Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
Impact of COVID-19 lockdown on the fine particulate matter concentration levels: Results from Bengaluru megacity, India

V. Sreekanth a,⇑, Meenakshi Kushwaha b, Padmavati Kulkarni a, Adithi R. Upadhya b, B. Spandana c, Vignesh Prabhu a

a Center for Study of Science, Technology & Policy, Bengaluru 560094, India
b ILK Labs, Bengaluru 560046, India
c Department of Physics, GITAM Institute of Science, GITAM (Deemed to be University), Visakhapatnam 530045, India

Received 31 May 2020; received in revised form 2 November 2020; accepted 11 January 2021
Available online 20 January 2021

Abstract

Leveraging the COVID-19 India-wide lockdown situation, the present study attempts to quantify the reduction in the ambient fine particulate matter concentrations during the lockdown (compared with that of the pre-lockdown period), owing to the highly reduced specific anthropogenic activities and thereby pollutant emissions. The study was conducted over Bengaluru (India), using PM$_{2.5}$ (mass concentration of particulate matter having size less than or equal to 2.5 $\mu$m) and Black Carbon mass concentration (BC) data. Open-access datasets from pollution control board (PCB) were also utilised to understand the spatial variability and region-specific reduction in PM$_{2.5}$ across the city. The highest percentage reduction was observed in BC$_{ff}$ (black carbon attributable to fossil fuel combustion), followed by total BC and PM$_{2.5}$. No decrease in BC$_{bb}$ (black carbon attributable to wood/biomass burning) was observed, suggesting unaltered wood-based cooking activities and biomass-burning (local/regional) throughout the study period. Results support the general understanding of multi-source (natural and anthropogenic) nature of PM$_{2.5}$ in contrast to limited-source (combustion based) nature of BC. The diurnal amplitudes in BC and BC$_{ff}$ were reduced, while they remained almost the same for PM$_{2.5}$ and BC$_{bb}$. Analysis of PCB data reveal the highest reduction in PM$_{2.5}$ in an industrial cluster area. The current lockdown situation acted as a natural model to understand the role of a few major anthropogenic activities (viz., traffic, construction, industries related to non-essential goods, etc.) in enhancing the background fine particulate matter levels. Contemporary studies reporting reduction in surface fine particulate matter and satellite retrieved columnar Aerosol Optical Depth (AOD) during COVID-19 lockdown period are discussed.

© 2021 COSPAR. Published by Elsevier B.V. All rights reserved.

Keywords: PM$_{2.5}$; Black carbon; Beta Attenuation Monitor

1. Introduction

Atmospheric Particulate Matter (PM) is known for its negative impacts on the solar radiation budget, air quality and health. Air pollution is known to affect almost every major human organ system: ranging from cardiovascular, respiratory to neurodegenerative diseases (Kim et al., 2015; Schraufnagel et al., 2019) and is the fourth major cause of mortality world-wide (Murray et al., 2020). In 2016 alone, long-term exposure to PM$_{2.5}$ caused more than 1.2 million deaths in India (HEI, 2019). Black Carbon aerosols (BC, which is mostly a subset of PM$_{2.5}$ because of its fine size), are a byproduct of incomplete combustion. Combustion generated aerosols are found to be better indicators of adverse health effects (Janssen et al., 2011), compared to PM$_{2.5}$. BC is also a strong absorber of solar radiation in the atmosphere and the second most contribu-
tor to global warming after CO$_2$ (Ramanathan and Carmichael, 2008). Globally, primary sources of urban PM are traffic, domestic fuel burning, industrial activities and miscellaneous anthropogenic activities (Karagulian et al., 2015). In addition to the above, in the Indian context, emissions from coal-based power plants is also listed as one of the major sources of PM (Guttikunda and Jawahar, 2014). While, construction activity, open garbage burning constitute majority of the miscellaneous activities (Banerjee et al., 2015; Rana et al., 2019).

Cities and governments around the world have implemented policy measures to reduce PM emissions. These measures have varying impacts on air quality and downstream health outcomes. For example, for the 2008 Olympics, Beijing implemented several policy measures that involved a combination of industry closure or relocation, strict traffic control and introduction of new emission standards. These measures were in place from late 2007 to late 2008, which led to improved air quality (Chen et al., 2013), reduced air pollution attributable mortality (He et al., 2016) and increased birth weights (Rich et al., 2015). Recently, a 10-day (21 May to 31 May 2018) strike by truck drivers in Brazil led to about 20% decline in PM$_{10}$, resulting from a complete pause on truck traffic, and overall reduction of other forms of transport (Leiria ao et al., 2020). The summer season odd–even car trail (a traffic rationing measure) over Delhi, India resulted in a decrease of traffic related PM$_{2.5}$ levels by 2% – 74% during traffic peak hours (Kumar et al., 2017).

On 11 March 2020, the World Health Organization (WHO), announced the COVID-19 (Novel Corona Virus Disease) outbreak as a pandemic. Enforced ‘social distancing’, to contain the spread of COVID-19, halted diverse anthropogenic activities across the globe. In response to the pandemic, India imposed a nationwide lockdown on 24 March 2020 (till 3 May 2020 and thereafter activities were relaxed in a phased manner), clamping down on vehicular and human movement for non-essential purposes. This had resulted in a near-curfew scenario in which normal private and public vehicles were banned and only the transport of essential goods and personnel was permitted. People were restricted to their homes and allowed to go out only in case of emergencies or to buy essentials like groceries or medicine. Non-essential commercial services were also on pause during the lockdown, leading to marked reduction in energy/goods consumption and solid waste generation. As a result, major anthropogenic activities potentially contributing to PM emissions, namely, traffic, construction, and possibly waste burning (due to lower waste output) were highly reduced.

Bengaluru (12.97 °N, 77.59 °E), the capital city of the state of Karnataka, located in the southern part of India is known as the ‘Silicon Valley’ of India owing to its IT (Information Technology) infrastructure. Various studies (e.g., Babu et al., 2002; Patil et al., 2013) have reported the air pollution levels of Bengaluru, which is also labeled as a non-attainment city (a polluted city violating the prescribed national air quality standards; MoEFCC, 2019). A recent emissions inventory study by Guttikunda et al. (2019) listed the transport sector (vehicular exhaust and on-road dust resuspension) as one of the primary sources of PM emissions in Bengaluru, contributing 56% and 70% to PM$_{2.5}$ and PM$_{10}$ emissions. Leveraging the lockdown situation, the current study attempts to quantify the reduction in fine PM (PM$_{2.5}$ and BC) over Bengaluru city in relation with the reduced anthropogenic activities, particularly vehicular movement, construction, and other non-essential small-scale industries.

2. Data, instrumentation and study locations

2.1. Data

Real-time PM$_{2.5}$ and BC measurements made at the Center for Study of Science, Technology and Policy (CSTEP), Bengaluru during the period from 1 March to 22 April 2020 are used in this study. Due to technical issues, BC data is not available from 23 April 2020; for uniformity all the analysis was restricted till 22 April 2020. Hourly open-access PM$_{2.5}$ data from the PCB’s continuous monitoring sites for the periods 1 March to 22 April 2019 and 1 March to 22 April 2020 are also used to support the inferences drawn based on the CSTEP data and to study the spatial variability (within Bengaluru) in the possible improvements in air quality.

2.2. Instrumentation

2.2.1. Beta Attenuation Monitor (BAM-1022)

A BAM (Model: 1022, Met One Instruments, Inc., USA) is used to measure near real-time PM$_{2.5}$. BAM-1022 uses the beta attenuation technique (beta source: $^{14}$C) to measure the mass concentrations of aerosol particles collected onto a glass fiber tape. The accuracy of the BAM-1022 meets the requirements of the USEPA (United States Environmental Protection Agency) class III FEM (Federal Equivalent Method). BAM-1022 (equipped with a manufacturer-supplied 2.5 μm size cut cyclone) operates at 16.7 LPM (liter per minute), with an inbuilt heating arrangement to avoid humidity related errors in the PM$_{2.5}$ measurements. The detection limit for the analyser is <1 μg m$^{-3}$ (24 h) and span measurement ranges from -15 to 10$^4$ μg m$^{-3}$. PM$_{2.5}$ data from the hourly channel of BAM-1022 alone is used for the analysis presented in this paper. More technical details on BAM-1022 can be found at https://metone.com/products/bam-1022/. The BAM-1022 was installed on the CSTEP terrace at a height of ~10 m from the ground and is ~110 m away from the major road.

2.2.2. Aethalometer (AE-33)

A seven-channel (wavelengths: 370, 470, 520, 590, 660, 880, and 950 nm) Aethalometer (Model: AE-33, Magee Scientific, USA) is used to measure real-time BC. AE-33...
is a fast-response instrument, which measures the spectral optical attenuation to estimate high temporal resolution BC, with the aerosol sample being collected onto a quartz fiber filter tape. Using wavelength specific mass absorption coefficients, absorbing aerosol mass concentration is estimated at all seven wavelengths. Due to the strong absorption characteristic of BC at 880 nm, the absorbing aerosol mass concentration measured at this wavelength is considered as BC. The dual-spot technique employed in AE-33 compensates for the spot loading effect, which is a typical measurement artifact for any filter-based absorption measurement. AE-33 utilises the spectral light-absorption measurements to apportion BC obtained from fossil-fuel combustion and wood burning sources (Sandradewi et al., 2008a, 2008b). Principally, the total measured BC is the sum of BC from fossil-fuel (BC\text{ff}) and wood/biomass burning sources (BC\text{bb}). A detailed description of the instrument working principle is given in Drinovec et al. (2015). The AE-33 sampling inlet was installed at a height of~8 m, above the ground level. The flow of the AE-33 is set to 2 LPM and data is logged at 1-minute averaging interval. The instrument is equipped with a 2.5-μm size cut cyclone and a bug filter. A detailed description on the aethalometer measurement uncertainties is given in Backman et al. (2017). For the analysis in the present study, values of BC, BC\text{ff}, and BC\text{bb} measured/estimated at 880 nm are used.

2.2.3. Pollution control board (PCB) PM\text{2.5}

To study the spatial variability and region-specific PM\text{2.5} levels, data from Central and State Pollution Control Boards’ (CPCB/SPCB’s) Continuous Ambient Air Quality Monitoring Stations (CAAQMS) was downloaded (https://app.cpcbccr.com/ccr/#/caaqm-dashboard-all/caaqm-landing/data) and analysed from four stations (of the 10 monitoring stations installed in Bengaluru), based on the data availability. The selected CAAQMS stations are (i) Peenya (PNY) (ii) BTM Layout (BTM), (iii) Hebbal (HBB) and (iv) Hombegowda Nagar (HMB). CAAQMS use reference-grade instrumentation for all criteria pollutant ambient concentration measurements. A quality check algorithm is applied on the CAAQMS data before its use. The algorithm includes removal of negative, fill and spurious values. This algorithm flagged ~2% data (hourly PM\text{2.5}). Daily aggregates are made only if ~75% of the data in a day is available after cleaning (Kumar et al., 2018). The geographical spread of the study stations is shown in Fig. 1. Meteorological fields (temperature, relative humidity, wind speed and wind direction, rainfall) from these stations are also used.

2.2.4. Global precipitation measurements (GPM)

Daily accumulated rainfall data used in the present study is acquired from gridded (0.1° × 0.1° spatial resolution) GPM precipitation products. GPM is a next-
generation satellite mission for observing the global precipitation characteristics with enhanced spatiotemporal resolution. GPM carries the first spaceborne dual frequency precipitation radar (Ku band at 13.6 GHz and Ka band at 35.5 GHz) and a multichannel GPM microwave imager. Several studies (e.g., Tang et al., 2016) compared GPM rainfall data with that of ground-based measurements and found good agreement. More technical details of GPM can be found elsewhere (Skofronick-Jackson et al., 2017) and are not repeated here.

2.2.5. Meteorological parameters

Data on meteorological variables (ambient temperature, Wind Direction and Wind Speed) are acquired from the meteorological monitoring system installed at PCB CAAQMS sites. All the meteorological sensors (National Institute for Standards and Technology-USA traceable) are mounted on a telescopic 10 m (above ground level) tower, sensor data directly interfaced with the Data Acquisition System along with pollutants data. Analysis of meteorological data from BTM is shown (based on data availability) in the current study. As the reference grade monitors measure dry PM$_{2.5}$, data on relative humidity (RH) is not shown. Daily mean values are generated by averaging hourly data.

2.3. Study sites

All the study sites (Fig. 1) are located within Bengaluru’s administrative boundary. The population of Bengaluru was estimated to be ~10 million in 2015 (Guttikunda et al., 2019). CSTEP is located close to the outer ring road in North Bengaluru. CSTEP’s proximity to the major road and a railway track makes it susceptible to traffic related pollution. Situated in the north-west part of the city, PNY is an industrial region. It houses small, medium and large-scale industries. Because of their contribution to high pollution levels in the city, most of the industries in this area are being shifted to outer regions of Bengaluru. BTM is one of the popular residential and commercial neighborhoods in South Bengaluru due to its proximity to the outer ring road and other important locations of the city. HBB monitoring station is located inside the green campus of Veterinary College, which is adjacent to one of the busiest major roads in North Bengaluru. HMB is also a residential layout near central Bengaluru.

3. Results

Days from 24 March (nationwide lockdown start date) through 22 April 2020 (30 days) constitute the period of reduced anthropogenic activity and are termed as event days (ED). To compare and contrast the pollution levels during ED against regular days, the study used data before the lockdown period (1 to 23 March 2020, termed as control days (CD)).

3.1. Meteorological parameters

The study period (CD and ED) spanned the months of March and April, both of which belong to the Indian summer season. Based on this, any observed differences in the pollution levels during CD and ED cannot be attributed to the synoptic scale variations in air-pollution levels. To rule out any possibility of modulation of air pollution levels by local meteorological conditions during CD and ED, we investigated the daily mean temperature ($^\circ$C), wind speed (WS, m s$^{-1}$), and wind direction (WD, $^\circ$) for the study period, using the data collected by PCB weather station. Daily accumulated rainfall (mm) is acquired from Global Precipitation Measurements (GPM) satellite observations. The temporal variation in the daily mean meteorological parameters is shown in Fig. 2 for the study period. There is no gross difference in the meteorological conditions during CD and ED, except in rainfall. There are three days during ED for which, the daily accumulated rainfall is greater than 10 mm, while it is only one day during CD. On 6 April, ~50 mm of daily accumulated rainfall was recorded. Mean temperature and WS values during CD and ED are ~22.6 ± 0.9 $^\circ$C, 1.0 ± 0.26 m s$^{-1}$ and 22.8 ± 0.2 $^\circ$C, 0.8 ± 0.12 m s$^{-1}$ respectively. During the whole study period, the WD is maintained at ~160$^\circ$.

3.2. PM$_{2.5}$ and BC measurements at CSTEP

The hourly PM$_{2.5}$ and BC measured at CSTEP are shown as a daily box and whisker plot in Fig. 3. ED (lockdown days) is shaded in gray. In the box plot, the solid red dot represents the mean, the range of the box indicates the 25th and 75th percentile values and the central line indicates the 50th percentile (median) value. The range of the whiskers indicates the 9th and 91st percentile values and the ‘+’ symbol indicates the outliers in the distribution. Qualitatively, it can be inferred from the plot that PM$_{2.5}$ levels during CD and ED have not varied greatly. In contrast, the BC levels were observed to be significantly low during ED compared to that in CD. Within the study period, PM$_{2.5}$ exhibited lowest values on the 7th (median and mean values of ~18 µg m$^{-3}$) and 10th of April (daily median value ~17 µg m$^{-3}$ and mean value ~18 µg m$^{-3}$), possibly due to the combined effect of lockdown and wet-removal by the rain on the previous days. Meanwhile, such a dip is not seen in BC. The mean ± standard deviation (median ± IQR) values of PM$_{2.5}$ for CD is 38 ± 15 µg m$^{-3}$ (36 ± 17 µg m$^{-3}$), while it is 30 ± 16 µg m$^{-3}$ (28 ± 13 µg m$^{-3}$) for ED (Table 1). By removing data for the rain affected days (7th and 10th of April), the ED PM$_{2.5}$ aggregates (mean and median) just increased by 1 µg m$^{-3}$. These numbers translate to a reduction of ~20% (8 µg m$^{-3}$) in mean and ~23% (8 µg m$^{-3}$) in median PM$_{2.5}$ values with respect to CD. Welch’s $t$-test was performed to understand the statistical significance of the reduction, which revealed that the daily mean and daily median PM$_{2.5}$ reductions were statistically significant
The mean ± standard deviation (median ± IQR) values of BC for CD was $7.0 \pm 4.7 \, \mu g/\text{m}^3$ ($6.1 \pm 4.6 \, \mu g/\text{m}^3$), while for ED, it was $3.1 \pm 3.1 \, \mu g/\text{m}^3$ ($2.7 \pm 1.7 \, \mu g/\text{m}^3$), which turns out to be a 55% reduction in BC. The $t$-test results show that the reduction in BC was highly significant ($p < 0.01$).

Fig. 4 shows the daily variation of the BC components ($\text{BC}_{\text{ff}}$ and $\text{BC}_{\text{bb}}$). During CD, $\text{BC}_{\text{ff}}$ contributed ~90% to

Fig. 2. Temporal variations of the meteorological parameters during pre-lockdown period (control days, CD) and lockdown period (event days, ED).
the total (BC). Clearly, there is a large reduction in the BC_{ff} during ED (compared to that in CD), which translated into BC reduction. The mean ± standard deviation (median ± IQR) values of BC_{ff} for CD was 6.2 ± 4.4 μg m^{-3} (5.4 ± 4.2 μg m^{-3}), while for ED, it was 2.3 ± 2.2 μg m^{-3} (2.0 ± 1.3 μg m^{-3}) (Table 2). This indicates a reduction of ~63% (3.9 μg m^{-3}, highly significant) in the mean and median BC_{ff} during ED. Quantitatively, there was no reduction in BC_{bb} values (CD mean: ~0.79 μg m^{-3}; ED mean: ~0.81 μg m^{-3}) due to the lockdown situation; in fact, a marginal increase was observed.

Fig. 5 shows the diurnal variations (computed from hourly median values) in PM_{2.5}, BC, BC_{ff} and BC_{bb} for CD and ED periods. All parameters exhibited the classical bi-modal diurnal variation as reported by various earlier studies (e.g. Sreekanth et al., 2018). For PM_{2.5}, there was a consistent decrease during ED, throughout the day (except for few early hours), maintaining a uniform diurnal amplitude (maximum-minimum, ~16 μg m^{-3}) during the study period. In the case of BC (and BC_{ff}), in addition to the reduction in the absolute values, diurnal amplitudes also shortened (~7.1 μg m^{-3} during CD vs 2.9 μg m^{-3} during ED). The morning peak (rush hour) in BC was reduced by ~6.2 μg m^{-3}, while the evening peak reduced by ~4.3 μg m^{-3}. There was no difference in the diurnal structure in BC_{bb} for CD and ED.

### 3.3. Pollution control board (PCB) PM_{2.5}

Fig. 6 shows the box plots obtained from PCB measured PM_{2.5} at four different locations in the city. The box plots are derived from the daily median PM_{2.5} (median is chosen rather than the mean, to avoid any possible influence of...
Fig. 5. Diurnal variation in median PM$_{2.5}$, BC, BC$_{ff}$, BC$_{bb}$. The red line represents pre-lockdown period (control days, CD), while the green line represents the lockdown period (event days, ED). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 6. PCB-measured PM$_{2.5}$ at various stations in Bengaluru. The red box represents data for 1–23 March, and the green box represents data for 24 March to 22 April. Data for 2019 is also shown to substantiate that the observed difference in PM$_{2.5}$ between pre-lockdown period (control days, CD) and lockdown period (event days, ED) is due to the lockdown situation. Data from only four PCB CAAQMS stations (out of 10 in Bengaluru) is shown due to the unavailability of PM$_{2.5}$ data from rest of the stations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
outliers on central tendencies) values. Making use of the multi-year measurements, data for the year 2019 is also shown in Fig. 6 to better understand whether the observed differences in CD and ED PM$_{2.5}$ are a result of the lock-down situation or a regular annual phenomenon (even though CD and ED periods are part of the same Indian summer monsoon season). Among the study sites, PNY has the highest PM$_{2.5}$, with a mean PM$_{2.5}$ during CD (ED) of $\sim 45 (35)$ $\mu$g m$^{-3}$, owing to its industrial nature. The box plots indicate that the PM$_{2.5}$ levels during the period from 24 March to 22 April 2019 are always higher than or similar to that in the period from 1 March to 23 March 2019. This observation confirms that the reduction in the observed PM$_{2.5}$ during ED can be attributed to the lock-down situation. PNY (an industrial location) observed the highest reduction in PM$_{2.5}$ levels ($\sim 10$ $\mu$g m$^{-3}$) during ED, followed by HMB, HBB ($\sim 6$ $\mu$g m$^{-3}$) and BTM ($\sim 4$ $\mu$g m$^{-3}$) (see Table 1 ). When translated to percentage reduction with respect to the CD conditions, PNY recorded the highest ($\sim 22$%), followed by HMB, HBB ($\sim 19$%) and BTM ($\sim 14$%). $t$-test results revealed that the reductions observed only over PNY and HMB are statistically significant (p < 0.05).

Fig. 7 shows the PM$_{2.5}$ diurnal variations across the PCB sites. The diurnal variations clearly exhibit both morning and evening peaks (BTM has multiple peaks). Clear spatial variability is seen in the levels and shape of the diurnal variations. PM$_{2.5}$ during ED is consistently low across all times of the day and across all sites compared with that of CD (except for a few early morning hours over HMB and HBB). The highest diurnal amplitude ($\sim 32$ $\mu$g m$^{-3}$) is observed over PNY, followed by HBB ($\sim 24$ $\mu$g m$^{-3}$).

4. Discussion

PM$_{2.5}$ and BC levels reduced during the COVID-19 nation-wide lockdown period (ED) over the city of Bengaluru. Few recent articles have also reported improvement in air quality and CO$_2$ levels in similar COVID-19 lockdown situations across the globe (e.g. Mahato et al., 2020; Calma, 2020; Myllyvirta, 2020). In the present study, the observed PM$_{2.5}$ reductions are not statistically significant over all the five study sites located within the Bengaluru city boundary (Fig. 1). During the lockdown period, a near-curfew scenario was observed with all non-essential travel, activities (e.g., construction), and industries being strictly prohibited; only emergency or essential services (e.g., hospitals, sanitation), travel (e.g. ambulance, food, dairy and grocery delivery trucks, goods trains), industries (e.g. food processing units) were exempt from the lockdown. The absolute values of PM$_{2.5}$ reduction was attributed to the lockdown situation, assuming that, the PM contribution from natural sources was almost constant across the study period (both control and lockdown periods are part of the 2020 summer monsoon season).

Guttikunda et al., (2019) have listed travel exhaust, domestic emissions, industries, dust, waste burning, gener-

![Fig. 7. Diurnal variations in median PM$_{2.5}$ measured by PCB at various stations in Bengaluru. The red line represents the pre-lockdown period (control days, CD), while green line represents the lockdown period (event days, ED). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)](image-url)
ator sets, and brick kilns as the major contributors to PM$_{2.5}$ emissions over Bengaluru (in addition to any natural sources such as open fires, sea-salt, biogenic, dust storms etc.). During March, dust is identified as a leading contributor to PM$_{2.5}$ over Bengaluru. Because of the multi-source nature of PM$_{2.5}$ and the fact that the source strengths of some of the major sources (e.g. dust, domestic emissions, generator sets) are independent of the lockdown situation, the reductions observed in their levels are relatively small (15–22%) and non-significant (over 2 study sites). In contrast, the observed PM$_{2.5}$ reductions during lockdown (ED) over CSTEP, PNY and HMB are significant. In the case of PNY, it is understood that most of the industries were shut during the lockdown and a considerable decrease was expected and observed. Over HMB, which is a residential site, a statistically significant 19% reduction was observed. BTM, which is again a residential site, experienced a non-significant reduction. Over residential areas, in general, domestic emissions dominate over other emission sources. HBB, which is located next to one of the busiest major roads, observed a non-significant decrease (~19%) in PM$_{2.5}$ levels. The non-significant reduction can be partly attributed to the atmospheric residence times of the fine particulate matter. In general, particles have lifetime of ~1 week to 10 days (based on their size). Changes in pollutant levels during the nationwide lockdown have been reported from several other cities across India (e.g., Kumar et al., 2020). On the basis of real-time PM$_{2.5}$ data, Navinya et al. (2020) studied PM$_{2.5}$ distribution over 17 cities in India to assess the reduction in PM$_{2.5}$ levels during the lockdown period compared to pre-lockdown levels. Ahmedabad (a city in western India) showed the highest reduction of 67.7%, while Mumbai (a city along the west coast of India) experienced a reduction of only 0.9% (Navinya et al., 2020). Mor et al. (2020) reported nearly 30% (6 $\mu$g m$^{-3}$) reduction in PM$_{2.5}$ over Chandigarh (a city in northern India) during the lockdown period. Jain and Sharma (2020) examined PM$_{2.5}$ levels from 38 monitoring stations located across New Delhi (Indian national capital, located in northern India) and reported an overall reduction of around 41% during the lockdown period. Sharma et al. (2010) evaluated changes in PM$_{2.5}$ levels over seven different cities across Rajasthan (largest Indian state, located in northern India). Ajmer showed the highest (47.62%), whereas Udaipur showed the least reduction (22.52%) in lockdown PM$_{2.5}$ levels (Sharma et al., 2010). Few researchers also reported reduction in columnar particulate matter during the lockdown period. Based on satellite aerosol optical depth (AOD) measurements over north India, Mahato and Ghosh, (2020) reported a reduction of around 32–40% in columnar aerosol burden during April 2020 (lockdown period) compared to the columnar aerosol burden in April 2018. The impact of COVID-19 lockdown on AOD has also been reported by Lokhandwala and Gautam, (2020).

BC and PM$_{2.5}$ (over CSTEP) recorded significant reduction. CSTEP, located close to the outer ring road experiences significant vehicular emissions. During control days, the average BC contribution to PM$_{2.5}$ is ~18%; moreover, the BC reduction during the lockdown period is primarily dictated by BC$_{fr}$. All of these arguments and inferences coalesce into the conclusion that the observed reduction in PM$_{2.5}$ levels are mostly due to suppressed vehicular activity and coal-based industrial activities during ED. BC$_{so}$, which corresponds to wood/biomass burning activities, is unaltered during the lockdown period, suggesting near constant biomass cooking emissions (mostly happening in the slum areas of Bengaluru) and background. As the lockdown situation is being implemented nation-wide, the transported anthropogenic component could be less than that of the pre-lockdown period. A similar study over Bhubaneswar (a city along the east coast of India) reported a 47% reduction in BC during the lockdown period when compared to the pre-lockdown level (Panda et al., 2020). Moreover, the generally present prominent bimodal peaks in the diurnal variation of BC were not observed during the lockdown period. Another similar study over European cities revealed a 37%–72% reduction in BC over a five-week period of restricted traffic in certain areas of the cities (Titos et al., 2015). The reduction in concentrations however were very local and did not improve the air quality in other areas of the city where the controls were not implemented. A week-long nationwide strike of truck operators that occurred in India in January 2009 provided another such model for a natural experiment. During the strike, data from another south Indian city, Hyderabad, revealed consistent reduction in BC and PM$_{2.5}$ due to a complete stop of truck traffic (Sharma et al., 2010).

Even though the lockdown was implemented as a mitigation strategy for a pandemic and not for improving the air quality, the unintended consequences here are a welcome side-effect. Our analysis could be used in deciding which aspects of the lockdown could continue in the post-pandemic situation, as a deliberate strategy for emissions reduction. Across the world and also in India, universities and schools are shut down with classroom instruction moving online, corporate offices are implementing work-from-home using online tools, and conferences and professional meetings are being held via webinars. Governments may consider which of these aspects can continue and contribute to lowered emissions. Implementing work-from-home policies alone may lead to co-benefits of air quality improvement and climate-change mitigation by cutting down transport-related emissions (Irwin, 2004).

5. Summary

This study examines the impact of a nation-wide COVID-19 lockdown on the air quality of Bengaluru, India. Concentrations of ambient PM$_{2.5}$ and Black Carbon (BC) at several locations in the city were used to compare the levels in the pre-lockdown (control days, CD) and during-lockdown (event days, ED) periods. Data for a total
of 53 days (23 CD and 30 ED) from five different locations in Bengaluru were analysed. During the lockdown (ED), the daily PM$_{2.5}$ levels reduced by ~15–22% (with respect to CD). A spatial variability was observed in the reductions of PM$_{2.5}$ in terms of magnitude and statistical significance. Concentration reductions were more pronounced in BC, with ED levels ~55% lower than CD levels. This reduction was completely driven by reduction in the fossil-fuel burning component (BC$_{ff}$) which constitutes ~90% of the total BC during CD. Specifically, there was a 63% reduction in BC$_{ff}$ levels during ED.

Declarations 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.

Acknowledgements

The authors acknowledge the Central Pollution Control Board (CPCB) and Karnataka State Pollution Control Board (KSPCB) for installing and maintaining the CAAQMS and making the data open access. Moreover, the authors are grateful to MacArthur Foundation for providing financial support to CSTEP for conducting air-pollution studies in Bengaluru. Authors are grateful to Dr Jai Asundi, Dr Pratima Singh, and Priyavrat Bhati for their support in establishing and maintaining the air pollution laboratory at CSTEP. Thanks are also due to Merla V Ramanaidu (Senior Engineer) for making available the data from the monitoring instruments installed at CSTEP during the lockdown period.

Declarations of Competing Interest

The authors declare no conflict of interest.

References

Babu, S.S., Satheesh, S.K., Moorthy, K.K., 2002. Aerosol radiative forcing due to enhanced black carbon at an urban site in India. Geophys. Res. Lett. 29, 1–4. https://doi.org/10.1029/2002GL015826.

Backman, J., Schmeisser, L., Virkkula, A., Ogren, J.A., Asmi, E., Starkweather, S., Sharma, S., Eleftheriadis, K., Utl, T., Jefferson, A., Bergin, M., Maakhtas, A., Tunved, P., Fiebig, M., 2017. On Aethalometer measurement uncertainties and an instrument correction factor for the Arctic. Atmos. Meas. Tech. 10, 5039–5062. https://doi.org/10.5194/amt-10-5039-2017.

Banerjee, T., Murari, V., Kumar, M., Raju, M.P., 2015. Source Apportionment of Airborne Particulates through Receptor Modelling: Indian Scenario. Atmos. Res. 164–165, 167–187. https://doi.org/10.1016/j.atmosres.2015.04.017.

Calma, J., 2020. Maps show drastic drop in China’s air pollution after coronavirus quarantine. The Verge https://www.theverge.com/2020/3/2/21161324/coronavirus-quarantine-china-maps-air-pollution, accessed on 28 March 2020.

Chen, Y., Jin, G.Z., Kumar, N., Shi, G., 2013. The promise of Beijing: Evaluating the impact of the 2008 Olympic Games on air quality. J. Environ. Econ. Manage. 66 (3), 424–443.

Drinovec, L., Močnik, G., Zoller, P., Prévôt, A.S.H., Rückstuhl, C., Coz, E., Rupakheti, M., Sciare, J., Müller, T., Wiedensohler, A., Hansen, A. D.A., 2015. The ‘dual-spot’ Aethalometer: An improved measurement of aerosol black carbon with real-time loading compensation. Atmos. Meas. Tech. 8, 1965–1979. https://doi.org/10.5194/amt-8-1965-2015.

Guttikunda, S.K., Nishad, K.A., Gota, S., Singh, P., Chanda, A., Jawahar, P., Asundi, J., 2019. Air quality, emissions, and source contributions analysis for the Greater Bengaluru region of India. Atmos. Pollut. Res. 10 (3), 941–953.

Guttikunda, S.K., Jawahar, P., 2014. Atmospheric emissions and pollution from the coal-fired thermal power plants in India. Atmos. Env. 92, 440–460.

He, G., Fan, M., Zhou, M., 2016. The effect of air pollution on mortality in China: Evidence from the 2008 Beijing Olympic Games. J. Environ. Econ. Manage. 79, 18–39.

Health Effects Institute. 2019. State of global air 2019. Special report.

Irwin, F., 2004. Gaining the air quality and climate benefit for telework. World Resources Institute. Retrieved from http://goo.gl/ldvkJU, accessed on 14th April 2020.

Jain, S., Sharma, T., 2020. Social and Travel Lockdown Impact Considering Coronavirus Disease (COVID-19) on Air Quality in Megacities of India: Present Benefits, Future Challenges and Way Forward. Aerosol Air Qual. Res. 20, 1222–1236.

Janssen, N.A., Hoek, G., Simic-Lawson, M., Fischer, P., Van Bree, L., Ten Brink, H., Keuken, M., Atkinson, R.W., Anderson, H.R., Brunekreef, B., Cassee, F.R., 2011. Black carbon as an additional indicator of the adverse health effects of airborne particles compared with PM10 and PM2.5. Environ. Health Perspect. 119 (12), 1691–1699.

Karagulian, F., Belis, C.A., Dora, C.F.C., Prüss-Ustün, A.M., Bonjour, S., Adair-Rohani, H., Amann, M., 2015. Contributions to cities’ ambient particulate matter (PM): A systematic review of local source contributions at global level. Atmos. Environ. 120, 475–483.

Kim, K.H., Kabir, E., Kabir, S., 2015. A review on the human health impact of airborne particulate matter. Environ. Int. 74, 136–143.

Kumar, M.K., Sreekanth, V., Salmon, M., Tonne, C., Marshall, J.D., 2018. Use of spatiotemporal characteristics of ambient PM2.5 in rural South India to infer local versus regional contributions. Environ. Pollut. 239, 803–811.

Kumar, P., Gulia, S., Harrison, R.M., Khare, M., 2017. The influence of odd–even car trial on fine and coarse particles in Delhi. Environ. Pollut. 225, 20–30.

Kumar, P., Hama, S., Omidvarboma, H., Sharma, A., Sahani, J., Abhijith, K.V., Debele, S.E., Zavala-Reyes, J.C., Barwise, Y., Tiwari, A., 2020. Temporary reduction in fine particulate matter due to ‘anthropogenic emissions switch-off’ during COVID-19 lockdown in Indian cities. Sustain. Cities Soc. 62 102382.

Leiriao, L., Debone, D., Pauliquevis, T., Rosário, N., Miraglia, S., 2020. Environmental and public health effects of vehicle emissions in a large metropolis: Case study of a truck driver strike in Sao Paulo, Brazil. Atmos. Pollut. Res. 11, 24–31.

Lokhandwala, S., Gautam, P., 2020. Indirect impact of COVID-19 on environment: A brief study in Indian context. Environ. Res. 188 109807.

Mahato, S., Ghosh, K.G., 2020. Short-term exposure to ambient air quality of the most polluted Indian cities due to lockdown amid SARS-CoV-2. Environ. Res. 188 109835.

Ministry of Environment, Forest & Climate Change (MoEFCC). 2019. National Clean Air Programme. http://moef.gov.in/wp-content/uploads/2019/05/NCAP_Report.pdf, accessed on 28 October 2020.

Mor, S., Kumar, S., Singh, T., Dogra, S., Pandey, V., Ravindra, K., 2020. Impact of COVID-19 lockdown on air quality in Chandigarh, India: understanding the emission sources during controlled anthropogenic activities. Chemosphere 263 127978.
Murray, C.J., Aravkin, A.Y., Zheng, P., Abbafati, C., Abbas, K.M., Abbasi-Kangevari, M., Abd-Allah, F., Abdalilah, A., Abdollahi, M., Abdollahpour, I., Abegaz, K.H., 2020. Global burden of 87 risk factors in 204 countries and territories, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019. The Lancet 396 (10258), 1223–1249.

Myllyvirta, L., 2020. Coronavirus has temporarily reduced China’s CO2 emissions by a quarter. 19 Feb. 2020, Carbon Briefs, https://www.carbonbrief.org/analysis-coronavirus-has-temporarily-reduced-chinas-co2-emissions-by-a-quarter, accessed on 30 March 2020.

Navinya, C., Vinoj, V., Pandey, S., 2020a. Evaluation of PM2.5 Surface Concentrations Simulated by NASA’s MERRA Version 2 Aerosol Reanalysis over India and its relation to the Air Quality Index. Aerosol Air Qual. Res. 20, 1329–1339.

Navinya, C., Patidar, G., Phuleria, H.C., 2020b. Examining effects of the COVID-19 national lockdown on ambient air quality across urban India. Aerosol Air Qual. Res. 20, 1759–1771.

Panda, S., Mallik, C., Nath, J., Das, T., Ramasamy, B., 2020. A study on variation of atmospheric pollutants over Bhubaneswar during imposition of nationwide lockdown in India for the COVID-19 pandemic. Air Qual. Atmos. Health. https://doi.org/10.1007/s11869-020-00916-5.

Patil, R.S., Kumar, R., Menon, R., Shah, M.K., Sethi, V., 2013. Development of particulate matter speciation profiles for major sources in six cities in India. Atmos. Res. 132–133, 1–11.

Ramanathan, V., Carmichael, G., 2008. Global and regional climate changes due to black carbon. Nat. Geosci. 1 (4), 221–227.

Rana, A., Jia, S., Sarkar, S., 2019. Black carbon aerosol in India: A comprehensive review of current status and future prospects. Atmos. Res. 218, 207–230. https://doi.org/10.1016/j.atmosres.2018.12.002.

Rich, D.Q., Liu, K., Zhang, J., Thurston, S.W., Stevens, T.P., Pan, Y., Kane, C., Weinberger, B., Ohman-Strickland, P., Woodruff, T.J., Duan, X., 2015. Differences in birth weight associated with the 2008 Beijing Olympics air pollution reduction: results from a natural experiment. Environ. Health Perspect. 123 (9), 880–887.

Sandraudewi, J., Prévôt, A.S.H., Weingartner, E., Schmidhauser, R., Gysel, M., Baltensperger, U., 2008a. A study of wood burning and traffic aerosols in an Alpine valley using a multi-wavelength Aethalometer. Atmos. Environ. 42, 101–112. https://doi.org/10.1016/j.atmosenv.2007.09.034.

Sandraudewi, J., Prévôt, A.S.H., Szidat, S., Perron, N., Alfarra, M.R., Valentín, A.L., Weingartner, E., Baltensperger, U.R.S., 2008b. Using aerosol light absorption measurements for the quantitative determination of wood burning and traffic emission contributions to particulate matter. Environ. Sci. Technol. 42, 3316–3323.

Schraufnagel, D.E., Balmes, J.R., Cowl, C.T., De Matteis, S., Jung, S.H., Mortimer, K., Perez-Padilla, R., Rice, M.B., Riojas-Rodriguez, H., Sood, A., Thurston, G.D., 2019. Air pollution and noncommunicable diseases: A review by the Forum of International Respiratory Societies’ Environmental Committee, Part 2: Air pollution and organ systems. Chest 155 (2), 417–426.

Sharma, A.R., Kharol, S.K., Badarinath, K.V.S., 2010. Influence of vehicular traffic on urban air quality-A case study of Hyderabad, India. Transport. Res. Part D: Transport Environ. 15 (3), 154–159.

Skofronick-Jackson, G., Petersen, W.A., Berg, W., Kidd, C., Stocker, E. F., Kirschbaum, D.B., Kakar, R., Braun, S.A., Huffman, G.J., Iguchi, T., Kistetter, P.E., 2017. The Global Precipitation Measurement (GPM) mission for science and society. Bull. Am. Meteorol. Soc. 98 (8), 1679–1695.

Sreekanth, V., Mahesh, B., Niranjan, K., 2018. Gradients in PM2.5 over India: Five city study. Urban Clim. 25, 99–108.

Tang, G., Ma, Y., Long, D., Zhong, L., Hong, Y., 2016. Evaluation of GPM Day-1 IMERG and TMPA Version-7 legacy products over Mainland China at multiple spatiotemporal scales. J. Hydrol. 533, 152–167.

Titos, G., Lyamani, H., Drinovec, L., Olmo, F.J., Mocnik, G., Alados-Arboledas, L., 2015. Evaluation of the impact of transportation changes on air quality. Atmos. Environ. 114, 19–31.