Response of ambient BC concentration across the Indian region to the nation-wide lockdown: results from the ARFINET measurements of ISRO-GBP

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In this study, we assess the response of ambient aerosol black carbon (BC) mass concentrations and spectral absorption properties across Indian mainland during the nation-wide lockdown (LD) in connection with the Coronavirus Disease 19 (COVID-19) pandemic. The LD had brought national cut-off of emissions from industrial, traffic (road, railways, marine and air) and energy sectors, though the domestic emissions remained fair unaltered. This provided a unique opportunity to delineate the impact of fossil fuel combustion sources on atmospheric BC characteristics. In this context, the primary data of BC measured at the national network of aerosol observatories (ARFINET) under ISRO-GBP are examined to assess the response to the seizure of emissions over distinct geographic parts of the country. Results indicate that average BC concentrations over the Indian mainland are curbed down significantly (10–40%) from pre-lockdown observations during the first and most intense phase of lockdown. This decline is significant with respect to the long-term (2015–2019) averaged (climatological mean) values. The drop in BC is most pronounced over the Indo-Gangetic Plain (>60%) and north-eastern India (>30%) during the second phase of lockdown, while significant reduction is seen during LD1 (16–60%) over central and peninsular Indian as well as Himalayan and sub-Himalayan regions. Despite such a large reduction, the absolute magnitude of BC remained higher over the IGP and north-eastern sites compared to other parts of India. Notably, the spectral absorption index of aerosols changed very little over most of the locations, indicating the still persisting contribution of fossil-fuel emissions over most of the locations.

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Introduction

It is well accepted that the short-lived climate forcing agents, such as atmospheric aerosols, cause significant regional and global climatic impact, in which the role of carbonaceous aerosols (through their impact on radiation, cloud and cryosphere) is unique due to a variety of reasons. The short atmospheric lifetime (5–10 days in the lower atmosphere) of these species makes it more challenging to model their spatio-temporal distributions and direct and indirect impact on climate accurately. Another challenge is to delineate the exact sources responsible for severe degradation of the environment and air quality in the real atmosphere due to entwined source and life cycle processes. Over the Indian region, the role of both biomass burning (arising mostly for domestic purposes such as the burning of wood, dung, rice straw, and other such material by the economically weaker sections of the society and seasonal forest fires and stubble burning), as well as extensive fossil fuel burning emissions (from industrial, energy and transport sectors) have competing region-specific impacts. However, experimental delineation of this remains elusive due to the co-existence of the ever-prevailing nature of these multiple sources, making it difficult to delineate the individual contributions to the total BC.

The nationwide lockdown (LD) imposed in India (along with several other countries) in connection with the COVID-19 pandemic resulted near to complete restriction of road, rail, marine and air traffic for nearly 6 weeks duration, in addition to shutting down of most of the industries, commercial and business establishments, malls, cinema halls, educational institutions and government and private establishments with a consequent large reduction in power generation. The most intense phase of the lockdown was from 25 March to 14 April (LD1), followed by gradual relaxation in phases; LD2 until 3 May, LD3 until 17 May and LD4 until 31 May. While several restrictions got removed from LD3 onwards, some of the restrictions are still in place like restrictions on international air travel, full restoration of rail services, the opening of educational institutions, cinema halls, etc. This lockdown, especially LD1 and LD2, being longer than the typical atmospheric lifetimes of aerosols, provided a unique opportunity to examine the impact on their ambient concentrations and how it got recharged in the phased relaxation of the restriction on traffic and industries in the later phases of LD and unlock.

In this paper, we present the results of the above on black carbon (BC) mass concentrations and absorption characteristics across Indian landmass, based on long-term primary data from the Aerosol Radiative Forcing over India Network (ARFINET) of aerosol observatories and the implications are discussed.

Data and methodology

Observational sites and database

Regular BC measurements from 19 observatories, where continuous data are available, have been used for this study. These stations are spread across India, as shown in Figure 1, and represent the regions of the Himalayas and sub-Himalayas, Indo-Gangetic Plain (IGP), eastern, central and peninsular India as delineated in Table 1.

Continuous measurements of BC mass concentrations are made at each of the stations using multi-wavelength Aethalometers (Model: AE-33, AE-31, AE-42; Magee Scientific, USA), which have been periodically inter-compared for their consistency. The instruments work on the principle of filter-based optical attenuation technique. To ensure consistency of BC measurements by different models of Aethalometers, we have adopted the technique reported by Gogoi et al., where the data from legacy instruments (AE-31 and AE-42) are compensated for loading effect and then inter-compared with AE-33 (reference) system. More details about the experimental techniques and correction schemes are found elsewhere. For the sites which are located at higher altitudes having reduced ambient pressures, the measured BC values were corrected further for obtaining true BC mass concentration ($M_{BC}$) following the procedure adopted by Moorthy et al.:

$$M_{BC} = M_{BC}^* \frac{P_0 T_0}{P T}$$

where $M_{BC}^*$ is the instrument measured raw BC mass concentration at ambient conditions and $P_0$ and $P$ are the standard and ambient pressure, and $T_0$ and $T$ are the corresponding temperatures.

Figure 1. Geographic positions of the ARFINET stations over India, the primary BC data from which are used in the present study. The colour scale indicates the altitude of the stations.
Table 1. Details of the ARFINET stations considered in the present study

| Station      | Station code | Longitude (°E) | Latitude (°N) | Altitude (m, a.s.l.) | Region                                      |
|--------------|--------------|----------------|---------------|----------------------|---------------------------------------------|
| Hanle        | HNL          | 78.95          | 32.78         | 4520                 | Himalayan and sub-Himalayan                |
| Kullu        | KLU          | 77.1           | 31.9          | 1154                 |                                            |
| Dehradun     | DDN          | 78.04          | 30.34         | 700                  |                                            |
| Namital      | NTL          | 79.3           | 29.2          | 1960                 |                                            |
| Lachung      | LCN          | 88.4           | 27.4          | 2700                 |                                            |
| Agra         | AGRA         | 78.02          | 27.18         | 169                  | Indo-Gangetic Plain                        |
| Gorakhpur    | GKP          | 83.38          | 26.75         | 85                   |                                            |
| Varanasi     | VNS          | 82.96          | 25.3          | 78                   |                                            |
| Agartala     | AGRT         | 91.25          | 23.5          | 43                   | North-eastern and Eastern India            |
| Shillong     | SHN          | 91.91          | 25.6          | 1033                 |                                            |
| Dibrugarh    | DBR          | 94.6           | 27.3          | 111                  |                                            |
| Bhubaneswar  | BBR          | 85.8           | 20.2          | 78                   |                                            |
| Nagpur       | NGP          | 79.15          | 21.15         | 300                  | Central and Peninsular India              |
| Hyderabad    | HYD          | 78.18          | 17.03         | 640                  |                                            |
| Bengaluru    | BLR          | 77.59          | 12.97         | 960                  |                                            |
| Goa          | GOA          | 73.83          | 15.46         | 70                   |                                            |
| Anantapur    | ATP          | 77.67          | 14.46         | 331                  |                                            |
| Ooty         | OTY          | 76.7           | 11.4          | 2520                 |                                            |
| Thiruvananthapuram | TVM | 77             | 8.5           | 2                   |                                            |

Figure 2. Temporal scales of the lockdown (LD) periods imposed by the Government of India to contain the spread of COVID-19 pandemic. The magnitude of social and travel restrictions varied with the progression of LD from 1 to 4. Nearly all road, rail, air, and marine travel services, along with factories, were suspended during LD1, which is the period of primary interest in the present study.

Lockdown periods and data deduction method

As stated earlier, the first phase of nationwide lockdown (LD1) commenced from 25 March (to 14 April 2020) and was preceded by a 14-hour voluntary Janata curfew on 22 March (Figure 2). During LD1, nearly all services and factories were suspended, restricting social gathering as well as road, passenger train, marine and air travel across the country. However, railway freight operations to transport essential goods were continued. During the second phase (LD2), conditional relaxations were implemented after 20 April for the regions where the infection has been contained or was minimal. This phase continued till 3 May 2020. In the third phase (LD3) from 4 to 17 May 2020, more relaxation of the vehicular movement was put in place, allowing movement of people and material through rail and road (though only on restricted timings), and air services were operated in a modest way as special cases. Offices and industries were opened with about 50% capacity, while other restrictions continued. The relaxations were increased during the 4th phase (LD4: 18–31 May 2020). At the end of LD4, the restrictions were lifted (termed as ‘Unlock-1’) in most of the areas, and traffic was mostly restored normal, except for a ban during night-time.

In view of the above, we examined the impacts of these on BC by considering the data in the following four distinct time segments:

(i) Pre-LD (A), 4–17 March 2020: This is chosen as the reference pre-lockdown periods for which characteristics of BC concentrations are examined till 7-days before lockdown.

(ii) Pre-LD (B), 18–24 March 2020: This period is chosen separately to understand the impact of Janata curfew on 22 March 2020, in addition to understanding the pre-lockdown concentrations of BC during the previous week of lockdown.

(iii) LD1 (A), 25–31 March 2020: Data for this period is examined separately during the first week of LD1 to delineate the rapid response of the complete cut-off of the emission sources as well as the impact of residual BC in the atmosphere emitted earlier, considering the typical residence time of BC ~ 5–10 days.

(iv) LD1 (B), 1–14 April 2020: This period is chosen to be ideal for a complete understanding of the impact
of lockdown after the first week of LD1, during which the residual BC from fossil fuel sources is expected to be highly subdued.

In addition to the above, we have considered continuous BC data collected for the period from January to May 2020 and examined its features with the climatological mean for the same period estimated using data for the previous five years (2015–2019), which was considered as a reference for the normal conditions.

Results and discussions

BC concentrations before and during LD1

We examine the impact of the phased lockdown on ambient BC mass concentration at different locations in the Box and Whisker plot in Figure 3. Despite the large spatial heterogeneity, which is to be expected due to the diverse nature and strength of the sources across the country, almost all stations show a significant decline in BC concentration through the entire phase of LD1 (25 March–14 April 2020) in comparison to the values that existed prior to the lockdown (4–24 March 2020); half of the stations showed increased reduction during the second half of the LD1. Until 7-days before lockdown, BC concentration as high as 8.72 ± 5.19 µg m⁻³ was observed at AGRT in north-eastern India (NEI), followed by AGRA (~5.5 ± 3.1 µg m⁻³) in IGP, whereas the lowest values (<1.5 µg m⁻³) were observed in the Himalayan stations. The maximum values of BC in the IGP and NEI exceeded 10 µg m⁻³. Moderate BC (<3 µg m⁻³) prevailed in peninsular India. This pattern is generally consistent with what has been reported in the normal years. Subsequently, BC concentrations were reduced to <4 µg m⁻³ over the Himalayan and peninsular Indian sites.

Thus, in general, there has been a significant decrease in the ambient BC concentration across India during the intense phase of the lockdown (LD1). Some deviations were seen at KLU, LCN and HYD, where the BC concentrations though decreased during the first week of LD1, subsequently the values increased during the second half of LD1 with BC higher than the pre-LD values. The increase in BC during the second half of LD1 can be attributed to local sources only as the air mass trajectories or the regional circulation is not supporting the transport of BC from elsewhere during this period.

The overall change in BC during LD1 from the pre-lockdown levels at different stations differed, as can be
seen from Table 2. The change (decrease) was highest at GKP (68.3%) in the IGP with an absolute reduction in BConcentration to as low as 2.43 µg m⁻³ during LD1, whereas decrease in BC during LD1 was lowest at NGP. It is interesting to note that there was a significant decrease in BC even at the remotest station Hanle (though the magnitude is small), despite its highly subdued anthropogenic activities. This decrease might represent the reduction in transported BC from the valleys.

**Deviations from the climatological mean**

As the lockdown spanned the period when the synoptic meteorology is in a transition from the dry winter conditions, with isolated pre-monsoon showers (as shown in Supplementary Figure) occurring in different parts of the country, the observations in Figure 3 would have the imprint of the seasonal transformation of BC sources and atmospheric dynamical processes, at least at some of the stations, in addition to the impact of the cessation of various emission sources during lockdown. With a view to delineating the impacts of the LD from the combined effects, we have considered the climatological average BC values for the period January to May by making use of the long-term measurements from 2015 to 2019 and considered this as the reference BC level prevailing during this period under normal conditions (i.e. in the absence of a LD). Figure 4 shows the time series of daily mean BC mass concentrations at each of these stations for the year 2020, against the corresponding time series of normal-state reference levels. It clearly shows the unambiguous impact of the lockdown across the entire region, with a stronger signature at urban locations than in rural and remote locations. Even the Himalayan stations depicted a significant reduction in BC during the lockdown. In general, the springtime enhancement of BC in the Himalayas is a consistent phenomenon, as has been reported earlier⁹-¹¹. This is also explicit from the historical data shown in the present study. However, not only that, spring time enhancements are suppressed during the LD in 2020, there is a significant decrease as well (as seen from the two top panels on the left and right of Figure 4). As long-range transport from the IGP contributes significantly to the BC loading at these high-altitude stations, the large drop in BC loading over the Himalayan stations during 2020 is a clear evidence of the impact of the reduced emissions over the plains.

This is further vindicated by Figure 5, in which we show the percentage decrease in BC from its climatological mean normal-state values (we call this the anomaly due to LD) for different phases of lockdown as a contour plot. In its top panel, we also show the average values of BC during the entire period of lockdown (i.e. LD1 to LD4). The figure reveals the significant impact across the entire region, being most pronounced over the IGP and eastern Indian stations during the LD2 phase. This is attributed to the continued suppression of emissions due to the prolonged lockdown and the absence of ‘recharging’. The influence of relaxation is reflected from LD3 onwards, as the atmosphere gets gradually charged with BC, and the strength of the LD anomaly decreases gradually and becomes highly localized by LD4. The only exception to this has been the urban location of HYD, the reasons for which need a separate investigation. Quantitatively, the LD anomaly during LD2 is >60% over the IGP, while it varied between 26% and 66% over the Himalayan/sub-Himalayan regions (where the average BC level itself is low) and 22% to 59% over the north-eastern and eastern locations of India. In the central and peninsular region, the highest decline of BC occurred at NGP and ATP (~60%) and least at southern high-altitude site OTY (~16%).

Despite this spatial pattern of the LD anomaly, the absolute magnitude of BC (as shown by the histograms in

**Table 2.** Percentage change in BC concentration from pre-lockdown (pre-LD) to lockdown-1 (LD-1) period. The colour bar shows different ranges of the percentage change in BC. The absolute change in BC is also shown in the last column

| Stations | Percentage change in BC from pre-LD to LD1 | Absolute change (ng m⁻³) |
|----------|------------------------------------------|-------------------------|
| HNL      | 31.4%                                    | 14.7                    |
| NTL      | 6.3%                                     | 67.3                    |
| DDDN     | 45.5%                                    | 694.5                   |
| KLU      | 67.5%                                    | 286.7                   |
| LCN      | 47.7%                                    | 380.3                   |
| AGRA     | 40.3%                                    | 2604.3                  |
| GKP      | 68.3%                                    | 5252.2                  |
| AGRT     | 43.6%                                    | 3307.7                  |
| BBR      | 8.7%                                     | 113.1                   |
| NGP      | 1.4%                                     | 29.6                    |
| HYD      | 9.8%                                     | 116.4                   |
| BLR      | 51.8%                                    | 2510.0                  |
| ATP      | 26.0%                                    | 449.3                   |
| GOA      | 49.6%                                    | 273.0                   |
| OTY      | 27.1%                                    | 335.5                   |
| TVM      | 18.5%                                    | 351.1                   |

| Percentage change | Absolute change |
|-------------------|-----------------|
| 0–10%             | 10–20%          |
| 20–30%            | 30–40%          |
| 40–70%            |                 |
Figure 4. Day to day variability of BC mass concentrations during the year 2020 (for the period from January to May), along with the average values of the years 2015–2019. The shaded colour indicates the standard deviations of the mean of the historical values.

the top panel of Figure 5) remained higher over the IGP and north-eastern sites of India compared to other regions. This indicates the still persisting contribution of fossil-fuel emissions to the ambient BC over these sites where the impact of several other sources (such as industries, thermal power plants or brick kilns), in addition to that of vehicular traffic, is prominent. Interestingly, Himalayan foothills, IGP and north-eastern part of India also showed a significant BC drop compared to the locations such as ATP, BLR, OTY and TVM, indicating larger decline in BC over the places where there are abundant non-transport fossil fuel emission sources (e.g. industries, thermal power plants, etc.) compared to the regions where the transport sector is a major contributor. Accordingly, the efficiency of BC removal from the atmosphere may vary from heavily loaded region to the least. Quantification of such gradients is important for climate impact studies, especially in the light of the elevated heat pump hypothesis\(^\text{12}\), which has demonstrated that perturbation to the regional monsoon through this mechanism is strongly dependent on the meridional gradient in elevated aerosol absorption.

On a regional perspective, the time series of the regional mean (daily) values of BC (averaged over all the stations for the year 2020 and for the climatological period 2015–2019) is shown in Figure 6. It is evident that the reduction in BC during LD1 (37.9%) and LD2 (52.5%), with respect to their pre-LD values, are quite unusual as against the corresponding values (11.8% and 23.7%) in climatological trend in BC over India. The
depletion of BC from the climatological mean value (anomaly) is sharp during LD1 (50%) and LD2 (55%). This indicates that the effect of lockdown is much higher than the seasonal change in BC over India.

Similar to BC, a statistically significant decline of PM$_{2.5}$, PM$_{10}$, NO$_2$, and CO has been reported across five megacities of India: Delhi, Mumbai, Chennai, Kolkata and Bengaluru during COVID-19 lockdown. The highest decline of PM$_{2.5}$ has been reported at Delhi (41%), followed by Mumbai (33%), Kolkata (23%), Bengaluru (22%) and Chennai (14%) during 25 March to 6 April 2020, in comparison to the pre-lockdown values measured during 10–20 March 2020. A higher depletion rate in the northern part of the country is quite interesting. In our present study also, the highest reduction in BC is seen over the northern and eastern parts of India, along with the Himalayan stations. Mahato et al. have also reported nearly fifty percent reductions in PM$_{10}$ and PM$_{2.5}$ concentrations at the north Indian site Delhi during the lockdown period compared to the pre-lockdown values. Air quality studies in 22 different cities at different regions of India have also shown an overall 43%, 31%, 10% and 18% decrease in PM$_{2.5}$, PM$_{10}$, CO and NO$_2$ due to the effect of restricted emissions during COVID-19, while showing an increase in O$_3$ concentrations over most regions.$^{15}$ Similarly, based on their observations at Bengaluru, Ajai et al. (this issue) have reported a significant (≈60%) reduction in BC from fossil fuel emission during LD1 and attributed it to the near-total suspension of traffic (road, rail and air).

Similar reductions in aerosol concentration and improvement in air quality due to lockdown and travel restrictions have been reported over several places across the globe.$^{16,17}$ A decline in the levels of PM$_{2.5}$, PM$_{10}$, SO$_2$, CO and NO$_2$ is reported over China$^{18}$, reduction in NO, NO$_2$ and CO concentrations over Brazil$^{19}$ and Barcelona$^{20}$, etc. Similarly, Ottmani et al. have shown the reduction in PM$_{10}$, SO$_2$ and NO$_2$ concentrations in Morocco, revealing the impact of long-range transported aerosols on reduced PM$_{10}$ concentrations during the lockdown. In Ecuador, Monserrate and Ruano$^{22}$ have reported significant reductions in NO$_2$ and PM$_{2.5}$ concentrations during the establishment of lockdown measures. Based on high-resolution space-borne data, Bauwens et al.$^{23}$ have reported reductions in pollution levels over widespread areas in China, Europe, South Korea and the U.S. during January–April 2020. Sicard et al.$^{24}$ have also reported a substantial reduction (∼56%) of NO$_2$ in Europe and China. All these reported studies showed positive consequences of air quality during the COVID-19 lockdown and the advantages of actualizing extreme measures to moderate a portion of the anthropogenic sources to implement the air quality controls.

**Evaluation of distinct source processes**

The spectral variation of BC absorption coefficient ($\sigma_{abs}$), usually represented using absorption Angstrom wavelength exponent ($\alpha_{abs}$), in the relation...
Figure 7. Frequency of occurrences of absorption Angstrom exponent ($\alpha_{abs}$) during pre-lockdown and lockdown periods.

Table 3. Mean and standard errors of the mean values of absorption Angstrom exponent ($\alpha_{abs}$) during the pre-lockdown (1–24 March 2020) and lockdown (25 March–30 April 2020) periods

| Station | Mean $\alpha_{abs}$ (before lockdown) | Mean $\alpha_{abs}$ (during lockdown) |
|---------|--------------------------------------|--------------------------------------|
| KLU     | 1.46 ± 0.04                          | 1.54 ± 0.05                          |
| NTL     | 1.02 ± 0.04                          | 0.88 ± 0.02                          |
| LCN     | 1.17 ± 0.04                          | 1.27 ± 0.04                          |
| AGRA    | 1.41 ± 0.04                          | 1.43 ± 0.03                          |
| AGRT    | 1.20 ± 0.04                          | 1.29 ± 0.02                          |
| BBR     | 0.89 ± 0.03                          | 1.18 ± 0.04                          |
| NGP     | 1.01 ± 0.03                          | 1.09 ± 0.02                          |
| HYD     | 0.87 ± 0.03                          | 1.03 ± 0.02                          |
| BLR     | 1.11 ± 0.04                          | 1.31 ± 0.04                          |
| ATP     | 1.10 ± 0.03                          | 1.23 ± 0.03                          |
| GOA     | 0.96 ± 0.04                          | 1.01 ± 0.03                          |
| OTY     | 1.08 ± 0.02                          | 1.17 ± 0.02                          |
| TVM     | 1.31 ± 0.02                          | 1.43 ± 0.03                          |

Values within this range indicate the presence of BC from mixed sources. Clarke et al.\textsuperscript{27} have reported that $\alpha_{abs}$ peak at 2.1 (1.2–2.2) for biomass burning aerosols and peak close to 1.0 (0.7–1.1) for aerosols from urban pollution.

In the above backdrop, we have examined the frequency of occurrences of $\alpha_{abs}$ for the pre-LD (1–24 March 2020) and LD (25 March–30 April) periods. This is shown in Figure 7, and the average values of $\alpha_{abs}$ prior to lockdown and during lockdown are given in Table 3. The observation shows very little change in $\alpha_{abs}$ over most of the locations except for a few locations such as ATP, BLR and TVM, where vehicular traffic is the major source of fossil fuel-based BC. On the other hand, nearly consistent values of $\alpha_{abs}$ (~1) at some of the locations (such as NTL, BBR, NGP, HYD, GOA and OTY) indicate the persisting impact of fossil fuel sources other than vehicular emission, which influence the absorption spectra of BC but do not significantly contribute to the absolute magnitude of BC concentrations. Similarly, $\alpha_{abs}$ at LCN, KLU, AGRA and AGRT also remains constant, but with steeper BC spectra ($\alpha_{abs} > 1$) during both pre-LD and LD periods. This observation indicates the variability in the relative strength in fossil fuel and bio-fuel sources across the country, having a competing effect in determining the absolute concentrations and spectral signatures of BC at different locations during the lockdown. It is not clear whether the drop in BC at a location is associated with the reduced emissions from the local transport sectors alone. This is because places like the Himalayan foothills.
the IGP, northeast region showed a significant drop compared to the locations such as ATP, BLR, OTY, TVM where the transport sector is a major contributor. This suggests that atmospheric lifetime and transport pathways are also a major factor in determining BC loading at any location.

To examine the possible impact of biomass burning sources, regional distribution of fire pixel counts (obtained from MODIS sensor onboard Terra satellite) during LD1, along with 7-days HYSPLIT air mass back trajectories ending at 500 m above ground level, are examined in Figure 8 at a few selected locations (KLU, LCN, AGRA, NGP, HYD, ATP, OTY and TVM) over which the BC concentrations during LD1(B) is higher than the values during LD1(A).

It is evident from the figure that most of these regions experienced moderate to the strong influence of biomass burning sources as the air mass trajectories spend long traverse time over the biomass burning regions before arriving at the receptor sites. For the north Indian sites, the trajectories are mainly confined to the continental regions, while the air mass trajectories pass over the oceanic region of Bay of Bengal before arriving at the receptor sites of peninsular India (viz. HYD, ATP, OTY and TVM). This explains the different behaviour of BC at different locations after the first week of LD1, where the
impact of regional sources of biomass burning aerosols and the associated transport pathways vary from one location to the other.

Apart from the biomass burning sources, the presence of local domestic fire activities can also contribute to the steeper BC spectra. For example, relatively higher values of $a_{\text{abs}}$ at KLU and AGRA during pre-lockdown and lockdown periods could be attributed to such activities. Kunial et al.\textsuperscript{28} have reported the influence of local biomass burning sources like fuel wood for cooking, forest fires, open waste burning, etc. contributing to the high BC concentrations over KLU, in addition to vehicular emissions.

On the other hand, nearly consistent values of $a_{\text{abs}}$ close to 1.0 at locations such as NTL, GOA, HYD are indicative of the prevailing BC mainly from fossil fuel sources, but with reduced concentrations during the LD1. At NTL, the background BC is reported to have emitted from the local household usage of fuel, in addition to vehicular emission and transported components from the nearby regions\textsuperscript{29}. Similarly, the source of BC over HYD is mainly of fossil fuel (average value of $a_{\text{abs}}$ ~ 1.05 ± 0.04 during MAM) rather than biofuel combustion\textsuperscript{30}. The present study indicates a consistent value $a_{\text{abs}}$ (~1.03 ± 0.16) indicating the presence of fossil fuel components even during the lockdown period. Based on the ground-based and satellite observation along with aerosol reanalysis products, Pandey and Vinoj\textsuperscript{31} have shown an unexpected increase (~ +20%) in aerosol optical depth over central India due to increased atmospheric moisture coupled with stagnant circulation condition.

The foregone observations clearly indicate that BC loading at any location is a function of distinct source strength, sink and advection pathways. Even though the observed BC drop during the lockdown reflects its response to cut-off of fossil fuel sources, especially the transport sector, delineating the actual contribution from different emission pathways to total BC load in the atmosphere is difficult without a combination of the observations and modelling. Based on modelling study conducted for March–May 2006, Kumar et al.\textsuperscript{32} reported that the anthropogenic emissions contribute 60–95% of the total BC loading in South Asia where BC emissions from residential, industrial, transport and power plant sectors contribute about 61%, 23%, 15% and 1% respectively. The present study indicates that though emissions from industrial and transport sectors reduced significantly during LD, the possible contribution from residential and seasonal biomass burning sources remained significant and played a dominant role in modulating the regional aerosol scenario over India during the COVID-19 lockdown.

Summary and conclusions

We have studied the response of ambient BC concentration across the Indian region during the national lockdown in connection with the COVID-19 pandemic. The major findings of the study are:

- Regional distribution of BC clearly shows the unambiguous impact of the lockdown across the entire region, with a stronger signature at urban locations than at rural and remote locations. The overall change (reduction) from the pre-lockdown levels differed at different stations having the highest decrease at Gorakhpur (68.3%) in the IGP, and the lowest reduction at Nagpur in the central India.

- A spectacular decline of BC during the lockdown periods of 2020, with respect to the five-year average for 2015–2019, is observed across the entire Indian region; being most pronounced over the IGP (>60%) and eastern India during LD2 while central and peninsular India as well as Himalayan and sub-Himalayan regions showed significant decline in BC (16–60%) during LD1.

- The absorption Angstrom exponent showed a very little change over most of the locations (indicating the still persisting contribution of fossil-fuel emissions to the ambient BC) except for a few locations where vehicular traffic is the major source of fossil fuel-based BC, and other sources (such as industries or thermal power plants) do not contribute significantly.

- Airmass back trajectories indicated the influence of advection across biomass burning sources contributing to aerosol loading at a few stations during the lockdown period.
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