 10 January 2021; revised 21 February 2022; accepted 1 March 2022

Studies in the recent past show improved air quality over India during the Covid-19 lockdown. This research attempts to characterize atmospheric aerosols in terms of $\alpha$ and AOD and their transformation over India during the pandemic lockdown. The type and particle distribution of aerosols, including gaseous species for five Indian regions were considered. Fine to coarse particle shift was observed in most regions. The northern region observed high $\alpha$ counts, implying crop residue burning season during the stringent lockdown. Thiruvananthapuram, in the south, showed an increase in PM, owing to the resumption of mobility post-lockdown. Hyderabad, however; observed increased PM$_{2.5}$ (2.79%) and AOD (37.23%) during Phase 1. Maritime (MT) aerosol predominated over Thiruvananthapuram, whereas urban/biomass burning (UBB) type decreased over the eastern region. Contributions from continental average (CA), maritime continental average (MCA), and MT were observed over Hyderabad, post-lockdown. In the central region, MCA was replaced by UBB and mixed type, with isolated episodes of clean continental (CC) and desert dust (DD). During lockdown phases, an increase in O$_3$ over western, northern, and central regions is attributed to increased temperature and decreased NO$_2$. A significant correlation with population density (PD) exists with NO$_2$ ($R^2 = 0.75$; $p < 0.05$), suggesting human mobility as a major contributor to NO$_2$ in the atmosphere during the lockdown period.

Keywords. Pollutants; aerosols; Ångstrom exponent; AOD; Covid-19 lockdown.

1. Introduction

Harmful effects of poor air quality on human health and the environment are inevitable. In 2012, about 11.6% of the deaths in the world were associated with outdoor and indoor air pollution and 1.5 million alone in India (WHO 2021). The air quality in Indian cities is adversely affected due to anthropogenic emissions from vehicles, coal-based power plants and industrial emissions (Singh et al. 2004; Prasad et al. 2006). Anthropogenic emissions increase the particulate matter (PM) and pollutant gases in the atmosphere. With restricted transportation and industrial emissions during COVID-19-induced lockdowns, the reduced anthropogenic contribution in the atmospheric pollutants

Supplementary material pertaining to this article is available on the Journal of Earth System Science website (http://www.ias.ac.in/Journals/Journal_of_Earth_System_Science).

Published online: 01 September 2022
rejuvenated the air quality across the globe. Recent studies largely converge with their results on the reduction in particulate matter (PM), and gaseous pollutants (NO₂, SO₂, CO) during the restricted periods. Also, an increase in O₃ levels has been reported in UK, with corroboration from similar studies conducted in China and Brazil (Nakada and Urban 2020). In an analysis of the world’s 50 most polluted cities (Rodríguez-Urrego and Rodríguez-Urrego 2020), a 12% decrease in PM₂.₅ concentration on average was reported during the contemporary period, with about a 30% decrease in Delhi, and a maximum decrease of 57% in Bogota. Studies carried out in the US (Zangari et al. 2020), UK (Jephcote et al. 2021), and Spain (Tobías et al. 2020) also observed a reduction in PM₂.₅, along with NO₂. However, such reduction is found to be inconsistent across the US (Bekbulat et al. 2020) and UK and is influenced by the meteorological conditions of the region as well (Jephcote et al. 2021).

In India, under the influence of the Covid-19 pandemic, after initial confinement on 22nd March 2020, a nationwide lockdown was implemented in four subsequent phases starting from 25th March for 21, 19, 14, and 14 days, respectively (table 1). Domestic and international transportation was restricted and ceased, along with the shutting down of major industries and small factories. These circumstances provided a natural mesocosm to understand the behaviour of different aerosols under reduced anthropogenic influence. In general, a high concentration of aerosols due to anthropogenic sources is observed during winter months (DJFM) in the Indian region (Babu et al. 2013), which witnessed a significant decline during the Covid-19 lockdown, when compared with usual pre-monsoon months. Satellite observations from NASA (2021) and ESA (2021) reported a significant drop in NO₂ and aerosol concentration in the Indian atmosphere during the lockdown. Restriction in the transportation and industrial sector resulted in a 60% improvement in air quality (Singh and Chauhan 2020), with a reduction in NO₂ and O₃ levels, as well as cooler land surface temperature (Naqvi et al. 2021). Average PM₂.₅ concentrations were under CPCB limits, with high values attributed to local meteorology (Kumar et al. 2020; Sharma et al. 2020). Region-based heterogeneity analysis of air pollutants also established the role of meteorological parameters in determining the impact of lockdown in the geographically diverse Indian subcontinent. For instance, the dust transport by westerly winds to Delhi and Kolkata led to increased PM₂.₅ concentrations (Singh and Chauhan 2020). Similarly, AERONET and satellite observations of air pollution during phase 1 of lockdown revealed an increase of ~20% in aerosols over central India, despite an overall decrease in pollutants by more than 40% in the country (Pandey and Vinoj 2021). Such unexpected increases here has been explained by meteorological phenomena and the increase in aerosols is partially related to higher humidity. Overall, reductions in PM are mainly found in north-west and Indo-Gangetic plains, followed by the southern and central regions (Singh et al. 2020). PM₂.₅ and NO₂ concentrations also reduced significantly in coastal cities (Agarwal et al. 2020; Singh and Chauhan 2020).

For a further nuanced understanding of PM and their regional variations during lockdown over India, examining the lockdown-induced atmospheric aerosol transformations can serve the purpose. A realistic characterization of aerosol properties can be carried out by employing the spectral dependence of aerosol optical depth (AOD) and Angstrom exponent (α) (Holben et al. 2001). The AOD gives aerosol loading in the atmosphere and the α describes qualitative information of particle size distribution (Ångström 1929; Kaufman et al. 1994). The concentration distribution of different pollutants in the urban and rural areas significantly influences the atmospheric aerosol formation and its composition. While the transport of aerosol particles can be attributed to

| Sl. no. | Lockdown phases     | No. of days | Start time      | End time     |
|--------|---------------------|-------------|-----------------|--------------|
| 1      | Pre lock down       | 23          | 1 March 2020    | 23 March 2020|
| 2      | 1st phase           | 21          | 25 March 2020   | 14 April 2020|
| 3      | 2nd phase           | 19          | 15 April 2020   | 3 May 2020   |
| 4      | 3rd phase           | 14          | 4 May 2020      | 17 May 2020  |
| 5      | 4th phase           | 14          | 18 May 2020     | 31 May 2020  |
| 6      | Post lockdown (unlock 1) | 30 | 1 June 2020    | 30 June 2020 |
the local and regional atmospheric circulations, different regions such as an industrial city, the associated transport process, dust lifted from the desert regions, etc., can act as the sources of aerosols. ARFINET (aerosol radiative forcing over India (ARFI)) from Indian Space Research Organization (ISRO) shows a significant and consistent increase in AOD over India since last three decades (Babu et al. 2013). Aerosol composition in India varies due to the significant contribution of natural aerosols (sea salt, desert dust, etc.) and biomass burning, besides anthropogenic emissions (Vinoj et al. 2010; Mukherjee and Vinoj 2020; Pandey et al. 2020). Based on the relationship between AOD and $\alpha$, the most prevalent aerosol types found are urban/biomass burning (UBB), continental average (CA), desert dust (DD), maritime (MT), and mixed type (Kaskaoutis et al. 2007, 2009; Kambezidis and Kaskaoutis 2008; Pathak et al. 2012). The $\alpha > 2$ indicates combustion byproducts with fine particles, while $\alpha < 1$ indicates coarser particles like sea salt and dust (Ångström 1961). Wavelength range from 340 to 1020 nm with AOD at 500 nm (Eck et al. 1999) has been adopted and modified by several authors, which demonstrates the reliable use of AOD and $\alpha$ in characterizing the aerosol type (Schuster et al. 2006; Kaskaoutis et al. 2007; Soni et al. 2011; Kumar et al. 2012; Sharma et al. 2014; Pawar et al. 2015).

The present study is carried out with two-fold objectives of (i) characterizing the aerosol type, its qualitative particle size distribution and transformation over selected Indian cities during the pandemic lockdown, and (ii) examining the effect of reduced mobility on the percentage change of individual aerosol concentrations by taking into account the transport and meteorological parameters. Five Indian regions (east, west, north, south, and central) were selected to cover a large spatial domain, with two major cities from each region, considering their different climate zones and geography and availability of the Central Pollution Control Board (CPCB) surface observation data. The results obtained for the lockdown phases are compared with pre- and post-lockdown to demonstrate the changes in aerosol compositions which the different study regions have undergone, and the role of meteorology and transport processes in affecting the types of aerosols over the selected sites during each phase. While the majority of studies in recent times have identified a decrease in emissions of different aerosols and gaseous species during the pandemic lockdown, this study aims to address the aerosol classification, transformation and qualitative size

Figure 1. Map of Indian cities showing surface measurement sites for different chemical species.
distribution without significant anthropogenic contributions over different cities in India, which is insightful in mitigating the effects of poor air quality over the urban environments of India.

2. Study areas

The five Indian regions of east, west, north, south, and central, along with two major cities of each region are considered for the study (figure 1). The cities selected here represent varied climatology and geography. The CPCB surface data for these cities is also accessible openly. The Köppen climate classification, which proposes five main climate groups based on seasonal precipitation and temperature patterns, has been used here to describe the climatology of selected cities (Peel et al. 2007). According to it, Chandigarh, Guwahati, and Jabalpur are classified under dry winter, humid and subtropical climates. Ahmedabad, Delhi, and Udaipur have been identified to be hot, Steppe type, while Bhopal, Hyderabad, Kolkata, and Thiruvananthapuram have tropical wet and dry (Savanna) type of climates (Mohammad and Goswami 2019). Details of the study regions and climatology based on ECMWF data, collected between 1999 and 2019, with 0.1°–0.25° resolution (climate-data.org 2021) are shown in table 2.

2.1 Eastern region (Guwahati and Kolkata)

The city of Guwahati in the eastern Himalayan region is surrounded by mountains and witnesses high average annual precipitation (table 2). River Brahmaputra flows on one side, while the Shillong plateau stands at the other end. The vehicular growth in the city has been reported to be very high in the past decade, along with increased economic activities. The coastal city of Kolkata is divided into different topographical regions (Dutta and Jinsart 2021). The Sundarban delta, located 154 km south of Kolkata, separates the city from the Bay of Bengal. Kolkata has a tropical climate with a very hot and humid summer (Census of India 2021). The maximum temperature in Kolkata during the summer (April–June) exceeds 40°C and the minimum is 12°C during winter (December–January).

2.2 Western region (Ahmedabad and Udaipur)

Ahmedabad, in western India, faces a very dry climate except that in monsoon. It has a hot semi-arid climate, with an average annual rainfall of about 80 cm (Gupta et al. 2019). The city experiences three major seasons – summer (March–July), winter (November–February), and monsoon, with occasional torrential rains (July–September) (IMD Pune 2021). Udaipur, located in the western region is the second selected city for this study. It is situated on the southern slope of the Aravalli Range and observes strong westerly winds from continental regions of Africa and the Middle East, which prevail all along the western region of India (Yadav et al. 2014).

2.3 Northern region (Chandigarh and Delhi)

In the north, the city of Chandigarh is located at the foot of the Shivalik Range. It is affected by both

| Sl. no. | Cities          | Altitude (m) | Rainfall (mm) | Annual mean air temperature (°C) | SO₂ | NO₂ | PM₁₀ | PM₂.₅ | (CPCB 2018) μg/m³ |
|--------|----------------|--------------|---------------|---------------------------------|-----|-----|------|-------|-------------------|
| 1      | Jabalpur       | 412          | 1277          | 24.6                            | 2   | 14  | 107  | 38    |                   |
| 2      | Mandideep      | 449          | 1183          | 25.4                            | 11  | 21  | 187  | 76    |                   |
| 3      | Guwahati       | 55           | 1698          | 24.6                            | 8   | 18  | 15   | 72    |                   |
| 4      | Kolkata        | 9.14         | 1735          | 26.8                            | 9   | 56  | 113  | 85    |                   |
| 5      | Chandigarh     | 321          | 979           | 24.1                            | 2   | 18  | 93   | 45    |                   |
| 6      | New Delhi      | 216          | 693           | 25.2                            | 8   | 60  | 250  | 145   |                   |
| 7      | Hyderabad      | 542          | 766           | 26.7                            | 6   | 28  | 118  | 56    |                   |
| 8      | Thiruvananthapuram | 10     | 1835          | 27                              | 8   | 23  | 48   | NA    |                   |
| 9      | Ahmedabad      | 53           | 753           | 27.3                            | 14  | 28  | 199  | 62    |                   |
| 10     | Udaipur        | 600          | 689           | 24.2                            | 10  | 33  | 119  | NA    |                   |

Table 2. (a) Climatology and (b) chemical concentration of different species from CPCB for the different regions of India.

Source: (a) climate-data.org and (b) CPCB report 2019.
Monssoon and western disturbances (Gupta et al. 2019). It has a sub-tropical climate. The average annual rainfall of the city is about 111.4 mm (IMD 2021). The capital city of Delhi lies over Delhi Ridge and Yamuna flood plains. It experiences a humid sub-tropical climate (Gupta and Mohan 2013), with high variation between summer and winter temperatures and precipitation. Increasingly heavy fogs and haze in winters raise serious concerns for the weather and climate in the region.

2.4 Southern region (Thiruvananthapuram and Hyderabad)

The coastal city of Thiruvananthapuram, in the southernmost part of India, has a tropical maritime climate. It is characterized by high humidity throughout the year with a monsoon season from April to October and a dry season from November to March. The city experiences high levels of particulate matter (PM) and other air pollutants due to industrial and vehicular activities, contributing to poor air quality.

Figure 2. (A) Time series of PM$_{10}$ and PM$_{2.5}$ for different Indian regions (a) east, (b) west, (c) north, (d) south, and (e) central. (B) Time series of O$_3$, SO$_2$ and NO$_2$ for different Indian regions (a) east, (b) west, (c) north, (d) south, and (e) central.
and monsoonal climate. It experiences a southeast monsoon from June to September and northeast monsoon during October to November (Roxy et al. 2014). Rivers originating from the Western Ghats pass through the coast and drain into the Lakshadweep Sea. The chain of backwaters on the coast is interconnected with each other through canals (Shaji 2019).

The city of Hyderabad lies inland of the southern Peninsula and has subtropical, low latitude semi-arid hot climate. It is characterized by hot and dry summer. The year here is divided into four seasons. The hot summer season is from March to May. May is generally the hottest month of the year. The period from June to September constitutes the south-west monsoon (SW rainy) season, while that...
of October and November forms the post-monsoon (NE rainy) season. The winter season is from December to February. The city is witnessing rapid industrialization (Census of India 2021; DCHH 2021).

2.5 Central region (Mandideep and Jabalpur)

In the central Indian region, Mandideep is a fast-developing industrial area near the capital city of Bhopal in Madhya Pradesh (Kori et al. 2019). Vindhyanchal Range and its associated hills lie in the central region of the district, while the Malwa plateau region is in the north. The plains of the Narmada valley occur in the southern part. It has a good fertile soil cover (Tiwari and Saxena 2011).

Jabalpur district lies at the junction of the Vindhyan and Satpura Ranges and forms part of the great central watershed of India. Narmada and its tributaries drain the district. The climate is characterized by a dry, hot summer, except during the southwest monsoon season. The cold season extends from December to February and is followed by the hot season from March to about the middle of June. The period from the middle of June to September is the south-west monsoon season. October and November form the post-monsoon or transition period (CGWB 2021).

3. Data description

The aerosols and gaseous concentration for the year 2018 are given in table 2. The datasets are obtained from CPCB surface observations (aqicn.org data platform) for the selected sites. The species considered are PM$_{2.5}$, PM$_{10}$, NO$_2$, SO$_2$, and O$_3$ for the duration from 1st Jan 2020 to 30th June 2020, covering all four phases of lockdown, along with pre-lockdown scenarios from 1st January to 24th March and post-lockdown periods from 1st June to 30th June (figure 2A, B). The MERRA-2 model outputs have been used (NASA, https://giovanni.gsfc.nasa.gov/giovanni/), which provide NASA’s atmospheric reanalysis, by utilizing the information from the Goddard Earth observing system model, Version 5 (GEOS-5) and atmospheric data assimilation system (ADAS). Both hourly and daily average datasets have been used for all the given locations. Hourly AOD at 550 nm and Angstrom exponent ($\alpha$) at wavelength 470–870 nm for a single level with a spatial resolution of 0.5°× 0.65° have been used in this study. Data from previous years (2016–2019) is used to assess the anomaly of AOD and $\alpha$. Due to the limited availability of long-term surface observations, data includes seasonal influences. The study uses active fire product from visible infrared imaging radiometer suite (VIIRS) to observe the forest fire and biomass burning events during each phase. Combined dark target and deep blue AOD at 550 nm from land and ocean, respectively, with 1-degree resolution, is used from MODIS-Terra MOD08 D3 v6.1 along with specific AERONET data (Supplementary figure S1; data for Delhi during the study period) to validate the MERRA-2 Model analysis over Indian region. This limitation for other considered sites was mainly due to the inaccessibility of the CPCB surface observations of past years and AERONET 2.0 data for the study period. To

![Figure 3. Validation of (MERRA-2) AOD against (MODIS) Terra. Each colour represents different lockdown phases.](image-url)
overcome this issue and avoid information loss, this study employed MERRA-2 Model and utilized MODIS-Terra MOD08 D3 v6.1 for the purpose of validation (figure 3). To understand the meteorological parameters, temperature, relative humidity (RH) and winds for the study regions, data from NCEP-DOE reanalysis-2 with 2.5-degree resolution has been used. National Oceanic and Atmospheric Administration (NOAA) back-trajectory analysis has been employed during each phase of lockdown to depict aerosol transportation (Supplementary figure S2). All the datasets were divided into pre-lockdown, four phases of lockdown and a one-month post-lockdown period. Demographic data was collected from reports of Census 2011 (Census of India 2021). The number of Covid-19 cases and the tests performed were taken from the Covid-19 tracker/India (https://www.covid19india.org). For Guwahati and Hyderabad, the low resolution of available data prompted the use of state data as representative of the study area.

4. Results and discussions

4.1 MERRA-2 model validation against MODIS

In this study, the aerosols have been categorized based on the relationship between AOD and $z$. The AOD at 550 nm is converted to 500 nm using the power law (equation 1).

$$AOD_{500\text{ nm}} = AOD_{550\text{ nm}}(500/550)^{-z},$$

where $z$, considered here, ranges from 470–870 nm (Kaskaoutis et al. 2007; Prasad and Singh 2007; Pawar et al. 2015).

Using the hourly AOD at 550 nm, with a spatial resolution of $0.5\times0.625^\circ$ (M2T1NXAER_5.12.4 for pre-, during (4 phases) and post-lockdown phases, the identification and classification of aerosol distribution over different cities was carried out. The AOD at 550 nm used here is from MERRA-2 model output, which was further validated with MODIS terra satellite observation. Figure 3 compares the MODIS daily AOD 550 nm and MERRA-2 hourly AOD 550 nm data (total data points 2930 for each data site), converted to daily mean from 1st March, 2020 to 30th June, 2020. In all the six phases, from pre- to post-lockdown, total 142 data points were taken to correlate the MERRA-2 model output. It is observed that both the datasets correlate strongly, as shown by the correlation coefficients ($r$) and fit indices, expressed as mean bias error (MBE) and root mean square error (RMSE) for pre-lockdown ($r = 0.91$, MBE = 0.019, RMSE = 0.121), phase 1 ($r = 0.95$, MBE = 0.073, RMSE = 0.147), phase 2 ($r = 0.88$, MBE = 0.018, RMSE = 0.057), phase 3 ($r = 0.91$, MBE = 0.062, RMSE = 0.090), phase 4 ($r = 0.92$, MBE = 0.071, RMSE = 0.130), and post-lockdown ($r = 0.91$, MBE = −0.027, RMSE = 0.066) phases.
| Location     | AOD (500 nm) | Angstrom exponent | Type of aerosol              | Reference                  | Assumed background concentration |
|--------------|--------------|-------------------|------------------------------|----------------------------|----------------------------------|
| Hyderabad    | <0.3         | $a_{380-570} < 0.9$ | Clean maritime               | Kaskaoutis et al. (2007)   | Maritime                         |
|              | >0.5         | $a_{380-570} < 1$  | Urban/Industrial             |                            |                                  |
|              | >0.6         | $a_{380-570} < 0.7$ | Desert dust                  |                            |                                  |
|              | Remaining    |                   | Mixed                        |                            |                                  |
| Dibrugarh    | <0.2         | $a_{380-1025} < 1.4$ | Continental average          | Pathak et al. (2012)       | Continental average              |
|              | >0.2         | $a_{380-1025} < 0.9$ | Maritime continental average |                            |                                  |
|              | >0.35        | $a_{380-1025} > 1$ | Urban/Biomass burning        |                            |                                  |
|              | >0.45        | $a_{380-1025} < 0.7$ | Desert dust                  |                            |                                  |
|              | Remaining    |                   | Mixed                        |                            |                                  |
| Pune         | <0.2         | $a_{440-570} < 1.6$ | Continental average          | Pawar et al. (2015)        | Maritime                         |
|              | <0.2         | $a_{440-570} < 0.9$ | Maritime continental average |                            |                                  |
|              | >0.35        | $a_{440-570} > 1$  | Urban/Biomass burning        |                            |                                  |
|              | >0.45        | $a_{440-570} < 0.7$ | Desert dust                  |                            |                                  |
|              | Remaining    |                   | Mixed                        |                            |                                  |
| Nairobi      | <0.2         | $a_{470-560} < 0.9$ | Clean maritime-influenced    | Boiyo et al. (2018)        | Clean continental                |
| Kampala      |              |                   |                              |                            |                                  |
| Dodoma       | >0.3         | $a_{470-560} > 1$  | Urban/Biomass burning        |                            |                                  |
|              | >0.6         | $a_{470-560} < 0.7$ | Desert dust                  |                            |                                  |
|              | Remaining    |                   | Mixed                        |                            |                                  |
| Present study| <0.2         | $a_{470-570} > 1$  | Continental clean background |                            | Clean continental                |
| Delhi        | <0.2         | $a_{470-570} < 0.9$ | Clean maritime-influenced    |                            |                                  |
| Chandigarh   |              |                   |                              |                            |                                  |
| Mandideep    | >0.3         | $a_{470-570} > 1$  | Urban/Biomass burning        |                            |                                  |
| Jabalpur     | >0.6         | $a_{470-570} < 0.7$ | Desert dust                  |                            |                                  |
|              | Remaining    |                   | Mixed                        |                            |                                  |
| Ahmedabad    | <0.2         | $a_{440-570} < 1.6$ | Continental average          |                            |                                  |
| Udaipur      | <0.2         | $a_{440-570} < 0.9$ | Maritime continental average |                            |                                  |
| Hyderabad    | >0.35        | $a_{440-570} > 1$  | Urban/Biomass burning        |                            |                                  |
| Kolkata      | >0.45        | $a_{440-570} < 0.7$ | Desert dust                  |                            |                                  |
|              | Remaining    |                   | Mixed                        |                            |                                  |
| Thiruvananthapuram | <0.15 | $A_{380-870} < 1.3$ | Clean maritime               |                            |                                  |
|              | >0.2         | $A_{380-870} > 1$  | Urban pollution/Biomass      |                            |                                  |
|              | >0.25        | $A_{380-870} < 0.7$ | Sea salt, dust               |                            |                                  |
|              | Remaining    |                   | Mixed                        |                            |                                  |
| Guwahati     | <0.2         | $a_{440-570} < 1.4$ | Continental average          |                            |                                  |
|              | <0.2         | $a_{440-570} < 0.9$ | Maritime continental         |                            |                                  |
|              | >0.35        | $a_{440-570} > 1$  | Urban/Biomass burning        |                            |                                  |
|              | >0.45        | $a_{440-570} < 0.7$ | Desert dust                  |                            |                                  |

*Note:* Acronyms used throughout for types of aerosols. MCA: Maritime continental average; UBB: urban/biomass burning; MT: maritime; CMT: clean maritime; DD: desert dust; CA: continental average; CC: clean continental; UP/BB: urban pollution/biomass burning; UI: urban industrial and Mixed type aerosols.
4.2 Temporal behaviour of air pollutants

The time series of PM concentrations along with that of gaseous species (figure 2A, B) for the ten Indian cities show an evident reduction, implying the improved air quality for the lockdown period. This is in agreement with other recent observations (Chowdhuri et al. 2020; Kumar 2020; Kumari and Toshniwal 2020; Mahato et al. 2020; Singh and Chauhan 2020).

Figure 5. Relationship between Ångström exponent ($\alpha$) and AOD for individual cities in different phases of lockdown. Undefined aerosol source is considered to be of mixed type.
| Cities           | Phase 1  | Phase 2  | Phase 3  | Phase 4  | Post  |
|------------------|----------|----------|----------|----------|-------|
| Chandigarh       | -25.16   | 26.47    | 2.74     | 17.37    | 23.13 |
| Delhi            | -27.46   | 37.82    | 6.24     | 16.27    | 32.04 |
| Kolkata          | -23.73   | 36.02    | -19.82   | 22.65    | -34.00|
| Guwahati         | -16.90   | -20.08   | -9.25    | -6.10    | -37.31|
| Mandideep        | 17.29    | -5.19    | -16.01   | -9.08    | 65.54 |
| Jabalpur         | -10.70   | 9.99     | -15.83   | -7.30    | 66.08 |
| Hyderabad        | 37.23    | -18.58   | -6.71    | -3.62    | -38.19|
| Thiruvananthapuram | -22.79   | -0.29    | -4.86    | -9.28    | -25.24|
| Ahmedabad        | 23.08    | -1.78    | -11.47   | -0.88    | 31.46 |
| Udaipur          | 12.46    | 9.15     | -21.25   | 50.16    | 2.32  |

Table 5. Percentage reduction in AOD 500 nm (all percentage changes are with respect to their previous lockdown phases).
Towards the east, Kolkata shows an average decrease in PM concentration. The pre-lockdown values for PM$_{10}$ (96.36 µg/m$^3$) and PM$_{2.5}$ (55.33 µg/m$^3$) reduce to 45.46 and 24.79 µg/m$^3$, respectively, during the lockdown. The post-lockdown concentrations of PM$_{10}$ and PM$_{2.5}$ were observed to be 40.02 and 15.79 µg/m$^3$, respectively, translating into a consistent reduction in PM$_{10}$ and PM$_{2.5}$ over the lockdown period. Similarly, for the city of Guwahati, the average concentration of PM$_{2.5}$ reduces to 43.01 µg/m$^3$ during the lockdown period. Guwahati witnessed a pre-lockdown concentration of 83.33 µg/m$^3$ that reduced to 40.32 and 19.56 µg/m$^3$ during the lockdown and post-lockdown phases, respectively. For both Kolkata and Guwahati, the gaseous species of NO$_2$ and SO$_2$ show a decrease in the overall emissions during the lockdown, which, however; is not observed for O$_3$. The concentration of O$_3$ decreases from 42.00 µg/m$^3$ in the pre-lockdown period to 8.4 µg/m$^3$ in 4th phase for Kolkata, whereas, for Guwahati, it increases from 19.59 µg/m$^3$ in the pre-lockdown to 32.66 µg/m$^3$ in the last phase of lockdown. This increasing trend, with a sharp jump in O$_3$ values, is set in phase 1 itself, and later during phase 4 and post-lockdown, it became as low as 29.46 µg/m$^3$ for Guwahati and 8.71 µg/m$^3$ for Kolkata.

In western India, the PM concentrations over Ahmedabad initially decrease during phase 1 and remain the same for later phases 2, 3, and 4, with an average of about 77.48 µg/m$^3$. Udaipur, lying at a higher altitude, shows an increase in PM concentrations as lockdown phases progress, which however decreases in the post-lockdown phase. The observed stagnation and increase in PM values in both cities are attributed to the transport of aerosols from UBB sources over the western and central Indian regions during phases 1 and 2. The sources of PM$_{10}$ are local vehicular traffic, while PM$_{2.5}$ largely results from long-range transport (Pohjola et al. 2002). This is also corroborated by the increase in NO$_2$ concentrations (figure 2B) and elevated VIIRS fire count (FRP) (figure 4), thus, indicating an increase in aerosols and also supplements the positive correlation between NO$_2$ and AOD (Ul-haq et al. 2017). The western city of Ahmedabad observed a gradual increase of PM$_{10}$ by 64.88% and PM$_{2.5}$ by 37%, due to impacts on local mobility during the post-lockdown. Additionally, other gaseous concentrations (O$_3$, NO$_2$, and SO$_2$) show an increase during this phase. However, there also occurs a simultaneous rise (peak) for PM$_{10}$ and PM$_{2.5}$ during post-lockdown (figure 2A). The gradual increase in PM and gaseous concentrations is associated with the resumption of mobility, however, the simultaneous sharp rise (peak) is attributed to the contribution from the dust transport. Reports of daily variability of the PM concentration in the city of Naples have highlighted several intense peaks due to the occurrence of extensive Saharan dust (SD) transport events, influencing the PM concentrations of the city for the period (March 18th to April 23rd) (Sannino et al. 2021). Most of the peaks are measured during post-lockdown over Ahmedabad, which can be associated with dust transport. This is also supported by the back trajectories over the region (Supplementary figure S2). AOD along with PM concentrations also show an increase in post-lockdown. Compared with previous years from 2016 to 2019, the z is observed to be higher in 2020 (Supplementary figure S3), which suggests the long-range transport of finer particles. During post-lockdown, Udaipur observes a decrease (increase) in AOD (z), compared to the mean of previous years (2016–2019), which is also corroborated by the increase in PM concentration (Supplementary figure S4). Further in the western region, NO$_2$ and SO$_2$ show a consistent decrease till phase 3, followed by a slight increase in concentrations later, due to the relaxations provided in subsequent phases of the lockdown. While the O$_3$ level in Udaipur showed no significant change in lockdown phases, Ahmedabad exhibited a slight decrease in phase 1, following which the concentrations continued to increase in phases thereafter.

In the northern region, Delhi showed an average decrease in PM from pre-lockdown (PM$_{10}$ = 185.78 µg/m$^3$; PM$_{2.5}$ = 78.27 µg/m$^3$) to lockdown concentrations (PM$_{10}$ = 147.90 µg/m$^3$; PM$_{2.5}$ = 58.46 µg/m$^3$). The post-lockdown concentrations were 133.21 and 50.00 µg/m$^3$ for PM$_{10}$ and PM$_{2.5}$, respectively. The summer months of March to May are the crop residue burning season over north India (Liu et al. 2020). High active fire counts, indicating crop residue burning activity from phase 2 to 4 during stringent lockdown has also been observed (figure 4). The post-lockdown exhibits a significant decrease in PM$_{2.5}$ concentrations. For Chandigarh, a reduction in average PM$_{2.5}$ concentration (3.01 µg/m$^3$) is observed during the lockdown period. It varied from a pre-lockdown concentration of 21.15–18.14 µg/m$^3$ during lockdown, and 24.03 µg/m$^3$ in post-lockdown. Further observations of gaseous pollutants in this region show the expected reduction in NO$_2$, however, with
an exception of Delhi in phase 1. During winter, usually the NO$_x$ stays longer in the shallow boundary layer, causing buildup of NO$_2$ in the atmosphere, compared to its shorter lifetime in summer (Val Martin et al. 2008). The persistence of NO$_2$ observed during phase 1 could possibly be attributed to the initial high of pre-lockdown, coinciding with the winter season of Delhi. Commencement of lockdown restricted the production of NO$_2$, which is observed in subsequent phases. An increase in O$_3$ can be attributed to the low availability of NO$_2$. While the study finds a consistent decrease in the levels of SO$_2$ in Delhi, the city of Chandigarh shows an increase in later phases of

Figure 6. Correlation between, % reduction in different species to the population density and Covid-19 cases (a–c); population density vs. Covid-19 cases (d); population density vs. number of tests performed (e). The number of tests performed until 31st May is shown in grey circles and until 20th June is shown by blue circles.
lockdown. This is possibly due to the increasing SO\textsubscript{2} emissions from coal-burning. Many coal-based thermal power plants were operational during the lockdown in the nearby regions of Chandigarh, which may have led to atmospheric transportation of SO\textsubscript{2} towards it (Mor et al. 2021). The increase in SO\textsubscript{2} is observed in Delhi and nearby regions such as Gurugram. In later phases, increased mobility caused the increase in SO\textsubscript{2} concentrations (CPCB 2021).

The southern region shows the dominance of UBB aerosol particles, with the influence of continental average (CA) and maritime (MT) traces during pre-lockdown and phase 1. Also, Hyderabad observes an increase in anthropogenic emissions ($\alpha > 1$) in phase 1. There is an observed decrease in fire emission of low intensity throughout India, but the central region shows an increase for the same. The restricted vehicular mobility in the city in phase 1 of lockdown resulted in the decrease of PM\textsubscript{10} in Hyderabad, whereas PM\textsubscript{2.5} showed a slight increase compared to pre-lockdown. Hyderabad was reported to have industrial and transportation activities of 20.86% and 28.78%, respectively (Ravindra et al. 2021). The fine particle concentration due to the forest fires may have increased the AOD over the central region during phase 1 (Mishra and Rathore 2021). The association of the large increase in fire counts over central and south-central India suggests the increase in fine particle concentration with a longer lifetime (Biswal et al. 2020; Mishra and Rathore 2021). The AOD and $\alpha$ increase (phase 1), indicate a decrease in dust particle concentration and an increase in fine transported particles. The anthropogenic contributions and fire count activities led to the observed increase in NO\textsubscript{2}. Hyderabad shows a drastic increase in NO\textsubscript{2}, which is corroborated by the observed FRP (fire radiative power).

The increase in PM, NO\textsubscript{2} (Ravindra et al. 2021), AOD and $\alpha$ for Hyderabad in the initial phases are followed by a decline in post-lockdown. Figures 2(B) and 5 show an increase in NO\textsubscript{2}, AOD (increased aerosol loading) and angstrom exponent (fine particles) over Hyderabad, which can be associated with forest fire season (March–May) over the region. The transport of biomass burning plumes toward Hyderabad by northerly winds has been reported by Badarinath et al. (2007). This is also reflected in active fire count observations during the same period. The biomass burning aerosols may also be produced by the burning of the vegetal residues in pre-monsoon, before the monsoon season rainfall (Kaskautois et al. 2009).

During the post-lockdown phase, Thiruvananthapuram shows a 159.36% increase in PM\textsubscript{2.5} and a 58.53% increase in PM\textsubscript{10} with respect to previous phases. The actual change in concentration for PM\textsubscript{2.5} is from 7.63 to 19.93 $\mu$g/m\textsuperscript{3}, while that of PM\textsubscript{10}, from 24.46 to 38.42 $\mu$g/m\textsuperscript{3}, owing to the resumption of mobility. SO\textsubscript{2} concentrations do not change significantly over Thiruvananthapuram, however; Hyderabad witnesses a slight decrease in SO\textsubscript{2} from pre-lockdown to phase 1, and later, a slight increase from phase 1 to phase 4, following which it drops again. Industrial emissions and transportation (increased mobility) activities appear to be the cause of the observed increase in SO\textsubscript{2}. During phase 1 of strict lockdown, Hyderabad was reported to have industrial and transportation activities of 20.86% and 28.78%, respectively (Ravindra et al. 2021). Several authors have reported an increase in Hyderabad’s average level of SO\textsubscript{2} (Ravindra et al. 2021; Tripathi 2021). During the entire duration of lockdown, O\textsubscript{3} concentration shows a slight increase over Hyderabad, whereas, it decreases over Thiruvananthapuram.

In the central region, PM\textsubscript{2.5} and PM\textsubscript{10} concentrations for the locations of Mandideep and Jabalpur show a decreasing trend over the entire lockdown period. However, on careful examination, these concentrations increased during the transition from phase 1 to phase 2 and declined in phase 3, and again increased in phase 4, followed by a decline in post-lockdown. An increase in PM\textsubscript{10} levels in phase 2 is reflected by the decreasing $\alpha$ values, and suggest the dominance of coarser particle. The hysplit back-trajectory (Supplementary figure S2) indicates dust or wind-driven aerosols from the northern region. The OMI (Ozone monitoring instrument) data for the same period shows high AOD in the northern region (Supplementary figure S5a). The hysplit back-trajectory (Supplementary figure S5b) for phase 1 also indicates the transport of wind from the northern region during this period, indicating fine particle transport ($\alpha > 1$). The reason for the increase in AOD and PM during phase 4 can be attributed to the nationwide relaxations. The unexpected decline of PM concentration and decrease in AOD in the post-lockdown phase in most cities is attributed chiefly to increased precipitation. It is observed that the monsoon covered the entire country on 26th June 2020, which is 12 days before its normal date (8th July). June observed 115% rainfall in 2020 as
compared to the long period average (IMD Monsoon Report 2020). Thus decrease in PM can be attributed to an increase in precipitation. The observed decline in AOD and PM can also be associated with severe cyclonic storm ‘NISARGA’ from 1st to 4th June in the Arabian Sea and low-pressure area, which formed over west-central Bay of Bengal (9–12 June) over central and western India (IMD Report 2020). The observed increase in fire count and FRP over the central region from phase 1 to 3 resulted in an increase in NO2 levels for both locations during this period. Increased relaxations contributed to further NO2 increase in the later phase, till post-lockdown. The SO2 concentrations increased for Mandideep, which is an industrially dominated city, suggesting industrial emissions as the cause of the SO2 increase. A decrease in SO2 levels is observed for Jabalpur. In Mandideep, no significant change in O3 concentration is observed until phase 4, following which, it increases drastically in the post-lockdown period. In Jabalpur, a sharp increase in O3 level is observed till phase 3, after which it declines over subsequent phases.

In comparison to Kolkata, the negative relationship between O3 and NO2 is prominent in Guwahati. The effect of wind speed on the transport and removal of O3 is likely the reason for the difference in its concentration in the two cities (Khiem et al. 2010). An increase in O3 concentration over the cities of western, northern and central regions (figure 2B) can be attributed to increasing temperature (Supplementary figure S6a–f) (Pulikesi et al. 2006; Han et al. 2011). Additionally, the low availability of NO2 causes an increase in O3 (Han et al. 2011), as NO2 acts as sinks for O3 (equation 2) in these regions throughout the lockdown period.

\[
O_3 + NO \rightarrow NO_2 + O_2.
\]  

(2)

Exceptionally, Thiruvananthapuram witnessed \(~27\%\) decrease in O3 concentration, whereas Kolkata witnessed a decrease of \(~71\%\) throughout the lockdown phases. Decreasing O3 in Kolkata is associated with urban thunderstorms and lightning events that occurred during the studied time frame (Chowdliuri et al. 2020).

4.3 Characterization of aerosols

The aerosols over the Indian region exhibit seasonal and intra-seasonal variability, which is mainly driven by the atmospheric dynamics, patterns of the seasonally varying air mass, regional monsoon system and spatio-temporal distributions of different pollutants (Ramachandran and Cherian 2008). In order to understand aerosol properties and their variations across the regions, several studies have widely used the relationship between aerosol loading (AOD) and particle size (\(2\)) (Eck et al. 1999; Pace et al. 2006; Kaskaoutis et al. 2007, 2009; Pathak et al. 2012; Pawar et al. 2015; Boiyo et al. 2018; Attri et al. 2021). This study characterizes the aerosols based on previous classifications adopted by the researchers (Kaskaoutis et al. 2007, 2009; Pathak et al. 2012; Pawar et al. 2015; Boiyo et al. 2018) for studying the aerosol types over different geographic environments and correlating the AOD-\(z\) (table 3, figure 5).

Pertaining to the complex meteorology and geographical diversity of the Indian subcontinent, maritime (MT), continental average (CA), and maritime continental average (MCA) have been used as background aerosol types. For instance, in Hyderabad and Pune regions, MT aerosols have been considered background aerosols, based on which distinctions have been made for different aerosol types and their sources (Kaskaoutis et al. 2007, 2009; Pawar et al. 2015). Considering the geographically different location of Dibrugarh, Pathak et al. (2012) assumed CA as background and MCA as additional background aerosol in fixing the threshold values for the AOD-\(z\) correlation (scatter plot). The types of aerosols identified using the AOD-\(z\) association are urban/industrial (UI) type (Hyderabad only), urban/biomass burning (UBB) (other cities taken in this study), maritime (MT), desert dust (DD) and mixed type aerosols (Eck et al. 1999; Pace et al. 2006). Hyderabad is a highly industrial and densely populated city with a concentration of AOD\(_{500}\) \(0.35\)–0.45 and higher, on a usual day without pollution (Latha and Badarinath 2005; Badarinath et al. 2007). AOD\(_{500}\) \(>0.5\) and \(z\)\(_{380–870}\) \(>1.0\) can be used to characterize the urban/industrial aerosols under high AOD, which also include contributions from the biomass burning episodes (Kaskaoutis et al. 2009). During this study, urban/industrial (UI) type aerosols with AOD \(>0.35\) and \(z\) \(>1\) are characterized for Hyderabad only, while for other regions, these are considered as urban/biomass burning (UBB) with AOD \(>0.3\) and \(z\) \(>1\). For Thiruvananthapuram, the urban pollution/biomass burning (UPBB) with AOD \(>0.2\) and \(z\) \(>1\) is considered.
The present study covers five geographically distinct regions of India, therefore, different backgrounds were assumed based on the representative threshold values of AOD and \( \alpha \) used in previous studies. The northern region is mostly affected by the western Thar desert and north-easterly wind flow, whereas the central region falls entirely in the dry sub-continent, with north-easterly wind flows. Thus, clean continental (CC) background aerosols (AOD \(< 0.2\) and \( \alpha > 1 \)) were assumed for the cities lying in northern and central Indian regions (Delhi, Chandigarh, Mandideep, and Jabalpur) (Boiyo et al. 2018). In the western region, Ahmedabad and Udaipur observe long-range desert dust (DD) and maritime (MT) aerosols, while the southern city of Hyderabad is prone to oceanic influence, hence MT aerosols were taken as background (AOD \(< 0.2, \alpha < 0.9 \)) (Pawar et al. 2015). Thiruvananthapuram, being the coastal city, is influenced by winds coming from the Arabian sea and Indian ocean during pre-monsoon and observes aerosols in the low AOD (AOD \(< 0.15, \alpha < 1.3 \)) range. Thus, clean maritime (CMT) aerosol has been considered as background (Kaskaoutis et al. 2007). Guwahati lies in the eastern Himalayan region and is surrounded by rural continental sites. It observes south-easterly wind flows from western parts of India, Bangladesh, and the Bay of Bengal. It is similar and closer to Dibrugarh city (Pathak et al. 2012), thus, this study assumes CA (AOD \(< 0.2, \alpha < 1.4 \)) as background and MCA (AOD \(< 0.2, \alpha < 0.9 \)) as additional background aerosol (Pathak et al. 2012). Further details on region-wise different characterizations for aerosols used in this study are provided in table 3.

4.4 Aerosol classification based on AOD and \( \alpha \)

From the anomaly of AOD and \( \alpha \), which is obtained from the difference between 2020 and the average of the past few years (2016–2019) for the duration of pre-monsoon and for the early month of monsoon (Supplementary figures S3 and S4), the observed changes in AOD and \( \alpha \) values below and above the baseline are attributed to Covid-19 lockdown. To eliminate the seasonal variability, the study considers the buffer range of \( \pm 0.2 \) and values of AOD and \( \alpha \) exceeding beyond it, to be likely due to the reduced mobility and meteorological influences, including long-range dust transport (Supplementary figures S3 and S4). The negative anomaly of AOD indicates cleaner air quality during 2020. Specifically, the negative anomaly of \( \alpha \) indicates a decrease in fine particle concentration over the regions for the duration of lockdown. The scatterplots depicting AOD-\( \alpha \) association help in determining the aerosol loading and source of fine and coarse particles in the regions, following which the characterization and identification of atmospheric aerosols over the Indian region for all six phases of pre-, during 4 phases and post-lockdown and its transition from one type to another was done (figure 5). Individual scatterplots for each study region are provided in the Supplementary data file (Supplementary figure S7a–e).

In the eastern region, high aerosol loading with fine particles is indicated in the pre-lockdown, which lies in the UBB category. Evidently, the city of Kolkata has UBB-type aerosols, with a dense population, whereas the heavy geographical vegetation and local farming practices in the northeast region of Guwahati contribute to UBB aerosols. In general, the high AOD and \( \alpha \) appear mainly due to accumulation mode aerosols observed over the Bay of Bengal (BoB) in the West Bengal region (Moorthy et al. 2010). In phase 1, despite lockdown restrictions, the UBB type aerosols show no significant reduction in both the cities and are also evident by the increased PM concentrations in Guwahati. Over north-eastern region, the observed FRP (50% confidence level) for pre-lockdown ranges from 0.018 to 30.17 MW (517 fire counts of 5657 values above 20 MW). While for phase 1, it varies from 0.009 to 23.31 MW (237 fire counts of 5977 values above 20 MW). In figure 4 and Supplementary figure S8, an overall reduction in FRP and NO\(_2\) is observed over the eastern region, however, a few places also show a slight increase. Thus, the aerosol fraction contribution starts decreasing from phase 1, with \( \alpha > 1.3 \) and AOD \( > 1 \), and gets completely diminished in phase 2. Further, in later phases, it continues to decrease, as observed in the PM concentrations (table 4). This suggests that biomass burning and anthropogenic activities, which were evident in the initial phases, largely stopped due to stringent restrictions in the later phases. During the last phase of lockdown, a significant amount of data points show high aerosol loading. There is a decrease in PM and AOD for Kolkata, due to wet deposition, resulting from the occurrence of cyclone Amphan (16–20 May 2020). During post-lockdown, the urban/biomass burning (UBB) activities restarted for different regions.
In western India, particles from different aerosol types, such as MCA, CA, and traces of UBB were observed during pre-lockdown. The AOD (>0.35) and \( \alpha > 1 \) over the western region indicate high aerosol loading, with fine particles during phase 1 (figure 5). Such an increase in UBB is due to the increase in fire counts during phase 1 (figure 4). In the later phases of lockdown, the concentration of fine particles decreased, as shown by decrease in \( \alpha \) from phase 2 to phase 4. Few episodes of the associated increase in AOD (>1) are seen for Ahmedabad during phase 3, followed by Udaipur in phase 4. Thus, during the transition from phase 3 to phase 4, the dominance of DD aerosols has been observed in both the cities and is reflected in PM concentrations, as the particles hover from UBB to mixed and DD categories. Further, an increase in the concentration of MCA aerosols has been found in phase 4 in the region. The increase in DD, as well as MT origin aerosols, can be attributed to the dominance of westerly and south-westerly winds from the western inland region and the Arabian Sea. However, in the post-lockdown period, the \( \alpha \) (fine particle concentration) increases for both cities. Thus, the aerosols in this period are predominantly mixed and DD type, with relatively finer particle sizes.

In the northern region, the dominant aerosol types in the pre-lockdown period are mainly UBB (anthropogenic) with fine particles and mixed type with coarse particles. From phase 1 to phase 4, aerosols are largely of mixed and DD categories, with diminished finer particles (from \( \alpha > 1 \) to \( \alpha < 1 \)) and increased AOD (from 0.3 to 0.5). In phase 1, the fine aerosols (\( \alpha > 1 \)) dissipated and were replaced by coarser aerosols (\( \alpha < 1 \)). Some data exceeding \( \alpha > 1 \) and AOD > 0.3 suggests the effect of relaxation at the transition of each subsequent lockdown phase. In phase 4 and the post-lockdown period, the majority of aerosols type lie under the DD category, with coarse particles over the northern region. In addition to the DD type, both cities observe an increase in UBB and CC aerosols in the post-lockdown, due to resumed anthropogenic activities in this period. Table 5 shows the percentage change in the AOD with respect to the previous phase. In general, there is a decreasing trend in the percentage change of AOD over most of the regions, except north, in the later phases of lockdown.

The southern region shows, dominantly, the distribution of urban pollution/biomass burning (UPBB) aerosols for Thiruvananthapuram and urban/industrial (UI) for Hyderabad, with the influence of CA and MT traces during pre-lockdown and phase 1. Also, in phase 1, Hyderabad observes an increase in anthropogenic emissions (\( \alpha > 1 \)) due to the usual business in the city, causing increased NO\(_2\) and UI type aerosols (Mishra and Rathore 2021). Thiruvananthapuram shows the influence of mixed-type aerosols in this phase, with the partial influence of CA type, as well. In phases 2 and 3, with decreasing \( \alpha \), it experiences a shift towards CMT aerosols. However, despite a decrease in \( \alpha \), traces of UI type prevailed over Hyderabad in these phases. In phase 4, a similar trend continued for both the cities, as Thiruvananthapuram shifted further towards MT aerosols and Hyderabad also witnessed the mixed type of category, with slight traces of UI aerosols. It is observed that all data points show \( \alpha < 1 \), indicating the dominance of coarser particles in phase 4. This is also reflected by a drastic increase in PM\(_{10}\) concentration in Hyderabad. During post-lockdown, AOD touched its least value in Thiruvananthapuram with CMT aerosols (e.g., sea spray) hovering over the city. Hyderabad showed contributions from CA, MCA, and mixed type aerosols.

In the initial phases of pre-lockdown and phase 1, the aerosols over central India are mainly of mixed and UBB type, along with slight traces of MCA type. The increase in UBB aerosol type is observed during phase 1. NO\(_2\) also increases as shown by the increase in fire count and FRP (Biswal et al. 2020; Mishra and Rathore 2021). The observed FRP with a 50% confidence level for pre-lockdown ranges from 0.009 to 7.30 MW (1065 fire counts out of 2698 values are above 20 MW) and for phase 1, it ranges from 0.39 to 11.56 MW (3707 fire counts out of 4531 values above 20 MW). During the transition from phase 1 to phase 2, the angstrom exponent (<1) decreases along with an increase in PM concentration in both cities. It can be inferred that the aerosols show the dominance of coarser particles in phase 2. This is attributed to the boundary layer mixing observed during phase 2 and wind transport from the north, as observed from hysplit back trajectories (Supplementary figure S2). During phase 3, a significant decrease in AOD for both Mandideep and Jabalpur reflects the reduced influence of DD aerosol, with a slight influence of clean continental (CC) and MCA. These influences can possibly be attributed to the south-westerly winds coming from the Arabian Sea and partial influence of winds from Indo-Gangetic
Plains (IGP). As the influence of westerly winds becomes stronger over the region in phase 4, the concentration of MCA type aerosols is observed in Jabalpur city, along with the sporadic increase in CC aerosols. The increase in CC aerosols is due to the additional wind flow from the IGP. Due to the predominance of coarser types with MCA aerosols in this phase, a significant decrease in fine particles ($\alpha > 1$) for much of this phase is observed. This is also supported by the significant increase in PM$_{10}$ concentrations (about 42% in Mandideep and 84% in Jabalpur) when compared to phase 3 values. In the post-lockdown period, the predominance of MCA aerosols dissipated and was instead replaced by UBB and mixed type with isolated episodes of CC and DD aerosols. This is largely due to the lifting of mobility restrictions, leading to increased anthropogenic contribution.

4.5 Population density and aerosol concentrations

An attempt has also been made to understand the effect of reduced mobility during imposed confinement on the percentage change of individual aerosol concentrations. Percent change in the species is provided in table 5. Population density (PD) in each study area has been used as a representative of the effect of lockdown on human mobility. PM$_{2.5}$, PM$_{10}$ and O$_3$ do not show any significant relationship with PD (figure 6), suggesting variability in the controlling factors (meteorology, industrial activities, etc.) for their concentrations across regions. NO$_2$ showed a significant relationship with PD ($R^2 = 0.75$; $p < 0.05$), suggesting human mobility (vehicular emissions) as the major contributor to NO$_2$ concentration in the atmosphere.

Aerosols are known to worsen respiratory conditions (Neuberger et al. 2004), and recent studies have found a positive relationship between the ambient aerosol concentration and Covid-19 fatalities (Chakraborty et al. 2020). The meteorological conditions such as temperature show positive associations, while humidity shows mixed association with Covid-19 cases (Kumar 2020). The results of the present study did not find any relationship between the ambient concentrations of pollutants to the cumulative increase in Covid-19 cases. However, there is a significant relationship with NO$_2$ concentrations, and in turn with O$_3$ (equation 2), which can be associated with respiratory ailments. Reduced NO$_2$ levels are attributed mainly to the low vehicular mobility and emissions during the lockdown, which might lead to elevated concentrations of O$_3$. It is also observed that there is no direct significant correlation between population density and Covid cases detected over the region, which is more likely a function of societal interactions.

5. Conclusion

This study documents the changes in atmospheric aerosols over selected Indian cities as a result of nationwide lockdown by exploring the relationship between AOD$_{500}$ and $\alpha$, wherein, AOD$_{550}$ mm is converted to AOD$_{500}$ nm using power law along with MERRA-2 reanalysis, CPCB observations, hyPLIT back-trajectories, VIIRS active fire and meteorological parameters. Using surface observations of atmospheric pollutants, namely O$_3$, NO$_2$, SO$_2$, CO, PM$_{2.5}$, and PM$_{10}$ and reanalysis data of MERRA-2 model, it is observed that the Covid-19 pandemic lockdown has a positive impact on the air quality over the Indian region, with a decrease in concentrations of PM, SO$_2$, and NO$_2$. An increase in urban/biomass burning (UBB) aerosols in northern (in phase 3 and phase 4), southern (in phase 1 in Hyderabad), eastern (in phase 1 in Guwahati) and western (in phase 1) regions is observed. PM$_{2.5}$, NO$_2$ and SO$_2$ concentrations support the reduction in anthropogenic emissions during the lockdown period for all the regions over India. Post-lockdown, the dominant dust fraction is supported by the increasing mobility along with the transported dust in different regions. There is a general shift from fine to coarse particle size in all regions, which suggests a lowered residence time of aerosol in the atmosphere during the lockdown. Statistical analyses of various parameters suggest that reduced mobility was the major factor for NO$_2$ reduction across different cities. This has implications on elevated O$_3$ concentrations, which may likely result in reduced ambient air quality.

With the considered five geographic regions of north, south, east, west, and central India, the major findings of the study in the six phases of lockdown are:

- In the northern region, aerosol transport is observed from the western region, known for agricultural burning in the summer season (March-May). The PM concentrations are also
influenced by the presence of coal-based power plants in the nearby areas.

- **PM\_2.5**, **PM\_10**, and **O\_3** do not show any significant relationship with **PD**, suggesting variability in the controlling factors (geographic locations, meteorology, industrial activities, etc.) for their concentrations across regions. For instance, in Delhi, the fine particle transport due to crop residue burning does not depend on the population density of the city. Similarly, decrease in PM concentration over Kolkata due to wet deposition by cyclone Amphan has no bearing on the **PD** of Kolkata.

- The western city of Ahmedabad observed peaks (rise) for both **PM\_10** and **PM\_2.5** during post-lockdown. Other than these, there is a gradual increase in PM concentrations, which is associated with the resumption of mobility. The sharp increase in PM concentrations, evident in peak is attributed to the long-range dust transport episodes. Udaipur witnessed a decrease in PM concentration, which can be due to the early monsoon over the region.

- The southern city of Hyderabad experienced a slight increase in **PM\_2.5** and active fire counts during phase 1 as compared to pre-lockdown, which is largely attributed to the usual industrial (20.86%) and transportation (28.78%) contribution over Hyderabad and forest fire season and related activities over the central and south-central region.

- During lockdown phases, the increase in **O\_3** over the cities of western, northern and central regions can be attributed to low availability of **NO\_2** and increasing temperature. The negative relationship between **O\_3** and **NO\_2** is prominent in Guwahati in comparison to Kolkata.

- In post-lockdown, however, the unexpected decline of PM and AOD concentrations in the central region is attributed to increased precipitation, when compared to the last phase of lockdown. The early monsoon arrival and several cyclonic circulations such as ‘NISARGA’ from 1st to 4th June in the Arabian Sea and the low-pressure area which formed over West-central Bay of Bengal have also influenced the pollutant concentration over the Indian region during post-lockdown.

Under reduced anthropogenic emissions, lockdown presented an opportunity to identify the dominant aerosol types and their characteristics in the selected study regions of India. Insights into regional influences such as crop residue burning in the north and forest fire in the central and south-central regions emphasized the significance of contextual aerosol characterization in assessing the effect of lockdown on air quality. Apart from local meteorology, synoptic scale events such as the Amphan cyclone in the Bay of Bengal, and long-range dust transports also influenced pollutant concentrations over the Indian region during the pandemic year. With the present study concentrating on ten cities, further possibilities can be directed towards exploring the spatial distribution of aerosol types encompassing the entire Indian region and parameters such as single scattering albedo (SSA), the relative contribution of fine mode to total optical depth ($\eta$) and fine AOD could provide useful insight into the UBB type aerosol patterns.

**Acknowledgements**

DM acknowledges the Department of Science and Technology (DST-WOSA) and IPDF grant by the Institute of Eminence (IoE), University of Hyderabad for the financial support. The authors acknowledge IoE grant, University of Hyderabad (UoH), Hyderabad and Physical Research Laboratory (PRL), Ahmedabad for the necessary support. Prof K Ashok, UoH is thanked for the constructive suggestions related to the manuscript. Central Pollution Control Board (CPCB) is acknowledged for the accessibility of surface observations. The authors acknowledge the European Centre for Medium Range and Weather Forecast (ECMWF) for the open accessibility of ERA5 hourly data and NOAA for back trajectory data and NASA for MODIS, VIIRS active fire, and MERRA-2 reanalysis aerosol datasets.

**Author statement**

Pradeep Attri: Study plan; data collection; analysis, conceptualizing of the problem, interpretation of results and drafting the manuscript. Siddhartha Sarkar: Data analysis and conceptualizing of the problem. Devleena Mani: Conceiving the research problem, suggestions, developing and editing of the manuscript.

**References**

Agarwal A, Kaushik A, Kumar S and Mishra R K 2020

Comparative study on air quality status in Indian and
Chinese cities before and during the Covid-19 lockdown period; *Air Qual. Atmos. Health* **13**(10) 1167–1178.
Ali M A and Assiri M E 2017 Spatio-temporal analysis of aerosol concentration over Saudi Arabia using satellite remote sensing techniques; *Geografa Malays. J. Soc. Space.* **12**(4).
Angström A 1929 On the atmospheric transmission of sun radiation and on the dust in the air; *Geogr. Ann.* **11**(2) 156–166.
Angström A 1961 Techniques of determining the turbidity of the atmosphere; *Tellus* **13**(2) 214–223.
Attri P, Sarkar S and Mani D 2021 April classification and transformation of aerosols over selected Indian cities during reduced emissions under Covid-19 lockdown; In: *EGU General Assembly Conference Abstracts EGU21-8677*.
Babu S S, Manoj M R, Moorthy K K, Gogoi M M, Nair V S, Kompalli S K, Satheesh S K, Niranjan K, Ramagopal K and Bhuyan P K 2013 Trends in aerosol optical depth over Indian region: Potential causes and impact indicators; *J. Geophys. Res. Atmos. GR.* **118**(20) 11,794–11,806.
Badarinath K V S, Khural S K, Chand T R K, Parvathi Y G, Anasuya T and Jyothsna A N 2007 Variations in black carbon aerosol, carbon monoxide and ozone over an urban area of Hyderabad, India, during the forest fire season; *Atmos. Res.* **85**(1) 18–26.
Bekbulat B, Joshua S A, Dylan B M, Allen R, Kelley C W and Julian D M 2020 PM2.5 and ozone air pollution levels have not dropped consistently across the US following societal COVID-19 lockdown and its impact on tropospheric NO2 concentrations over India using satellite-based data; *Heligton 6*(9).
Boiyo R, Kumar K R and Zhao T 2018 Spatial variations and trends in AOD climatology over east Africa during 2002–2016: A comparative study using three satellite data sets; *Int. J. Climatol.* **38** 1221–1240.
Calvin J, Hansell A L, Adams K and Gulliver J 2021 Changes in air quality during Covid-19 ‘Lockdown’ in the United Kingdom; *Environ. Pollut.* **272** 116011.
Chakraborty P, Jayachandran S, Padalkar P, Sathlou L, Chakraborty S, Kar R, Bhaumik S and Srivastava M 2020 Exposure to Nitrogen dioxide (NO2) from vehicular emissions could increase the Covid-19 pandemic fatality in India; *Eyects J. Remote Sens. Space Sci.* **22**(1) 81–93.
Han S, Bhan H, Feng Y, Liu A, Li X, Zeng F and Zhang X 2011 Analysis of the relationship between O3, NO and NO2 in Tianjin, China; *Aerosol Air Qual. Res.* **11**(2) 128–139.
Holben B N, Tancre D, Smirnov A, Eck T F, Slutsker I, Abuhassan N, Newcomb W W, Schafer J S, Chatenet B and Lavenu F 2001 An emerging ground-based aerosol climatology: Aerosol optical depth from AERONET; *J. Geophys. Res. Atmos.* **106**(D11) 12,067–12,097.
IMD Pune 2021 Retrieved from http://www.imdpune.gov.in/Temp_Extremes/histext2010.pdf.
IMD monsoon Report 2021 Retrieved from https://static.pib.gov.in/WriteReadData/userfiles/End%20of%20Season%20Report_2020.pdf.
Jephcoat C, Hansell A L, Adams K and Gulliver J 2021 Changes in air quality during COVID-19 ‘lockdown’ in the United Kingdom; *Environ. Pollut.* **272** 116011.
Kambezidis H D and Kaskaoutis D G 2008 Aerosol climatology over four AERONET sites: An overview; *Atmos. Environ.* **42**(8) 1892–1906.
Kaskaoutis D G, Badarinath K V S, Khural S K, Sharma A R, and Kambezidis H D 2009 Variations in the aerosol optical properties and types over the tropical urban site of Hyderabad, India; *J. Geophys. Res. Res.* **114**(D22).
Kaskaoutis D G, Kambezidis H D, Hatziathanastassiou N, Kosmopoulos P G and Badarinath K V S 2007 Aerosol climatology: Dependence of the Angstrom exponent on wavelength over four AERONET sites; *Atmos. Chem. Phys.* **7**(3) 7347–7397.
Kaufman Y J, Gitelson A, Karnieli A, Ganor E, Fraser R S, Nakajima T, Mattoo S and Holben B N 1994 Size distribution and scattering phase function of aerosol particles retrieved from sky brightness measurements; *J. Geophys. Res. Atmos.* **99**(D5) 10,341–10,356.
Khiem M, Ooka R, Huang H, Hayami H, Yoshihado H and Kawamoto Y 2010 Analysis of the relationship between changes in meteorological conditions and the variation in summer ozone levels over the Central Kanto area; *Adv. Meteorol.* **2010**.
Kori R, Saxena A, Wankhade H, Baig A, Kulshreshtha A, Mishra S and Sen S 2019 Recent status of ambient air quality index of Mahindra industrial area, Madhya Pradesh, India; *Int. J. Inf. Res. Rev.* **06**(08) 6429–6433.
Kumar S 2020 Effect of meteorological parameters on spread of Covid-19 in India and air quality during lockdown; Sci. Total Environ. 745 141021. https://doi.org/10.1016/j.scitotenv.2020.141021.

Kumar S, Kumar S, Singh A K and Singh R P 2012 Seasonal variability of atmospheric aerosol over the north Indian region during 2005–2009; Adv. Space Res. 50(9) 1220–1230.

Kumari P and Toshniwal D 2020 Impact of lockdown measures during Covid-19 on air quality – A case study of India; Int. J. Environ. Health Res. 32(3) 1–8.

Latha K M and Badarinath K V S 2005 Spectral solar attenuation due to aerosol loading over an urban area in India; Atmos. Res. 75(4) 257–266.

Liu T, Mickley L J, Singh S, Jain M, de Fries R S and Marlier M 2021 Impact of nationwide COVID-19 lockdown on aerosol optical depth and bimodal aerosol size distributions in the Helsinki metropolitan area; Water Air Soil Poll. 225 189–201.

Mishra M K and Rathore P S 2021 Impact of nationwide Covid-19 lockdown on Indian air quality in terms of aerosols as observed from the space; Aerosol Air. Qual. Res. 21(4).

Mukherjee T and Vinoj V 2020 Atmospheric aerosol optical depth and its variability over an urban location in eastern India; Nat. Hazards 1–15. https://doi.org/10.1007/s11069-019-03636-x

Nakada L Y K and Urban R C 2020 Covid-19 pandemic: Impacts on the air quality during the partial lockdown in São Paulo state, Brazil; Sci. Total Environ. 730 139087.

Ramachandran S and Cherian R 2008 Regional and seasonal variability of atmospheric aerosol parameters over the north Indian region during 2005–2010; Atmos. Environ. 42 7304–7311.

Ramachandran S and Cherian R 2008 Regional and seasonal variability of atmospheric aerosol parameters over the north Indian region during 2005–2010; Atmos. Environ. 42 7304–7311.

Sharma M, Kaskaoutis D G, Singh R P and Singh S 2014 Seasonal variability of atmospheric aerosol parameters over Greater Noida using ground sunphotometer observations; Aerosol Air Qual. Res. 14(3) 608–622.

Sharma S, Zhang M, Gao J, Zhang H and Kota S H 2020 Effect of restricted emissions during Covid-19 on air quality in India; Sci. Total Environ. 728 138878.

Shehzad K, Sarfraz M and Shah S G M 2020 The impact of Covid-19 as a necessary evil on air pollution in India during the lockdown; Environ. Pollut. 266 115080.
Singh R P and Chauhan A 2020 Impact of lockdown on air quality in India during Covid-19 pandemic; *Air Qual. Atmos. Health* **13**(8) 921–928.

Singh R P, Dey S, Tripathi S N, Tare V and Holben B 2004 Variability of aerosol parameters over Kanpur, northern India; *J. Geophys. Res. Atmos.* **109**(D23).

Singh V, Singh S, Biswal A, Kesarkar A P, Mor S and Ravindra K 2020 Diurnal and temporal changes in air pollution during Covid-19 strict lockdown over different regions of India; *Environ. Pollut.* **266** 115368.

Soni K, Singh S, Bano T, Tanwar R S and Nath S 2011 Wavelength dependence of the aerosol Angstrom exponent and its implications over Delhi, India; *Aerosol Sci. Technol.* **45**(12) 1488–1498.

Suqin H, Bian H, Feng Y, Liu A, Li X, Zeng F and Zhang X 2011 Analysis of the relationship between O₃, NO and NO₂ in Tianjin, China; *Aerosol Air Qual. Res.* **11**(2) 128–139.

Tiwari M K and Saxena A 2011 Change detection of land use/landcover pattern in and around Mandideep and Obedullaganj area, using remote sensing and GIS; *Int. J. Eng. Technol.* **2**(3) 398–402.

Tobías A, Carnerero C, Reche C, Massagué J, Via M, Minguillón M C, Alastuey A and Querol X 2020 Changes in air quality during the lockdown in Barcelona (Spain) one month into the SARS-CoV-2 epidemic; *Sci. Total Environ.* **726** 138540.

Tripathi A 2021 Air pollution in four Indian cities during the Covid-19 pandemic; *Int. J. Environ. Sci.* **78**(4) 696–717.

Turaloğlu F S, Nuhoglu A and Bayraktar H 2005 Impacts of some meteorological parameters on SO₂ and TSP concentrations in Erzurum, Turkey; *Chemosphere* **59**(11) 1633–1642.

Ul-Haq Z, Tariq S and Ali M 2017 Spatiotemporal patterns of correlation between atmospheric nitrogen dioxide and aerosols over South Asia; *Meteorol. Atmos. Phys.* **129**(5) 507–527.

Val Martin M, Honrath R E, Owen R C and Li Q B 2008 Seasonal variation of nitrogen oxides in the central North Atlantic lower free troposphere; *J. Geophys. Res. Atmos.* **113**(D17).

Vinoj V, Satheesh S K and Moorthy K K 2010 Optical, radiative, and source characteristics of aerosols at Minicoy, a remote island in the southern Arabian Sea; *J. Geophys. Res. Atmos.* **115**(D1).

WHO 2021 Retrieved from World Health Organization 2016, *Ambient Air Pollution: A Global Assessment of Exposure and Burden of Disease*.

Yadav R, Sahu L K, Jaaffrey S N A and Beig G 2014 Distributions of ozone and related trace gases at an urban site in western India; *J. Atmos. Chem.* **71**(2) 125–144.

Zangari S, Hill D T, Charette A T and Mirowsky J E 2020 Air quality changes in New York city during the Covid-19 pandemic; *Sci. Total Environ.* **742** 140496.

Corresponding editor: Suresh Babu