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Impact of aerosols on surface ozone during COVID-19 pandemic in southern India: A multi-instrumental approach from ground and satellite observations, and model simulations

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Abstract

The World Health Organization (WHO) declared the coronavirus disease of 2019 (COVID-19) as a pandemic due to its widespread global infection. This has resulted in lockdown under different phases in many nations, including India, around the globe. In the present study, we report the impact of aerosols on surface ozone in the context of pre-lockdown (01st - 24th March 2020 (PLD)), lockdown phase1 (25th March to 14th April 2020 (LDP1)), and lockdown phase 2 (15th April to 03rd May 2020 (LDP2)) on clear days at a semi-arid site, Anantapur in southern India using both in situ observations and model simulations. Collocated measurements of surface ozone (O3), aerosol optical depth (AOD), black carbon mass concentration (BC), total columnar ozone (TCO), solar radiation (SR), and ultraviolet radiation (UV-A) data were collected using an Ozone analyzer, MICROTOPS sunphotometer, Ozonometer, Aethalometer, and net radiometer during the study period. The diurnal variations of O3 and BC exhibited an opposite trend during three phases. The concentrations of ozone were ~10.7% higher during LDP1 (44.8 ± 5.2 ppbv) than the PLD (40.5 ± 6.0 ppbv), which mainly due to an unprecedented reduction in NOx emissions leading to a lower O3 titration by NO. The prominent increase in the surface ozone during LDP1 is reasonably consistent with the observed photolysis frequencies (j (O1D)) through Tropospheric Ultraviolet and Visible (TUV) model. The results show that a pronounced spectral and temporal variability in the AOD during three lockdown phases is mainly due to distinct aerosol sources. The increase in AOD during LDP2 due to long-range transport can bring large amounts of mineral dust and smoke aerosols from the west Asian region and central India, and which is reasonably consistent with the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) air mass back trajectories and Moderate Resolution Imaging Spectroradiometer (MODIS) fire counts analysis over the measurement location. Overall, a drastic reduction in BC concentration (~8.4%) and AOD (10.8%) were observed in the semi-arid area during LDP1 with correspondence to PLD. The columnar aerosol size distributions retrieved from the spectral AODs followed power-law plus unimodal during three phases. The absorption angstrom exponent (AAE) analysis reveals a predominant contribution to the BC from biomass burning activities during the lockdown period over the measurement location.

1. Introduction

The Coronavirus disease of 2019 (COVID-19) is an infectious disease initially recognized in Wuhan, Hubei Province of China, late in December 2019. The World Health Organization (WHO) announced COVID-19 as a pandemic due to widespread global infection (WHO, 2020). The number of people globally infected by COVID-19 was around 37.6 million cases and 1.1 million deaths as of October 12, 2020 (WHO, 2020). This has resulted in lockdown under different phases in many of the nations around the globe. To control the rapid spread of the pandemic, the Indian government has imposed a strict lockdown for more than two months in different phases to control the pandemic. Therefore, the lockdown affected transportation, restricted construction and industrial activities, leading to plummeting air pollutants. Jain and
Sharma (2020) reported that the concentration of PM$_{2.5}$, PM$_{10}$, NO$_2$, and CO declined by ~41%, ~52%, ~51%, and ~28% during the lockdown phase in comparison to the before lockdown in Delhi, respectively. Sharma et al. (2020) reported that around 43%, 31%, 10%, and 18% decreased in PM$_{2.5}$, PM$_{10}$, CO, and NO$_2$ in India was observed during the lockdown period compared to previous years. Kanniah et al. (2020) mentioned that the restricted industrial activities and vehicular emissions during the lockdown period resulted in a significant decrease of AOD and tropospheric NO$_2$ over the East Asian region. Filonchyk et al. (2020a) documented a significant decrease of CO and NO$_2$ (20% and 30%) concentration during the COVID-19 period compared to the same period after Lunar New Year 2019 over East China. Earlier studies mostly focused on particulate matter, trace gases based on satellite observations (e.g., Mahato et al., 2020; Nakada and Urban, 2020; Sicard et al., 2020; Xu et al., 2020). However, a better understanding of aerosols can contribute to the adoption of effective measures to reduce air pollution, and real-time monitoring data are essential to obtain detailed variations during the lockdown period better.

Atmospheric aerosols made significant contributions to the Earth's climate system and human health (Ramanathan et al., 2001; Martin et al., 2003; Zhao et al., 2006a,b; IPCC, 2013; Kalluri et al., 2019). The primary sources of air pollution are combustion from vehicles, power generation plants, landfill sites, and unsustainable farming. The uncertainty of aerosols impact on surface ozone (O$_3$) mainly depends on the optical properties of regional aerosols, chemical composition, production, and loss rates (Meloni et al., 2003; Badarinath et al., 2008; Li et al., 2011). In the troposphere, ozone is formed photochemically by the oxidation of carbon monoxide, methane, non-methane hydrocarbons, and other volatile organic compounds (VOCs) in the presence of sufficient solar radiation (Jenkin and Clemitshaw 2000; Badarinath et al., 2008; Gopal et al., 2014b; Lingaswamy et al., 2017).

Anantapur represents a semi-arid continental region of Andhra Pradesh, India. It has geographically situated on the boundary of a semi-arid and rain shadow region. A small scale Industrial and vehicular emissions, forest fires, agricultural and biomass burning constitute significant sources of local anthropogenic aerosols; aerosols from both local and long-range transport constitute significant sources of natural aerosols (Gopal et al., 2015, 2016; Kalluri et al., 2020). The nationwide lockdown during the time of the COVID-19 pandemic, industrial, construction, and transportation activities is mostly absent over Anantapur. Therefore, a quantitative assessment of air pollution was necessary to limit air quality, mostly when such alternative control measures were necessary. The measurements were taken only on clear sky days at Anantapur using both in situ observations. The lockdown phases included in the present study are namely pre-lockdown (01$^{st}$ March to 24th March 2020) henceforth termed as PLD; lockdown phase 1 (LDP1) from 25th March to 14th April 2020; lockdown phase 2 (LDP2) from 15th April to 03$^{rd}$ May 2020. The number of the dataset for PLD, LDP1, and LDP2 consisted of 8, 7, and 4 days, respectively.

The main objectives addressed in this paper are a) To investigate the diurnal variability in surface ozone, black carbon mass concentration, solar radiation, and UV-A radiation on clear sky days under different phases b) The spatial and temporal distribution of aerosol optical depth (AOD), Nitrogen dioxide (NO$_2$) concentrations during three lockdown phases c) The columnar size distribution (CSD) function inferred by numerical inversion of spectral AOD. Finally, we evaluated the impact of AOD on photolysis frequencies (j (O$_1^+$D) using the Tropospheric Ultra-violet and Visible radiation model over the measurement location.

2. Site description

The collocated measurements of AOD, TCO, O$_3$, BC, incoming solar radiation (SR), and UV-A radiation has carried out from the roof of a building in the Department of Physics, Sri Krishnadevaraya University (SKU, 14.62$^\circ$ N, 77.65$^\circ$ E, 331 m asl), situated away of 12 km from Anantapur town (Fig. 1). Geographically, Anantapur has located on the boundary of a semi-arid and rain shadow region in the southern Indian state of Andhra Pradesh. Moreover, the measurement location is situated...
just beside national highways NH44 and 7 km away from NH42. The average rainfall over measurement location is about 350 mm during the southwest monsoon, which contributes more than 60–70% to the total annual rainfall, and the rest of the rainfall has contributed by the northeast monsoon period (Reddy et al., 2016; Hussain et al., 2018).

3. Instrumentation

3.1. In-situ measurements

3.1.1. Surface ozone

Surface ozone (O$_3$) concentrations continuously have been carried out using on-line analyzers (Model: 49i for O$_3$, Thermo Scientific, USA) during the measurement period. The ozone monitoring instrument uses the UV photometry technique (Huntzicker and Johnson, 1979). Ultraviolet light at a wavelength of 253.84 nm has been used as a light source where ozone has strong absorption. The O$_3$ analyzer was zero calibrated with dry air, and span calibration of the O$_3$ analyzer has carried out using a multi-point internally assembled O$_3$ generator. The lowest detection limit of the analyzer is 0.5 ppbv, and the response time is the 20s.

3.1.2. Microtops II sunphotometer and ozonometer

The spectral AOD at five distinct narrow-band spectral wavelengths (ranging from Far UV to Near IR), total columnar ozone (TCO), and columnar water vapor content (WV) were retrieved from Microtops II handheld sun photometer and ozonometer manufactured by the Solar Light Company Inc., USA. Microtops II sun photometer estimates the integrated columnar spectral AOD and WV by measuring direct solar irradiance at 380, 500, 870, 936, and 1020 nm through optical collimators with a full field view of 2.5° (Morris et al., 2001). More details about principle, measurement techniques, calibrations, limitations have been given elsewhere (Ichoku et al., 2002; Kumar et al., 2010; Gopal et al., 2015). The description of columnar size distribution has been given in the Supplementary Material Section (SM) S1.

3.1.3. Black carbon mass concentration

The BC mass concentration was obtained from the seven-channel (370, 470, 520, 590, 660, 880, and 950 nm) Aethalometer (Model AE-42 of Magee Scientific, California, USA) by operating at 4 LPM of flow rate with the recording time base of 3 min interval. The Aethalometer is working on the principle of optical transmission (Hansen et al., 1984). The uncertainties in the aethalometer technique arise from multiple scattering effects in quartz filter tape and shadowing/loading effects. Weingartner et al. (2003) suggested a correction factor of 2.14 for multiple scattering corrections that vary with different aerosol types, and the shadowing/loading factor R is significant for pure soot particles and almost negligible for mixed aerosols. More details about measurement principles, data analysis, correction schemes were described in several earlier studies by Arnott et al. (2005); Virkula et al. (2007); Weingartner et al. (2003); and hence not discussed more here.

The absorption coefficient ($\sigma_{ab}$) and absorption angstrom exponent ($\alpha_{ap}$) can be calculated as

$$\sigma_{ab} = \frac{(BC) \times 14625 \times 10^{-3}}{\lambda^2 C^2 R} \text{Mm}^{-1}$$

(1)

$$\alpha_{ap} = \frac{\Delta \log(\sigma_{ab})}{\Delta \log(\lambda)}$$

(2)

3.1.4. Radiation measurements

The UV-A radiation has been measured by using a precision UV-A radiometer (MS-212 A) with high reliability. It works using the Ultra Violet Selective filter detection principle and provides 30-min interval data (Lokeswara Reddy et al., 2020). The combination of a well-designed GaAsP photodiode and UV-A filter promises high performance to measure the UV-A between the wavelengths of 315–400 nm. The incoming shortwave solar radiation (SR) was measured using the DeltaOHM LPNET14 pyranometer. The pyranometer produces a millivolt analog signal that is directly proportional to the irradiance be measured.

3.2. Satellite retrieved tropospheric and columnar NO$_2$ and aerosol optical depth

The Ozone Monitoring Instrument (OMI) sensor aboard the Earth Observing System (EOS) Aura satellite provides daily global measurements of tropospheric NO$_2$ and Columnar NO$_2$ (Krotkov et al., 2017). The satellite follows a sun-synchronous orbit, passing over each location at ~13:30 local time (Bechle et al., 2013). In the present study, We used the OMI Level-3 daily global gridded (0.25 × 0.25°) Nitrogen Dioxide Product (OMNO2d v003) with 30% Cloud Screened obtained from Giovanni (http://www.esrl.noaa.gov/) (GES DISC Dataset, 2019; Krotkov et al., 2017). The NO$_2$ data product was selected in the grid between 77 and 78° E and 14–15° N during three episodes over the study region. The spatial distribution of AOD (at 550 nm) has been obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite. We used daily observations of AOD from both MODIS Terra (MOD08_D3) and Aqua (MYD08_D3) collection 6.1 Level 3 product during three episodes (Levy et al., 2013). The detection of heavy smoke was introduced in Collection 6.1 compared with Collection 6 (Filonchyk et al., 2020h).

In the present study, we have used a combined Dark Target (DT) Deep Blue (DB) AOD at 550 nm, which takes advantage of both dark target (Levy et al., 2013) and deep blue (Hsu et al., 2013) algorithms.

3.3. MODIS fire counts and air mass back-trajectory analysis for source apportionment

To identify the aerosol long-range transport process, we retrieved the MODIS fire-count data and 5-day backward trajectories obtained from the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Draxler and Rolph, 2003). The MODIS (4 mm and 11 mm channels) provides the fire count information based on brightness temperature algorithm and algorithm distinguish fire pixels into three categories: low confidence (0–30%), nominal confidence (30–80%), and high confidence (>80%). In the present study, data with high confidence (>80%) were considered.

3.4. TUV model

Tropospheric Ultraviolet and Visible radiation model (TUV) version 5.3 was used to estimate the photolysis frequencies (j (O’D)) during the three lockdown phases examined in this study (Madronich, 1993). The model was designed by the National Center for Atmospheric Research (NCAR, United States), and which uses the discrete-ordinate algorithm (DISORT) with four streams and estimates the actinic flux spectra with a wavelength range of 280–420 nm in 1 nm steps and resolution. The AOD, Single Scattering Albedo (SSA), Angstrom exponent (AE), and altitude were required to test aerosol influence on photolysis rates. In the present study, based on the geographical region and air mass trajectory types, we have chosen five aerosol types available from Hess et al. (1998) for new aerosol mixtures and estimated AOD values. The estimated AOD is well-matched with the real-time AOD and estimated required SSA. The J-value impact factor (JIF) is defined as the observed photolysis frequencies ratio to the photolysis frequencies at AOD equal to 0 (Flynn et al., 2010; Wang et al., 2019). Generally, the JIF values less than 1 indicate that the aerosols decrease the photolysis frequencies.
4. Results and discussion

4.1. Diurnal variability in solar radiation, UV-A, surface ozone, and black carbon mass concentration

Fig. 2a-d examines the diurnal variability in SR, UV-A, O\textsubscript{3}, and BC mass concentration for PLD, LDP1, and LDP2. The diurnal variation of SR (UV-A) shows increased from morning hours onwards and reached a peak value during afternoon hours and again starts to decrease till evening hours (Fig. 2a and b). The diurnal variation in both O\textsubscript{3} and BC trends shows oppositely and exhibits an obvious variability in three phases. Even though LDP1 O\textsubscript{3} is systematically higher than other phases, they exhibit a similar diurnal pattern of O\textsubscript{3} was observed. The concentrations of O\textsubscript{3} were ~10.7\% higher during LDP1 (44.8 ± 5.2 ppbv) than the PLD (40.5 ± 6.0 ppbv). The concentrations of O\textsubscript{3} generally increased during the LDP1, possibly because lower fine particle loadings led to less scavenging of HO\textsubscript{2} and, as a result, greater O\textsubscript{3} production. These results illustrate the importance of reactions between gaseous and particulate pollutants, but clearly, lowering the NOx emissions and VOCs will be needed to control O\textsubscript{3}. Lal et al. (2000) reported daytime change in the O\textsubscript{3} level is mainly depends on the solar intensity, anthropogenic photochemical reactions, and meteorological conditions. The diurnal BC showed two peaks, one peak in the morning (07:00–08:00 LT) and the other in the evening (20:00–22:00 LT), while the morning peak is predominant than the evening peak (Fig. 2d). During PLD, vehicular emissions were relatively high, and the observed magnitude of the morning peak was high. However, during the lockdown days, the morning peak was considerably low due to the absence of transport sectors. On the lockdown days, the agricultural emissions were considerably higher, and the observed magnitude of the evening peak was reasonably high, whereas, on pre-lockdown days, the peak was relatively lower than lockdown days. Several villages are located to the south at the distance of 0.5 km over the measurement location, and in April month, it suffers maximum advection of agriculture and waste burning. The relatively lower BC observed in LDP1, and LDP2 indicate that the strict implementation of the lockdown in this area turned to be effective in decreasing the BC over Anantapur.

To understand aerosols impact on j (O\textsubscript{1}D), we performed the TUV model for three different atmospheric conditions, i.e., PLD, LDP1, and LDP2. Fig. 3(a-d) illustrates the situ measured O\textsubscript{3}, AOD, TUV model estimated photolysis frequencies (j (O\textsubscript{1}D)), and JIF values at 14:00 IST for PLD, LDP1, and LDP2. The maximum O\textsubscript{3} concentration was observed in the day time (14:00 IST) about 57.4 ± 5.0, 59.4 ± 6.7, 55.4 ± 2.9 ppbv for PLD, LDP1, and LDP2, respectively (Fig. 3a). The corresponding photolysis frequencies were about 3.24 × 10\textsuperscript{-5}, 3.36 × 10\textsuperscript{-5}, 3.1 × 10\textsuperscript{-5} s\textsuperscript{-1}, respectively (Fig. 3c). The estimated JIF values for PLD, LDP1, and LDP2 were about 0.77, 0.81, and 0.76, confirming that aerosols strongly impact photolysis frequencies during the study period (Fig. 3). Sharma et al. (2020) revealed that the surface ozone was increased by about 17\% during the lockdown period compared to previous years over 22 major cities in India. Jain and Sharma (2020) revealed that the surface ozone was increased by about ~7\% and ~3\% during the lockdown phase than the pre lockdown in Chennai and Bangalore, respectively. A significant
Fig. 3. Day time (14:00 IST) variation of (a) Surface ozone (b) Aerosol optical depth (c) Dependence of $j(O_1 D)$ on AOD (d) $J$-value impact factor for PLD, LDP1 and LDP2.

Fig. 4. Spatial distribution of aerosol optical depth and tropospheric NO$_2$ during the PLD, LDP1 and LDP2.
enhancement in O3 concentration was observed from pre-lockdown days to triple-lockdown by 22% over Kannur (Resmi et al., 2020). Li et al. (2011) reported that the changes in photolysis rates concern atmospheric aerosols accounted for 2–17% surface ozone reduction over Mexico City. Gharibzadeh et al. (2021) reported a decrease in ozone concentration on dusty days due to a significant decrease in photolysis rates; thus, the depletion of ozone occurred. Dickerson et al. (1997) concluded that absorbing aerosols significant reduces the O3 mixing ratios approximately 24 ppbv than the other aerosol types. Li et al. (2005) found that absorbing aerosols resulted in a 5–20% decrease in surface O3 production in the Houston area. Wang et al. (2019) reported that aerosols cause a significant decrease in j (O1D) by 27% and 33% compared to an aerosol-free atmosphere (AOD = 0) for summer winter, respectively.

4.2. Spatial and temporal distributions in trace gases and aerosols

To study the effect of lockdown on aerosols and trace gases, we analyzed the spatial and temporal distribution of AOD (550 nm) and NO2 over the measurement location. Fig. 4 shows the spatial distribution of AOD and tropospheric NO2 during PLD, LDP1, and LDP2 over Southern India. The color bar in the figure represents the AOD/NO2, and the marked symbol 'circle' in red color indicates the observation site. Large concentrations of aerosol (>0.30) are observed over Anantapur.

Fig. 5. Temporal variation of (a) Near-surface ozone (b) Tropospheric NO2 (c) Black carbon (d) Columnar ozone (e) Columnar NO2 (f) Water vapor for three phases.
during PLD. During the LDP1, a significant reduction of AOD (<0.25) was observed; however, enhancement in the aerosol concentration (>0.30) was observed during LDP2. The measurement location has mainly surrounded by farmers who undertake several agricultural activities; however, the back trajectories revealed that the aerosols originated from the Northwest region also contribute to this location (Gopal et al., 2014a, 2017; Kalluri et al., 2016, 2017). Meanwhile, tropospheric NO\textsubscript{2} showed the highest (>15 × 10\textsuperscript{14} mol/cm\textsuperscript{2}) during PLD and gradually decreases to a minimum of <15 × 10\textsuperscript{14} mol/cm\textsuperscript{2} during the lockdown period.

Fig. 5 a-f shows the daily variability in O\textsubscript{3}, BC mass concentration, TCO, WV, and satellite retrieved tropospheric and columnar NO\textsubscript{2} for PLD, LDP1, and LDP2 over the measurement location. The results showed distinct variations that occurred during PLD, LDP1, and LDP2. For example, O\textsubscript{3} (TCO) ranges from 30.3 to 43.7 ppbv (252-263DU), with a mean, were about 38.9 ± 5.32 ppbv (259 ± 4DU) during PLD. The corresponding mean for LDP1 and LDP2 were about 44.6 ± 3.4 ppbv (266 ± 8 DU) and 36.5 ± 3.0 ppbv (261±3DU), with a relative change of 14.7% (2.4%) and –6.0% (0.7%) is observed than PLD (Fig. 5 a,d).

However, the mean concentrations of tropospheric NO\textsubscript{2} (columnar NO\textsubscript{2}) during PLD, LDP1, and LDP2 days have noticed about 1.72 × 10\textsuperscript{15} (3.81 × 10\textsuperscript{15}), 1.20 × 10\textsuperscript{15} (3.25 × 10\textsuperscript{15}), and 1.0 × 10\textsuperscript{15} mol/cm\textsuperscript{2} (3.26 × 10\textsuperscript{15} mol/cm\textsuperscript{2}), and which showed a decrease by 36% (14.5%) from pre-lockdown days to lockdown days (Fig. 5b,e). The BC was decreased from 1.51 ± 0.27 μg/m\textsuperscript{3} before lockdown to 1.30 ± 0.09 μg/m\textsuperscript{3} after lockdown, and a relative change of –13.4% was observed (Fig. 5c). During the lockdown period, the O\textsubscript{3} lapse rate due to the titration of NO might be less than its photochemical production from its precursors, and this may be the primary reason for the enhancement in O\textsubscript{3} observed.

### 4.3. Spectral variation of aerosol optical depth and absorption coefficient

Fig. 6a-d examines the spectral variation of AOD, absorption coefficient, and temporal variation of AE and absorption angstrom exponent (AAE) for PLD, LDP1, LDP2 over Anantapur. Importantly, the higher AODs occurred in lower wavelengths, and the lower AODs are common in higher wavelengths. The mean AOD values at 380 nm were about 0.48 ± 0.09, 0.44 ± 0.1, 0.55 ± 0.08 for PLD, LDP1 and LDP2, respectively, while the corresponding values at 1020 nm are 0.15 ± 0.03, 0.11 ± 0.02 and 0.20 ± 0.06, respectively (Fig. 6a). During LDP2, the magnitude of AOD was observed relatively higher at near-IR regions due to the predominance of coarse mode scattering particles (mineral dust), and which is fairly consistent with the high mass loading and size distribution observed in LDP2. The low AOD values were observed during LDP1 due to small scale industries shutdown near the measurement location. However, the long-range transport can bring large amounts of mineral dust aerosols and smoke particles from west Asian and central India to the site and are responsible for increasing AOD during LDP2 over the site (Fig. 8). It is also clearly demonstrated from Fig. 6b that the absorption coefficient decreases with the increase in wavelength during three phases. This study shows that strong absorbing aerosols may lead to high absorption at shorter wavelengths, which is more pronounced during PLD than other phases. An obvious variation of AE and AAE can be seen during three episodes. The mean values of AAE were about 1.30 ± 0.07, 1.39 ± 0.08, and 1.46 ± 0.02, during PLD, LDP1, and LDP2, respectively (Fig. 6c). The AE corresponding mean values were about...

![Fig. 6. Spectral variation and temporal variations of (a) aerosol optical depth (b) absorption coefficient (c) Angstrom exponent (d) Absorption angstrom exponent for three phases.](image-url)
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The presence of dust is indicated by the fact that the high AOD corresponds to the low AE during LDP2. The AAE < 1.0 corresponds to non-absorptive components while the group 1.0 < AAE ≤ 1.1 is attributed to the presence of BC-rich aerosols in the atmosphere from the fossil fuel burning process (Liu et al., 2018a,b). On the other hand, AAE lies between 1.1 < AAE ≤ 1.3 represents mixed carbonaceous aerosols emitted from both fossil fuel and biomass burning activities over the observational site. Further, the remaining group via., AAE > 1.3, can be attributed to biomass burning emitted BC aerosols. At the observation site, the magnitude of AAE (1.1 < AAE ≤ 1.3) revealed that the mixed carbonaceous type of aerosols during PLD emitted from both fossil fuel and biomass burning activities. In contrast, the values of AAE > 1.3 during LDP1 and LDP2 were attributed to BC from biomass burning activities processes over the measurement location.

4.4. Columnar aerosol size distributions and derived parameters

Fig. 7 illustrated the columnar size distributions and derived parameters ($R_{\text{eff}}$, $N_c/N_a$, $m_1$, $N_c$, and $N_a$ from the columnar size distributions for three phases. The CSD derived from the obtained AOD spectra over Anantapur is consistently followed by power law + unimodal during three episodes. It indicates that distinct sources availability in all phases. The value of $R_{\text{eff}}$ generally depends on the relative contribution of coarse to fine particles, while the value of $m_1$ depends on both total aerosols and the concentration of the coarse mode particles (Moorthy and Satheesh, 2000). From the interdependency of $m_1$ and $R_{\text{eff}}$, it is evident that the lower values of $R_{\text{eff}}$ and $m_1$ during LDP1 are associated with the decrease in the total concentration. High mass loading (118 mg m$^{-2}$) and effective radius (0.19 μm) occurred during LDP2 and are attributed to a significant abundance of coarse (natural) aerosols. The $N_c$ were $7.51 \times 10^9$, $5.18 \times 10^9$, and $9.77 \times 10^9$ during PLD, LDP1, and LDP2, respectively. The ($N_c/N_a$) values were about $1.50 \times 10^{-3}$, $1.08 \times 10^{-3}$, and $1.83 \times 10^{-3}$ for PLD, LDP1, and LDP2. Na, Nc, and Nc/Na values were observed minimum during LDP1 and reached a maximum during
LDP2. The \( \text{N}_2 \) and Na showed a significant decrease in LDP1 compared to the PLD due to the immediate shutdown of small-scale industries, including cement plants, lime kilns, slab polishing, stone crushing, and brick-making industries. However, The \( \text{N}_2 \) and Na in LDP2 are higher than that in PLD and LDP1, which most likely biomass burning fires dominate, generating finer mode particles and long-range transported dust. An increase in Na/Na ratio indicates the coarse mode aerosols dominance in the size spectrum during LDP2 compared to the LDP1, and it is considered responsible for flattening the AOD spectrum (Dumka et al., 2008; Kumar et al., 2009). Fig. 8 illustrates the fire counts merged with back trajectories during the LDP2. During LDP2, the potential source of absorbing aerosol, as identified through fire count analysis, significant biomass burning activities, and vast agricultural fields in central India, appeared as a red dot. The air masses generally originate northwesterly and pass over central India before reaching the observation site during LDP2.

5. Conclusion

The study explains aerosols impact on ozone production during the COVID-19 pandemic period on all clear sky days. The essential findings derived from the results are summarized below. The concentrations of ozone were \( \sim 10.7\% \) higher during LDP2 (44.8 \pm 5.2 ppbv) than the PLD (40.5 \pm 6.0 ppbv). Overall, a drastic reduction in BC concentration (\( \sim 8.4\% \)) and AOD (10.8%) were observed during LDP1 than PLD over the measurement location. The AAE analysis reveals a predominant source field of absorbing aerosol, as identified through fire count analysis, significant biomass burning activities, and vast agricultural fields in central India, appeared as a red dot. The air masses generally originate northwesterly and pass over central India before reaching the observation site during LDP2.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jastp.2020.105491.

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