The Impact of Lockdown on eBC Mass Concentration over a Semi-arid Region in Southern India: Ground Observation and Model Simulations

Surya Nagi Reddy Palle[†], Chakradhar Rao Tandule[†], Raja Obul Reddy Kalluri, Balakrishnaiah Gugamsetty, Rama Gopal Kotalo^{*}, Lokeswara Reddy Thotli, Bhavyasree Akkiraju, Siva Sankara Reddy Lingala

Aerosol and Atmospheric Research Laboratory, Department of Physics, Sri Krishnadevaraya University, Anantapur, Andhra Pradesh, India

ABSTRACT

In the present study, we focused on the impact of lockdown on black carbon (eBC) mass concentrations and their associated radiative implications from 01st March to 30th June 2020, over a semi-arid station, i.e., in the district of Anantapur in Southern India. The mean eBC mass concentration was observed before lockdown (01st–24th March 2020) and during the lockdown (25th March–30th June 2020) period and was about 1.74 ± 0.36 and $1.11 \pm 0.14 \mu\text{g m}^{-3}$, respectively. The sharp decrease (~35%) of eBC mass concentration observed during the lockdown (LD) period as compared with before lockdown (BLD) period, was mainly due to the reduction of anthropogenic activities and meteorology. Furthermore, during the entire LD period, the net composite forcing at the top of the atmosphere (TOA) and at the surface (SUR) varied from -4.52 to -6.19 Wm^{-2} and -22.91 to -29.35 Wm^{-2} , respectively, whereas the net forcing in the atmosphere (ATM) varied from 17.27 to 23.16 Wm^{-2} . Interestingly, the amount of energy trapped in the atmosphere due to eBC is 11.19 Wm^{-2} before LD and 8.56 Wm^{-2} during LD. It is concluded that eBC contributes almost 43–50% to the composite forcing. As a result, the eBC atmospheric heating rate decreased significantly (25%) when compared to before lockdown days to lockdown days.

Keywords: COVID-19, Equivalent black carbon, Fossil fuel, Radiative forcing, Semi-arid

1 INTRODUCTION

In terms of urbanization and population, India is one of the fastest-growing countries in the world. Being exceedingly vulnerable to air quality, it is a well-known global hotspot of air pollution which regularly severe. A recent study by Thomas *et al.* (2019), over the Indian region showed that the number of hazy days increases at ~2.6 days per year according to the biomass burning activities. In this situation, the World Health Organization (WHO) declared coronavirus disease 2019 (COVID-19) as a pandemic due to widespread global infection with its first outbreak in Wuhan, Hubei, China. Globally, as of 5th July 2021, there have been 183.37 Million confirmed cases of COVID-19, including 3.97 Million deaths, resulting in lockdown in many countries worldwide. In India, the first COVID-19 positive confirmed case was reported on 30th January 2020 in India's Southern state, Kerala (Prasad *et al.*, 2020). Henceforth, the number of confirmed COVID-19 positive cases closed at 500; the first nationwide lockdown (named Janata Curfew) for fourteen hours was on 22nd March 2020. This curfew was imposed suspending passenger travel both by air and on road, except essential sectors in the entire country. The rules framed by the government resulted in the reduction of human activities during the COVID-19 pandemic which impacted the air quality and helped in improving/understanding the air quality. Therefore, it provided an excellent opportunity for the government to implement a strategic plan focused on

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^{*} Corresponding Author:
krgverma@yahoo.com

[†] These authors contributed equally to this work

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emphasizing multi-pollutant emission reductions and overall air pollution-related risk.

Investigations on air quality over Indian regions during this unprecedented lockdown showed a significant improvement in air quality (Chauhan and Singh, 2020; Jain and Sharma, 2020; Sarfraz *et al.*, 2020; Kalluri *et al.*, 2021). The parameters used by the investigators in the above-said investigations in quantifying the air quality are particulate matter (PM), nitrogen oxides (NO₂), sulfur dioxide (SO₂), ozone (O₃), carbon monoxide (CO), and meteorological parameters. For example, Sharma *et al.*, 2020 reported a reduction of 43% in PM₁₀, 31% in PM_{2.5}, 18% in NO₂, and 10% in CO, during the lockdown period compared to the previous years. On the other hand, negligible changes in SO₂ and growth in O₃ by 17% are seen over India. Hence, there was a unique prospect to retrieve the anthropogenic interference on air quality aspects from the local to the global scales during the lockdown situation.

One of the essential constituents of particulate matter is equivalent black carbon (eBC). The incomplete combustion of fossil fuels and biomass burnings are the primary sources of eBC aerosols in the atmosphere (Li *et al.*, 2020; Petzold *et al.*, 2013). eBC is a graphitic form of carbon particles with unique physical properties and can impact regional air quality (Kaur *et al.*, 2020). Due to its absorbing nature in short-wave and long-wave radiation regions, it has tremendous climate implications (IPCC, 2013), especially over south Asia where absorbing aerosols abundance is high (Fan *et al.*, 2021; Shalini *et al.*, 2020; Kalluri *et al.*, 2020b; Reddy *et al.*, 2019). Hence, eBC has considered the second most potent climate forcing agent between carbon dioxide and methane (Gogoi *et al.*, 2019; Jacobson, 2001). Absorbing aerosols like eBC aerosols can significantly heat the atmosphere and cool the surface (Kalluri *et al.*, 2016, 2020a) also heat the surface (for example, eBC on snow (Kang *et al.*, 2020)), resulting in a net positive forcing on Earth-atmospheric system (Gogoi *et al.*, 2017). Keeping this in view the eBC aerosols and radiative forcing impact due to the COVID-19 lockdown from 25th March to 20th June 2020 and the similar data from the corresponding dates of the years from 2016 to 2019 over a semi-arid location, Anantapur has been reported and also presented in Table 1.

2 SITE DESCRIPTION AND METHODOLOGY

2.1 Site Description

This study analyses the impact of social and travel lockdown on aerosol properties over Anantapur, semi-arid, rain shadow Rayalaseema region in the peninsular Indian state of Andhra Pradesh. The observational site (Department of Physics, Sri Krishnadevaraya University) in Anantapur district is situated on the southern edge of the Anantapur town, as shown in Fig. 1. The observational site is approximately 10 km away from the city's centre, situated beside the national highway 42 (Anantapur–Chennai) and just 7 km away from the national highway 44 (Hyderabad–Bangalore). Additionally, the observational site is close to the railway route connecting Bangalore and other north Indian megacities. This observation site experiences frequent droughts and the second-lowest rainfall in India. The southwest monsoon contributes > 60–70% of the total rainfall, and the average rainfall is only ~150 mm during the northeast monsoon period (Raja Obul Reddy *et al.*, 2016). The possible aerosol sources are present at this site during the summer (March–May) including agricultural burning activities, fossil fuel burning activities, and transported/windblown dust from north-western winds (Kalluri *et al.*, 2017; Gopal *et al.*, 2014, 2015, 2016). Domestic burning is the main aerosol source in winter (December–February) (Gopal *et al.*, 2017; Lingaswamy *et al.*, 2017; Kalluri *et al.*, 2016).

Table 1. eBC mass concentrations during before lockdown and during lockdown periods for the years 2016–2020.

	2016	2017	2018	2019	Avg (2016–2019)	2020
BLD	2.23 ± 0.36	2.07 ± 0.54	2.30 ± 0.23	2.33 ± 0.85	2.23 ± 0.11	1.74 ± 0.37
LDP1	2.27 ± 0.43	2.69 ± 0.60	2.50 ± 0.42	2.16 ± 0.66	2.40 ± 0.23	1.54 ± 0.36
LDP2	1.93 ± 0.39	2.23 ± 0.61	1.97 ± 0.36	2.07 ± 0.75	2.05 ± 0.13	1.59 ± 0.20
LDP3	1.35 ± 0.25	1.62 ± 0.29	1.37 ± 0.28	1.61 ± 0.31	1.48 ± 0.14	1.07 ± 0.19
LDP4	1.04 ± 0.33	1.47 ± 0.44	1.50 ± 0.23	1.44 ± 0.41	1.36 ± 0.21	0.73 ± 0.11
LDP5	1.27 ± 0.13	0.84 ± 0.12	0.90 ± 0.16	1.13 ± 0.28	1.03 ± 0.20	0.47 ± 0.07

Fig. 1. Map of India showing various observational site (green circles) under ISRO-ARFI Project in which the present study location of Anantapur, Andhra Pradesh, and Google map showing the Department of Physics, Sri Krishnadevaraya University campus (Measurement Location) is highlighted.

The government of India imposed lockdown for more than two months with several relaxations in different phases. The timeline of the lockdown with restrictions and relaxations is given in Table 2. These phases are namely before lockdown (01st March–24th March), henceforth termed as BLD (24 days); lockdown 1.0 (LDP1; 21 days) from 25th March to 14th April; lockdown 2.0 (LDP2; 19 days) from 15th April to 03rd May; lockdown 3.0 (LDP3; 14 days) from 04th May to 17th May; lockdown 4.0 (LDP4; 14 days) from 18th May to 31st May; lockdown 5.0 (LDP5; 30 days) from 01st June to 30th June; the entire lockdown period (LD; 98 days) from 25th March to 30th June (LD considered as the mean for all the lockdown phases).

2.2 Meteorology

Meteorological conditions play a crucial role while discussing variations of aerosols at a particular site. The surface meteorological parameters [viz., temperature (T in $^{\circ}\text{C}$), relative humidity (RH in %), wind speed (WS in m s^{-1}), and wind direction (WD in $^{\circ}$)] have been measured on a day-to-day basis at the observational site by employing Automatic Weather Station (AWS) (Campbell Scientific, made in Canada). Fig. 2 shows the day-to-day variation of air temperature, relative humidity, wind speed, and wind direction during the study period. The daily mean surface air temperature varied in the range of 28–38 $^{\circ}\text{C}$ (29–37 $^{\circ}\text{C}$), whereas RH varied in the range of 21–73% (18–65%) during 2020 (2019). The winds are mostly from the southwest, with a maximum wind speed of $\sim 7 \text{ m s}^{-1}$ during both years. Thus, the meteorological conditions during both years almost resemble the same except in magnitude.

2.3 Instrumentation

Simultaneous eBC mass concentration measurements and spectral aerosol optical depths (AODs)

Table 2. Detailed timeline of the lockdown with restrictions, relaxations, and the number of reported COVID-19 positive cases in India.

S.No.	Timeline Phase	Period	Restrictions/Relaxations	# of COVID-19 positive cases in India*
1	Before Lockdown (BLD)	01 st March–24 th March 2020	No restrictions	445
2	Lockdown 1.0 (LDP1)	25 th March–14 th April 2020	Nearly all services (except emergency services) and factories were suspended. The transport of essential goods through rail and road.	10,817
3	Lockdown 2.0 (LDP2)	15 th April–03 rd May 2020	Same restrictions as Lockdown 1.0 but with conditional relaxation promised after 20 April 2020. Permit for Agricultural businesses, as well as shops selling farming supplies, cargo vehicles, public works programs with instructions to maintain social distancing, banks, and government centers distributing benefits.	31,288
4	Lockdown 3.0 (LDP3)	04 th May–17 th May 2020	Normal movement is permitted in green zones (No positive cases) with buses limited to 50 % capacity. Orange zones (fewer positive cases) would allow only private and hired vehicles but no public transportation. The red zones (high positive cases and a high doubling rate) would remain under lockdown.	52,920
5	Lockdown 4.0 (LDP4)	18 th May–31 st May 2020	Buses, auto-rickshaws, cabs can operate; Metro, air and rail services remain suspended, except those allowed with special permits; All shops, except those in malls and containment zones, can open; Restaurants can function, but only for take-away; Night curfew from 18:00 to 07:00 IST for non-essential services; Schools, colleges, malls to remain shut; Religious, political gatherings prohibited; Weddings cannot have more than 50 guests and funerals not more than 20.	94,949
6	Lockdown 5.0 (LDP5)	01 st June–30 th June 2020	The reopening was planned in three phases. The first phase was implemented on 8 th June to reopen shopping malls, religious places, hotels, and restaurants; Large gatherings are still banned; no restrictions on inter-state travel; night curfews from 21:00 to 05:00 IST.	4,14,802
Total positive cases:				6,05,221 (As on 30 th June, 2020)

* Data extracted from <https://www.covid19india.org/>

have been carried out regularly by deploying a seven-channel Aethalometer and five-channel MICROTOS-II Sunphotometer, respectively. In the present study, quality-controlled data sets have been used for the respective lockdown phases.

The employed MICROTOS-II Sunphotometer measures the intensity of direct solar irradiance at five narrow-band spectral channels centred at 380, 500, 870, 936, and 1020 nm through optical collimators with a full field view of 2.5°. The spectral AOD and total columnar water vapour content are the salient parameters in the sunphotometer determined based on the Bougher-Lambert-Beer law. Further details of the instrument, like working principle, theory, data analysis, and calibration techniques, have been published elsewhere (Ichoku *et al.*, 2002; Hussain *et al.*, 2018). Sunphotometer data is not accessible after 01st May 2020 due to unfavourable sky conditions.

Measurements of eBC aerosol mass concentration have been carried out using a seven-channel

Fig. 2. Variation in daily average temperature (°C) and relative humidity (%) along with wind rose plot showing local wind direction and distribution of wind speed (m s^{-1}) over the study location during the months of March–June for the years 2019 and 2020.

(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. Before considering the analysis data, correction of the loading effect for the raw data was applied, as described in Virkkula *et al.* (2007). As a result, Aethalometer manufacturers have reported $\pm 5\%$ uncertainty (Allen *et al.*, 1999; Hansen, 2005). However, further details about measurement principles, data analysis, correction schemes were described in several earlier studies by Arnott *et al.* (2005); Virkkula *et al.* (2015, 2007); Weingartner *et al.* (2003); and hence not discussed more here.

2.4 MERRA-2 BC

Gridded BC data ($0.625^\circ \times 0.5^\circ$ longitude-by-latitude resolution) was retrieved from NASA's Modern Era Retrospective Analysis for Research and Applications, Version-2 (MERRA-2) re-analysis data for the measurement period (<https://disc.gsfc.nasa.gov/datasets/>). More detailed information about MERRA-2 is available elsewhere (Lasko *et al.*, 2018; Qin *et al.*, 2019). The gridded value geographically closest to a study region is selected as the comparison object for observation in this site. The black carbon aerosol transport is examined in the study using reanalysis wind data from MERRA, (Rienecker *et al.*, 2011) reanalysis products at a grid resolution of 0.25° by 0.25° (<http://mirador.gsfc.nasa.gov/>).

In addition to a standard meteorological analysis, MERRA-2 includes an aerosol analysis, as described in Randles *et al.* (2017). Aerosols in MERRA-2 are simulated with a radiatively coupled version of the Goddard Chemistry, Aerosol, Radiation, and Transport model (GOCART; Chin *et al.*, 2002; Colarco *et al.*, 2010). GOCART treats the sources, sinks, and chemistry of 15 externally mixed aerosol mass mixing ratio tracers: dust (five noninteracting size bins), sea salt (five noninteracting size bins), hydrophobic and hydrophilic black and organic carbon (eBC and OC, respectively; four tracers), and sulfate (SO_4^{2-}). Both dust and sea salt have wind speed- dependent emissions (Tandale *et al.*, 2020). Primary sulfate and carbonaceous aerosol species are emitted principally from fossil fuel combustion, biomass burning, and biofuel consumption, with additional biogenic sources of organic carbon. Secondary sources of sulfate include chemical oxidation of sulfur dioxide gas (SO_2) and dimethyl sulfide (DMS), and we include a database of volcanic SO_2 emissions and injection heights.

The hourly mean Boundary Layer Height (BLH), were obtained from ERA-5 (<https://cds.climate.copernicus.eu/cdsapp#!dataset/reanalysis-era5-single-levels?tab=form>).

2.5 Estimating the Fossil Fuel and the Biomass Burning Component of Equivalent Black Carbon Mass Concentrations

After applying the loading effect correction algorithm, the corrected eBC mass concentration data has been apportioned to identify the fossil fuel and biomass burning contribution to the total eBC measured. The power-law aerosol absorption coefficients (σ_{abs}) is proportional to $\lambda^{-\alpha}$, where α is the absorption Ångström exponent, and λ is the wavelength which describes the spectral dependence of the absorption coefficient (Ångström, 1964). Consequently, for a wavelength pair, it can be derived using the following relation:

$$\frac{\sigma_{abs}(\lambda_1)}{\sigma_{abs}(\lambda_2)} = \left(\frac{\lambda_1}{\lambda_2} \right)^{-\alpha} \quad (1)$$

In general, coal-burning, or fossil fuel emissions, contain more eBC than other light-absorbing compounds, thus ($\alpha_{FF} \sim 1$) is also applicable to combustion of fossil fuels (Kirchstetter *et al.*, 2004; Zotter *et al.*, 2017). The aerosols produced by biomass combustion, on the other hand, are composed of light-absorbing organic substances and eBC, therefore $\alpha_{BB} \sim 2$ is relevant to biomass combustion (Sandradewi *et al.*, 2008a; Zotter *et al.*, 2017). They show strong light absorption in the near UV region of the spectrum and have a minimal contribution in the near IR region of the spectrum. With this background, Sandradewi *et al.* (2008a) developed a two-component Aethalometer model to obtain a qualitative measure of the relative presence of fossil fuel burning and biomass burning sources in the measured eBC. This model utilizes the light absorption by fossil fuel and wood-burning sources with the basic assumption that fossil fuel and wood burning are the dominating sources of carbonaceous aerosols. Hence, the corrected σ_{abs} obtained from the Aethalometer is the sum of σ_{abs}^{FF} due to fossil fuel burning and σ_{abs}^{BB} due to biomass burning:

$$\sigma_{abs}(\lambda) = \sigma_{abs}^{FF}(\lambda) + \sigma_{abs}^{BB}(\lambda) \quad (2)$$

Using Beer-Lambert's Law, the relation between the corrected σ_{abs} , λ , and α for biomass burning (BB) and fossil fuel burning (FF) is:

$$\frac{\sigma_{abs}^{FF}(370 \text{ nm})}{\sigma_{abs}^{FF}(880 \text{ nm})} = \left(\frac{370}{880} \right)^{-\alpha_{FF}} \quad (3)$$

$$\frac{\sigma_{abs}^{BB}(370 \text{ nm})}{\sigma_{abs}^{BB}(880 \text{ nm})} = \left(\frac{370}{880} \right)^{-\alpha_{BB}} \quad (4)$$

For a given value of α_{FF} and α_{BB} , the values for $\sigma_{abs}^{FF}(370 \text{ nm})$, $\sigma_{abs}^{FF}(880 \text{ nm})$, $\sigma_{abs}^{BB}(370 \text{ nm})$, and $\sigma_{abs}^{BB}(880 \text{ nm})$ have computed using Eqs. (2)–(4). According to this study, α_{FF} and α_{BB} values are 1, 2 respectively, which were comparable to those in the literature (Kaur *et al.*, 2020; Kumar *et al.*, 2020; Rajesh and Ramachandran, 2017; Vaishya *et al.*, 2017). The contributions of fossil fuel burning (eBC_{FF} @ 880 nm) and biomass burning (eBC_{BB} @ 880 nm) to total eBC @ 880 nm are then derived via the corresponding mass absorption cross section (MAC) values (MAC_{BB} and MAC_{FF}, respectively):

$$\text{eBC @ 880 nm} = (\text{eBC}_{FF} @ 880 \text{ nm}) + (\text{eBC}_{BB} @ 880 \text{ nm}) \quad (5)$$

$$\text{eBC}_{FF}(880 \text{ nm}) = \frac{\sigma_{abs}^{FF}(880 \text{ nm})}{\text{MAC}_{FF}(880 \text{ nm})} \quad (6)$$

$$\text{eBC}_{BB}(880 \text{ nm}) = \frac{\sigma_{abs}^{BB}(880 \text{ nm})}{\text{MAC}_{BB}(880 \text{ nm})} \quad (7)$$

where MAC_{FF} (880 nm) and MAC_{BB} (880 nm) is 16.6 m²g^{−1} taken from the manufacturer (Hansen, 2005). Zotter *et al.* (2017) reported that there is no significant difference between MAC_{FF} to MAC_{BB} at 880 nm. Hence the same MAC value was taken for both MAC_{FF} and MAC_{BB}.

The limitations of the deconvolution of eBC to eBC_{FF} and eBC_{BB} using this two-component Aethalometer model is that assuming the fossil fuel and wood burning are the dominating sources of black carbon aerosols. It is also known that wind-blown dust is one of the light-absorbing aerosols, especially absorbing UV regime (e.g., 370 nm in Aethalometer). This absorption by dust particles in shorter wavelengths may be difficult to identify the absorption of eBC_{BB}. One more limitation is that assumption of appropriate values for α_{FF} and α_{BB} . This model is sensitive on the selected wavelength range and the prior assumed α_{FF} and α_{BB} values, as some studies used the 370–880 nm (Dumka *et al.*, 2018; Kaur *et al.*, 2020; Vaishya *et al.*, 2017), others the 470–950 nm (Kumar *et al.*, 2020; Sandradewi *et al.*, 2008a, b; Zotter *et al.*, 2017) and 370–950 nm (Rajesh and Ramachandran, 2017). Assumed α_{FF} ranged between 0.9–1.1 and α_{BB} between ~1.7–3.5 values by (Schnaiter *et al.*, 2003, 2005; Kirchstetter *et al.*, 2004; Sandradewi *et al.*, 2008a, b; Stockwell *et al.*, 2016; Diapouli *et al.*, 2017; Rajesh and Ramachandran, 2017; Vaishya *et al.*, 2017; Zotter *et al.*, 2017; Dumka *et al.*, 2018; Kaur *et al.*, 2020; Kumar *et al.*, 2020).

2.6 Estimation of the Short-wave Direct Aerosol Radiative Forcing

The short-wave direct aerosol radiative forcing (SDARF) estimated by using the standard atmospheric model, Santa Barbara Discrete Ordinate Radiative Transfer (SBDART), which uses the discrete ordinates radiative transfer (DISORT) integration of the radiative transfer equations. Several investigators reported that this model is well suited to estimate the earth-atmosphere system's radiation budget (Aruna *et al.*, 2016; Babu *et al.*, 2002; Kant *et al.*, 2020; Moorthy *et al.*, 2009). The necessary and significant inputs for computing SDARF are spectral AOD, spectral single scattering albedo (SSA), and the scattering phase function. The AOD and eBC mass concentration data sets have been obtained from MICROTOPS sun photometer and Aethalometer during the entire phases. The SSA, Phase function, Angstrom exponent data sets were obtained from the optical properties of aerosols and clouds (OPAC) model (Hess *et al.*, 1998). Additional inputs like surface albedo, atmospheric profiles of temperature, pressure, columnar ozone, and water vapor content are necessary to estimate shortwave radiative forcing in SBDART model. Surface reflection collected by the 8-Day, Level 3 Moderate Resolution Imaging Spectroradiometer (MODIS)

onboard Terra (MOD09A1) and Aqua (MYD09A1) satellites at different wavelengths (0.469, 0.555, 0.645, 0.859, 1.24, 1.64, and 2.13 μm) were used to calculate the surface spectral albedo. The columnar ozone and water vapour content datasets from the MICROTOPS Ozonometer have also been obtained.

Shortwave direct radiative forcing at surface, atmosphere, and top of the atmosphere and their associated heating rates (K day^{-1}) within the atmosphere are estimated using this model. The details are furnished elsewhere (Liou, 2002). Due to the lack of sunphotometer AOD values after LDP3, the aerosol radiative forcing was estimated only for BLD, LDP1, LDP2, and LDP3. Therefore, the value reported for LD for forcing related parameters is the mean values from LDP1 to LDP3 only.

3 RESULTS AND DISCUSSION

3.1 Impact of Lockdown on eBC Mass Concentration

Fig. 3 shows the temporal change in the diurnal concentrations of eBC, eBC_{FF}, and eBC_{BB} before and during the lockdown overlaid by atmospheric boundary layer height. It has been noticed from the figure that, irrespective of phase in lockdown, the concentration of eBC and eBC_{FF} is low during the noon hours. Two prominent peaks are noticed, primary peak during the morning hours around 06:00–07:00 h and another less prominent peak (also known as nocturnal peak) during the evening hours around 19:00–20:00 h for all the periods. These diurnal variations result from the various eBC local emission sources and their strengths and atmospheric boundary layer height. In general, the height of atmospheric boundary layer (ABL) starts increasing from 06:00–07:00 h and reaches the maximum at 14:00–15:00 h. Later on, it starts decreasing till 19:00 h and tends to be invariable from 20:00 to 06:00 h (Fig. 3). Chan *et al.* (2012) found a strong correlation between ABL and incoming solar radiation. After the sunrise, a gradual increase in the radiation onset breaking the aerosols trapped in the residual layer (caused due to the night-time inversions) leading to a sharp increase in near-surface pollutants concentration (eBC: primary peak) popularly known as fumigation effect. As the day advances, due to the impact of thermal buoyancy, ABL increases rapidly and redistributes aerosols vertically in deep ABL, making the concentration of eBC minimum at the surface level. The solar radiation tends to diminish as the day progresses, especially in the evening. After sunset, the turbulent mixing weakens, and thus ABL deforms to a shallow stable ABL near the earth's surface (Siva Kumar Reddy *et al.*, 2021). The thermal inversions separate residual layer downwards and night-time traffic emissions leading to the nocturnal peak can be observed in the diurnal eBC cycle. The impact of ABL on diurnal eBC is commonly seen in all the phases, irrespective of the years. But the magnitude of the eBC concentrations varies from phase to phase in the year 2020 compared with 2019. During the year 2019, from Figs. 3(a)–3(f), the magnitude of the eBC concentrations gradually decreased due to the seasonal effect; the Indian summer monsoon. The magnitudes of eBC concentration during 2020 also follow the same trend as 2019 but with remarkable reductions. These remarkable reductions in eBC concentrations in the year 2020 might be attributed to the movement restrictions on all public and private vehicles imposed to control the spread of the COVID-19 pandemic, as shown in Table 1. It is interesting to note that when compared with 2019, the concentrations of eBC_{FF} in the year 2020 decreased from before LD to LDP4 due to vehicular movement restrictions and an increase in the eBC_{BB}. People who live near the sampling site often cook with wood fuel and participate in a variety of farming activities, which may led to the rise in eBC_{BB}. Since the two-component Aethalometer model assumes the possible source of eBC is from fossil fuel combustion and biomass burning, the decrease in vehicular emission increases the share of eBC_{BB}. After LDP4, relaxations have allowed the public to resume their daily activities with minimal restrictions; hence, eBC_{FF} starts dominating over eBC_{BB} in Anantapur. To have a better understanding of the impact of LD on the surface eBC, eBC_{FF}, and eBC_{BB} concentrations, we herewith illustrate the mean eBC, eBC_{FF}, and eBC_{BB} concentrations for each LD phase (derived from daily mean values) along with those relative changes between 2019 and 2020 as shown in Fig. 4. The concentration of eBC_{FF} in (Fig. 4(a)) 2020 shows exponential decrease from BLD ($1.4 \pm 0.4 \mu\text{g m}^{-3}$) to LDP5 ($0.4 \pm 0.1 \mu\text{g m}^{-3}$), whereas eBC_{BB} (Fig. 4(b)) showed increase in LDP1 and attained a peak value of $0.6 \pm 0.1 \mu\text{g m}^{-3}$ during LDP2 and started decreasing from LDP3. While considering the mean variation between BLD and DLD during

Fig. 3. Effects of lockdown on diurnal variation of equivalent black carbon (eBC-blue) mass concentrations, equivalent black carbon concentrations from fossil fuel (eBC_{FF}-red), and biomass burning (eBC_{BB}-black) in compared with 2019 (a–g) & 2020 (h–n) scaled to the left side. The Atmospheric boundary layer height is represented with values overlaid on line plot (Green) scaled to the right side. a and h represent before lockdown, b and i–lockdown period 1, c and j–lockdown period 2, d and k–lockdown period 3, e and l–lockdown period 4, f and m–lockdown period 5, g and n–mean for lockdown period 1–5. Complete details and dates for the lockdowns are provided in the text.

Fig. 4. Phases wise mean eBC concentration values contribution of fossil fuel combustion (a) and biomass burning (b), during in 2019 (orange) and 2020 (green) along with absolute change in respective values between 2020 and 2019 (violet). Values illustrates on top of the orange and green bars are the percentage share of with respect to the total eBC during 2019 and 2020 respectively, whereas values on violet bar are the relative change in percentage between 2020 and 2019.

2020, it has witnessed a decrease of 33.95% in eBC and 47.19% in eBC_{FF} with a 23.49% increase in eBC_{BB}. When compared the relative change between 2020 and 2019, eBC_{FF} always showed decreasing tendency. However, eBC_{BB} showed an increasing tendency from LDP1 to LDP4 with relative change as high as 161% during LDP2. Moreover, to have a much clearer understanding of the impact of the unprecedented cessation of human activities during the lockdown on the regional aerosol concentration, the percentage of contribution of eBC_{FF} and eBC_{BB} to the total eBC for the respective phase is shown over each bar in Fig. 4. One can observe that in the year 2020, eBC_{FF} decreased from LDP1 (where nearly all services and factories were suspended, except emergency services) to LDP4. When the travel restrictions are resumed (i.e., during LDP5), eBC_{FF} increased from 58% in LDP4 to 79% in LDP5. This pattern was not observed in the year 2019.

As shown in Table 2, the mean eBC concentration in the year 2020 during BLD, LDP1, LDP2, LDP3, LDP4, and LDP5 is much lower when compared with the same periods during 2016–2019. eBC emissions declined from 1.66 ± 0.5 to $1.07 \pm 0.49 \mu\text{g m}^{-3}$ (35 %) during the lockdowns period over Anantapur, as compared to the same period in the previous 4 years (2016–2019). eBC emissions during BLD was decreased from 2.23 ± 0.11 to $1.74 \pm 0.37 \mu\text{g m}^{-3}$ (22%), in LDP1 from 2.40 ± 0.23 to $1.54 \pm 0.36 \mu\text{g m}^{-3}$ (36%), in LDP2 from 2.05 ± 0.13 to $1.59 \pm 0.20 \mu\text{g m}^{-3}$ (22%), in LDP3 from 1.48 ± 0.14 to $1.07 \pm 0.19 \mu\text{g m}^{-3}$ (28%), in LDP4 from 1.36 ± 0.21 to $0.73 \pm 0.11 \mu\text{g m}^{-3}$ (46%) and in LDP5 from 1.03 ± 0.20 to $0.47 \pm 0.07 \mu\text{g m}^{-3}$ (54%) as compared to the same period in the last 4 years. It was observed that eBC concentration, when compared with BLD 2016–19,

there is also a noticeable decrease in the BLD phase of 2020. The government of India has imposed specific emission control measures over various industrial sectors, which have played a significant role in keeping the particulate emission in control and including that of eBC. Among those control measures, the nationwide implementation of Bharat Stage (BS) emission standards in 2000 were followed more rigorous criteria with Bharat stage IV (sulfur content of 50 ppm) in 2010 and Bharat Stage VI norms (sulfur content of just 10 ppm) in 2020 along with steps to improve the fuel quality. BS-VI norms significantly reduce contents like sulfur, lead, benzene, and much more, improves the octane/cetane number for petrol/diesel. A recent investigation on long-term variation from 2007 to 2015 of surface eBC aerosol mass concentration over India showed a significant decreasing trend with $0.07 \mu\text{g m}^{-3} \text{y}^{-1}$ over peninsular India and $0.242 \mu\text{g m}^{-3} \text{y}^{-1}$ overall the Indian region (Manoj *et al.*, 2019). Similar decreasing trend of $0.02 \mu\text{g m}^{-3} \text{month}^{-1}$ over the eastern Himalayan region between 2009 to 2015 was reported by Sarkar *et al.* (2019). Ravi Kiran *et al.* (2018) have reported $0.27 \mu\text{g m}^{-3}$ decrease per year over tropical site Gadanki during 2008 to 2017. There was a dramatic drop in eBC levels during the lockdown days in the year 2020 due to numerous restrictions and curfews imposed to combat the COVID-19 pandemic, which reduced anthropogenic emissions over Anantapur.

3.2 Intercomparison of Observed and Model eBC Concentrations

We have observed the impact of the lockdown restrictions on surface eBC concentrations. Now, we would like to look at the response of the model data during the lockdown restrictions and compare the observed and model data. We have used MERRA-2 surface mass concentration of carbon black (BCSMAS) model data for validation with ground-based observation data for our current analysis. The phase-wise mean observed and MERRA-2 BC concentrations along with bias values are shown in Fig. 5(a). It can be found that the MERRA-2 component has a clear variation for the lockdown phases in the year 2020. However, the bias between observed and MERRA-2 during 2020 is consistently low when compared with 2019 data. During 2019, the bias is always higher than 0.30, while it is below 0.30 for 2020, irrespective of the sign. Also, the daily mean basics observed and MERRA-2 BC are well correlated in both the years with R values of 0.71 and 0.80 for the years 2019 and 2020, respectively as show in Fig. 5(b). In the lockdown period in 2020, MERRA-2 BC shows lower values than the corresponding period in previous year (2019). MERRA-2 satellite-based BC data also showed improved air quality at Anantapur during the lockdown. Based on the lockdown phase-wise mean, the correlation between observed and MERRA-2 are very strong, 0.94 and 0.99 for the years 2019 and 2020 (Fig. 5(c)). We can also see that the MERRA-2 has underestimated the eBC concentrations in both the years, except for few days where the concentrations are below $1 \mu\text{g m}^{-3}$. Therefore, it can be hypothesized that MERRA-2 BC concentrations perform better in low pollution levels than in higher pollution levels. However, Zhao *et al.* (2021) noticed the overestimated MERRA-2 BC concentrations in Nanjing City, where the concentration levels are much higher when compared to our study. They also found a good correlation between observed and MERRA-2 BC on monthly mean values (0.93) rather than daily mean values (0.78). Qin *et al.* (2019) also reported that MERRA-2 BC concentrations are overestimated (averagely 101.6% higher) than ground-based observations; however, the ground-based and MERRA-2 mass concentrations of BC were highly correlated (0.77) over Beijing.

3.3 Shortwave Direct Aerosol Radiative Forcing

Table 3. provides SBDART input parameters and shortwave direct aerosol forcing for before and during lockdown phases. The positive sign in relative change denotes an increase, whereas the negative sign denotes a reduction in the AOD value. The AOD levels decreased some what from 0.39 (BLD) to 0.37 (DLD). The relative change of AOD between BDL and DLD is -03.60% for the 2020 phases and 13.09% for the 2019 phases. When comparing the AOD values observed between 2020 and 2019 phases before LD, AOD values decreased by only 12.41% . During DLD, it decrease by 28.95% , a comparably substantial decline in AOD during 2020 phase. Under normal circumstances, residual crop burning and continental dust particles associated with higher wind speed are responsible for high AOD values observed during the month's March–May over the observational location (Kalluri *et al.*, 2016).

Fig. 5. Comparison of observed eBC concentrations with MERRA-2 BC concentration for various lockdown phases (a) and the values over the bar represents the bias between observed and modelled values, red for 2019 and blue for 2020. Validation of MERRA-2 BC at (b) daily level and (c) phase wise mean with observations.

A regional synthesis of eBC, eBC_{FF}, eBC_{BB}, and AOD, having noted for various lockdown phases, attempted to estimate the radiative forcing due to composite and eBC aerosols before and during the lockdown phases. The mean picture of the phase-wise averaged SDARF due to composite aerosols at the top of the atmosphere (TOA), in the atmosphere (ATM), and at the surface (SUR) over study location is illustrated in Fig. 6. The surface and TOA forcing due to composite aerosols increased by 11.33% from -27.88 Wm^{-2} (BLD) to -24.89 Wm^{-2} (DLD) at the surface and only 3.62% increase from -05.47 Wm^{-2} (BLD) to -5.27 Wm^{-2} (DLD) at TOA. The atmospheric forcing from BLD to DLD has been reduced from 22.41 Wm^{-2} to 19.61 Wm^{-2} , almost a 13% reduction. Interestingly, a negative trend was observed from BLD to DLD during the 2020 phases, whereas it is positive during the 2019 phases. The high surface forcing might be due to large scattering particles inhibiting the solar radiation reaching the earth's surface.

Table 3. SBDART input parameters and shortwave direct aerosol forcing for before and during lockdown phases.

			2019	2020	% change (2019 vs. 2020)	% change (BLD vs. DLD)	
						2019	2020
Aerosol Optical Depth		BLD	0.44	0.39	−12.41	13.09	−03.62
		DLD	0.50	0.37	−28.95		
Single Scattering Albedo		BLD	0.93	0.95	1.52	00.45	−01.60
		DLD	0.94	0.93	−0.53		
Total Columnar Ozone (DU)		BLD	247.77	265.00	6.72	08.51	02.78
		DLD	269.79	272.47	0.99		
Water Vapor (cm)		BLD	1.65	2.17	27.31	26.28	07.68
		DLD	2.15	2.35	8.73		
Composite aerosol Radiative forcing (W m ^{−2})	Surface	BLD	−31.66	−27.88	−12.71	08.25	−11.33
		DLD	−34.39	−24.89	−32.05		
	Atmosphere	BLD	26.71	22.41	−17.52	04.75	−13.31
		DLD	28.01	19.61	−35.26		
	Top of Atmosphere	BLD	−04.95	−05.47	09.92	25.18	−03.62
		DLD	−06.38	−05.27	−18.95		
eBC aerosol Radiative forcing (W m ^{−2})	Surface	BLD	−10.63	−08.58	−21.30	−21.11	−28.71
		DLD	−08.60	−06.43	−28.90		
	Atmosphere	BLD	14.45	11.19	−25.44	−21.94	−26.56
		DLD	11.59	08.56	−30.03		
	Top of Atmosphere	BLD	03.82	02.60	−37.83	−24.30	−19.73
		DLD	02.99	02.14	−33.35		
eBC contribution to total forcing (%)	Surface	BLD	33.58	30.79	08.65	29.23	17.52
		DLD	25.01	25.83	−03.22		
	Atmosphere	BLD	54.09	49.93	08.01	26.62	13.37
		DLD	41.39	43.67	−05.37		
	Top of Atmosphere	BLD	77.07	47.59	47.30	48.73	16.14
		DLD	46.87	40.48	14.63

Fig. 6. The shortwave direct aerosol radiative forcing due to composite (bar) and eBC (symbol and line) aerosols, the light green bar, and blue sphere line plot representing the 2020 phases and the cyan bar with patterns and red squares plot represents 2019 phases for comparison.

The SDARF is due to eBC represents the difference between the SDARF for aerosols with and without the eBC component. To estimate the forcing due to eBC alone, optical parameters for aerosols have been deduced again, keeping BC concentration equal to zero and constructed columnar AOD for the eBC-free atmosphere from OPAC. The surface forcing due to the eBC component is -08.58 Wm^{-2} during BLD and -06.43 Wm^{-2} during LD, which contributes almost 25–30% contribution to the composite aerosol forcing. The eBC forcing at TOA is 2.60 before LD and 2.14 during LD, with a 40–47% contribution to the composite forcing. Interestingly, the amount of energy trapped in the atmosphere due to eBC is 11.19 before LD and 8.56 during LD. i.e., eBC contributes almost 43–50% to the composite forcing. When compared the 2020 phases with the 2019 phases, the eBC contribution to the composite forcing in the 2020 phases is reduced to 60%, 50%, and 33% at SUR, ATM, and TOA concerning the 2019 phases. The positive forcing at the TOA arises due to the absorption by black carbon in the atmosphere, which also leads to a net cooling effect (negative forcing) at the surface. During LD, the composite atmospheric heating rate was significantly lower (0.55 K day^{-1}) than BLD (0.63 K day^{-1}), i.e., 13% reduction. On the other hand, the equivalent heating rate was slightly greater (0.79 K day^{-1}) than BLD (0.75 K day^{-1}), implying a 5% increase in the 2019 phases. Due to eBC over Anantapur, the atmosphere's overall heating rate is 0.31 K day^{-1} before LD and is reduced to 0.24 K day^{-1} during LD. During the lockdown phases, the heating rates due to composite aerosols decreased by 13%, whereas it is 25% due to eBC aerosols. It indicates that the restrictions on vehicular emission and anthropogenic activities during lockdown phases have significantly influenced the eBC aerosols concentrations rather than composite aerosols.

The magnitude of the aerosol radiative forcing depends not only on the aerosol composition but also on the column abundance. Consequently, it is a strong function of the AOD. The aerosol forcing efficiency is generally defined as the rate at which the atmosphere is “forced” per unit of aerosol optical depth, increasing as the AOD increases. To understand the impact of lockdown on forcing efficiency over Anantapur we also analyzed the aerosol forcing efficiency in different lockdown phases. Before LD, the net TOA and SUR forcing efficiency were about -14.18 and $-72.30 \text{ Wm}^{-2} \tau^{-1}$, respectively. For the DLD, the corresponding values were about -14.16 and $-66.89 \text{ Wm}^{-2} \tau^{-1}$, respectively.

4 CONCLUSIONS

The effect of unprecedented cessation of human activities during the COVID-19 pandemic was studied using in-situ based observations of eBC aerosols and their implications to short wave radiative properties from 01st March to 30th June 2020 over a semi-arid station in Southern India. The salient outcomes from the present investigation are as below:

1. The mean eBC mass concentration before and during LD was found to be $1.74 \mu\text{g m}^{-3}$, and $1.12 \mu\text{g m}^{-3}$, i.e., decreases by more than ~35% during LD than BLD due to the reduction of anthropogenic activities and meteorology.
2. Due to the restricted vehicular emission during the lockdown period, the contribution of fossil fuel burning to total eBC showed a distinct variation between BLD (81%) and DLD (64%).
3. A good correlation between observed and MERRA-2 BC concentrations is found with a correlation coefficient greater than 0.70.
4. During LD, the net forcing at the top of the atmosphere and the surface due to composite aerosols varied from -4.52 to -6.19 Wm^{-2} , and -22.91 to -29.35 Wm^{-2} , respectively, and net forcing in the atmosphere changes in the range 17.27 to 23.16 Wm^{-2} .
5. The contribution of eBC alone to the composite forcing within the atmosphere during LD (BLD) was found to be 43.64% (49.93%), respectively.
6. The restrictions on vehicular emission during the lockdown phases have significantly influenced the eBC rather than composite aerosols. The heating rate justifies this with a 13% reduction due to composite and a 25% reduction due to eBC aerosols.

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