Tuijin Jishu/Journal of Propulsion Technology
ISSN:1001-4055
Vol. 44 No.4 (2023)

Trends of Atmospheric Black Carbon Concentration over the Bengaluru

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Abstract:This study investigates the spatial and temporal variations of atmospheric black carbon (BC) concentrations in Bangalore, focusing on the period from June 2018 to May 2020. BC mass concentrations were measured using a portable micro-Aethalometer (model: AethLabs AE-51) at seven different locations, representing a range of land use types from rural to urban areas. The study aimed to assess BC pollution levels, identify hotspots, and understand the factors influencing BC concentrations. The results revealed significant variations in BC concentrations among the different locations. The highest BC concentrations were observed in urban traffic and industrial areas, with average concentrations of 6.21 µg/m³ and 6.78 µg/m³, respectively. Urban centres also exhibited high BC levels, with an average concentration of 7.40 µg/m³. In contrast, rural areas recorded the lowest BC concentrations, with an average of 2.51 µg/m³. These findings highlight the influence of anthropogenic activities and land use patterns on BC pollution levels. Diurnal variations in BC concentrations exhibited distinct patterns, with significant peaks during morning and evening hours, primarily associated with increased traffic emissions. The study also identified seasonal trends, with higher BC concentrations observed during winter months, attributed to stable atmospheric conditions and increased fuel consumption for heating purposes. Notably, BC concentrations were generally lower during summer months due to higher wind speeds and increased vertical mixing of pollutants. The findings of this study emphasize the need for targeted mitigation strategies to reduce BC pollution in Bangalore. The identified hotspots, such as urban traffic and industrial areas, require specific attention to mitigate the adverse health and environmental effects of BC emissions. Furthermore, the study underscores the importance of comprehensive air pollution management approaches that consider both local emissions and meteorological factors to effectively tackle BC pollution.

Keywords:*Black carbon, Urban Air pollution, Seasonal Variation, Diurnal Variation, Air quality Monitoring.*

1. Introduction

The introduction of atmospheric aerosols, whether originating from anthropogenic activities or natural sources, can have both direct and indirect effects on the Earth's climate system. These aerosols play a significant role in climate change and the overall atmospheric radiation budget. Various activities such as incomplete biomass/biofuel combustion (e.g., residential cooking and heating), the burning of fossil fuels such as diesel and coal, forest fires, and crop residue burning, release substantial quantities of black carbon (BC) particles into the atmosphere (Ramanathan and Carmichael, 2008; Bond et al., 2013; Tiwari et al., 2016). Black carbon emissions are the second-largest contributor to climate warming after CO_2(Park et al., 2010; Bond et al., 2013; Singh et al.,

2017, Vaishya et al., 2017). BC directly affects climate by absorbing sunlight and indirectly through alterations in cloud properties and precipitation efficiency (Ramanathan and Carmichael, 2008; Lohmann and Feichter, 2005). The presence of BC in the atmosphere leads to reduced visibility, the formation of dense haze, fog, and smog, which impacts both regional and global climate, human health, and vegetation. Additionally, BC plays a unique and crucial role in the Earth's climate system by absorbing solar radiation, influencing the melting of snow and ice cover, and modulating cloud processes (Ramanathan and Carmichael, 2008; Lohmann and Feichter, 2005).

Aerosols not only have a global impact but are also associated with significant health effects, particularly in relation to cardiopulmonary and respiratory diseases (Stoeger et al., 2006). They also contribute to reduced visibility (Jiang et al., 2005; Khan et al., 2018) discovered that atmospheric BC particles, due to their sub-micron size range, have lifetimes ranging from several days to weeks and can be transported over thousands of kilometers, thereby influencing regional climate change. The long-range transport of fine particles can exacerbate BC concentrations in urban areas, which are already affected by local urban emissions. In a modeling analysis, Singh et al., 2014, estimated that the urban increment, including contributions from urban traffic and other urban sources, accounted for an average of 18%, 33%, 39%, and 43% of total $PM_{2.5}$ in suburban environments, the urban background, near roads, and near busy roads, respectively.

Black Carbon (BC), which is one of the anthropogenic aerosols and a light-absorbing component of the atmospheric aerosol system, is emitted into the atmosphere through the incomplete combustion of fossil fuels, biofuels, and biomass burning. It plays a unique role in the climate system (Bansal et al., 2019). BC aerosols efficiently absorb solar radiation across visible and infrared wavelengths. Marinoni et al. (2010)noted that they exhibit strong light absorption characteristics over a wide range of wavelengths, leading to atmospheric heating, surface cooling, and impacts on regional climate and air quality (Ramanathan and Carmichael, 2008; Bond et al., 2013, Bansal et al., 2019). BC aerosols have a longer atmospheric lifetime in the lower troposphere and significantly influence regional climate, making them a primary contributor to atmospheric radiative heating (Bansal et al., 2019).

Meteorological parameters, such as wind speed (WS), planetary boundary layer (PBL) heights, relative humidity (RH), and solar radiation (SR) during long-range transport, govern the concentrations of BC in the atmosphere, as observed by (Bond et al., 2013). Previous studies have highlighted the impact of rainfall on BC mass concentrations through scavenging processes (Tiwari et al., 2013; Ramanathan et al., 2005; Latha and Badrinath, 2005). The Intergovernmental Panel on Climate Change (IPCC) reported a mean direct radiative forcing of 0.4 $W \cdot m^{-2}$ due to global BC aerosols (IPCC-2013). Additionally, Levy et al. (2007) emphasized the significant contribution of BC aerosols to global warming through solar radiation absorption, ranking BC as the second most important warming agent in the atmosphere after CO_2(Bond et al., 2013). Babu and Moorthy (2001)proposed that the wet deposition process serves as the primary mechanism for removing carbonaceous aerosols (fine-sized particles) from the atmosphere.

Rana et al. (2019) have documented that India ranks as the second-largest emitter of soot particles (BC) globally. Consequently, monitoring efforts for BC have been initiated in India over the past decade, revealing high BC aerosol concentrations in the northern region. These elevated BC levels in northern India have implications for regional climate, including alterations in precipitation patterns (Satheesh and Ramanathan, 2000; Babu et al., 2002; Latha and Badrinath, 2004; Safai et al., 2013; Lee et al., 2013; Kompalli et al., 2014; Saha and Despiau, 2009; Safai et al., 2013; Mues et al., 2017; Kalluri et al, 2017). Paliwal et al. (2016)reported that BC emissions in India primarily stem from domestic fuel combustion (47%) and industrial emissions (22%), with the remainder attributed to the transport sector (17%), open biomass/biofuel burning (12%), and other sources (2%). It was highlighted the significant increase in anthropogenic emissions, particularly in South Asia, which has resulted in severe air quality concerns. Understanding and characterizing air pollutant sources, their impact on local and regional environments, and conducting radiative forcing assessments on local and global scales, as well as health impact studies, are crucial aspects.

Against this backdrop, this study focuses on the investigation and presentation of black carbon concentrations in the Bangalore region. Bangalore, the capital of Karnataka, holds the distinction of being the first information technology hub in India and is often referred to as the "Silicon Valley" of India. In 2007, the Greater Bengaluru Municipal Corporation was established through the amalgamation of approximately 100 wards from the former Bangalore MahanagarPalika, along with seven city municipal councils, 110 surrounding villages, and a town municipal council. The city has witnessed a rapid growth in the Information Technology industry, resulting in significant traffic congestion. Furthermore, the construction of housing to accommodate the expanding population has contributed to air pollution in the form of resuspended dust. Over the past decade, there has been a substantial increase in the demand for housing, leading to the expansion of the city beyond its previous boundaries. These factors have collectively contributed to the rise in air pollution levels in the Bangalore region.

To comprehensively estimate the atmospheric black carbon (BC) emission load over Bengaluru, the present study critically examines real-time atmospheric BC observations recorded during 2018-2020. The analysis encompasses data collected from seven stations located in different settings, including rural, peri-urban, airport zone, urban residential, urban traffic, urban center, and industrial areas. The study specifically focuses on investigating the seasonal and diurnal variations in atmospheric BC concentrations at all seven stations during 2018-2020, aiming to provide a better representation of the geographical distribution of BC levels in the region.

2. Site description, data, and instrumentation

From June 2018 to May 2020, data on black carbon (BC) concentrations and meteorological parameters were collected at seven distinct locations in Bangalore, also known as the "Silicon Valley," the capital of Karnataka (Figure 1). These locations encompassed zones of transition between rural and urban land use, situated between the outer boundaries of urban and regional centers and the rural environment. Further details regarding the sites and their descriptions can be found in Table 1.

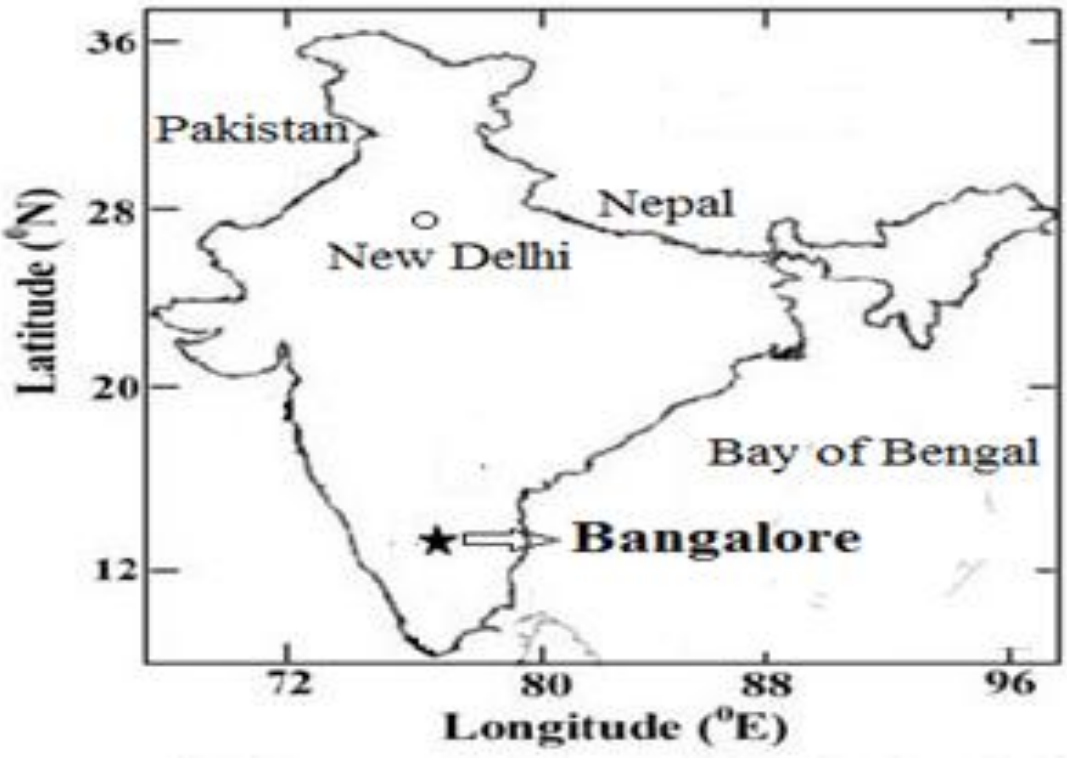

Figure 1: Map of India indicating sampling location (Bangalore)

Table 1: Details of the Sampling Sites

Sl.No	Station Name	Lat	Long	Elevation(m)	Type
1	Dabaspete	13°13'41"N	77°14'32"E	928	Rural
2	Kumbalgodu	12°52'53"N	77°26'47"E	761	Peri-urban
3	Devanahalli	13°14'32"N	77°42'34"E	897	Airport
4	Jayanagara	12°55'18"N	77°35'00"E	909	Urban Residential
5	Corporation	12°58'02"N	77°35'13"E	907	Urban Traffic
6	City railway Station	12°58'39"N	77°34'13"E	902	Urban Center
7	Peenya	13°01'42"N	77°31'11"E	905	Industrial

During the study period, the BC mass concentrations in Bangalore were measured using a portable micro-Aethalometer (model: AethLabs AE-51; San Francisco, CA, USA; https://aethlabs.com) in real-time (Chakrabarty et al., 2012). The instrument used for measurements, the AethLabs AE-51, has been previously described in detail in studies such as (Arnott et al., 2005; Cheng et al, 2014; Dumka et al., 2013; Virkkula et al., 2007), including information on data correction methods for factors like loading and shadowing effects. In a recent study by Cheng et al. (2013), a comparative measurement of two Aethalometer models (AE-51 and AE-31) was conducted under varying relative humidity conditions (55% to 90%), and the results showed satisfactory performance. Based on this, the AE-51 model was utilized at different locations across Bangalore (latitude: 12°58'N; longitude: 77°34'E; altitude: 900 m above sea level), which is situated in the southern part of India on the Deccan Plateau. The data collected from the study period, covering 2018-2020, has been analyzed at the seven stations mentioned earlier, with hourly data obtained from different activity sites as listed in Table 1.

3. Results and discussion

The analysis of atmospheric BC concentrations in Bangalore revealed significant spatial and temporal variations during the study period. The measured BC mass concentrations exhibited distinct patterns across the different monitoring sites, reflecting variations in local emission sources and atmospheric dynamics. Among the monitored locations, the urban center sites consistently exhibited higher BC levels compared to the rural and suburban sites, indicating the influence of anthropogenic activities and traffic emissions in densely populated areas. The kerbside station recorded the highest BC concentrations, highlighting the impact of localized vehicular emissions in close proximity to busy roads.

Table 2: Seasonal Variation in Atmospheric BC Concentration in Bangalore

	Rural	Peri-urban	Aiport	Urban Residential	Urban Traffic	Urban Center	Industrial
Monsoon	2.28	2.69	2.83	2.46	4.64	4.70	3.73
Post-Monsoon	2.49	3.08	2.87	3.70	6.07	6.34	6.75
Winter	2.97	4.40	3.65	4.82	8.98	11.67	11.12
Summer	2.37	3.28	2.81	3.15	5.62	7.43	6.51

3.1 Seasonal variation in atmospheric BC concentration

The seasonal variation in atmospheric BC concentrations for different site categories in Bangalore is displayed in Table 2. The table provides a comprehensive overview of BC concentrations during the monsoon, post-monsoon, winter, and summer seasons In the rural areas, BC concentrations exhibited seasonal fluctuations ranging from 2.28 $\mu g/m^3$during the monsoon to 2.97 $\mu g/m^3$during the winter season. Similarly, peri-urban areas displayed BC concentrations ranging from 2.69 $\mu g/m^3$in the monsoon to 4.40 $\mu g/m^3$in winter. The airport location showed a variation from 2.83 $\mu g/m^3$in the monsoon to 3.65 $\mu g/m^3$ in winter, while urban residential areas exhibited concentrations ranging from 2.46 $\mu g/m^3$in the monsoon to 4.82 $\mu g/m^3$in winter.Significantly higher BC concentrations were observed in areas associated with urban traffic and urban center categories. Urban traffic areas displayed a range of BC concentrations from 4.64 $\mu g/m^3$during the monsoon to 8.98 $\mu g/m^3$in winter, while urban centers recorded concentrations from 4.70 $\mu g/m^3$during the monsoon to 11.67 $\mu g/m^3$in winter. Industrial areas also exhibited substantial BC concentrations, ranging from 3.73 $\mu g/m^3$during the monsoon to 11.12 $\mu g/m^3$in winter.During the post-monsoon season, BC concentrations in the rural areas ranged from 2.49 $\mu g/m^3$to 3.70 $\mu g/m^3$across other site categories. The summer season displayed BC concentrations ranging from 2.37 $\mu g/m^3$to 7.43 $\mu g/m^3$across different site categories (Figure 2).

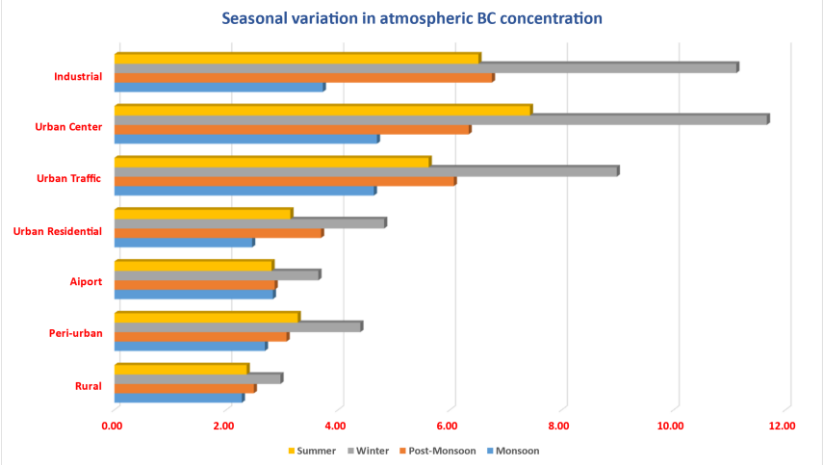

Figure 2: Seasonal variation in atmospheric BC concentration

These results highlight the seasonal variability in BC concentrations and its association with different site categories. The highest BC concentrations were consistently observed during the winter season, attributed to stable atmospheric conditions, lower wind speeds, and increased fuel consumption for space heating. In contrast, the summer season exhibited lower BC concentrations due to higher wind speeds and increased vertical mixing and dispersion of pollutants.The observed seasonal patterns align with previous studies that have reported higher BC levels during winter compared to summer. These findings are consistent with incomplete combustion of organic material and increased emissions during the colder months. Similar seasonal variations have been reported for other pollutants such as $PM_{2.5}$ and Polycyclic Aromatic Hydrocarbons (PAHs) in previous studies.

Understanding the seasonal variations in BC concentrations is crucial for developing effective air pollution mitigation strategies. The findings emphasize the need for targeted measures to reduce emissions from urban traffic, industrial activities, and other anthropogenic sources during periods of higher BC concentrations. Moreover, promoting cleaner technologies, adopting sustainable practices, and enhancing urban planning can help mitigate BC pollution and improve air quality in Bangalore.

3.2 Monthly variation of atmospheric BC concentration

The monthly variation in atmospheric BC concentrations across different site categories in Bangalore is presented in Table 3. The table provides a comprehensive overview of BC concentrations from June to May, reflecting the seasonal changes throughout the year.

In rural areas, BC concentrations ranged from 1.75 $\mu g/m^3$in April to 3.19 $\mu g/m^3$ in January. The highest concentrations were observed during the winter months of December and January, with values reaching up to 10.33 $\mu g/m^3$in December. The lowest concentrations were generally observed in April and May. Similarly, peri-urban areas displayed variations in BC concentrations, ranging from 2.30 $\mu g/m^3$in April to 4.81 $\mu g/m^3$in January. The highest concentrations were observed during the winter months, consistent with the trend observed in rural areas. The lowest concentrations were observed in April and May. At the airport location, BC concentrations ranged from 2.11 $\mu g/m^3$in April to 3.92 $\mu g/m^3$in January. The highest concentrations were observed in December and January, aligning with the peak winter season. The lowest concentrations were generally observed in August. Urban residential areas exhibited BC concentrations ranging from 2.20 $\mu g/m^3$in September to 5.10 $\mu g/m^3$in January. The highest concentrations were consistently observed during the winter months, while the lowest concentrations were observed in September (Figure 3).

The observed monthly variations in BC concentrations highlight the influence of seasonal factors on air pollution levels in Bangalore. The highest concentrations were consistently observed during the winter months, attributed to stable atmospheric conditions, lower wind speeds, and increased fuel consumption for heating purposes. In contrast, the lowest concentrations were generally observed in the summer months, which can be attributed to higher wind speeds and increased vertical mixing and dispersion of pollutants.

These findings are in line with previous studies that have reported similar trends for BC and other particulate matter pollutants. The results emphasize the need for targeted air pollution control measures, particularly during the winter season when BC concentrations are significantly higher. Implementing measures to reduce emissions from traffic, industrial activities, and residential sources can contribute to improved air quality and human health in Bangalore.

3.3 Diurnal variation of atmospheric BC concentration

The diurnal variation of atmospheric BC concentration at different locations in Bangalore was analyzed using the data provided in the table. The concentrations were measured hourly over a 24-hour period for various site categories including rural, peri-urban, airport zone, urban residential, urban traffic, urban center, and industrial areas.

Throughout the diurnal cycle, the atmospheric BC concentrations exhibited distinct patterns at each location. At rural sites, the concentrations ranged from 2.33 µg/m³ during the late-night hours (around 3 a.m.) to 2.82 µg/m³ during the morning hours (around 10 a.m.). The diurnal variation was relatively stable with minor fluctuations, indicating a consistent level of BC concentration in the rural environment (Table 4). In peri-urban areas, the atmospheric BC concentrations ranged from 3.10 µg/m³ during the late-night hours to 3.76 µg/m³ in the morning hours. The concentrations showed a similar diurnal pattern to the rural locations, but with slightly higher values, suggesting a slightly greater influence of local emissions in peri-urban areas.

Table 3: Monthly Variation in Atmospheric BC Concentration in Bangalore

	Rural	Peri-urban	Aiport	Urban Residential	Urban Traffic	Urban Center	Industrial
June	**2.59**	**3.00**	**3.12**	**2.69**	**4.94**	**4.86**	**4.15**
July	**2.33**	**2.85**	**2.99**	**2.57**	**4.72**	**4.99**	**3.91**
August	**2.19**	**2.56**	**2.71**	**2.39**	**4.56**	**4.56**	**3.33**
September	**2.00**	**2.36**	**2.53**	**2.2**	**4.34**	**4.37**	**3.52**
October	**2.26**	**2.67**	**2.52**	**3.57**	**5.49**	**5.66**	**5.7**
November	**2.73**	**3.49**	**3.21**	**3.82**	**6.65**	**7.01**	**7.8**

December	**2.91**	**4.35**	**3.62**	**4.77**	**8.96**	**11.07**	**10.33**
January	**3.19**	**4.81**	**3.92**	**5.1**	**9.71**	**12.42**	**12.22**
February	**2.81**	**4.03**	**3.41**	**4.6**	**8.28**	**11.51**	**10.81**
March	**2.76**	**3.84**	**3.25**	**3.52**	**6.47**	**8.81**	**7.76**
April	**1.75**	**2.30**	**2.11**	**2.51**	**4.57**	**5.44**	**5.09**
May	**2.59**	**3.70**	**3.08**	**3.41**	**5.82**	**8.04**	**6.68**
Annual Avg.	**2.51**	**3.33**	**3.04**	**3.43**	**6.21**	**7.40**	**6.78**

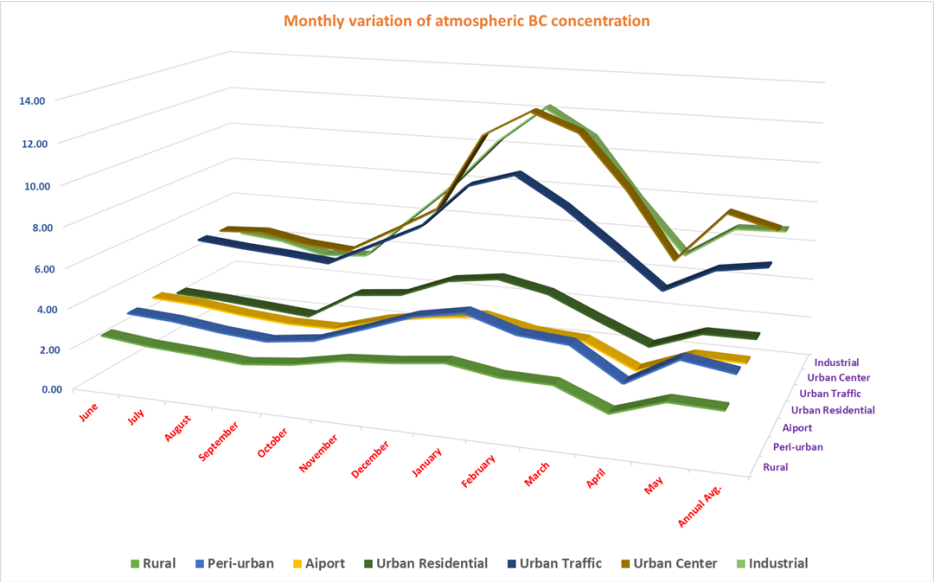

Figure 3: Seasonal variation in atmospheric BC concentration

At the airport zone, the diurnal variation of atmospheric BC concentrations ranged from 2.90 µg/m³ during the late-night hours to 3.38 µg/m³ in the morning hours. The concentrations followed a similar pattern to the rural and peri-urban areas, indicating a relatively consistent level of BC pollution in the airport vicinity. In urban residential areas, the atmospheric BC concentrations ranged from 2.71 µg/m³ during the late-night hours to 4.10 µg/m³ in the morning hours. The concentrations exhibited a significant increase during the morning hours, suggesting the influence of morning traffic and domestic activities on BC emissions.

Urban traffic locations showed the highest diurnal variation, with atmospheric BC concentrations ranging from 4.47 µg/m³ during the late-night hours to 7.55 µg/m³ in the morning hours. These areas experienced a substantial increase in BC concentrations during the morning hours, which can be attributed to the heavy traffic flow and associated emissions. Urban center sites exhibited similar diurnal patterns, with atmospheric BC concentrations ranging from 4.94 µg/m³ during the late-night hours to 9.06 µg/m³ in the morning hours. The concentrations remained relatively high throughout the day, reflecting the intense urban activities and traffic emissions in these areas. Industrial locations showed diurnal variations in atmospheric BC concentrations ranging from 5.10 µg/m³ during the late-night hours to 8.24 µg/m³ in the morning hours. These sites demonstrated relatively higher concentrations during the morning hours, likely due to industrial activities and associated emissions (Figure 4).

The overall diurnal average atmospheric BC concentrations across all locations in Bangalore were 2.51 µg/m³ for rural areas, 3.33 µg/m³ for peri-urban areas, 3.04 µg/m³ for the airport zone, 3.46 µg/m³ for urban residential areas, 6.26 µg/m³ for urban traffic locations, 7.48 µg/m³ for urban center sites, and 6.83 µg/m³ for industrial

Hours	Rural	Peri-Urban	Airport Zone	Urban Residential	Urban Traffic	Urban Center	Industrial
1	2.27	3.01	2.80	2.58	4.76	4.94	5.10
2	2.26	2.99	2.72	2.58	4.70	4.88	4.97
3	2.24	2.97	2.69	2.53	4.59	4.76	5.00
4	2.23	2.95	2.65	2.47	4.47	5.16	5.19
5	2.24	2.95	2.66	2.58	4.85	5.43	5.45
6	2.31	3.04	2.73	2.67	5.37	6.38	6.52
7	2.41	3.17	2.86	3.02	6.25	7.36	7.47
8	2.50	3.41	3.02	3.74	7.07	8.18	7.69
9	2.71	3.62	3.24	4.10	7.52	8.72	8.10
10	2.82	3.75	3.34	4.04	7.55	9.06	8.24
11	2.78	3.76	3.38	3.78	6.79	8.45	7.24
12	2.63	3.50	3.19	3.75	6.12	7.75	6.80
13	2.52	3.40	3.05	3.81	5.90	7.59	6.49
14	2.51	3.28	2.99	3.96	5.79	7.71	6.51
15	2.47	3.29	3.00	3.98	6.20	7.40	6.49
16	2.49	3.34	3.04	3.98	6.68	8.19	6.92
17	2.58	3.41	3.13	4.04	6.98	8.69	7.39
18	2.65	3.50	3.23	4.24	7.88	9.56	8.03
19	2.72	3.59	3.35	4.17	8.16	9.73	8.31
20	2.79	3.69	3.41	4.03	7.84	9.32	8.21
21	2.73	3.60	3.31	3.44	7.20	8.92	7.95
22	2.59	3.42	3.16	3.19	5.91	7.54	7.00
23	2.44	3.19	3.03	2.90	5.31	6.39	6.09
24	2.33	3.10	2.90	2.71	5.07	5.37	5.45
24 H- Avg	**2.51**	**3.33**	**3.04**	**3.46**	**6.26**	**7.48**	**6.83**
Std.Dev	**0.19**	**0.27**	**0.24**	**0.64**	**1.15**	**1.58**	**1.12**

areas. The standard deviation values indicate the variability of atmospheric BC concentrations within each location. The highest standard deviations were observed in urban traffic locations (1.15 μg/m³) and urban center sites (1.58 μg/m³), suggesting significant fluctuations in BC levels throughout the day. In conclusion, the diurnal variation analysis of atmospheric BC concentrations in Bangalore revealed distinct patterns at different locations, reflecting the influence of various factors such as traffic emissions, local activities, and industrial

sources. The findings highlight the importance of considering the temporal variation of BC pollution in understanding its sources and impacts on air quality in urban areas.

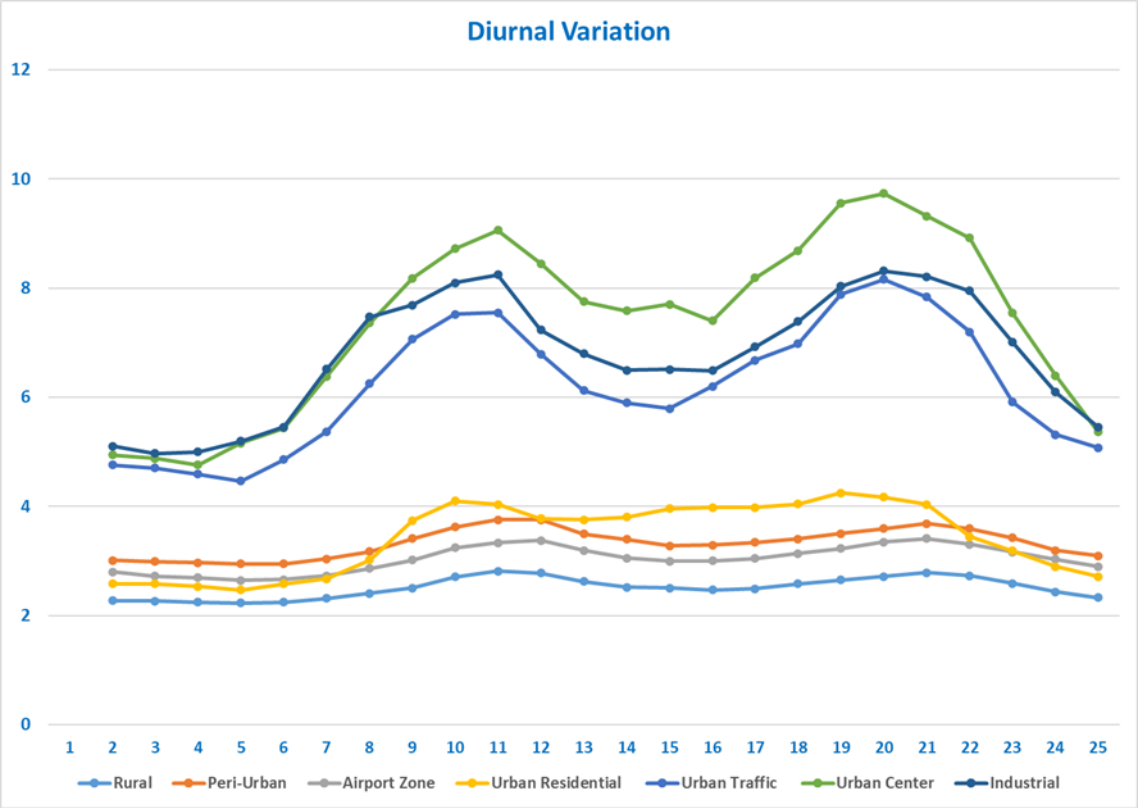

Figure 4: Diurnal variation in atmospheric BC concentration

Table 4: Diurnal Variation in Atmospheric BC Concentration in Bangalore

3.4 Variation in atmospheric BC concentration at different sites

The average BC concentrations observed at different sites in Bangalore provide valuable insights into the levels of pollution in each area. The following discussion examines the average BC concentrations and draws conclusions based on the provided values (Figure. 5 and Table 5):

1. Rural: The average BC concentration in rural areas was measured to be 2.51 µg/m³. This relatively lower concentration indicates that rural locations experience less pollution compared to urban areas. The presence of natural surroundings and fewer anthropogenic activities contribute to the relatively cleaner air quality in rural regions.
2. Peri-urban: The average BC concentration in peri-urban areas was found to be 3.33 µg/m³. Peri-urban areas, which lie on the outskirts of urban centers, experience a transition from rural to urban characteristics. The slightly higher BC concentration in peri-urban areas suggests an increase in pollution levels compared to rural locations due to the proximity to urban activities and emissions.
3. Airport: The average BC concentration in the airport zone was recorded as 3.04 µg/m³. Airports, being busy transportation hubs, experience higher levels of pollution due to aircraft emissions, ground transportation, and other related activities. The measured BC concentration reflects the influence of these sources but remains relatively lower compared to urban centers.
4. Urban Residential: The average BC concentration in urban residential areas was observed to be 3.43 µg/m³. Residential areas in urban settings are influenced by various pollution sources, including vehicular

emissions, cooking activities, and domestic heating. The measured BC concentration indicates the impact of these sources on the air quality of urban residential locations.

5. Urban Traffic: The average BC concentration in urban traffic areas was found to be 6.21 μg/m³. These locations are characterized by heavy traffic flow, congested roadways, and significant vehicular emissions. The substantially higher BC concentration indicates the strong influence of traffic-related pollution, emphasizing the need for effective measures to mitigate air pollution in these areas.

6. Urban Center: The average BC concentration in urban center areas was recorded as 7.40 μg/m³. Urban centers, which include downtown areas and commercial districts, experience intense human activities, including heavy traffic, industrial operations, and densely populated areas. The higher BC concentration at urban center locations highlights the cumulative effect of multiple pollution sources and the need for targeted pollution control strategies.

7. Industrial: The average BC concentration in industrial areas was measured to be 6.78 μg/m³. Industrial zones are characterized by the presence of manufacturing facilities, power plants, and other industrial activities. These activities often emit significant amounts of pollutants, including BC. The elevated BC concentration at industrial sites indicates the contribution of industrial emissions to air pollution in the surrounding areas.

In conclusion, the average BC concentrations at different sites reflect the varying degrees of pollution levels in each location. Rural areas exhibit relatively lower BC concentrations, indicating cleaner air quality, while urban areas, particularly urban traffic, urban center, and industrial sites, exhibit higher concentrations due to the influence of traffic emissions, intense human activities, and industrial operations. These findings emphasize the importance of implementing effective pollution control measures, especially in urban centers and industrial areas, to mitigate the adverse effects of BC pollution and improve overall air quality.

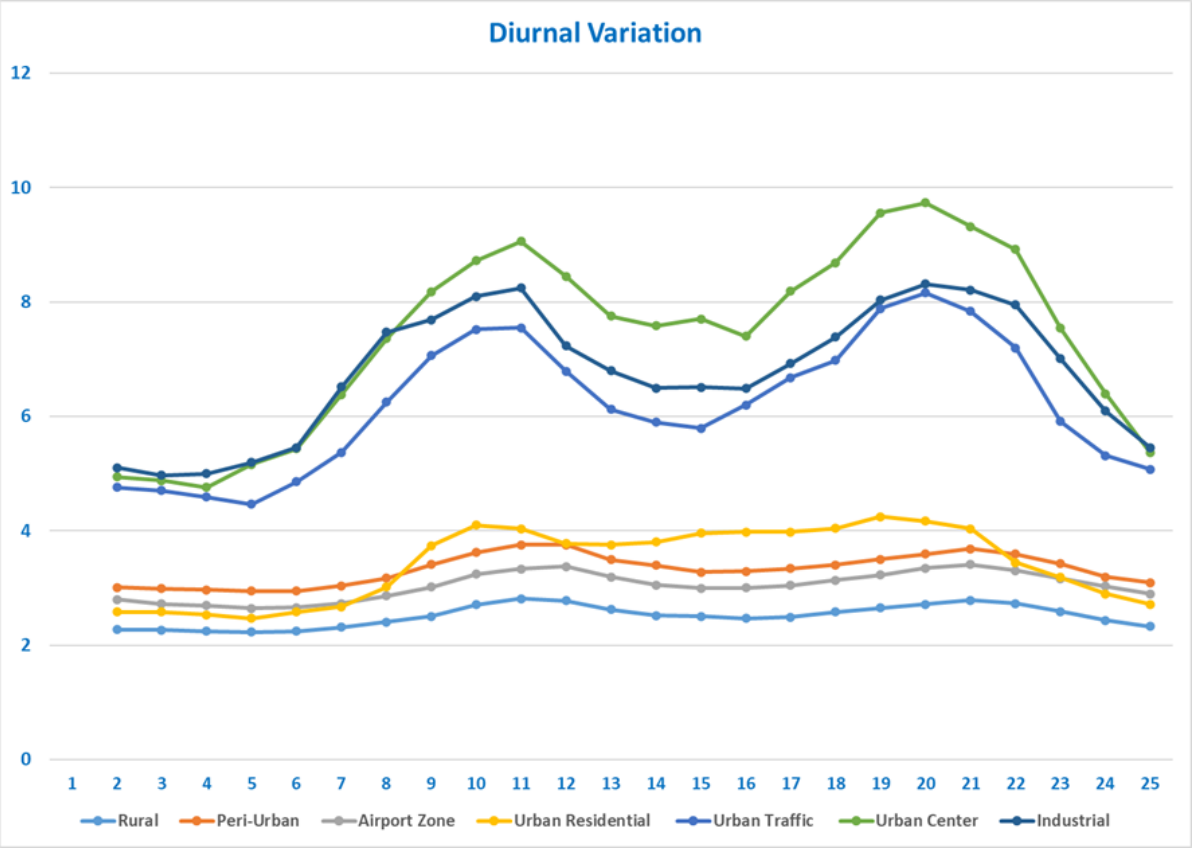

Figure 5: Average variation in atmospheric BC concentration

Table 5: Data for Average variation in atmospheric BC concentration

Site	Average concentration variation
Rural	2.51
Peri-urban	3.33
Airport	3.04
Urban Residential	3.43
Urban Traffic	6.21
Urban Center	7.40
Industrial	6.78

4. Conclusions

In this study, the atmospheric black carbon (BC) concentrations were investigated at various locations in Bangalore. The measurements provided valuable insights into the spatial and temporal variations of BC pollution in the city. The findings revealed that BC concentrations were generally higher in urban areas compared to rural locations, with urban traffic, urban centers, and industrial zones exhibiting the highest levels of BC pollution. Diurnal variations showed significant peaks during morning and evening hours, primarily attributed to traffic emissions. The study also highlighted seasonal trends, with higher BC concentrations observed during winter months due to stable atmospheric conditions and increased fuel consumption for heating purposes. Additionally, the influence of meteorological factors, such as wind speed and planetary boundary layer height, was evident in the observed BC variations. The study's results underscore the need for targeted mitigation strategies to reduce BC pollution, especially in high-traffic areas and industrial zones, to safeguard public health and improve overall air quality in Bangalore. Further research and comprehensive air pollution management approaches are crucial to mitigate the adverse impacts of BC emissions and promote sustainable urban environments.

Acknowledgement: The authors would like to express heartfelt thanks to Dr. Suresh Tiwari, Indian Institute of Tropical Meteorology Department, New Delhi Unit, New Delhi 110060, India. For constant guiding andproviding instruments for the measurement of Black Carbon.

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