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ARTICLE

Some Features of Black Carbon Aerosols Connected with Regional Climate Over Pristine Environment

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ABSTRACT

The authors report the results of aethalometer black carbon (BC) aerosol measurements carried out over a rural (pristine) site, Panchgaon, Haryana State, India during the winter months of 2021–2022 and 2022–2023. They are compared with collocated and concurrent observations from the Air Quality Monitoring Station (AQMS), which provides synchronous air pollution and surface meteorological parameters. Secular variations in BC mass concentration are studied and explained with variations in local meteorological parameters. The biomass burning fire count retrievals from NASA-NOAA VIIRS satellite, and backward airmass trajectories from NOAA-ERL HYSPLIT Model analysis have also been utilized to explain the findings. They reveal that the north-west Indian region contributes maximum to the BC mass concentration over the study site during the study period. Moreover, the observed BC mass concentrations corroborate the synchronous fire count, primary and secondary pollutant concentrations. The results were found to aid the development of mitigation methods to achieve a sustainable climate system.

Keywords: Carbonaceous aerosols; Dual-spot technique; Temporal variations; Primary and secondary pollutants; Stubble burning; Long-range transport; Satellite products

1. Introduction

Black carbon (BC) is regarded as a gas tracer of combustion inefficiency, and a precursor of carbon dioxide and tropospheric ozone [1]. It has a negative effect on health because it is a key structural part of

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fine particulate matter, which transports numerous other chemical components [2] and is a major contributor to aerosol-induced air pollution [3–5]. BC is abundant in the environment, including soils, ice, sediments, and the air. BC was discovered to make up 12–31% of the sedimentary organic components at two deep ocean locations that are thousands of years old [6]. During the industrial era, the consumption of fossil fuels and biofuels increased significantly, resulting in a considerable increase in atmospheric BC emissions [7–14]. Approximately 20% of BC is emitted by the combustion of biofuels, 40% by the combustion of fossil fuels, and 40% by the combustion of open biomass [3,15]. India is the world's second largest BC emitter after Africa [3,16] with emissions expected to climb substantially in the future decades [17]. This is mostly because low-efficiency home fuel combustion accounts for 47% of Indian BC emissions, followed by industry emissions (22%), transportation (17%), and open burning (12%) [18]. In Indo Gangetic Plains (IGP), wintertime BC concentrations are large (around 60%), caused by emissions from biofuel combustion for cooking and heating in the residential home sector [19]. Because of the level of industrialisation, transportation density, and fuel usage for electricity generation and in households, the BC concentrations will inevitably be very area dependent and seasonally fluctuating [20].

With a lifespan of a few days to weeks, BC is a transient air contaminant, unlike other potent greenhouse gases, (carbon dioxide and methane with life cycles of more than 100 and 12 years respectively). The longevity of BC in the atmosphere, its impact on clouds, and its optical qualities are all affected by interactions with other aerosol components. BC is produced in conjunction with several aerosols and aerosol precursor gases. BC readily combines with other aerosol components in the atmosphere. This mixing enhances BC's light absorption, improves its ability to form liquid-cloud droplets, changes its ability to form ice nuclei, and modifies its atmospheric removal rate [21]. During its brief atmospheric lifetime, BC is transported regionally and across continents. Precipitation and surface contact remove atmospheric pollutants within a few days to weeks. As a result, BC concentrations in remote regions of the atmosphere are substantially lower than in source regions [22]. BC has a climate forcing of 1.1 W/m^2, it warms the Earth by absorbing sunlight, heating the atmosphere, reducing albedo when it settles on snow and ice (direct effect), and indirectly interacting with clouds [3]. Through a variety of extremely intricate processes, BC influences the features of ice clouds and liquid clouds. These mechanisms include increasing the number of liquid cloud droplets, increasing precipitation in mixed-phase clouds, and affecting the number of ice particles and cloud extent. The ensuing radiative changes in the atmosphere are regarded as BC's indirect climatic consequences [23]. Due to its light-absorbing qualities, BC also contributes significantly to low visibility [24]. It has the highest ability to absorb light per unit mass in the atmosphere. Because of its high absorption over a wide wavelength range, it has the potential to considerably neutralise or even reverse the "white house" effect caused by aerosol scattering [25,26].

The atmospheric BC poses a significant hazard to human health both directly through exposure to toxic chemicals and indirectly through climate change and their impact on life-supporting systems on Earth because of long-range transport and growing population [27]. During its short period of residence, it causes various health problems like cardiovascular disease, respiratory problems, cancer and even birth defects. Recent studies on the health effects of airborne particles demonstrate a clear link between combustion-derived particles, notably BC, and cardiovascular disease and mortality (CVD and CVM) [28,29]. Population exposure to BC is significant, with over 60 million people recognized as living in BC concentration hotspots (wintertime mean, > 20 ug/m^3) [19]. The megacity's attributable proportion of overall cardiovascular disease mortality (CVM) burden to BC exposures is 62%. The semiurban area accounted for approximately 49% of the overall BC-attributable CVM burden across the IGP. More than 400,000 lives might be saved each year from CVM by prioritising emission reductions from the combustion of

domestic biofuel in semi-urban areas, diesel oil in transportation, and coal in megacities' thermal power plants and brick kiln industries [19]. It was concluded that BC, rather than PM, could be an effective supplemental air quality indicator for assessing air quality health concerns [30]. Reducing BC has been suggested as one of the simplest strategies to slow down short-term global warming by the IPCC and other climate researchers [31]. Because BC is readily taken from the atmosphere by deposition, concentrations respond swiftly to reductions in emissions. Thus, reducing BC emissions represents a viable mitigation technique that could lower anthropogenic global climate forcing in the short term while also slowing the corresponding rate of climate change [32].

To analyse the problem of air pollution, it is critical to understand its sources, the impact of various meteorological elements on dispersion, and the topography of a city [33]. Due to its short residence time, complicated interactions with other atmospheric pollutants, inadequate monitoring (especially in India), and significant effects on the environment and human health, BC is a threat to everyone and needs to be mitigated. In this study, BC mass concentrations were reported during the winter period at a rural site in North India. The basic objectives were to determine temporal variations in BC concentration (diurnal, day to night, weekdays to weekends), its interactions with other air pollutants (PM2.5, PM10, CO, Ozone, C_6H_6) meteorology, influence of other parameters like fire events and wind dispersion patterns.

2. Material and methodology

The BC measurements in the present study were made with a Magee Scientific, USA Next-Generation Aethalometer Model AE33 (**Figure 1D**). It provides a real-time readout of the BC mass concentration at each data point at the specified time basis [34–37]. Once-a-minute BC data was obtained from aethalometer which was then averaged depending upon plot type (variation). For diurnal variation and weekday to weekend studies, full data was used (without any average), while for day to night contrast studies, daily mean data was used. For correlation purposes, daily averaged values of BC and other variables were used. It detects optical attenuation by measuring the attenuation of the light beam passed through the sample location. This equipment continually collects and examines aerosol particles. An aerosol-rich air stream is passed through the filter strip at a measured flow rate. At the same time, the strip is illuminated by light-sensitive detectors, which measure the intensity of light passing through the unilluminated part of the strip, which serves as a reference point, compared to the collection point. As the optically absorbing material accumulates, the intensity of the light passing through it gradually decreases. A decrease in light intensity from one measurement to the next is interpreted as an increase in the material being collected. That increased amount is divided by the known airflow to calculate the concentration. Moreover, the instrument used in the present study collects two sample points of the same intake airflow at different collection rates and analyses them simultaneously. These two results are mathematically combined to eliminate the "Filter Loading Effect" nonlinearity and accurately measure the aerosol concentration. In addition, the analysis is performed at 7 optical wavelengths covering the spectrum from 370 nm to 950 nm. More details are available in Sonbawne et al. (2021) [38]. The mass concentration of BC is estimated by using the following formula available in the User Manual [39].

$$BC = S*(DATN/100) / [(1-G) *\sigma_{air} * C * (1-K*ATN) *AT] \quad (1)$$

where S is spot area (sq. cm), ATN is optical attenuation, F is flowrate (LPM), T is time (sec), σ_{air} is mass absorption cross-section (m^2/g), C is multiple scattering parameters, K is compensation parameter and G is leakage parameter.

The increase in optical absorption at shorter wavelengths can be interpreted as the presence of so-called "brown" carbonaceous material, which is usually an indicator of emissions from biomass burning [40].

A Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model was utilized to create backward trajectory plots. It replicates the dispersion

and trajectory of substances carried and diffused through the atmosphere at various ranges ranging from local to global. It also computes pollutant dispersion, chemical transformation, and deposition in the atmosphere. In this study vertical trajectory model was used in obtaining backward trajectories at a height of 100 m and a duration of 96 hours. The whole month's trajectories were averaged for the monthly frequency trajectory plot (with a new trajectory starting every 6th hour) [41,42].

The region's fire count data was taken from the Fire Information for Resource Management System (FIRMS). It disseminates almost real-time active fire data from the MODIS and the VIIRS, with the latter's data being used due to its significantly higher resolution. The VIIRS was onboard the Suomi National Polar-orbiting Partnership (Suomi NPP) and NOAA-20 satellites, which were jointly operated by NASA and NOAA. VIIRS gathers visible and infrared pictures, as well as worldwide studies of the Earth's surface, atmosphere, cryosphere, and ocean. VIIRS expands on observations made by similar sensors aboard previously deployed satellites, such as NASA's MODIS and NOAA's Advanced Very High-Resolution Radiometer (AVHRR). VIIRS snow cover and sea ice algorithms have been optimized for compatibility with MODIS snow cover and sea ice datasets, ensuring continuity between MODIS and VIIRS data products and allowing for comparison of snow and sea ice data across MODIS, VIIRS, and beyond to simplify long-term climate data records [43].

For the present study, a rural station, Panchgaon (28.317°N, 76.916°E, 285 m above mean sea level) in Haryana State was chosen, which is situated around 50 km away from Delhi, India. **Figure 1A** displays a schematic diagram of the experimental site and the location of observations. It can be seen from the figure that in the northeast direction, two industrial hubs, namely, Manesar and Gurugram are present. Every time the northeasterly wind blows, pollutants are transported to the study site [44]. The site is located approximately five kilometres south of the Delhi-Jaipur National Highway (NH48) and is surrounded by Aravalli hillocks with an average altitude of around 200 m. Moreover, the Aethalometer, as depicted in the figure, was set up on the Institute Building's terrace (roughly 15 m AGL) free of surrounding terrain such as tall buildings and trees that would disrupt the flow patterns of BC particles in the air. The site is polluted by distant stationary sources such as brick kilns and mobile sources such as nighttime traffic, especially when heavy vehicles circulate on NH48. Open burning is also taken into consideration as one of the local sources of BC aerosols because of the rural setting around the study site.

Figure 1. A photograph depicting (A) Geography around the Amity University Haryana (AUH), (B) Areal view of the University Complex, (C) Four-stored Academic Block 'A' and its terrace where a suit of sensing instruments is installed, and (D) Multi-wavelength Aethalometer used for continuous measurements of simultaneous BC mass concentration (ng/m^3) and Biomass Burning (%).

3. Results and discussion

The results of the analysis of the observations made in the winter months of 2021–2022 and 2022–2023 are presented and discussed, and salient features are summarized in the following sub-sections. The mean diurnal change in BC mass concentration during the study period is illustrated in **Figure 2**. The last two weeks of December and the first week of January showed the highest BC aerosol pollution throughout the day at the study site, during this time the temperature at the sites plummets to a minimum. A high concentration during morning hours and early night hours is also apparent from the contour map (**Figure 2**). Such variations are further explained in the sub-section 3.1. The reduction in BC concentra-

tion with the progression of the season is apparent (December > January > February). As it is a rural site, BC concentrations are moderate throughout the study period.

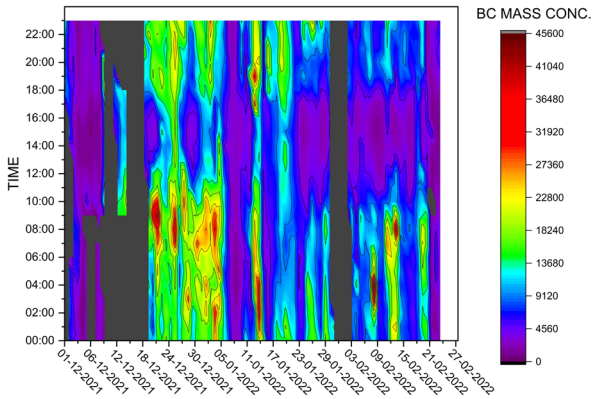

Figure 2. Composite diagram of BC concentration (ngm^{-3}) over Panchgaon during the winter period of 2021–2022.

3.1 Diurnal variation in BC aerosol mass concentration

Some notable diurnal variations were observed during the study period at the site. Diurnal variations can be utilized to understand the effect of meteorology and human activities, and PBL which influence the pollution levels in the atmosphere. Such variations help in the assessment of the relative air quality throughout the day. **Figure 3** depicts diurnal variations during December 2021, January, and February 2022. There is a distinct bi-modal distribution in the diurnal variation in BC mass concentration, with a major peak occurring in the morning and a secondary peak occurring in the evening hours (early night). The morning peak is ascribed to be due to the influence of transit associated with school-going children, office-going employees/workers, and the start of stores, among other things. As the day progresses, greater solar heating causes a deeper and more turbulent boundary layer, resulting in faster dispersion and hence dilution of BC near the surface [45]. A minimum diurnal concentration of BC is apparent during late afternoon hours (around 16:00 h). This late afternoon minimum is owing to the renowned effect of local boundary layer thickness and dynamics. The secondary peak is caused by the fumigation effect. The increase in BC concentration during the night could be attributed to the frequent instances of burning activities in the location, mostly to provide warmth against the cold during the winter months, which is rather usual in rural areas. Low-level inversion-like conditions lead to the formation of a boundary layer or mixing height during the study period [5,46], which predominates for a longer time during the night and early morning hours, resulting in reduced diffusion of submicron size aerosols [47–49]. This is consistent with the results reported by other investigators [50–53].

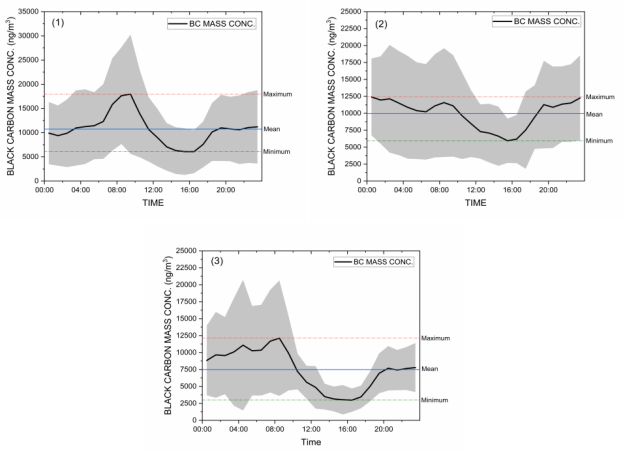

Figure 3. Monthly mean diurnal variations [(1) December 2021, (2) January 2022, (3) February 2022] observed during the study period of winter 2021–2022. The grey shaded portion around the mean curve in each frame indicates the variability in each data point. The range of BC mass concentration (maximum, average and minimum) observed in each month is also indicated in the figure.

Table 1 depicts the maximum, minimum, and mean diurnal values of BC mass concentration for each month. December exhibited maximum mean concentration, and the pollution level was mostly consistent. January exhibited middling concentration values, with an unequal distribution of high and low BC concentration days. For February the lowest BC pollution was observed, with a moderate spread of daily values from the mean value. The decrease in BC aerosols with winter progresses is possibly due to the seasonal meteorology change, and utilization of some inefficient (polluting) heating sources in the houses during wintertime.

Table 1. Percentage deviation of BC mass concentration against its mean value during the study period.

Month	Maximum (ng/m^3)	Minimum (ng/m^3)	Mean (ng/m^3)	Above mean (percentage)	Below mean (percentage)
December	17953.61	6076.94	10750.20	20.45%	20.45%
January	12414.95	5949.72	9949.95	14.30%	23.84%
February	12118.22	2975.34	7492.09	30.05%	35.49%

3.2 Day-night variations in BC aerosols

This sub-section addresses the aspect of how BC aerosols vary during daytime and nighttime. As nighttime weather circumstances differ greatly from daytime weather conditions, notably the planetary boundary layer (PBL) height, ambient temperature, and wind speed would impact the presence of pollutants in the air. **Figure 4** shows day to nighttime contrast. The BC nighttime concentration nearly invariably prevails as compared to the daytime concentration [54]. The high BC concentrations observed during December month are most likely due to the impact of regional meteorological variables (such as temperature, wind speed, direction, humidity, and so on) and these are modulated by stubble-burning activity in and around the study region [55]. The level of BC in the land air rises at night when there is a predominant land breeze. The ventilation coefficient rapidly decreases at night because the nocturnal boundary layer is shallower than the daytime counterpart and the wind speeds are lower [56]. The dates with high peaks during daytime as well as nighttime are majorly due to the local meteorology, long-range transport, and inversion conditions [57,58], as there could not have been a major difference in the local pollution sources in such a short duration.

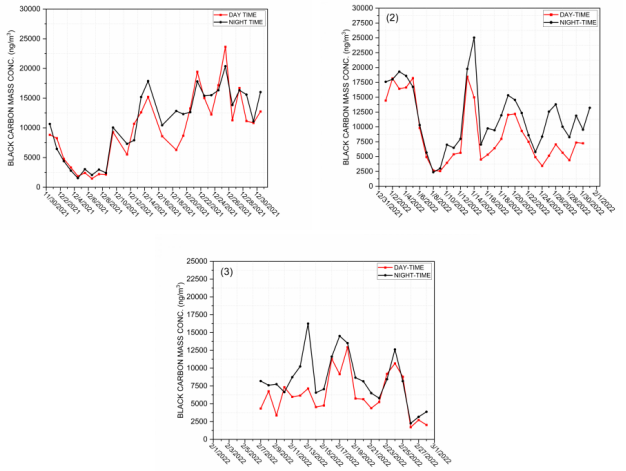

Figure 4. Monthly mean day and night variations in BC aerosols observed during the investigation period of winter 2021–2022. [(1) December 2021, (2) January 2022, (3) February 2022]

3.3 Weekdays and weekends variations in BC aerosols

The impact of anthropogenic activities and associated meteorological processes on BC aerosols during weekdays and weekends are studied in this sub-section. This variation mostly signifies the influence of anthropogenic activities on pollutant concentrations.

Figure 5 shows that BC mass concentrations are higher during the weekdays than on weekends [59], which corresponds to higher human activity during the weekdays [60]. Vehicles are a key source of BC aerosols, which are more prevalent during the weekdays than on weekends (and higher concentration during weekdays strengthens this presumption). Since most anthropogenic activities (industries, biomass burning etc.), apart from transportation, are ongoing throughout the week, it might be possible to estimate the contribution of vehicles in the BC concentration in an area by comparing the BC concentration on weekdays and weekends (especially between 8 and 9 a.m.). Even in this variance, the occurrence of a bimodal distribution demonstrates the importance of meteorology over anthropogenic activities. The higher concentrations during evening time on weekends can be attributed to the weekend effect (increased tendencies of hanging out, shopping, cinema, village house visits etc. on weekends). This effect is most dominant during December month, although high human activities, as well as

the compressed boundary layer, can be the reason for this pollution peaking [61,62]. During January month, weekdays dominated weekends by a considerable margin and the difference between weekdays and weekends aerosol concentration during the midnight got maximum, which was completely opposite of what we observed during rest two months. The marginal increase in BC mass concentration during weekends in the early hours of February could be due to additional sources of small gatherings with waste burning for warmness in the vicinity of the study site.

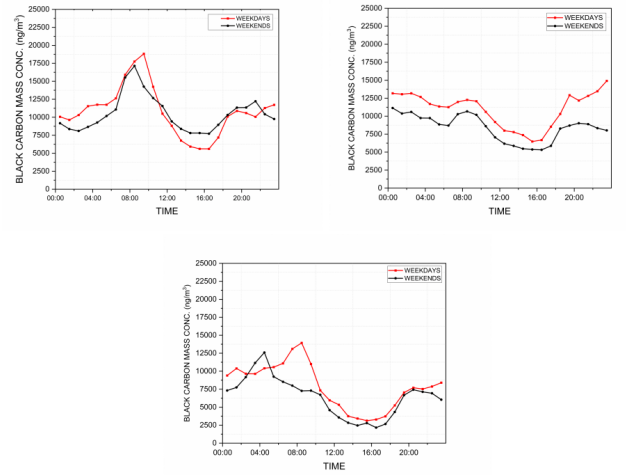

Figure 5. Monthly mean diurnal variation of BC on weekdays and weekends during the study period. [(1) December 2021, (2) January 2022, (3) February 2022]

3.4 Interaction between BC aerosols and meteorological parameters

The unexpected trends observed over three months indicate that there must be some factor(s) influencing the quantity of BC aerosols in the air. To have a better understanding of this, the concurrent time fluctuations in BC mass concentration and key meteorological parameters (humidity, temperature, and wind speed) were examined, and the findings are described in this section.

Association between relative humidity (RH) and BC aerosols

The graphs in **Figure 6** show the association between RH with BC mass concentration. Such relationships between BC concentration and relative humidity can be made use of to examine the nature of the aerosols (hydrophilic or hydrophobic) at the study site, and any hindrance by humidity can affect their residence time. **Figure 6** shows the trend in daily average values of BC and RH (in steps of 10%) for the three months. Even though no sharp positive or negative relation is visible, there are multiple instances where a decreasing trend is apparent, and some peaks and troughs are visible (at the same time or with some lag). Higher RH values associated with lower BC concentration were noticed in January and February months. The negative relationship between RH and BC aerosols was also reported by various researchers [63,64]. The negative relation might implicate towards the abundance of absorbing type aerosols over this region, and possible scavenging of aerosols under high humid conditions. This negative interaction is not totally consistent throughout the study period, demonstrating the complexity of these pollutants (hydrophilic versus hydrophobic, interaction with other parameters) and the potential influence of other meteorological conditions.

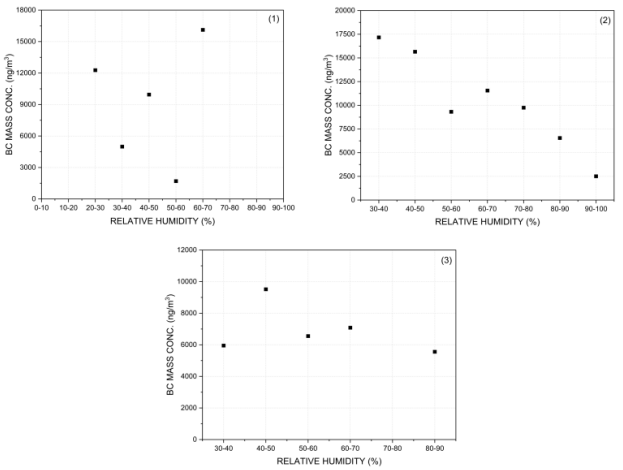

Figure 6. Relationship between BC mass concentration and RH in (1) December 2021, (2) January 2022, and (3) February 2022.

Interaction between temperature and BC mass concentration

Figure 7 depicts the daily mean variation of BC mass concentration with temperature (in a 2-degree interval). It is clear from the figure that there is no systematic relationship between BC mass concentration and temperature. During December and January

(winter) months, BC mass concentration initially increased with an increase in temperature up to about 18 degrees, and subsequently, this trend decreased at the higher temperature of around 20 degrees. This relationship was found to be inverse i.e. initially decrease in BC mass concentration up to about 20 degrees and increased up to 22 degrees at the end of winter season (February 2022). This could be due to limited data size, variability in the local boundary layer height and source strength of BC aerosols in the study region.

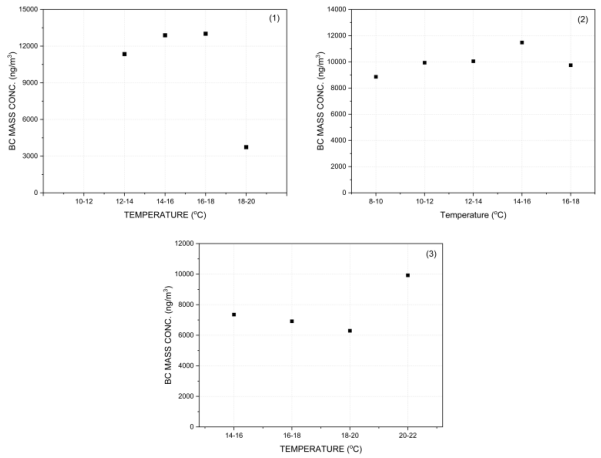

Figure 7. Relationship between BC mass concentration and temperature (1) December 2021, (2) January 2022, and (3) February 2022.

Most of the time, it is clear from the figure that higher temperature values are associated with lower BC concentration. The relationship between BC and temperature can be bidirectional, like temperature can influence BC and vice versa. BC aerosols have light absorbing properties [24], so they can lead to an increase in ambient temperature. When temperature rises, more convective activity leads to the dispersion of aerosols in an enlarged boundary layer [65].

Wind speed and BC mass concentration

The relationship between BC mass concentration and wind speed during the study period is depicted in **Figure 8**. Here daily averages of BC concentrations are plotted with daily averages of wind speed.

It is apparent from **Figure 8** that the relationship between wind speed and BC aerosols in the air is negative [66]. When wind speed increases BC mass concentration at the site decreases, because BC aerosols have a very small size (less than 2.5 microns), wind plays an important role in the dispersion of these microscopic aerosols in the air. Wind direction, wind speed, and proximity and direction of aerosol sources to the monitored site are crucial because the dispersion of aerosols due to wind occurs in two directions: wind disperses pollutants from a site to surroundings as well as from the surrounding to that site. The wind also has an impact on the BC mass concentration, like the other two parameters (temperature and relative humidity) under examination. All three graphs show this negative connection, however, there are some inconsistencies in the trend of these two parameters, but the concentration of BC was always low during high wind speeds however the opposite wasn't always true, showing mixed outcomes at low wind speeds. Other studies among researchers also showed mixed results depending on wind speed, direction, and lengths of wind period [67]. Local wind and long-range air mass trajectories influence the aerosol concentrations, the latter one is depicted in section 3.6.

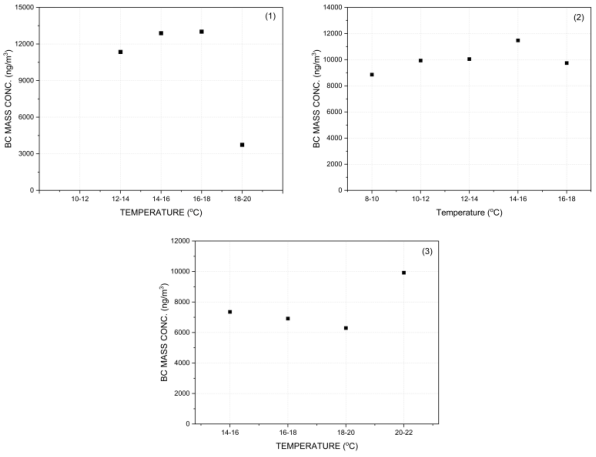

Figure 8. Same as Figure 6, but for wind speed intervals for the three months, (1) December 2021, (2) January 2022, (3) February 2022.

Correlation analysis between BC mass concentration and meteorological parameters

Pearson correlation coefficient between BC and meteorological parameters was calculated to determine the linear correlation. Its value is in the –1.0 to 1.0 range. A perfect negative correlation is shown by a correlation of –1.0, and a perfect positive cor-

relation is shown by a correlation of +1.0. No linear relationship exists between the two variables, as indicated by a correlation of 0.

We can infer from **Table 2** that the wind speed and BC mass concentration, as well as the daily minimum temperature, are always negatively correlated. The association between relative humidity, on the other hand, is negative for two months and positive for the remaining one, like maximum temperature association, but for opposite months. This variation in trend over the course of the three months demonstrates the presence of another parameter that was regulating BC mass concentrations during that time, and these might be associated with time lag/lead.

Table 2. Correlation coefficients were calculated between BC mass concentration and meteorological parameters.

	Temperature (Max.)	Temperature (Min.)	Wind speed	Relative humidity
December 2021	–0.37	–0.44	–0.23	0.26
January 2022	0.34	–0.45	–0.44	–0.58
February 2022	0.48	–0.06	–0.53	–0.11

3.5 Affinity between BC aerosols and other air pollutants

In this section, the associations between BC aerosols and other air pollutants are discussed. Air pollutants focussed on this section are PM2.5, PM10, CO, Ozone, and Benzene. Because of the certain common sources (combustion based) and types (BC-PM) between these parameters some kind of interaction can be expected. For the correlation plots, daily average values of variables are taken. And, due to data irregularities, data for 2022–2023 winter is taken for charting (of all variables).

Relationship between BC aerosol and PM2.5 concentration

For the months of December, January, and February, a regression analysis was performed between BC aerosols and PM2.5, which is depicted in **Figure 9**. BC is a part of particulate matter, which means it will make some proportion of PM at the study site, to check its extent, a correlation coefficient was calculated.

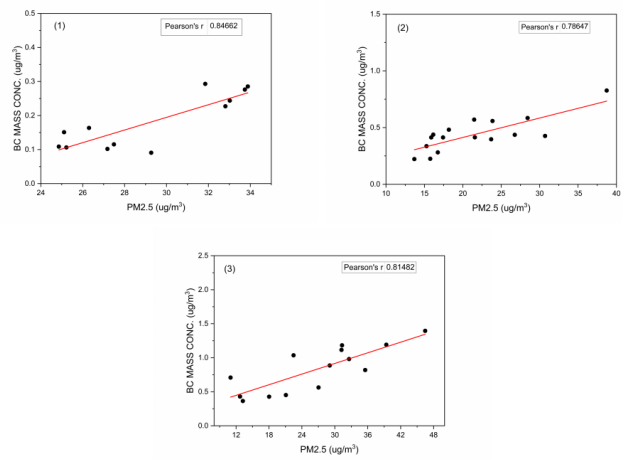

Figure 9. Association between BC aerosols and PM2.5. [(1) December 2021, (2) January 2022, (3) February 2022]

The correlation coefficient between BC mass concentration and PM2.5 was positive, with values of 0.84, 0.78, and 0.81 for December, January, and February respectively. This positive correlation indicates a significant and steady proportion of BC aerosols in PM2.5 [68] throughout the three months at the study site. The modest associations could be attributed to differences in the sources of BC and PM2.5 (and PM2.5 is a secondary pollutant too) [69]. These findings are congruent with those published in the literature by other researchers [5].

BC aerosol and PM10 concentration

The following plots (**Figure 10**) depict the correlation between BC aerosols and PM10 during the December, January, and February months.

The correlation coefficient between BC and PM10 was low with values of 0.48 for December, 0.08 and 0.001 for the January and February months, respectively. PM10 is made up of course (soil-derived dust particles, pollens) as well as fine particles (PM2.5), while BC aerosols are very fine particles (part of PM2.5), so moderately poor correlation for PM10 than PM2.5 is inherent, but in this case, the coherence between PM10 and BC was too low. The residence time of PM10 (coarser) particles is usually shorter than its fine particle subpart. The ambiguous relationship between PM and BC may be explained by the fact that when coupled with the stagnant atmosphere at low temperatures in

winter [70], PM and BC concentrations are potentially influenced by both autochthonous and input particles (source difference) [68].

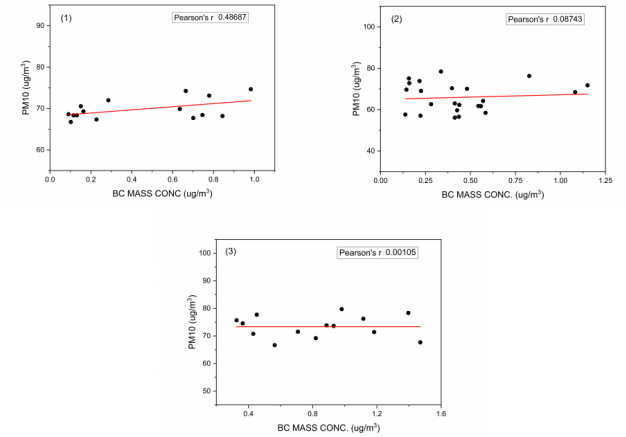

Figure 10. Same as Figure 9, but for PM10.

BC aerosols and CO

The following plots (**Figure 11**) show the regression analysis of BC aerosols and carbon monoxide during the December, January, and February months.

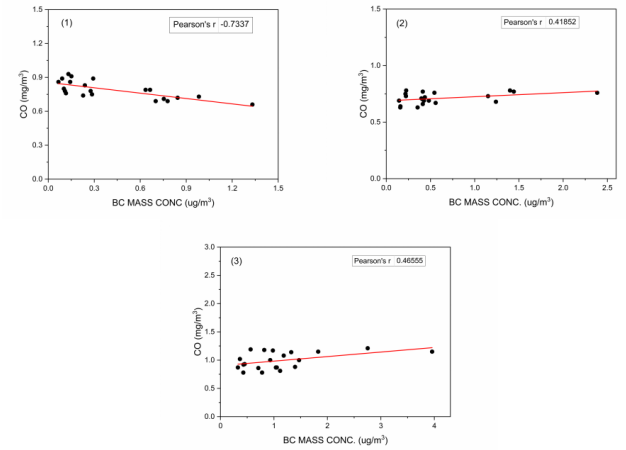

Figure 11. Same as Figure 9, but for CO.

The obtained correlation of BC aerosol and carbon monoxide was ambiguous throughout the three months, significantly negative for the December month (–0.73) while positive for the January and February months (0.41 and 0.46 respectively). Other studies have also reported a similar positive correlation between CO and BC, where both share common sources [70]. As both BC aerosols and CO are by-products of incomplete combustion, some positive correlation between the two is expected, but in this case, it was not significant. Such ambiguity could be a result of data limitations, different composition, and nature of variables in the atmosphere as well as differences in combustion processes (types) at the sources, even meteorology, but their extent is unknown.

BC aerosols and O_3

The following plots (**Figure 12**) depict the regression analysis of BC aerosols and ozone during December, January, and February 2022.

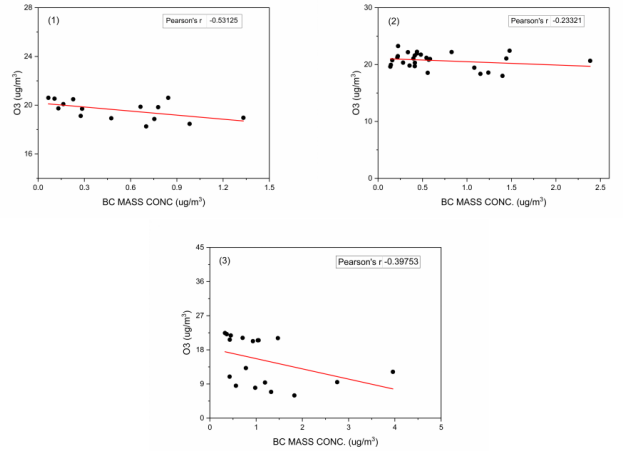

Figure 12. Same as Figure 9, but for ozone.

A negative association between BC aerosols and surface ozone was observed, with correlation coefficient values of –0.53 for December, –0.23 for January, and –0.39 for February, which matched with other studies [71,72]. These two parameters show opposite characteristics, e.g., BC peaks during the morning and early night hours and plummets during the afternoon (diurnal variations) while ozone peaks during the afternoon (high temperature). The hindrance in ozone formation reaction is possibly the major reason for the antagonist relationship. Research works have shown that by absorbing solar energy, BC lowers the photolysis coefficient, influencing the quantity of ozone near the ground [73]. The absorbing impact of BC heats the air above the BL, suppressing and delaying the growth of the BL, finally leading to a shift in surface ozone through an alteration in the contributions from chemical and physical processes (photochemistry, vertical mixing, and advection) [74].

BC aerosols and benzene

The following plots (**Figure 13**) depict the regression analysis of BC aerosols and benzene, for

the December, January, and February months.

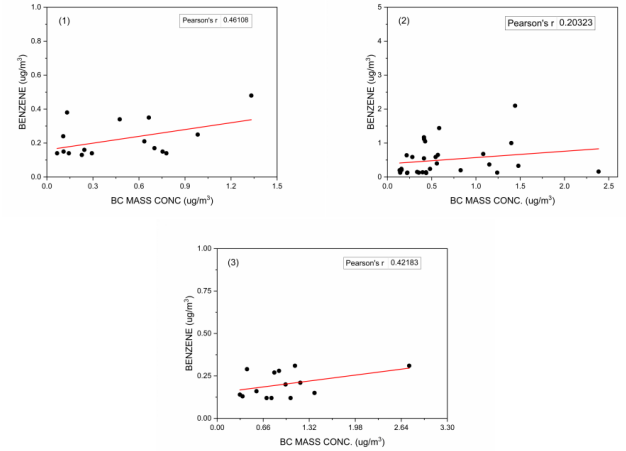

Figure 13. Same as Figure 9, but for Benzene.

A moderately positive correlation can be observed between BC and benzene for three months (0.46, 0.20, and 0.42 for December, January, and February, respectively) (**Table 3**). Benzene emissions are more concentrated towards chemical processes (chemical industry, brick kiln, smoking etc.). A positive correlation between the two can signify the possible contribution from surrounding chemical industries/brick kilns to the BC mass concentration [75]. Mostly brick kilns are in proximity to the study sites. There hasn't been much research into the interaction of BC with benzene.

Table 3. Correlation coefficient between BC aerosols and various air pollutants.

	PM2.5	PM10	O_3	CO	C_6H_6
December	0.84	0.48	–0.53	–0.73	0.46
January	0.78	0.09	–0.23	0.41	0.20
February	0.81	0	–0.39	0.46	0.42

3.6 Long-range transport of BC aerosols

Back trajectory maps were created using the HYSPLIT dispersion model to analyse the long-range transport of BC mass concentration to this site. Long-range transport is depicted using properly colour coded Trajectory Frequency and Cluster Means plots. Trajectory frequency has an average of hundreds of backward trajectories during a month, run for 96 hours at a height of 100 m at the study site.

Airmass characteristics during December 2021, January, and February 2022

The airmass back trajectory analysis shows that pollutants in the northwest direction contribute the most pollution (approximately 69%). This significant contribution is primarily the result of stubble burning events in Punjab State and the north-west districts of Haryana. Although stubble burning events are lower in December than in November (peak season), they are still sufficient to raise pollution levels at the study site. During January 2022, pollution dispersion is more widespread in the site's surrounding areas. The most came from the northwest (43%) direction. Wind is the most important factor in pollutant dispersion, and it correlated well with BC concentrations in January. The pollution outbreak during February appears to be dominated (78%) by the regions lying in the northwest direction. Wind speed during this month was found to be weak.

Relationship between fire count and BC mass concentration

The fire events, mostly from open burning and associated combustion processes (one of the principal sources of BC aerosols), are likely to have an impact on the BC mass concentration at the site. The analysis of data for December 2021, January, and February 2022 indicates no significant relationship between fire count and BC mass concentration. The reasons could be either a large separation between the fire locations and the aerosol monitoring site or unfavourable wind conditions. There were some overlapping peaks in both, but they were not consistent across the study period. Although there appear to be some similarity, nevertheless open burning is one of the major sources of BC aerosols in these regions. Studies have indicated a direct relationship between surface BC levels and biomass burning [76], and BC is an excellent aerosol indicator of wildfires and biomass burning [77,78].

4. Conclusions

The motivation of the present study was to better understand the undulations in BC mass concentration and their relationship with natural/anthropogenic activities and variations in surface-level meteoro-

logical parameters during winters 2021–2022 and 2022–2023.

The key findings from the study are listed below:

● The mass concentration of BC aerosols was found to be lower and well within the safety range as compared to any urban site.

● The diurnal variation of BC mass concentration exhibited two maxima, one in the morning and the other in the late evening hours.

● The night-time BC concentrations are low as compared to those during the daytime, possibly due to less human activity, low temperature, and strong winds at night. This clearly demonstrates the significance of meteorological parameters in modulating BC concentrations over Panchgaon. Importantly, the influence of transport processes (both local and long-range) on BC variations over Panchgaon caused by surrounding Aravalli hillocks (valley-like) and resulting katabatic wind-flow patterns should not be ignored.

● Weekday BC concentrations were found to be higher than the weekend BC concentrations. Additionally, midday concentrations of BC are higher than nighttime ones. This might be a result of the high daytime convective activity, which aids in lifting more BC aerosols from the study site's surface and the vicinity.

● BC mass concentrations at the study site are found to be significantly influenced by both local and long-range sources.

● Relative humidity exhibits a negative relationship with BC mass concentration, indicating that the BC aerosols above the study area are predominantly absorbing (hydrophobic), leading to local warming.

● Although no substantial relationship was found between changes in temperature and BC mass concentration it may have an indirect role via local convective boundary layer dynamics.

● Throughout the study, there was a significant negative relationship between wind speed and BC mass concentration. The obvious reasons for this are the dispersion, dilution, and ventilation processes involved in the BC particle transformations.

● BC had a strong positive relationship with PM2.5 and a weak association with PM10 mass values, indicating some common source.

● A negative correlation between BC and O_3 indicates that BC may inhibit O_3 formation.

● A moderate positive correlation was found between BC and Benzene mass concentration, which might be due to nearby brick kilns located close to the study site.

● Trajectory analysis of long-range transport indicates that BC aerosols in the northwest (NW) direction contribute the most (50–60%). This is attributed mainly to stubble-burning activity in that direction.

● Fire emissions (count) from stubble-burning activity had a limited correlation with BC mass concentration, which may be attributed to the low number, poor brightness of the fire, low winds, and greater separation between the source (fire site) and the study location.

Author Contributions

Saurabh Yadav: Data downloading, analysis, plotting, table compilation and draft preparation. Panuganti C.S. Devara (Corresponding Author): Research idea, conceptualization, methodology, review, and editing. S. M. Sonbawne: Data analysis and plotting. B. S. Murthy: Data retrieval and analysis. S. Tiwari: Data analysis. S. Wadhwa: Data curation. A. Kumar: Data analysis and plotting. All authors read and approved the final manuscript.

Conflicts of Interest

The authors reported no potential conflicts of interest.

Data Availability Statement

The datasets used in this study are available on request by contacting the Corresponding Author of the paper.

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