Multitechnique Observations on the Impacts of Declining Air Pollution on the Atmospheric Convective Processes During COVID-19 Pandemic at a Tropical Metropolis

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***Abstract*— The present study addresses the impacts of reduced anthropogenic activities during the lockdown period of COVID-19 pandemic on the aerosol concentration, treated as heat absorbing agent, and on the related atmospheric processes, using ground-based and spaceborne measurements over a highly polluted Indian metropolis, Kolkata. The investigation reveals that reduced aerosol concentrations during the pre-monsoon of 2020, when the lockdown was implemented, decreased atmospheric instability as indicated by low values of the convective available potential energy (CAPE). This hindered the abundance of aerosols above the atmospheric boundary layer. Also, micro rain radar (MRR) observations showed a significant reduction of convective precipitation occurrences over Kolkata during this period. The back trajectory analysis has revealed the absence of continental component toward the wind clusters associated with rain occurrences during pre-monsoon 2020. This resulted in increased occurrences of stratiform rain events during the pre-monsoon of 2020 compared to the same period of previous years.**

***Index Terms*— Aerosols, anthropogenic activities, atmospheric instability, back trajectory, black carbon (BC), convective processes, COVID-19 pandemic, precipitation.**

I. Introduction

THE extraordinary situation which occurred during the pre-monsoon period, namely, March–May of 2020 due to the halting of the economic activities due to COVID-19 pandemic resulted in a drastic fall of air pollution level over the present study location Kolkata (22.57° N, 88.37° E), India. This provided a unique opportunity to investigate the atmospheric processes in these unusual environmental conditions. Studies of several researchers revealed the reduction of air pollution and improved air quality during the COVID-19 pandemic over the globe [1], [2]. Noticeable decrease in the pollution level is also seen over the Indian subcontinent during post lockdown period [2], [3]. Though there have been several studies evaluating the effects of lockdown on air pollution over Indian region including Kolkata, nevertheless, the studies evaluating the impacts of reduced anthropogenic activities on the dynamics of atmospheric processes are lacking. Chowdhuri *et al.* [4] reported a reduction of lightning activities as a consequence reduced level of pollution; however, their study is based on correlation between number of lightning flashes from TRMM data and pollutant concentration without consideration of any changes in dynamical behavior of atmospheric processes. In the present study, we have studied the effects of reduced anthropogenic activities on the atmospheric instability and convective processes and precipitation from ground- and spaced-based measurements, and also using the model outputs of different atmospheric measurements. The study region Kolkata is a highly polluted, densely populated tropical metropolis located near the land ocean boundary in eastern India. Kolkata air quality is mainly controlled by the local emissions due to heavy anthropogenic activities which experiences high concentration of black carbon (BC) in comparison with other urban Indian locations [5], [6]. The aerosol environment prevailing over Kolkata has already been reported [5]–[8]. However, the imposed lockdown, which eventually occurred during the pre-monsoon season (March–May) in Kolkata, has caused to drastically curtail anthropogenic activities and almost wipe out emissions from the transport sectors. Against this backdrop, changes in aerosol environment have been assessed from the spaceborne observations of Moderate Resolution Imaging Spectro-radiometer (MODIS) and MetOp-B satellite platform. Surface BC concentration measurements from the aethalometer operated at the study location have also been investigated. Usually in the pre-monsoon season, Kolkata experiences frequent convective events, aided with high convective available potential energy (CAPE) [5], [6], [9], [10]. Studies revealed that changes in concentration of heat absorbing aerosols, such as BC, alter the temperature profile of the air column resulting in an increased CAPE favoring convection [11]. An abundance of heat absorbing aerosols can also flatten the temperature lapse rate and suppress the convective growth [5]. However, this unusual environment with reduced pollution due to stringent anthropogenic activities during pre-monsoon 2020 over Kolkata has motivated us to probe into the

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prevailing convective phenomena using multitechnique observations. Also, the atmospheric instability in terms of CAPE during 2020 pre-monsoon has been estimated from radiosonde measurements and compared with the same observed during the previous three years. The frequencies of occurrences of the convective and stratiform rain events have been investigated with Ka-band micro rain radar (MRR) during pre-monsoon 2020 compared to 2017–2019. In addition, the impacts of restricted anthropogenic activities and reduced convections on the vertical profile of aerosol have also been investigated with the help of the lidar observations aboard the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO).

Due to its location near the land–sea boundary, the atmospheric features of Kolkata are influenced by both continental and maritime activities. Hybrid Single Particle Lagrangian Integrated Trajectory (HYPSLIT) back trajectory model has been used to investigate the contributions of continental and maritime components on the precipitation which occurred during the 2020 pre-monsoon in comparison with the pre-monsoon period of 2017–2019.

The present study deals with the following:

1) The presentation of experimental data of BC from Kolkata, to examine the role of reduced aerosols as heat absorbing particles during the lockdown phase.
2) The effect of reduced aerosol concentration on CAPE values that is responsible for reduced convective activities.
3) The impact of reduced convective activities on the occurrences of convective and stratiform rain events.
4) The contributions of continental and maritime components toward the wind clusters associated with rain occurrences during pre-monsoon under changed atmospheric conditions.
5) The vertical transport of aerosols affecting the elevated aerosol layer above the boundary layer in the changed aerosol environment during lockdown period.

The results are examined in the light of usual anthropogenic activities during the same period of 2017–2019. The present study, the kind of which is yet to be reported in open literature, has been feasible due to the special location of Kolkata near the land–sea boundary and availability of the experimental data with aethalometer, MRR, and laser precipitation monitor (LPM), in addition to other satellite measurements and model data.

II. Data, Instruments, and Methodology

Surface BC concentration has been obtained from a seven-channel aethalometer (AE-31; Magee Scientific), continuously operated at the Institute of Radio Physics and Electronics, University of Calcutta, Kolkata. The calibration procedure of aethalometer is already reported [6]. The absorption at 880-nm wavelength has been used to measure BC concentration as it is closest to the absorption peak at 830 nm for BC [5], [6], [8]. The BC data collected in the heart of the city are representative of the highly polluted environment of Kolkata, although there are some variations of pollutant levels in different parts of the city depending on vehicular traffic conditions. Aerosol optical depth (AOD) at the wavelength 0.55 μm has been obtained from daily level 2 data (MYD04) of MODIS available at a spatial resolution of 10 km [12]. To assess the presence of absorbing aerosols in the troposphere, the daily absorbing aerosol index (AAI) data have been retrieved from the space-based observations of GOME-2 of the MetOp-B satellite platform with a spatial resolution of $1^\circ \times 1^\circ$ at 340 and 380 nm [13]. CAPE has been derived from the radiosonde measurements over Kolkata by India Meteorological Department (IMD) obtained twice daily, 05:30 and 17:30 India Standard Time (ISt) and available from the website of the University of Wyoming (station number: 42809) (http://weather.uwyo.edu/upperair/sounding.html). For the present study, the data at 17:30 IST are considered as convective activities over Kolkata usually occur in afternoon hours [14].

It may be noted that for the estimation of the BC, AAI, AOD, and CAPE during the pre-monsoon period of 2017–2020, the rainy days are excluded to avoid wet scavenging effect of aerosols due to precipitation [5]. The rainy days are identified from the rain rate data of Thies Clima LPM operated over the present location, Kolkata [15].

Back trajectory analysis of the air mass for the rainy days has been made from the global reanalysis data products of National Oceanic and Atmospheric Administration (NOAA) using the Trajectory Statistics (TrajStat) software. The trajectory calculations obtained are according to HYSPLIT model as explained by Stein *et al.* [16].

Aerosol profile information has been obtained from the cloud-free aerosol extinction profiles level 3 data (CAL_LID_L3_Tropospheric_APro_CloudFree-Standard-V4) of CALIPSO. Monthly data at a spatial resolution of $5^\circ \times 2^\circ$ during both day and night time are used [17].

The numbers of convective and stratiform rain events over Kolkata have been further obtained from the MRR measurements operated at the present study location, Kolkata. MRR is a frequency modulated continuous wave (FM-CW) radar, working on the Doppler principle at 24.1 GHz and vertically pointing upward, that measures the profiles of different rain parameters like rain rate, radar reflectivity, rain drop size distribution, and fall velocity from 200 m up to a height of 6 km [18].

III. Results and Discussion

The variations of the surface BC concentration, AOD, and AAI during 2020 pre-monsoon in comparison with the pre-monsoon season of 2017–2019 over Kolkata are shown by the box and whisker plot in Fig. 1. Kolkata air has experienced minimum BC concentration during the pre-monsoon of 2020 with mean (median) value of 1.19 μg/m^3(1.2 μg/m^3) compared to the same period of previous years under consideration. The mean (median) values of BC during pre-monsoon season of 2017 to 2019 are, respectively, 4.3 (4.306 μg/m^3), 4.64 (4.62 μg/m^3), and 4.4 μg/m^3 (4.46 μg/m^3) as revealed from Fig. 1(a). BC is recognized as the major heat absorbing

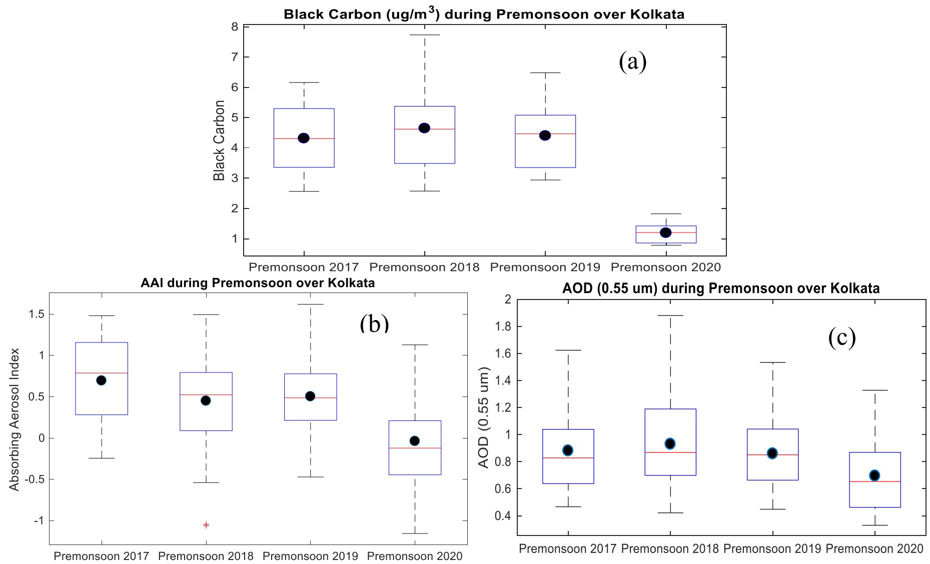

Fig. 1. Box and whisker plot of (a) Surface BC concentration, (b) AAI, and (c) AOD over Kolkata for the years 2017– 2020 during the pre-monsoon. Median is denoted by red horizontal line in the box, mean is shown by filled circle. The tops and bottoms of each box are, respectively, the 75th and 25th percentiles of the data points. The distances between the tops and bottoms are the interquartile ranges. The top and bottom of the vertical whisker lines represent the 95th and 5th percentiles of the statistical data. The line in the middle of each box indicates the median value. The mean value is indicated by filled circles in the box plot [19]. Outlier values are indicated by red + sign.

particulate matters over an urban metropolis like Kolkata [5], [6], [8], [14].

This significant decrement of surface BC concentration during restricted anthropogenic activities has an impact on the AAI over Kolkata, a positive value of which indicating the dominance of heat absorbing aerosols. The AAI variation estimated from MetOp-B satellite products during the pre-monsoon months is shown in Fig. 1(b). The mean (median) AAI value during pre-monsoon 2020 is negative, -0.038 (-0.121) indicating the paucity of heat absorbing aerosols, whereas the same values are 0.7 (0.78), 0.45 (0.52), and 0.50 (0.48) during the pre-monsoon season of 2017–2019, respectively, over Kolkata [Fig. 1(b)]. The AOD at 0.55 μm from MODIS has also shown a decreased mean (median) value of 0.69 (0.65) during the pre-monsoon 2020. On the other hand, mean (median) AOD was 0.9 (0.83), 0.93 (0.9), and 0.86 (0.85) during the pre-monsoon season of 2017–2019, respectively [Fig. 1(c)]. So, the reduction of the anthropogenic activities due to lockdown has resulted in significant decrement of the surface BC concentration, AAI, and AOD values during 2020 over the study location as revealed from both the ground-based and spaceborne remote sensing data sets.

Previous studies have shown that pollutant aerosols which also act as cloud condensation nuclei warm the air parcels in an air column resulting in increased atmospheric instability that invigorates convection and precipitation [11]. The unprecedented reduction of aerosol concentration during the lockdown period has prompted us to investigate the instability of the atmosphere in terms of CAPE from radiosonde measurements by the IMD during 2020 in comparison with the pre-monsoon period of the 2017–2019. The instability index CAPE, which indicates the buoyant energy available to accelerate an air parcel vertically upward in the atmosphere, is indicative of the development of convective processes [20]. Kolkata experienced drastically diminished mean (median) CAPE value of 711 J/kg (563 J/kg) during 2020 which is not the usual scenario during the pre-monsoon period (Fig 2). The mean (median) CAPE values were 2545 (2899 J/kg), 1794 (1695 J/kg), and 2384 J/kg (2370 J/kg) during the pre-monsoon season of 2017–2019, respectively, as shown in Fig. 2. This diminished CAPE has impacts on the convective events during the pre-monsoon months of 2020 over the present location. So, the present atmospheric conditions over Kolkata during lockdown characterized by the low aerosol concentration and diminished atmospheric instability have led us to investigate the occurrences of convective rain events during 2020 compared to the 2017–2019 pre-monsoon. The impacts of reduced CAPE during the lockdown period are manifested in the occurrence of rain events in the pre-monsoon period as observed with MRR operated at the study location.

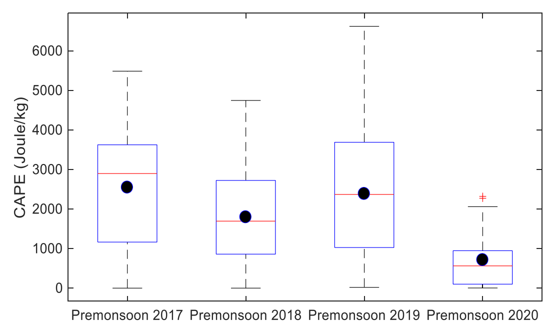

Fig. 2. Box and whisker plot of the CAPE over Kolkata during the pre-monsoon for the years 2017–2020.

A rain event having no presence of bright band is identified as a “convective event,” whereas if bright band structure is present throughout the event, this is designated as a “stratiform event” [10], [18]. The events which occurred for greater than 5 min are only considered. For the stratiform events, the maximum rain rate is less than 10 mm/h and for convective rain, it is greater than 10 mm/h [18]. There has to be a

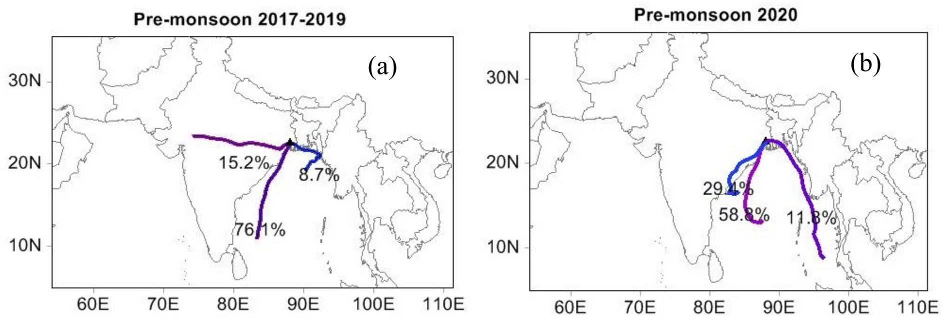

Fig. 3. Back trajectories cluster (at 2000 m agl) for the rainy days during the pre-monsoon over Kolkata for the years (a) 2017–2019 and (b) 2020.

TABLE I
PERCENTAGE OCCURRENCES OF CONVECTIVE AND STRATIFORM RAIN EVENTS IN THE PRE-MONSOON PERIOD (MARCH–MAY) OF 2017–2020 AT KOLKATA

Year	Convective rain Percentage (%)	Stratiform rain Percentage (%)	Total number of rain events considered
2017	68.75%	18.75%	48
2018	68%	18.4%	38
2019	74.35%	17.9 %	39
2020	**45.2 %**	**52.4 %**	**42**

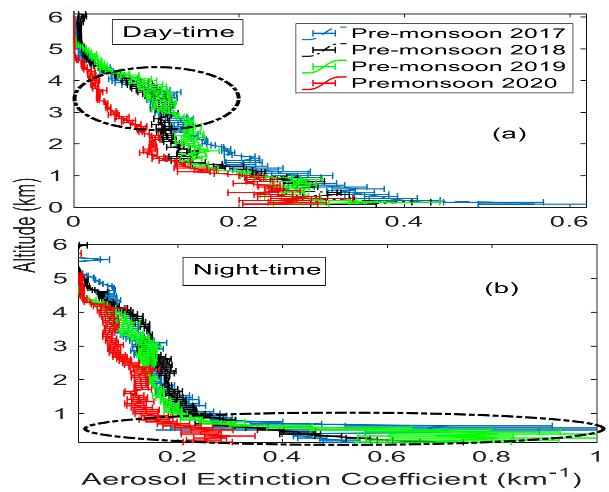

Fig. 4. Height profiles of AEC (/km) over Kolkata obtained from CALIPSO at 532 nm during. (a) Daytime and (b) night time for the pre-monsoon for the years 2017–2020.

gap of 15 min between two consecutive events. It may be noted that the rain events showing features of both convective and stratiform rains are identified as mixed types which are excluded from the present analysis [10]. The statistics of percentage occurrences of the two types of rain events are given in Table I, excluding the mixed type events.

It is evident from Table I that the convective events dominated during the pre-monsoon period in 2017–2019 which is a normal scenario [5], [6], [8], [10]. However, the percentage of stratiform events has significantly increased and even exceeded the percentage of convective events during the pre-monsoon of 2020. Due to the reduced CAPE, the air parcel lacked the sufficient positive buoyant force required for the updraft of the air mass to form convective clouds and, thus, caused much less dominance of convective rain in the pre-monsoon of 2020. This indicates the weakening of convective processes due to much less abundance of heat absorbing aerosols in the absence of anthropogenic activities.

The genesis of convective activities which dominates the pre-monsoon season over Kolkata is attributed to dry, westerly or north-westerly wind inflow from the Chotonagpur plateau region of Jharkhand and southerly warm, moist, wind incursion from the Bay of Bengal giving rise to a highly unstable atmosphere [21]. A cluster analysis of five day back trajectories of air mass at 2000 m above ground level (agl) for all the rainy days of pre-monsoon months during 2017-2019 is done for the location of Kolkata. This reveals a distinct component of air flow from the western or north-western directions to the present location [Fig. 3 (a)]. Long-range transports are conspicuously represented by the trajectory analysis above the boundary layer, and 2000-m agl is considered for the present study [5], [8], [22]. This usual scenario during pre-monsoon season over Kolkata is seen to have altered during the rain events of the pre-monsoon months of 2020 when the reduced anthropogenic activities have occurred. The trajectory clusters of the rainy days of pre-monsoon 2020 are characterized mostly by coastal and maritime components and no distinct continental component is observed, as revealed in Fig. 3(b). This absence of the north-westerly wind cluster during 2020 is due to reduced convective activities over the land surface. The dominant maritime wind contribution to the wind cluster and the absence of distinct continental components during the pre-monsoon are responsible for the increased percentage of stratiform rain occurrence compared to convective events in 2020.

The mean profiles of aerosol extinction coefficient (AEC) at 532 nm in cloud-free condition for daytime and night time during pre-monsoon as obtained from CALIPSO data are shown in Fig. 4 for 2017–2020 over Kolkata. Usually, an elevated aerosol concentration above the boundary layer is observed during the daytime of the pre-monsoon period over the present study location, as also reported from other Indian locations [23]. The secondary aerosols peak around 2.8–4 km (highlighted by dashed circle) during pre-monsoon (daytime) for years 2017–2019 is seen to have disappeared during pre-monsoon 2020 [Fig. 4(a)]. The reduced anthropogenic activities and consequent decreased convection over the present study location have caused suppression of the elevated aerosol layer formed above the atmospheric boundary layer during daytime for the pre-monsoon months of 2020. Also, a significant reduction of aerosol concentration below 1 km (indicated by dashed circle) during night time is seen in 2020 compared to the previous years [Fig. 4(b)]. The absence of secondary peaks during night time in normal years is due to the fact that convection is negligible during this time so most of the aerosols are concentrated near the surface within the atmospheric boundary layer as revealed from the enhanced AEC below 1 km [6], [14]. During 2020, due to restricted human activities, aerosol concentration is significantly low near the surface during night hours which is also supported by the surface BC measurements. It may be noted that the satellite observations of MODIS, MetOp-B, and CALIPSO do not exclusively represent locally generated aerosol concentration at a particular location. They, however, give a gross picture of aerosol environment over Kolkata in commensurate with the local aethalometer measurements [5], [6], [14].

IV. Conclusion

The effects of city lockdowns on aerosol environment in relation to the prevailing atmospheric instability and precipitation have been investigated using ground-based and spaceborne observations over a highly polluted metropolitan location, Kolkata, India. The lockdown has caused a drastic drop in heat absorbing aerosol content of the atmosphere. The atmospheric instability in terms of CAPE has notably decreased during the pre-monsoon 2020 which has coincided with the lockdown phase in comparison with the same period of 2017–2019. Owing to reduced CAPE, the rain event occurrence pattern has altered during the pre-monsoon 2020 in comparison with the normal pre-monsoon years 2017–2019. The unusual dominance of stratiform rain has been observed over Kolkata during the pre-monsoon 2020 from Ka-band MRR. The rain events of 2020 pre-monsoon have occurred mainly from the maritime contribution of wind flow. A distinct continental component of wind flow from the north–west/west of Kolkata, which significantly contributes to the convective genesis, is not observed during the lockdown phase. The restricted anthropogenic activities and the reduced convection have caused suppression of the secondary aerosol peak above the boundary layer during the pre-monsoon of 2020 over the present location.

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