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Assessment of the coronavirus disease 2019 (COVID-19) pandemic imposed lockdown and unlock effects on black carbon aerosol, its source apportionment, and aerosol radiative forcing over an urban city in India

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ABSTRACT

A nationwide lockdown was imposed in India due to the Coronavirus Disease 2019 (COVID-19) pandemic which significantly reduced the anthropogenic emissions. We examined the characteristics of equivalent black carbon (eBC) mass concentration and its source apportionment using a multiwavelength aethalometer over an urban site (Ahmedabad) in India during the pandemic induced lockdown period of year 2020. For the first time, we estimate the changes in BC, its contribution from fossil (eBC_f) and wood (eBC_wf) fuels during lockdown (LD) and unlock (UL) periods in 2020 with respect to 2017 to 2019 (normal period). The eBC mass concentration continuously decreased throughout lockdown periods (LD1 to LD4) due to enforced and stringent restrictions which substantially reduced the anthropogenic emissions. The eBC mass concentration increased gradually during unlock phases (UL1 to UL7) due to the phase wise relaxations after lockdown. During lockdown period eBC mass concentration decreased by 35%, whereas during the unlock period eBC decreased by 30% as compared to normal period. The eBC_f concentrations were higher by 40% during lockdown period than normal period due to significant increase in the biomass burning emissions from the several community kitchens which were operational in the city during the lockdown period. The average contributions of eBC_f and eBC_wf to total eBC mass concentrations were 70% and 30% respectively during lockdown (LD1 to LD4) period, whereas these values were 87% and 13% respectively during the normal period. The reductions in BC concentrations were commensurate with the reductions in emissions from transportation and industrial activities. The aerosol radiative forcing reduced significantly due to the reduction in anthropogenic emissions associated with COVID-19 pandemic induced lockdown leading to a cooling of the atmosphere. The findings in the present study on eBC obtained during the unprecedented COVID-19 induced lockdown can provide a comprehensive understanding of the BC sources and current emission control strategies, and thus can serve as baseline anthropogenic emissions scenario for future emission control strategies aimed to improve air quality and climate.

1. Introduction

Corona Virus Disease 2019 (COVID-19) is an infectious disease caused by the virus named Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV 2) (Lai et al., 2020). World Health Organisation (WHO) declared COVID-19 a pandemic due to its rapid spread and associated mortality (https://www.who.int/emergencies/diseases/novel-coronavirus-2019). COVID-19 proved to be most dangerous for the elderly and people with medical problems such as cardiovascular and chronic respiratory diseases (Pagani et al., 2020). The COVID-19 virus spreads through small respiratory droplets produced during coughing or sneezing. These droplets (larger than 10 μm) can travel for 7 to 8 m (Bourouiba, 2020) and will sediment nearby due to gravitational settling, pollute the environment, leading to the rise of direct and indirect transmission of the virus. The virus has a lifetime of up to three days. The droplets smaller than 10 μm can stay airborne in the atmosphere and is another easy mode of transmission of COVID-19 virus which can travel much further in the air (Bourouiba, 2020; Lindsley et al., 2014). In the human respiratory system the aerosols with an aerodynamic diameter less than 2.5 μm (PM2.5) can directly penetrate the alveoli (Feng et al., 2020). It has been reported that the size of the particle exhaled by COVID-19 patients during coughing, sneezing, or
Table 1
Details of lockdown and unlock phases in 2020 during COVID-19 pandemic over Ahmedabad.

| Lockdown and unlock phases | Period (day number) | Remarks |
|----------------------------|---------------------|---------|
| Lockdown 1.0 (LD1)         | 25 Mar–14 Apr (85–105) | • Educational institutions, industries, and hospitality services were suspended.  
• Transport services (road, rail, and air) were suspended, with exceptions of essential goods transport, fire, police, and emergency services  
• Only milk and medicine shops were permitted to remain open  
• All the places of worship were restricted for public  
• Night curfews were in effect from 7 p.m. to 7 a.m. |
| Lockdown 2.0 (LD2)         | 15 Apr–03 May (106–124) | • Lockdown restrictions continued  
• Night curfews were in effect from 7 p.m. to 7 a.m. |
| Lockdown 3.0 (LD3)         | 04–17 May (125–138) | • Normal movement in the non-containment zones  
• Central government offices were operational with 50% attendance  
• Night curfews were in effect from 7 p.m. to 7 a.m. |
| Lockdown 4.0 (LD4)         | 18–31 May (139–152) | • Lockdown restrictions in containment zones  
• Markets, shops, and offices to run in the non-containment zones  
• Night curfews were in effect from 7 p.m. to 7 a.m. |
| Unlock 1.0 (UL1)           | 01–30 Jun (153–182) | • Economic activities were permitted between 8 a.m. to 7 p.m. in non-containment zones  
• Transport and city buses were operational with 60% and 50% capacity respectively  
• Private buses, autorickshaws, and two wheelers permitted with restrictions  
• Night curfews were in effect from 9 p.m. to 5 a.m. |
| Unlock 2.0 (UL2)           | 01–31 Jul (183–213) | • Lockdown implemented in the containment zones  
• Cinema halls, gymnasiums, swimming pools, and entertainment parks were suspended  
• Night curfews were in effect from 10 p.m. to 7 a.m. |
| Unlock 3.0 (UL3)           | 01–31 Aug (214–244) | • Shops and establishments were operational till 8 p.m.  
• Hotels and restaurants operational until 10 p.m.  
• Night curfews removed |
| Unlock 4.0 (UL4)           | 01–30 Sep (245–274) | • Schools, colleges, and other educational institutions remain closed  
• Street vendors were allowed to resume business  
• Hospitality industry, hotels, and restaurants were operational till 11 p.m.  
• Autorickshaws, cabs, and private vehicles allowed with limited seating capacity |
| Unlock 5.0 (UL5)           | 01–31 Oct (275–305) | • Cinema halls and multiplexes were operational with 50% capacity  
• The government and private buses were permitted to operate with 75% capacity  
• Religious gatherings allowed with restrictions |
| Unlock 6.0 (UL6)           | 01–30 Nov (306–335) | • UL6.0 guidelines were in force |

Unlock phases:
- LD1: Lockdown 1.0 (31 Mar to 31 May, 2020)
- LD2: Lockdown 2.0 (1 May to 31 May, 2020)
- LD3: Lockdown 3.0 (1 June to 30 June, 2020)
- LD4: Lockdown 4.0 (30 June to 30 August, 2020)
- UL1: Unlock 1.0 (1 June to 30 August, 2020)
- UL2: Unlock 2.0 (30 August to 30 September, 2020)
- UL3: Unlock 3.0 (30 September to 30 November, 2020)
- UL4: Unlock 4.0 (30 November to 31 December, 2020)
- UL5: Unlock 5.0 (1 January to 31 March, 2021)
- UL6: Unlock 6.0 (1 April to 30 April, 2021)
- UL7: Unlock 7.0 (1 May to 31 May, 2021)

Remark: The lockdown restrictions were announced by the state government of Gujarat, India, and each phase lasted for 14 days. The first lockdown phase started on 25 March 2020 and lasted for 14 days, followed by subsequent phases with varying restrictions until 31 March 2021.

breathing ranged from < 0.25 μm to about 10 μm (Santarpia et al., 2020). Hence, the recommended way to contain the spread of COVID-19 virus is physical and social distancing, wearing multi-layered face mask, hand sanitising (with soap or alcohol based sanitizer liquid), and lockdown. Globally, as of 06 October 2021, there have been 235,673,032 confirmed cases of COVID-19, including 4.8 million deaths (https://covid19.who.int/).

As a containment strategy many countries all over the world imposed lockdown after the middle of March 2020, which led to a decline of anthropogenic emissions to a large extent. Although the COVID-19 pandemic has significantly affected the human life (social and economic conditions), but its containment strategy significantly improved the air quality throughout the globe (because of the decrease in anthropogenic emissions) (Baldasano, 2020; Bashir et al., 2020; Chauhan and Singh, 2020; Chen et al., 2020b,a; Dantas et al., 2020; He et al., 2020; Kalluri et al., 2021; Kumar et al., 2020; Li et al., 2020; Mahato et al., 2020; Navinaya et al., 2020; Sharma et al., 2020).

Several studies reported reduction in particulate matter (PM2.5) during the lockdown period over Beijing (50%), Chennai (19–43%), Delhi (35%), Dubai (11%), Europe (14%), Hyderabad (26–54%), Kolkata (24–36%), Los Angeles (4%), Mumbai (14%), New York (32%), Shanghai (50%), United States of America (10%), and Wuhan (42%) (Chauhan and Singh, 2020; Hammer et al., 2021; Kumar et al., 2020; Sircar et al., 2020). The Government of India implemented a nationwide lockdown from March 25 to May 31, 2020 in four phases (Table 1) as a result of which industries, commercial establishments, government and private establishments, academic institutes, shopping malls, cinema halls, public parks, sports complex, public transport (road, rail and air) were shut down. The lockdown phase 1.0 (LD1), phase 2.0 (LD2), phase 3.0 (LD3), and phase 4.0 (LD4) were for 21 days (March 25 to April 14, 2020), 19 days (April 15 to May 3, 2020), 14 days (May 4 to May 17, 2020), and 14 days (May 15 to May 31, 2020), respectively (Table 1). LD1 was the strictest epidemic control phase, followed by gradual relaxation in LD2, LD3 and LD4 phases (Table 1). The unlock phases are the economic restoration stages after the stringent lockdown phases. The Google community mobility data (based on Google Maps) provides insights into the human movement and residential activities and their impact throughout the pandemic period with reference to baseline days (i.e. before the pandemic outbreak)(Hannah et al., 2020). The Google community mobility data of transit station (a tracer for fossil fuel combustion) and residential (a tracer for biomass burning) exhibit significant decrease in vehicular emissions and increase in biomass burning exclusively during 2020 lockdown period, respectively over the study location Ahmedabad (Figs. 1 and 2).

Studies have reported a significant decrease in anthropogenic activities (vehicular movement, industrial and other commercial activities, construction work, etc.) across the country during the lockdown period (Chauhan and Singh, 2020; Dhaka et al., 2020; Goel et al., 2021; Mahato et al., 2020). After fourth phase of lockdown the Government of India announced systematic relaxation in the lockdown restrictions (unlock phase 1 (UL1): 01 to 30 June, UL2: 01 to 31 July, UL3: 01 to 31 August, UL4: 01 to 30 September, UL5: 01 to 31 October, UL6: 01 to 30 November, and UL7: 01 to 31 December) in order to restart the economy (Table 1). The lockdown and systematic unlock phases provided an opportunity to investigate the effect on temporal variation of black
carbon aerosol, and its potential sources over an urban and industrialised location in western India.

Black Carbon (BC) aerosol strongly absorbs solar and terrestrial radiation over a wide spectral regime and causes positive radiative forcing resulting in atmospheric warming (Jacobson, 2001). The major sources of BC in the atmosphere are from (1) on-road and off-road (fossil fuel) engines; (2) residential biomass fuels; (3) industrial fossil fuel and biomass combustion; and (4) open burning of biomass (Chen et al., 2017). The atmospheric lifetime of BC is around a week in the lower troposphere (Ramanathan and Carmichael, 2008) however, BC exhibits significant spatial and temporal variability in its sources and emissions (Rajesh and Ramachandran, 2018; Kalluri et al., 2020). BC aerosol affects the visibility, air quality, human health causing respiratory and lung diseases (Mauderly and Chow, 2008), crop yields (Chameides et al., 1999), terrestrial and aquatic ecosystem (Forbes et al., 2006), monsoon (Wang et al., 2009), and glaciers (Lau et al., 2006; Li et al., 2016). BC is one of the important contributors to global warming and is next only to carbon dioxide (CO$_2$) with a total climate forcing of 1.14 W m$^{-2}$ (0.17–2.10 W m$^{-2}$) (Bond et al., 2013). The large uncertainty in the radiative forcing of BC aerosol arises due to large temporal and spatial variabilities in BC sources and emissions (Bond et al., 2013), uncertainty in its size distribution, and its mixing state (IPCC, 2013). Hence, studies on BC aerosols attain significance because of their influence on climate change and human health.

A number of earlier studies have reported the changes in BC mass concentration at several locations in the world during the COVID-19 pandemic period. However, the source apportionment of BC has not been reported yet. In the present study, we have utilised a multiwavelength aethalometer instrument based on optical attenuation technique to measure light absorbing BC which is defined as equivalent black carbon (eBC) (Andreae and Gelencsér, 2006). Further, we have utilised the aethalometer model to derive the source apportionment of eBC.
The black carbon mass concentration measurements were conducted at Physical Research Laboratory (PRL), Ahmedabad (23.03°N, 72.55°E, 55 m above mean sea level) in western India (Fig. 1). Ahmedabad, is an urban, densely populated (population in excess of 7 million, https://censusindia.gov.in) and the largest city in the state of Gujarat. Ahmedabad is the economic and commercial hub of Gujarat. It is the second largest producer of cotton in India and is referred to as the Manchester of the East because it supports a large textile industry. The city has several small, medium, and large scale industries and has two thermal coal-fired power plants. The aerosol emissions over this urban and industrialised location is dominated by the dual influence of traffic and industrial activities (Ramachandran and Kedia, 2010). The meteorological parameters (temperature (°C), relative humidity (%), wind speed (m s⁻¹), and rainfall (mm)), were collected through a wireless meteorology station (Davis Vantage Pro2+, USA). The meteorology station is mounted above the roof of the PRL main building. At the outset, air temperature, relative humidity and wind speed exhibit similar pattern for the study phases during 2017–2019, and 2020 (Fig. 1b). The temperature increases from LD1 to LD4 during 2017–2019 and 2020, then gradually decreases afterward during unlock phases (Fig. 1b). The relative humidity (RH) increases from LD1 to UL3 and decreases thereafter. The maximum RH is found during UL3 (August) (80% (2017–2019) and 91% (2020)) (Fig. 1b). The maximum mean surface wind speed is found during UL1 (June) to UL4 (September) during the study period over Ahmedabad (Fig. 1b). The rainfall is typically distributed from UL1 (June) to UL4 (September) during the study period over Ahmedabad (Fig. 1b). This comparison confirms that the meteorology was more or less similar during 2017–2019 and 2020. Further, in order to examine the potential source regions and the transport pathways of pollutants over the study location, seven day air back trajectory analysis is conducted corresponding to an altitude of 500 m above ground level using the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model (version 4.9) (Draxler and Hess, 1998). The back trajectory analysis results show similar source regions and the transport pathways, and do not exhibit any significant variations during the years 2017 to 2020 over Ahmedabad (Fig. 3).

3. Measurements and methodology

3.1. Instrumentation

Aethalometer (AE31, Magee Scientific, USA) was used to measure the equivalent black carbon (eBC) mass concentration at seven wavelengths (0.37, 0.47, 0.52, 0.59, 0.66, 0.88 and 0.95 μm). In aethalometer the relation between black carbon mass loading and attenuation is linear for lower attenuation and it is non linear for higher attenuation values due to filter loading effect (Gundel et al., 1984). The black carbon mass concentration measurements need to be compensated for filter loading effect (Weingartner et al., 2003; Schmid et al., 2006; Collaud Coen et al., 2010). We have corrected the AE31 data using Schmid et al. (2006) (the details are discussed in Rajesh and Ramachandran (2020)). The uncertainty in eBC mass concentration which arises due to other instrumental artifacts such as filter spot area, flow rate, and detector response is estimated to be within 10%. The light absorption at 0.88 μm is considered to be mainly from BC aerosols as the absorption of other aerosols is not significant at this wavelength (Jing et al., 2019). The aerosol absorption coefficient (βabs) is estimated from the eBC mass concentration using the mass specific cross section given by the manufacturer (Rajesh and Ramachandran, 2020). A total of more than 0.3 million eBC data points at a temporal resolution of 5 minutes over Ahmedabad during 01 Mar 2017 to 31 December 2020 are utilised in the present study (Table 2). The data measured during local festivals (Holī, Navratri, Dussehra, Deepavali, and Gujarati new year) are not included in the study, as the magnitudes of eBC were quite high (2–4 times) during these festivals due to significant increase in the vehicular emissions (Ramachandran and Rajesh, 2007). We have investigated the anomaly (%) in eBC mass concentration and its potential sources for the COVID-19 pandemic imposed lockdown (LD) and unlock (UL) periods (2020) with respect to mean eBC values for the respective period from 2017 to 2019. The anomalies calculated as ((eBC in 2020 - mean eBC during 2017–2019)/mean eBC during 2017–2019) x 100 are expressed in % corresponding to different phases of LD and UL. The eBC mass concentration data corresponding to 2017 to 2019 is considered as the reference eBC values prevailing under normal conditions and this period now onwards will be referred to as normal period (meaning without any lockdown restrictions).
3.2. Source apportionment of black carbon

To apportion the sources of BC, the aethalometer model proposed by Sandradewi et al. (2008) is used to estimate the relative contribution from fossil fuel and wood fuel combustion to the total eBC mass concentrations. The eBC aerosol from fossil fuel combustion has higher absorption at 0.95 μm, whereas the eBC aerosol from wood fuel burning has higher absorption at 0.37 μm (Sandradewi et al., 2008). Optical properties of BC aerosols emitted from biomass burning are highly uncertain due to the uncertainty in combustion factors, burned areas, types of fuels, the flaming and smoldering phases of burning, as well as atmospheric conditions (Gyawali et al., 2009). The absorption Ångström exponent values for fossil and wood fuels have been documented to be in the range of 0.9–1.1, and 1.5–3.0 respectively (Kirchstetter et al., 2004; Day et al., 2006; Lewis et al., 2008; Sandradewi et al., 2008; Fuller et al., 2014). Equations relating absorption coefficient ($\beta_{\text{abs}}$), wavelengths, and absorption Ångström exponent ($\alpha$) for fossil fuel and wood fuel are given following Sandradewi et al. (2008) as

$$
\frac{\beta_{\text{abs}}(0.37 \, \mu m, ff)}{\beta_{\text{abs}}(0.95 \, \mu m, ff)} = \left[ \frac{0.37}{0.95} \right]^{-\alpha_{ff}}
$$

$$
\frac{\beta_{\text{abs}}(0.37 \, \mu m, wf)}{\beta_{\text{abs}}(0.95 \, \mu m, wf)} = \left[ \frac{0.37}{0.95} \right]^{-\alpha_{wf}}
$$

Fig. 3. Seven-day air back trajectory at 500 m above ground level during 2017–2019 compared with 2020 over Ahmedabad for (a) LD1 (25 March–14 April), (b) LD2 (15 April–03 May), (c) LD3 (04–17 May), (d) LD4 (18–31 May), (e) UL1 (01–30 June), (f) UL2 (01–31 July), (g) UL3 (01–31 August), (h) UL4 (01–30 September), (i) UL5 (01–31 October), (j) UL6 (01–30 November), and (k) UL7 (01–31 December). The vertical bars (2017–2019) represent ±1σ from the mean.
corresponding to years 2020, 2019, 2018, and 2017 respectively. LD refers to lockdown and UL corresponds to unlock conditions. A total of 260, 268, 229, and 266 days of eBC mass concentrations data were used in the present work during the period 01 March 2017 to 31 December 2020. A study we have used the Santa Barbara DISORT (DIScrete Ordinates Radiative Transfer) model in the wavelength range of 0.2 to 4.0 µm (Ricchiazzi et al., 1998). The spectral (0.2–4.0 µm) aerosol optical properties (aerosol optical depth (AOD), single scattering albedo (SSA), and asymmetry parameter (ASY)) as a function of relative humidity are computed using Optical Properties of Aerosols and Clouds (OPAC) model (Hess et al., 1998) which serves as an input to SBDART model. In OPAC model the number concentration of aerosol components is iteratively changed to meet the following criteria: (i) the root mean square difference between the OPAC computed AOD and MODerate resolution Imaging Spectroradiometer (MODIS) retrieved AOD (in the wavelength range of 0.4–1.0 µm) is < 0.03, (ii) OPAC soot mass concentration is same as the measured eBC mass concentration, and (iii) OPAC estimated SSA agrees within ±1% of Ozone Monitoring Instrument (OMI) derived SSA (Ramachandran and Kedia, 2010). The OPAC estimated ASY values for urban aerosols are utilised in the estimation of ARF as was done earlier (Ramachandran et al., 2012). It may be noted that measured black carbon mass concentration is given as inputs to OPAC model to constrain the OMI SSA. ARF is computed using 8 radiative streams at an interval of 1 h, and 24 h averages are obtained for each phase given in Table 1. The ARF at the top of the atmosphere (T) and surface (S) is defined as the change in the net (down-up) flux with and without aerosols as

\[
ARF_T = \text{Flux(net) (aerosol) }_T - \text{Flux(net) (no aerosol) }_T
\]

\[
ARF_S = \text{Flux(net) (aerosol) }_S - \text{Flux(net) (no aerosol) }_S
\]

The energy trapped within the Earth’s atmosphere due to atmospheric aerosols is denoted as atmospheric forcing (ARFₐ), which is derived as the difference between the ARF at the top of the atmosphere (100 km) and the surface. A positive ARFₐ represents a net gain of radiative flux in the atmosphere leading to a warming of the Earth-atmosphere system, while a negative ARFₐ indicates a net loss and thereby cooling. The absorbed energy in the atmosphere is converted into heat and termed as the atmospheric solar heating rate (dT/dt, K d⁻¹) induced due to aerosols which is calculated as

\[
\frac{dT}{dt} = g \frac{ARF}{C_p \Delta P}
\]

where \( g \) is the specific heat capacity of air at constant pressure, \( g \) is the acceleration due to gravity, and \( \Delta P \) is the pressure difference (300 hPa, corresponds to ~3 km) (Liou, 1980). Typically, most of the atmospheric aerosols are concentrated near Earth’s surface to up to 3 km (Ramachandran and Kedia, 2010). The ARF during unlock phases UL1 to UL4 varied from 1.87 to 2.0 the contribution of eBCff to total eBC decreased by 14% (Rajesh et al., 2021).}

| Period       | Phases | 2020 | 2019 | 2018 | 2017 |
|--------------|--------|------|------|------|------|
| 25 Mar–14 Apr| LD1    | 21   | 21   | 21   | 21   |
| 15 Apr–03 May| LD2    | 19   | 19   | 19   | 19   |
| 04–17 May    | LD3    | 14   | 14   | 14   | 14   |
| 18–31 May    | LD4    | 14   | 14   | 14   | 14   |
| 01–30 Jun    | UL1    | 30   | 29   | 28   |      |
| 01–31 Jul    | UL2    | 31   | 31   | 31   |      |
| 01–31 Aug    | UL3    | 31   | 30   | 30   |      |
| 01–30 Sep    | UL4    | 30   | 28   | 30   |      |
| 01–30 Oct    | UL5    | 16   | 21   | 21   | 27   |
| 01–30 Nov    | UL6    | 25   | 30   | 28   | 30   |
| 01–31 Dec    | UL7    | 29   | 30   | 24   | 31   |
| Total        | 260    | 268  | 229  | 266  |

T.A. Rajesh and S. Ramachandran Table 2 Number of days of eBC mass concentration measurements over Ahmedabad during the period 01 March 2017 to 31 December 2020. A total of 260, 268, 229, and 266 days of eBC mass concentrations data were used in the present work corresponding to years 2020, 2019, 2018, and 2017 respectively. LD refers to lockdown and UL corresponds to unlock conditions. where \( \alpha_{ff} \) and \( \alpha_{wf} \) are absorption Ångström exponents corresponding to fossil and wood fuels respectively, eBCff can be calculated using the above equations as

\[
eBC_{ff} = eBC \cdot \left( \frac{\rho_{albedo(0.95 \mu m, ff)}}{\rho_{albedo(0.95 \mu m)}} \right)
\]

\[
eBC_{wf} = eBC \cdot \left( \frac{\rho_{albedo(0.95 \mu m, wf)}}{\rho_{albedo(0.95 \mu m)}} \right)
\]

The contributions from wood fuel (eBCwf) is the difference between the total eBC and eBCff mass concentrations. In the present study the mean \( \alpha_{wf} \) value obtained from the burning experiments conducted earlier with different types of wood fuels used in the study region (details regarding the burning experiments and results obtained are given in Rajesh et al., 2021) is used. Based on those findings, in the present study we have used \( \alpha_{wf} \) as 1.0 and \( \alpha_{ff} \) value of 1.87 appropriate to the study location Ahmedabad (Rajesh et al., 2021), whereas the commonly used \( \alpha_{ff} \) value is 2.0. We have reported that when \( \alpha_{ff} \) varied from 1.87 to 2.0 the contribution of eBCff to total eBC decreased by 14% (Rajesh et al., 2021).
could not be estimated as MODIS AOD and OMI SSA were found to be contaminated due to cloudy/overcast conditions, and further they were available only for a very limited (few days) during the above said phases.

4. Results and discussion

4.1. eBC mass concentration

At the outset, eBC mass concentrations during COVID-19 pandemic lockdown phases are significantly lower than that of the 3 year mean 2017–2019 eBC data (normal period) (Fig. 4). The bimodal distribution of the eBC mass concentration is observed during the lockdown and unlock periods, with the morning peak between 7 and 9 h and the evening peak during 20 to 21 h (Fig. 5). The morning (first) peak occurs due to the increase in anthropogenic activities, and atmospheric boundary layer dynamics (Rajesh and Ramachandran, 2017). The evening (second) peak arises owing to decreasing atmospheric boundary layer height and increasing road traffic (Rajesh and Ramachandran, 2017). The minimum eBC concentrations also exhibit two troughs - in afternoon (15 to 16 h) due to strong convection which pushes atmospheric boundary layer to the maximum height and due to low traffic density, and early morning (3 to 4 h) due to minimal anthropogenic activities and removal of BC aerosols from the atmosphere by gravitational settling (Fig. 5) (Rajesh and Ramachandran, 2017). During LD1, LD2, LD3, and LD4 phases, the morning and evening peak eBC concentration decreases due to the lower vehicular emissions when compared to normal period (2017–2019). In the UL1 phase the diurnal distribution of eBC mass concentration is similar to normal period due to relaxation in lockdown restrictions after approximately 2 months (Table 1). The relaxation in UL1 phase includes permission to conduct economic activities between 8 to 19 h, and ply public transport (city buses) with 50 % capacity, private vehicles, autorickshaws, and two wheelers with restrictions (Table 1). During UL2 to UL7 phases the eBC is lower than the normal period (Fig. 5) due to the imposition of various restrictions and night curfews (Table 1) which reduces the anthropogenic emissions over Ahmedabad (Rajesh et al., 2021).

The average eBC concentrations during LD1, LD2, LD3, and LD4 were 3.1, 2.3, 1.9, and 1.6 μg m⁻³ respectively. The eBC mass concentrations were 40%, 40%, 29%, and 33% lower than normal period (Fig. 6) due to the enforced lockdown restrictions which substantially reduced the anthropogenic emissions. During the lockdown period the maximum (3.1 μg m⁻³) eBC is found during LD1, then eBC decreases gradually with minimum (1.6 μg m⁻³) in LD4 due to increase in atmospheric boundary layer height and higher wind speed (Fig. 1). An increasing trend in the eBC concentration from UL1 to UL7 was due to the phase wise relaxations after COVID-19 pandemic induced lockdown (Table 1). During the unlock phases of UL5, UL6, and UL7, eBC concentrations were found to be 39%, 53%, and 38% lower than the respective normal
period (Fig. 6) due to the post lockdown restrictions and imposed night curfews (Table 1). The maximum concentration was observed during UL5, whereas minimum concentration was observed during LD4. On an average, due to COVID-19 pandemic imposed lockdown period (LD1 to LD4) the eBC mass concentration decreased by 35%, whereas during the unlock period (UL1 to UL7) it decreased by 30% as compared to normal period over the study location. During lockdown (LD1 to LD4) and unlock (UL1 to UL7) periods, the mean eBC mass concentrations are estimated to be 2.2±0.7 μg m⁻³ (3.5±1.3 μg m⁻³ for normal period) and 4.3±2.3 μg m⁻³ (6.9±4.7 μg m⁻³ for normal period) respectively over Ahmedabad.

4.2. eBCff and eBCwf mass concentrations

During the pandemic period eBCff concentrations decrease from LD1 to LD4 then increase afterward over Ahmedabad (Fig. 6). The eBCff mass concentrations are lower by 56% (LD1), 50% (LD2), 42% (LD3), and 42% (LD4) than normal period (Fig. 6) due to COVID-19 pandemic imposed restrictions. eBCff concentrations decrease from LD1 to UL3, and increase rapidly from UL4 to UL7 (Fig. 6). It is interesting to note that eBCff concentrations are higher than normal period by 52%, 17%, 81%, 70%, 53%, and 117% during LD1, LD2, LD3, LD4, UL1, and UL2 respectively (Fig. 7) due to significant increase in the biomass burning from the several community kitchens that were operational in the city (https://ashaval.com/coronavirus-ngo-ahmedabad-0521919/). Various non government organisations (NGOs) and communities in Ahmedabad (Janvikas, Akshaya Patra Foundation, Yuva Unstoppable, Elixir Foundation, Jana Gana Mana Yana, Gurudwaras, Karnavati Tamil Sangam, Gujarat Rajasthan Maitri Sangh, etc.) came forward to feed the stranded labourers, daily wagers, migrants and homeless underprivileged people by operating several community kitchens in the city (https://ashaval.com/coronavirus-ngo-ahmedabad-0521919/). The community kitchens were using wood fuel exclusively for cooking, thereby, leading to a large increase in wood fuel emissions of BC.

The contribution of eBCff in total eBC dominates throughout lockdown and unlock phases and is maximum during UL3 (96%) and minimum during LD1 (63%), while the contribution of eBCwf is maximum during LD1 (37%) and minimum during UL3 (4%) over Ahmedabad (Fig. 8). Highest eBCff contribution to the total eBC occurs during UL1 to UL4 (monsoon) as fossil fuel combustion processes dominate the BC emissions, while highest eBCwf contribution is observed during lockdown period (LD1 to LD4) due to significant increase in the wood burning. The increase in the contribution of eBCwf is attributed to the operation of several community kitchens which used wood fuel for cooking, whereas the corresponding decrease in eBCff occurs due to the decrease in emissions from transport, industry, and other anthropogenic activities which primarily use fossil fuel.

The eBCwf concentrations increase by 55% during lockdown period in 2020 when compared to normal period over Ahmedabad. During the lockdown period (LD1 to LD4) the eBCwf mass concentration decreases by 45%, whereas during the unlock period (UL1 to UL7) eBC mass concentration decreases by 25% as compared to normal period which is correlated well with the Google transit station data (Fig. 2). During lockdown (LD1 to LD4) period, the mean eBCff and eBCwf mass concentrations are 1.5±0.3 μg m⁻³ (3.0±1.0 μg m⁻³ for normal period) and 0.7±0.4 μg m⁻³ (0.5±0.3 μg m⁻³ for normal period) respectively, whereas during unlock (UL1 to UL7) period the values are 3.5±1.7 μg m⁻³ (5.9±3.7 μg m⁻³ for normal period) and 0.7±0.5 μg m⁻³ (1.0±0.8 μg m⁻³ for normal period) respectively, over Ahmedabad. The mean contributions of eBCff and eBCwf to total eBC mass concentrations are found to be 70% and 30% respectively during lockdown (LD1 to LD4) period, whereas these values are 87% and 13% respectively during the normal period. The mean contributions of eBCff and eBCwf during the unlock

Fig. 6. Daily averaged variation of eBCff and eBCwf mass concentration over Ahmedabad during the study phases (LD1, LD2, LD3, LD4, UL1, UL2, UL3, UL4, UL5, UL6, and UL7) of 2017–2019 and 2020.
periods (UL1 to UL7) of 2020 are not distinctly different than the normal period - eBC$_{ff}$ and eBC$_{wf}$ are 83% and 17% respectively in 2020 as compared to 86% and 14% during the normal period. In summary, the study reveals similar contribution from fossil fuel and wood fuel component of eBC mass concentration during the unlock periods (2017–2020), whereas significant temporal variability in eBC$_{wf}$ in total eBC mass concentrations during lockdown period (2020) as compared to the normal period (2017–2019) due to the dominant usage of wood fuel in the various community kitchens operated in the city.

4.3. Day-night variation of eBC, eBC$_{ff}$, and eBC$_{wf}$ mass concentrations

We investigated the characteristic behavior of eBC aerosols and its contribution from fossil fuel (eBC$_{ff}$) and wood fuel (eBC$_{wf}$) during the day time and night time period. The day and night time variation in eBC mass concentrations is governed by the diurnal variation in atmospheric dynamics and anthropogenic emissions. The eBC mass concentration measured between sunrise and sunset time is termed day time eBC, and eBC mass obtained in the remaining time period is referred to as night time eBC. In Ahmedabad, night time eBC is higher than day time eBC (Rajesh and Ramachandran, 2017). The percentage contribution of day time eBC is higher during UL1 and UL2 as the length of day (time interval between sunrise and sunset) is longer which increases the time scale of anthropogenic emissions. The percentage contribution of day and night time eBC mass concentration is similar to those observed during pandemic year and normal period (Fig. 9).

The percentage contribution of night time fossil fuel component of black carbon (eBC$_{ff}$) mass concentration during lockdown period is lower than the normal period (Fig. 9) due to the imposed night curfews (Table 1). On the contrary, the night time eBC$_{wf}$ concentrations are higher during lockdown period due to the operation of several community kitchens in the city which were cooking lunch and dinner on a massive scale. During lockdown period, night time eBC, eBC$_{ff}$, and eBC$_{wf}$ concentrations are higher by about a factor of 1.5, 1.6, and 1.3 (1.6, 1.8, and 0.9 for normal period) respectively than day time due to shallow atmospheric boundary layer during night time resulting in trapping of pollutants in a lesser volume which leads to higher eBC mass concentration. The night time percentage contribution of eBC$_{ff}$ and eBC$_{wf}$ dominates during the study period except during UL1 and UL2 over Ahmedabad due to the longer days resulting in more anthropogenic activity (Fig. 9). During lockdown period, the mean percentage contributions of day and night time eBC$_{ff}$ are 28% and 43% (31% and 56% for
normal period) respectively, whereas day and night time \(eBC_{ff}\) contributions are 13% and 16% (7% and 6% for normal period) over Ahmedabad. It may be noted that the sum of day and night time \(eBC_{ff}\) and \(eBC_{wf}\) contribution is 100% (Fig. 9). The \(eBC_{ff}\) contribution reduces by 10% and 30% during day and night time respectively, whereas the contribution from \(eBC_{wf}\) increases by a factor of 2 and 3 during day and night time respectively during lockdown period when compared to normal period (Fig. 9). The increase in \(eBC_{wf}\) concentration during lockdown can only be attributed to the increase in the wood fuel emissions and reduction in fossil fuel emissions.

4.4. Aerosol radiative forcing and heating rate

Surface and top of the atmosphere aerosol radiative forcing are correlated with the observed AOD and SSA respectively (Fig. 10). Higher AOD results in higher surface cooling (Fig. 11). Top of the atmosphere forcing is negative during the study phases (LD1, LD2, LD3, LD4, UL1, UL2, UL3, UL4, UL5, UL6, and UL7) in 2017–2019 and 2020 over Ahmedabad (Fig. 11). The decrease in anthropogenic atmospheric aerosol loading has led to a significant reductions (-30%) in aerosol radiative forcing and atmospheric heating rate during the COVID-19 pandemic period over Ahmedabad. The 20% and 25% reduction in the surface and atmospheric forcing due to aerosols matches well with the 20% reduction in AOD during the pandemic period 2020 when compared to 2017–2019 (normal period). The minimum heating rate occurs during LD1 in 2017-2019 and 2020 (Fig. 11). The decrease in anthropogenic atmospheric aerosol loading has led to a significant reductions (-30%) in aerosol radiative forcing and atmospheric heating rate during the COVID-19 pandemic period over Ahmedabad. The 20% and 25% reduction in the surface and atmospheric forcing due to aerosols matches well with the 20% reduction in AOD during the pandemic period 2020 when compared to 2017–2019 (normal period). Thomas et al. (2021) also reported 20–25% reduction in ARF over the Indo Gangetic Plain outflow region of the Bay of Bengal during the lockdown period. The atmospheric forcing and heating rate reduced by 20% and 15% over Kanpur and Gandhi College respectively.
during the lockdown period LD1 as compared to 2019 (Sarla et al., 2021). Thus, it is clear that the reduction in anthropogenic emissions due to COVID-19 pandemic induced lockdown resulted in a cooling of the atmosphere as the aerosol induced atmospheric heating rate was lower.

4.5. Comparison with other results

The black carbon concentrations measured over Ahmedabad are compared with the BC data observed over different locations in India and world during the COVID-19 lockdown period (Table 3). The mean eBC during lockdown period over Ahmedabad is lower than eBC values measured over urban sites of India (Agra, Bengaluru, Delhi, Gorakhpur, Jamshedpur), and higher than other urban measurement sites in the world (Dammam, Hangzhou, Massachusetts, Milan, Suzhou) (Table 3). The measured eBC mass concentration over coastal continental sites (Goa, Thiruvananthapuram), rural site (Anantapur), and urban (Bhubaneshwar) are lower than Ahmedabad (Table 3). The black carbon mass concentration reduced significantly between before and during lockdown by > 40% over Bhubaneshwar, Chongqing, Hangzhou, Milan, and Suzhou (Table 3). Ahmedabad also recorded 35% reduction in the black carbon concentration during lockdown period when compared to normal period (2017–2019). Thus, on an average the eBC mass concentrations have reduced by more than 35% across the globe.

5. Summary and conclusions

This study comprehensively assessed the black carbon mass concentration, its source apportionment, and radiative implications during the COVID-19 pandemic imposed lockdown (LD) and unlock (UL) periods over an urban location (Ahmedabad) in India. We investigated the change in the above aerosol characteristics measured during lockdown and unlock periods with respect to the respective data corresponding to 2017 to 2019 (normal period). The major findings and results obtained from study are summarized as follows:

- The eBC mass concentration continuously decreased throughout lockdown periods (LD1 to LD4) due to the enforced lockdown restrictions which substantially reduced the anthropogenic emissions. eBC increased during unlock phases (UL1 to UL7) due to the phase wise relaxations after COVID-19 pandemic induced lockdown. The eBC mass concentrations were 40% (LD1), 40% (LD2), 29% (LD3), and 33% (LD4) lower than normal period due to the enforced lockdown restrictions. During lockdown period (LD1 to LD4) the eBC mass concentration decreased by 35%, whereas during the unlock period (UL1 to UL7) eBC decreased by 30% as compared to normal period (2017–2019).
- During lockdown (LD1 to LD4) and unlock (UL1 to UL7) periods, the mean eBC mass concentrations were 2.2±0.7 μg m⁻³ (3.5±1.3 μg m⁻³ for normal period) and 4.3±2.3 μg m⁻³ (6.9±4.7 μg m⁻³ for normal period) respectively over Ahmedabad.
- The mean contributions of eBC eff and eBC wf to total eBC mass concentrations were 70% and 30% respectively during lockdown (LD1 to LD4) period, whereas these values were 87% and 13% respectively during the normal period. During unlock (UL1 to UL7) period, the mean contributions of eBC eff and eBC wf were estimated to be 83% and 17% (86% and 14% during normal period) respectively.
- Night time average eBC values were always higher than day time BC values as the atmospheric boundary layer was shallow during night time resulting in trapping of pollutants in a lesser volume. The eBC eff contribution reduces by 10% and 30% during day and night time respectively, whereas the contribution from eBC wf increases by a factor of 2 and 3 during day and night time respectively during lockdown period when compared to normal period, thereby, confirming the increase in wood fuel emissions during lockdown.

![Variation of mean (a) aerosol optical depth and (b) single scattering albedo over Ahmedabad during the study phases (LD1, LD2, LD3, LD4, UL5, UL6, and UL7) of 2017–2019 and 2020. The vertical bars represent ±1σ variation from the mean values. The relative change is given in percentage (%), where negative and positive values show decrease and increase respectively in 2020 with respect to 2017–2019 mean.](image-url)
Fig. 11. Variation of aerosol radiative forcing at the (a) top of the atmosphere, (b) surface, (c) atmosphere, and (d) atmospheric heating rate over Ahmedabad during the study phases (LD1, LD2, LD3, LD4, UL5, UL6, and UL7) of 2017–2019 and 2020. The aerosol radiative forcing could not be performed during UL1 to UL4 phases (refer text for details (Section 3.3)). The relative change is given in percentage (%), where negative value shows a decrease in 2020 with respect to 2017–2019 mean.
Black carbon mass concentration levels and relative changes over different locations in India and world during COVID-19 lockdown period. The change in percentage (%) is negative indicative of a decrease in black carbon mass concentration during lockdown period with reference to normal/pre-lockdown period.

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Table 3

| Location              | Lockdown period | BC concentration (μg m⁻³) | Change (%) | References              |
|-----------------------|-----------------|---------------------------|------------|-------------------------|
| Ahmedabad             | 25 March–31 May | 2.2–0.7                   | 35         | Present study           |
| Agartala              | 25 March–31 May | 4.47                      | 45         | Gogoi et al. (2021)     |
| Agra                  | 25 March–31 May | 4.02                      | 40         | Gogoi et al. (2021)     |
| Anantapur             | 25 March–3 May  | 1.30±0.09                 | 13         | Kalluri et al. (2021)   |
| Bengaluru             | 25 March–31 May | 2.49                      | 52         | Gogoi et al. (2021)     |
| Bhubaneswar           | 22 March–1 June | 0.96                      | 47         | Panda et al. (2021)     |
| Delhi                 | 25 March–31 May | 2.8±0.9                   | 64         | Goel et al. (2021)      |
| Goa                   | 22 March–20 April | 1.1±0.2                   | 42         | Shalik et al. (2021)    |
| Gorakhpur             | 25 March–31 May | 6.83                      | 68         | Gogoi et al. (2021)     |
| Hyderabad             | 25 March–31 May | 0.83                      | 10         | Gogoi et al. (2021)     |
| Jamshedpur            | 25 March–31 May | 2.7±0.9                   | 71         | Ambade et al. (2021)    |
| Thiruvananthapuram    | 25 March–31 May | 1.47                      | 19         | Gogoi et al. (2021)     |

The surface and atmosphere forcing reduced by 20% and 25% respectively during the pandemic period 2020 as compared to 2017–2019. The reduction in anthropogenic emissions due to COVID-19 pandemic induced lockdown resulted in a cooling of the atmosphere as the aerosol induced atmospheric heating rate was lower.

The current study experimentally illustrates the role of atmospheric aerosol during a pandemic and normal period thereby enabling us to understand its importance and its radiative impact. The result indicates that although industrial and vehicular emissions reduced significantly during lockdown due to stringent restrictions, however, the contribution from residential emissions (biomass burning) is found to be significant. These results on eBC mass concentrations due to the unprecedented COVID-19 lockdown provides us comprehensive insights into the BC sources and current emission control strategies, thereby, revealing the changes in pollutant emissions during COVID-19 lockdown, which are important for future emission control strategies aimed to improve human health, environment, and climate.

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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