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RESEARCH ARTICLE

A study on the trends and seasonal fluctuations of black carbon aerosols in the elevated region of Ooty, Western Ghats, Tamil Nadu, India

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Abstract

The accelerating effects of climate change, driven by rising greenhouse gas emissions, necessitate identifying key contributors like aerosols, mainly black carbon (BC), due to their significant impact on global warming. This study investigates the temporal and seasonal dynamics of BC aerosols in Ooty, Tamil Nadu, India, using a decade (2013–2023) of data from an Aethalometer. Annual BC concentrations varied from 0.51 µg/m^3 (2020) to 1.1 µg/m^3 (2023), with a decadal mean of 0.75 ± 0.26 µg/m^3. Distinct seasonal variations were observed, with summer BC concentrations ranging from 0.9 to 1.6 µg/m^3 (mean: 1.3 µg/m^3) and monsoon values significantly lower at 0.2–0.5 µg/m^3 (mean: 0.4 µg/m^3). Winter exhibited a seasonal mean of 1.1 µg/m^3, while post-monsoon BC concentrations averaged 0.6 µg/m^3. Temperature (20–28.6°C), relative humidity (49–93%), and rainfall (0.4–7.81 mm/day) influenced the observed trends. April consistently showed peak BC levels (up to 1.87 µg/m^3), while 2020 recorded the lowest due to reduced emissions. Seasonal trends revealed increasing BC levels from December to April, declining during the monsoon months (June–November). These findings underscore the need for sustained monitoring and mitigation strategies in high-altitude regions to address BCs' climatic impacts, aiding global efforts against climate change.

Keywords

black carbon aerosols; climate change; high-altitude atmosphere; seasonal patterns; temporal variations

Introduction

Climate change has become an urgent global concern in recent decades, fundamentally reshaping the Earths' atmospheric dynamics and disrupting established weather and temperature patterns. This transformation is primarily driven by the escalating concentrations of greenhouse gases, such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), which act as heat-trapping agents within the Earths' atmosphere, leading to a progressive increase in global temperatures. Notably, the IPCC 5th Assessment for 2022 revealed that the average global temperature had exceeded pre-industrial levels by 1.15 °C, underscoring the swift pace of change. In the array of factors influencing Earths' temperature, aerosols are a significant climate system component. These tiny particles, suspended in the atmosphere, vary in size from nanometers to micrometres (1). Carbonaceous aerosols, the dominant type, elicit both cooling and warming effects by scattering or absorbing solar radiation, depending on their composition, size, and structure. Aerosols such as sulfate cool the atmosphere by scattering sunlight, while black carbon (BC) absorbs radiation, contributing to warming (2). BC is particularly significant among aerosols due to its high warming potential of 2000 times greater than CO_2 and its role as the second-largest contributor to global warming (3).

The deposition of BC on high-albedo surfaces, such as snow and glaciers, accelerates melting by reducing surface reflectivity (4). Additionally, BC particles alter cloud dynamics by acting as nuclei for condensation, reducing droplet sizes, and influencing precipitation patterns (5). These disruptions are magnified in high-altitude ecosystems, where temperature gradients are sensitive to aerosol-induced radiative changes. Regions like the Western Ghats are particularly vulnerable due to their role as biodiversity hotspots and dependence on stable hydrological cycles. The Western Ghats, a UNESCO World Heritage Site, represent a high-altitude ecosystem of global importance. Unique weather patterns, seasonal rainfall, and varying temperatures characterize these mountain ranges. However, increased anthropogenic activities such as tourism, vehicular emissions, and diesel generator usage (6) have led to a steady influx of aerosols, particularly BC. Studies conducted in comparable high-altitude regions, including the Himalayas and the Tibetan Plateau, have shown that BC concentrations negatively impact air quality, snowmelt, and the radiative budget (7,8). For instance, research in the central Himalayan region revealed substantial seasonal variations in BC, with winter peaks due to biomass combustion (9,10). Similar effects were observed in the Tibetan Plateau, where BC deposition on glaciers accelerated ice mass loss (11).

In Ooty, situated at an altitude of 2520 m, anthropogenic activities compound natural aerosol sources, creating unique interactions within the atmosphere. Its significance as a hill station and the ISRO ARFI environmental observatory operation provides an ideal setting for studying aerosol-climate interactions. Research shows that BC concentrations in Ooty are influenced by long-range transport and local emissions, reflecting broader atmospheric trends (12,13). Furthermore, the sensitivity of high-altitude ecosystems like the Western Ghats necessitates a detailed understanding of BCs' seasonal and temporal variations and their influence on radiative processes and weather patterns. This study extends beyond physical aerosols by also considering bioaerosols, airborne fragments of microorganisms, plants, and other biological matter. These aerosols, classified as viable or non-viable, contribute to the spread of infectious agents, allergens, and respiratory disorders (14). High-altitude conditions characterized by lower temperatures, UV radiation, and reduced water availability can affect bioaerosol viability and distribution (15). With its varying altitudinal gradients and environmental monitoring facilities, Ooty provides a unique opportunity to study bioaerosols alongside physical aerosols.

Despite being a key contributor to global warming and air quality degradation, BC aerosols remain underexplored in high-altitude environments. Given the complex interplay between aerosols, meteorological factors, and ecological systems, this study aims to quantify BC variations in Ooty, emphasizing their seasonal and temporal characteristics. Additionally, by analyzing bioaerosols at the ISRO ARFI Environmental Laboratory, this research investigates their implications for health and climate in the region. The findings aim to inform strategies for pollution control, climate mitigation, and conservation in sensitive high-altitude ecosystems like the Western Ghats.

Materials and Methods

Description of the study site

Udhagamandalam, also popularly known as Ooty, is located in the Western Ghats (Latitude - 11° 25'27" N, Longitude - 76°43'27" E) of southern India and distinguished by its serene environment and distinctive climatic conditions, attributable to its position within one of the regions' highest mountain ranges. The presence of the Indian Space Research Organisation Aerosol Radiative Forcing in India (ISRO ARFI) Environmental Observatory, situated at an altitude of 2520 meters above sea level, underscores the scientific and ecological relevance of this area (Fig. 1). Nonetheless, as a prominent hill station and a favoured

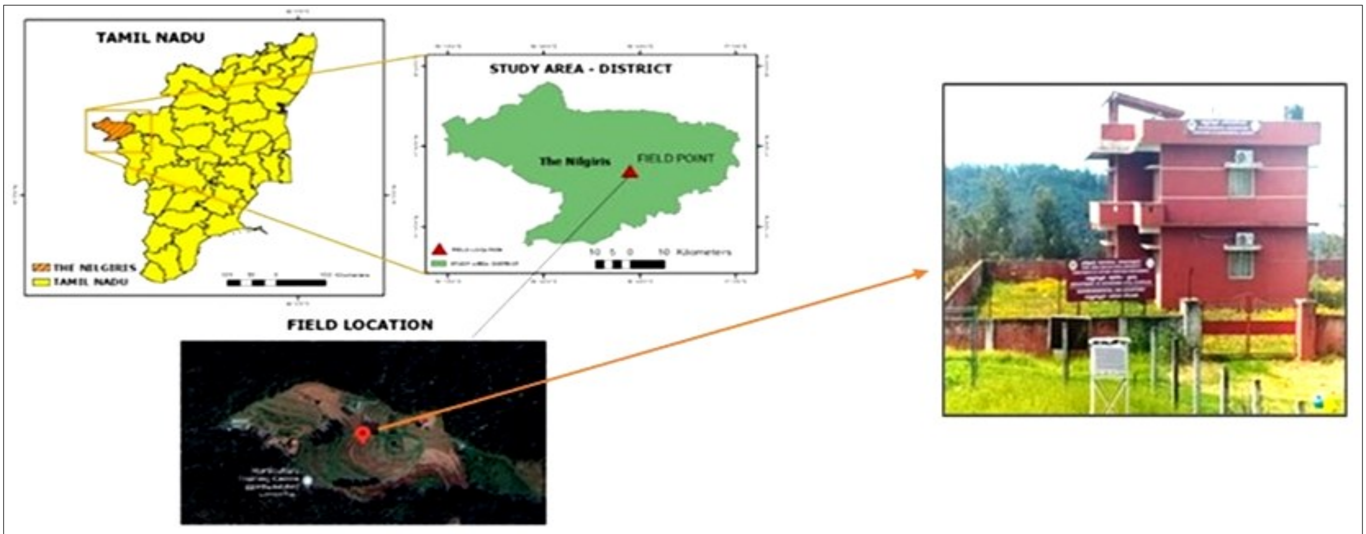

Fig. 1. ISRO-ARFI study site at Ooty, Tamil Nadu.

tourist destination, Ooty experiences a considerable increase in vehicular traffic, particularly during peak tourism periods (Feburay-May). These vehicles' combustion of fossil fuels, combined with emissions from diesel generators and industrial processes, results in the atmospheric release of black carbon particles (13, 16). This underscores the critical need for systematic monitoring and mitigation strategies to address black carbon pollution and safeguard this region's environmental integrity and ecological equilibrium.

Black carbon aerosols continuous monitoring using an aethalometer (AE-31)

This study focused on the continuous real-time measurement of Black Carbon (BC) aerosols using the seven-channel Aethalometer (model AE-31, Magee Scientific, USA) at the Aerosol Radiative Forcing over India Network (ARFINET) observatory. Data collection was conducted at a temporal resolution of 5 minutes over approximately 10 years, from January 2013 to July 2023, excluding 2016, when the instrument was undergoing maintenance due to a combination of monsoon hurricanes and a technical snag. The lack of data in 2016 was acknowledged, and the missing data points were not included in the long-term trend analysis. This ensured that the absence of data in a single year did not skew the overall temporal trends or affect the statistical validity of the study. The Aethalometer is a well-established and robust instrument widely used in aerosol research to quantify ambient BC mass concentrations in diverse environments, including remote, urban, and high-altitude locations. The AE-31 model was chosen for its capability to provide real-time, high-resolution measurements of BC concentrations across multiple wavelengths, making it suitable for aerosol characterization in diverse settings. However, limitations such as sensitivity to filter loading effects and humidity may introduce minor biases in BC measurements, requiring careful data correction. Numerous studies have validated its reliability and applicability in studying aerosol characteristics. (17-23).

As the aerosol collection substrate, the Aethalometer employs a quartz fibre filter tape selected for its high purity, thermal stability, and humidity resistance. Aerosol particles in the sampled air are deposited onto the filter as a discrete spot. The instrument measures the attenuation of light passing through the filter, which decreases in intensity due to absorption by the deposited particles. This attenuation is directly proportional to the BC loading on the filter tape. To determine the BC concentration, the instrument calculates the difference in light transmission between the particle-laden sample spot and a reference spot on the filter. The corresponding absorption coefficient is then computed, representing the light absorption by BC particles in the sample. The Aethalometer operates at seven optical wavelengths (350, 470, 520, 590, 660, 880, and 970 nm). Among these, the attenuation measured at 880 nm is considered the standard for BC quantification, as BC predominantly absorbs light at this wavelength, with minimal interference from other aerosol components. Factory-calibrated wavelength-dependent conversion factors are applied to translate absorption coefficients into "equivalent BC mass" concentrations.

This instruments' capability to provide high temporal resolution and multi-wavelength data makes it an invaluable tool for monitoring BC aerosols in diverse atmospheric settings. By analyzing the long-term BC dataset collected, this study aims to uncover trends and variations in BC mass concentrations, contributing to a better understanding of the role of BC aerosols in atmospheric processes and their impact on the environment of Ooty, Tamil Nadu, India.

Meteorological data obtained from IMD

The India Meteorological Department (IMD) systematically collects extensive meteorological data through its observatories, weather stations, and remote sensing instruments network. This data undergoes rigorous processing, quality assurance, and often interpolation onto a grid to generate comprehensive spatial representations of various meteorological parameters. Gridded data, within the context of the IMD, refers to meteorological and climatological datasets organized in a grid format. This approach involves dividing the geographical domain into grid cells, where each cell corresponds to a specific location and contains meteorological attributes such as temperature, precipitation, and humidity. These gridded datasets are widely applied in scientific research and operational domains, including weather forecasting, climate modelling, and environmental studies. In this study, IMDs' gridded data complements the primary dataset by providing spatially distributed meteorological parameters, helping to contextualize the BC measurements about broader meteorological patterns. While the gridded data aligned well with observed trends, some discrepancies were observed during localized extreme events, where the grids' resolution failed to capture finer regional variations, potentially introducing small biases into the analysis. The IMD provides gridded observation datasets for maximum temperature (TMAX) and minimum temperature (TMIN) with a spatial resolution of 1°×1° and a temporal resolution of daily intervals. Ground-based meteorological observations from stations across India form the foundation for these datasets subjected to stringent quality control procedures. To ensure compatibility with rainfall and future datasets, the maximum and minimum temperature data were refined to a resolution of 0.25°×0.25°. IMD gridded precipitation data is also available at the exact 0.25°×0.25° spatial resolution. Since 1951, these datasets have been developed using an average of 3100 meteorological stations daily, making them a key reference dataset for India.

IMD gridded datasets covering January 2013 to June 2023 for the present study were utilized as reference data. The collected data includes relative humidity, rainfall, wind speed, and maximum and minimum temperatures. This dataset critically analyzed meteorological trends and variations over the specified period.

Statistical analysis

A statistical analysis investigated potential linear relationships between black carbon (BC) concentration and various dependent variables. Standard deviation estimates were computed using MS Excel, while correlation coefficients between BC concentration and each dependent variable were calculated using Origin and R software. This correlation analysis aimed to assess the nature and strength of associations between variables, with correlation coefficients ranging from -1.0 to 1.0. A positive correlation indicates that an increase in one variable corresponds to a rise in the other. In contrast, a negative correlation implies that an increase in one variable is associated with a decrease in the other. A correlation coefficient 0 suggests no significant relationship, indicating that the variables are statistically independent.

Results

Monthly variations in BC concentration and meteorological parameters

The study identified higher black carbon (BC) concentrations in March across multiple years: 1.63 μg/m^3 (2013), 1.7 μg/m^3 (2015), 1.55 μg/m^3 (2017), 1.66 μg/m^3 (2018), 1.49 μg/m^3 (2021), 1.41 μg/m^3 (2022), and 1.43 μg/m^3 (2023). April concentrations were slightly lower, with 1.87 μg/m^3 (2014), 1.44 μg/m^3 (2019), and 0.96 μg/m^3 (2020). Over the entire study period, the annual average BC concentrations were: 0.88 μg/m^3 (2013), 0.85 μg/m^3 (2014), 0.82 μg/m^3 (2015), 0.84 μg/m^3 (2017), 0.85 μg/m^3 (2018), 0.57 μg/m^3 (2019), 0.51 μg/m^3 (2020), 0.58 μg/m^3 (2021), 0.62 μg/m^3 (2022), and 1.1 μg/m^3 (2023), resulting in an overall mean of 0.75 ± 0.26 μg/m^3. Notably, the BC concentration was lowest in 2020 (Table 1).

Seasonal analysis of BC aerosol concentration and meteorological parameters

BC concentrations during summer ranged from 0.9 μg/m^3 to 1.6 μg/m^3, averaging 1.3 μg/m^3. This season was associated with warmer temperatures (average 26.5°C) and relative humidity of 69.8%. In contrast, monsoon BC concentrations were lower, ranging from 0.2 μg/m^3 to 0.5 μg/m^3, with an average of 0.4 μg/m^3. Post-monsoon concentrations ranged from 0.3 μg/m^3 to 0.9 μg/m^3, with a mean of 0.6 μg/m^3. The monsoon period featured significant rainfall (6.6 mm/day) and cooler temperatures (24.1°C), while post-monsoon conditions saw temperatures averaging 23.46°C and relative humidity of 84.74 % (Fig. 2–5). The data also covers seasonal BC concentrations and meteorological parameters (winter, summer, monsoon, post-monsoon) from 2013 to 2023. Winter BC concentrations ranged from 0.6 μg/m^3 to 1.4 μg/m^3, with an average of 1.1 μg/m^3. During winter, temperatures averaged 23.3°C (Fig. 2), rainfall was 0.9 mm/day (Fig. 3), and relative humidity averaged 63.2% (Fig. 4). Seasonal trends (Fig. 5) showed BC concentrations increasing from December to April, followed by a decrease from June to November, a pattern observed across all years. Ambient temperatures fluctuated between 20°C and 28.6°C. Relative humidity varied from 49 % to 93 % (Fig. 3), and rainfall exhibited seasonality, with higher values from July to October (5.70–7.81 mm) and lower values from December to March (0.40–3.8 mm) (Fig. 4).

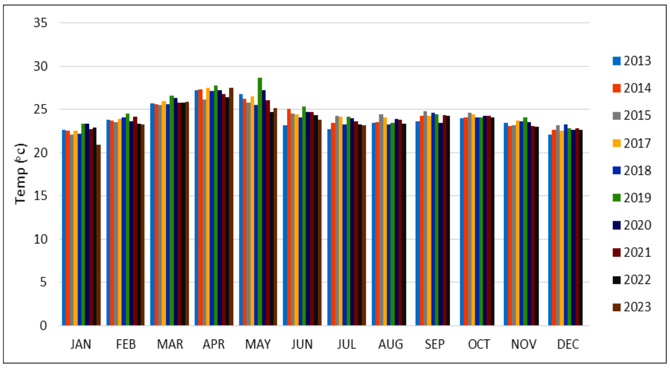

Fig. 2. Monthly variation of temperature over the years of 2013 to 2023.

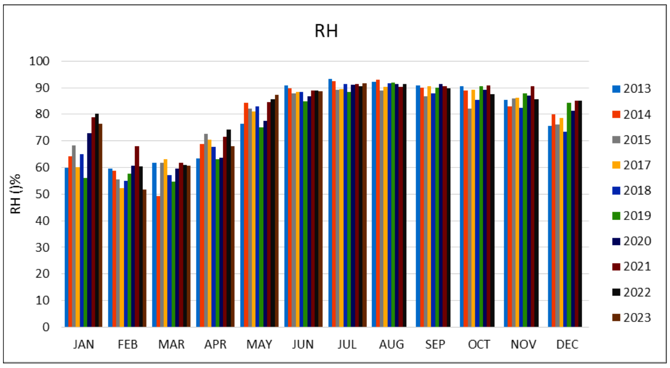

Fig. 3. Monthly variation of Relative humidity over the years of 2013 to 2023.

Table 1. Monthly average of BC concentration during different years

	2013	2014	2015	2017	2018	2019	2020	2021	2022	2023	Avg	St. Dev	Min	Max
Jan	1.4	1.13	0.97	1.06	1.26	0.73	0.39	0.45	0.73	0.56	0.87	0.33	0.39	1.4
Feb	1.29	0.62	1.57	1.12	1.3	0.44	0.94	1.33	0.92	1.26	1.08	0.33	0.44	1.57
Mar	1.63	1.53	1.71	1.55	1.66	1.41	0.76	1.49	1.41	1.43	1.46	0.25	0.76	1.71
Apr	1.62	1.89	1.48	1.16	1.22	1.44	0.97	1.43	1.27	1.13	1.36	0.25	0.97	1.89
May	1.09	1.11	1.08	0.97	1.06	0.33	0.91	0.62	0.68	-	0.87	0.26	0.33	1.11
Jun	0.37	0.69	0.46	0.48	0.48	0.43	0.26	0.2	0.26	-	0.40	0.14	0.2	0.69
Jul	0.3	0.2	0.31	0.31	0.25	0.31	0.22	0.17	0.18	-	0.25	0.06	0.17	0.31
Aug	0.35	0.44	0.43	0.34	0.16	0.12	0.27	0.17	0.23	-	0.28	0.11	0.12	0.44
Sep	0.46	0.39	0.65	0.48	0.36	0.3	0.23	0.22	0.12	-	0.36	0.15	0.12	0.65
Oct	0.65	0.78	0.25	0.86	0.63	0.32	0.43	0.26	0.28	-	0.50	0.22	0.25	0.86
Nov	0.66	0.59	0.17	0.76	0.5	0.4	0.34	0.19	0.72	-	0.48	0.21	0.17	0.76
Dec	0.68	0.74	0.7	0.98	1.3	0.6	0.33	0.36	0.53	-	0.69	0.29	0.33	1.3

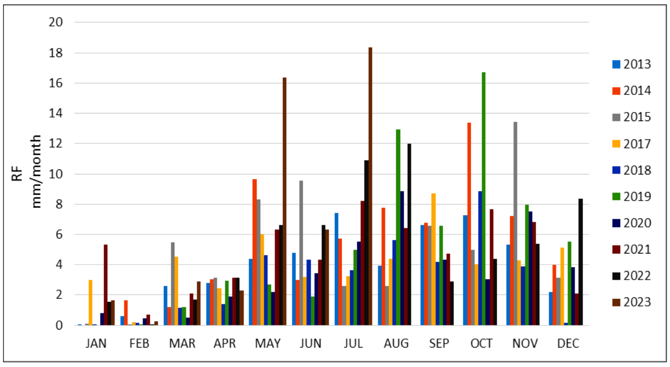

Fig. 4. Monthly variation of rainfall over the years of 2013 to 2023.

Discussion

Monthly variations in BC concentration and related meteorological parameters

The continuous daily average black carbon (BC) concentrations from January 2013 to April 2020 are shown in Fig. 5. The lowest BC concentration recorded during this period was 0.12 ± 0.06 μg/m^3 in August 2019 and 0.12 ± 0.09 μg/m^3 in September 2020, while the highest concentration of 1.89 ± 0.44 μg/m^3 occurred in April 2014 (Fig. 6). A clear inter-annual fluctuation in BC levels was observed, with significantly elevated concentrations between March and May compared to other months. The annual variation in monthly mean BC concentrations, depicted in Fig. 6, reveals a consistent trend, with the lowest values observed from July to September and the highest from February to April.

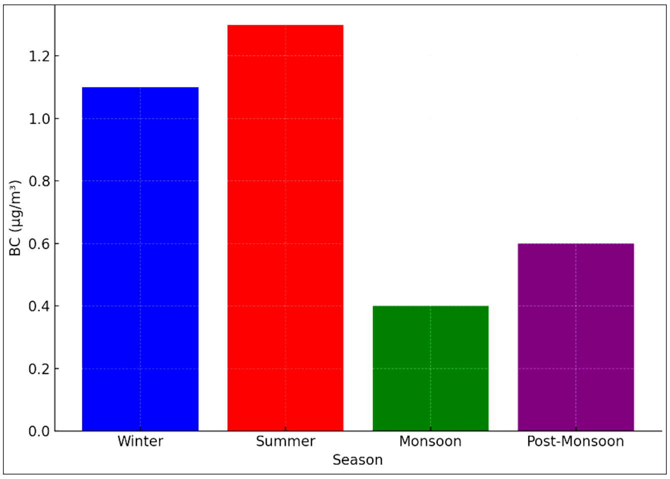

Fig. 5. Seasonal variation of black carbon aerosol concentration.

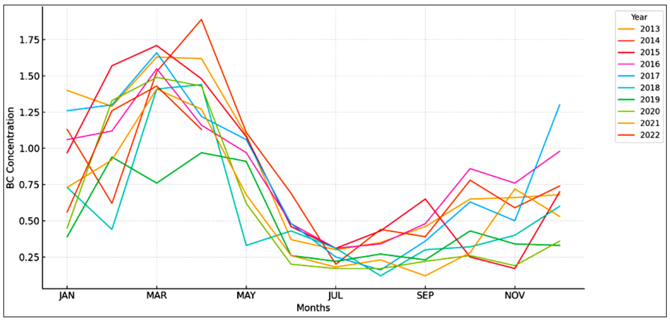

Fig. 6. Monthly variation of black carbon aerosol concentration from 2013 to 2023.

The average annual BC concentration in Ooty was comparable to those recorded at other high-altitude stations. For example, peak BC concentrations of 0.109 ± 0.027 μg/m^3 during the pre-monsoon period at the Himalayan aerosol observatory in Hanle (24). Similarly, the Nepal Climate Observatory Pyramid (NCOP) in the Himalayas reported BC concentrations of 340 ng/m^3 in April (25). The overall annual mean BC concentration in Ooty was 0.75 ± 0.26 μg/m^3, which is consistent with earlier findings at the same location (0.67 ± 0.36 μg/m^3) (25). In contrast, the mean BC concentration at Kodaikanal (2133 m above sea level) was higher at 2.10 ± 0.72 μg/m^3. At Madurai (101 m above sea level), the concentration was even more significant, reaching 5.10 ± 2.40 μg/m^3 (26). These results suggest that BC concentrations at Kodaikanal and Madurai were notably higher than in Ooty.

Seasonal analysis of black carbon aerosol concentrations and meteorological parameters

Fig. 6 displays the seasonal mean concentrations of black carbon (BC) across four seasons: winter, summer, monsoon, and post-monsoon. The average BC concentrations for each season during the study period were 1.3 ± 0.09 μg/m^3 in summer, 1.10 ± 0.09 μg/m^3 in winter, 0.60 ± 0.06 μg/m^3 in post-monsoon, and 0.4 ± 0.06 μg/m^3 in monsoon. These findings reveal a clear seasonal pattern, with BC concentrations peaking during the summer months (March to May) and reaching their lowest during the monsoon season (Fig. 5).

The higher BC levels observed in summer can be attributed to several factors, including increased atmospheric turbulence, vertical pollutant mixing, and a more active atmospheric boundary layer. During summer, the enhanced turbulence caused by higher temperatures allows for more significant vertical mixing of pollutants, raising BC concentrations at the surface level. Longer daylight hours and stronger solar radiation also increase the energy available for the atmospheric processes, contributing to BC dispersal. Additionally, summer wind patterns, particularly those influenced by large-scale atmospheric circulation, may promote the transportation of aerosols over long distances, further contributing to elevated BC concentrations. For example, regional transport of BC particles from lower altitudes, where pollution sources like vehicular emissions and biomass burning are more concentrated, could elevate BC concentrations in higher-altitude locations like Ooty (11, 23). Furthermore, local emission sources, such as biomass burning and traffic from tourism-related activities, also exacerbate the accumulation of BC during this period.

The monsoon season, in contrast, sees significantly lower BC concentrations, primarily due to the cool temperatures (typically ranging from 15-19°C), heavy rainfall, and the washout effect. During the monsoon, wind patterns bring moist air from oceanic regions, carrying higher moisture content and increasing precipitation. The persistent rainfall effectively removes BC from the atmosphere through scavenging processes, and the winds' dynamic nature promotes vertical mixing and dispersion of pollutants. The absence of the stagnant air conditions seen during the summer contributes to the rapid removal of BC, leading to significantly lower concentrations (0.4 ± 0.06 µg/m^3). These wind-driven and precipitation-driven meteorological conditions aid in the reduction of BC, ensuring its dilution and removal from the ambient air.

Post-monsoon months also showed reduced BC concentrations, likely due to limited convective activity and lower temperatures. As the influence of monsoon rains wanes and air stability increases, the wind patterns become less dynamic. Winds may shift to more land-based patterns, which could bring reduced moisture and lower vertical mixing. This is compounded by the temperature drop after the rains, further inhibiting the dispersion and mixing of aerosols. BC concentrations gradually increased in winter, mainly due to anthropogenic activities such as bonfires and forest fires, which are more frequent during this season.

From 2017 to 2020, BC concentrations exhibited significant variability, with fluctuations noted on seasonal, monthly, and even hourly timescales of temperature, relative humidity, and rainfall (Figs. 7-9). These variations are mainly influenced by local wind patterns, which can either concentrate or disperse aerosols depending on their intensity and direction. The presence of wind systems capable of vertical mixing—especially in the post-monsoon period—can spread BC aerosols across greater distances, enhancing concentrations at local sites such as Ooty. This suggests that the wind direction, speed, and other atmospheric dynamics play essential roles in determining BC dispersal and retention during different seasons.

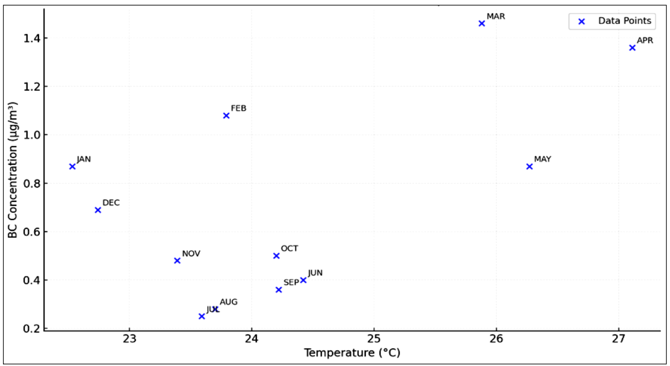

Fig. 7. Correlation between the BC concentration and temperature (2013–2023).

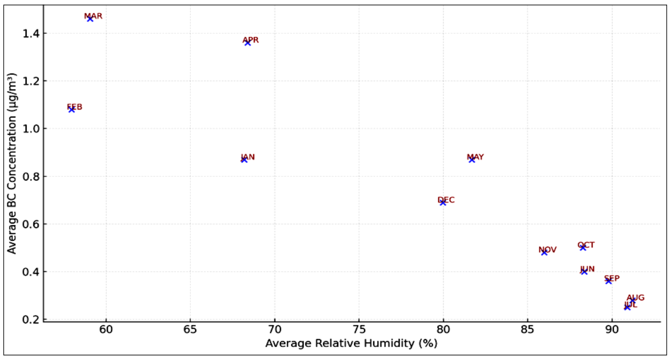

Fig. 8. Correlation between the BC concentration and relative humidity (2013–2023).

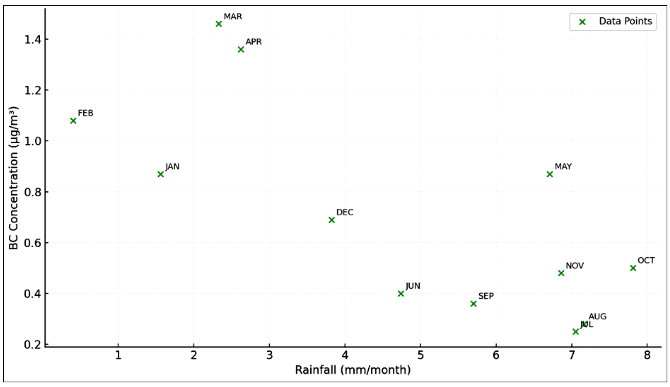

Fig. 9. Correlation between the BC concentration and rainfall (2013–2023).

The seasonal BC concentration patterns observed in this study align with findings from previous research. For instance, peak BC concentrations in March and April at Manora Peak in Nainital mirror the trends at our study site. Likewise, higher BC concentrations in summer followed by winter, with the lowest values in the monsoon season, were found at other high-altitude stations (26). In contrast, stations like Madurai and Kodaikanal exhibited higher BC concentrations during winter, a pattern also observed in Dehradun (27). These observations emphasize the influence of boundary layer dynamics, seasonal wind patterns, and prevailing meteorological conditions (like temperature and humidity) on BC levels (28). Overall, the data suggest that the study site is relatively clean, likely due to its mountainous location, a barrier to local and regional pollution sources. The topographic influence on wind patterns ensures natural meteorological processes disperse or dilute local emissions. The findings underscore the importance of regulating anthropogenic emissions, mainly from transportation, industrial activities, and biomass burning. Targeted mitigation strategies in the Western Ghats should include stricter vehicle emission controls, promoting cleaner fuels, and expanding public transportation networks. Enhancing forest management to reduce biomass burning can further lower BC levels. These strategies, applicable regionally and beyond, could significantly reduce air pollution. Moreover, insights from the 2020 lockdown emphasize the potential for long-term pollution reduction by effectively enforcing emission standards.

Conclusion

The study on black carbon (BC) aerosols in Ooty, Tamil Nadu, reveals significant seasonal variations in BC concentrations, with the highest levels typically observed from March to May, driven by increased vehicular traffic and biomass burning, and the lowest during the monsoon season, when rainfall and cooler conditions help to clear the air. The average annual BC concentration in Ooty over the study period (2013-2023) was 0.75 ± 0.26 µg/m^3. While Ootys' BC levels are lower than those in nearby lower-altitude areas, such as Madurai, the concentration still peaks during dry seasons, correlating with biomass burning and an influx of tourists. Key strategies to mitigate pollution include controlling emissions from vehicles, promoting clean transportation alternatives like electric vehicles, encouraging clean cooking technologies in rural areas, and implementing sustainable forest management practices to prevent biomass burning. Additionally, increasing public awareness, especially among locals and tourists, and enhancing air quality monitoring systems can be critical in managing pollution. These efforts would help reduce BC levels, improve air quality, protect public health, and preserve the delicate ecosystems in the region.

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Authors' contributions

All the authors contributed equally to the research and writing of this article.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

References

1. Kowsalya M, Sebastian SP, Jayabalakrishnan RM. Aerosol black carbon measurement at high altitude western ghats location of Ooty, Tami Nadu. Int J Environ Clim Change. 2020;10(12):390–96. https://doi.org/10.9734/ijecc/2020/v10i1230314
2. Myhre G, Myhre CL, Samset BH, Storelvmo T. Aerosols and their relation to global climate and climate sensitivity. Nat Edu Know. 2013;4(5):7.
3. Takemura T, Suzuki K. Weak global warming mitigation by reducing black carbon emissions. Sci Rep 2019;9(1):4419. https://doi.org/10.1038/s41598-019-41181-6
4. Flanner MG, Zender CS, Randerson JT, Rasch PJ. Present-day climate forcing and response from black carbon in snow. J Geophys Res: Atmos. 2007;112(D11). https://doi.org/10.1029/2006JD008003
5. Ramanathan V, Carmichael G. Global and regional climate changes due to black carbon. Nature Geosci. 2008;1(4):221–27. https://doi.org/10.1038/ngeo156
6. Valentini S, Barnaba F, Bernardoni V, Calzolai G, Costabile F, Di Liberto L, et al. Classifying aerosol particles through the combination of optical and physical-chemical properties: Results from a wintertime campaign in Rome (Italy). Atmos Res. 2020;235:104799. https://doi.org/10.1016/j.atmosres.2019.104799
7. Mor V, Dhankhar R, Attri SD, Soni VK, Sateesh M, Taneja K. Assessment of aerosols optical properties and radiative forcing over an Urban site in North-Western India. Environ Techno. 2017;38(10):1232–44. https://doi.org/10.1080/09593330.2016.1221473
8. Vachaspati CV, Begam GR, Ahammed YN, Kumar KR, Reddy RR. Characterization of aerosol optical properties and model computed radiative forcing over a semi-arid region, Kadapa in India. Atmos Res. 2018;209:36–49. https://doi.org/10.1016/j.atmosres.2018.03.013
9. Kumar RR, Soni VK, Jain MK. Evaluation of spatial and temporal heterogeneity of black carbon aerosol mass concentration over India using three year measurements from IMD BC observation network. Sci Total Environ. 2020;723:138060. https://doi.org/10.1016/j.scitotenv.2020.138060
10. Kumar R, Ghude SD, Biswas M, Jena C, Alessandrini S, Debnath S, et al. Enhancing accuracy of air quality and temperature forecasts during paddy crop residue burning season in Delhi via chemical data assimilation. J Geophys Res: Atmos. 2020;125(17):e2020JD033019. https://doi.org/10.1029/2020JD033019
11. Dhar P, Banik T, De BK, Gogoi MM, Babu SS, Guha A. Study of aerosol types and seasonal sources using wavelength-dependent Ångström exponent over North-East India: ground-based measurement and satellite remote sensing. Adv Space Res. 2018;62(5):1049–64. https://doi.org/10.1016/j.asr.2018.06.017
12. Sarangi B, Ramachandran S, Rajesh TA, Dhaker VK. Black carbon linked aerosol hygroscopic growth: Size and mixing state are crucial. Atmos Environ. 2019;200:110–18. https://doi.org/10.1016/j.atmosenv.2018.12.001
13. Priyanga S, Boomiraj K, Jothimani P, Kannan B, Dheebakaran G, Maheswari M. A decadal, temporal and seasonal variation of black carbon aerosol at high altitude region of Ooty, Tamil Nadu, India. Int J Environ Clim Change. 2023;13(9):3414–25. https://doi.org/10.9734/ijecc/2023/v13i92719
14. Viegas C, Monteiro A, Santos DM, Faria T, Caetano LA, Carolino E, et al. Filters from taxis air conditioning system: A tool to characterize driver's occupational exposure to bioburden?. Environ Res. 2018;164:522–29. https://doi.org/10.1016/j.envres.2018.03.032
15. Acosta-Martinez V, Van Pelt S, Moore-Kucera J, Baddock MC, Zobeck TM. Microbiology of wind-eroded sediments: Current knowledge and future research directions. Aeol Res. 2015;18:99–113. https://doi.org/10.1016/j.aeolia.2015.06.001
16. Shree S, Natha RM, Jayabalakrishnan M, Maheswari M, Kumaraperumal R. Comparative analysis of aerosol optical properties over high altitude region of western ghats in southern India. Int J Environ Clim Change. 2022;12(10):1060–66. https://doi.org/10.9734/ijecc/2022/v12i1030899
17. Hansen AD, Rosen H, Novakov T. The aethalometer—an instrument for the real-time measurement of optical absorption by aerosol particles. Sci Total Environ. 1984 Jul 1;36:191–96. https://doi.org/10.1016/0048-9697(84)90265-1
18. Novakov T, Ramanathan V, Hansen J, Kirchstetter T, Sato M, Sinton J, Sathaye J. Large historical changes of fossil-fuel black carbon aerosols. Geophy Res Lett. 2003;30(6):1–4. https://doi.org/10.1029/2002GL016345
19. Satheesh S, Moorthy KK, Babu SS, Vinoj V, Dutt C. Climate implications of large warming by elevated aerosol over India. Geophysical Res Lett. 2008;35(19):1–6. https://doi.org/10.1029/2008GL034944
20. Babu SS, Chaubey JP, Moorthy K, Gogoi MM, Kompalli SK, Sreekanth V, et al. High altitude (∼ 4520 m amsl) measurements of black carbon aerosols over western trans-Himalayas: Seasonal heterogeneity and source apportionment. J of Geophys Res: Atmospheres. 2011;116(D24). https://doi.org/10.1029/2011JD016722
21. Gogoi MM, Moorthy KK, Kompalli SK, Chaubey JP, Babu SS, Manoj M, Prabhu TP. Physical and optical properties of aerosols in a free tropospheric environment: Results from long-term observations over western trans-Himalayas. Atmos Environ. 2014; 84:262–74. https://doi.org/10.1016/j.atmosenv.2013.11.029
22. Bernardoni V, Elser M, Valli G, Valentini S, Bigi A, Fermo P, Vecchi R. Size-segregated aerosol in a hotspot pollution urban area: Chemical composition and three-way source apportionment. Environ Poll. 2017;231:601–11. https://doi.org/10.1016/j.envpol.2017.08.040
23. Babu SS, Manoj MR, Moorthy KK, Gogoi MM, Nair VS, Kompalli SK, et al. Trends in aerosol optical depth over Indian region: Potential causes and impact indicators. J Geophys Res: Atmosp. 2013;118(20):11–794. https://doi.org/10.1002/2013JD020507

24. Marinoni A, Cristofanelli P, Laj P, Duchi R, Calzolari F, Decesari S, et al. Aerosol mass and black carbon concentrations, a two-year record at NCO-P (5079 m, Southern Himalayas). Atmos Chem Phy. 2010;10(17):8551–62. https://doi.org/10.5194/acp-10-8551-2010

25. Udayasoorian C, Jayabalakrishnan RM, Suguna AR, Gogoi MM, Babu S. Aerosol black carbon characteristics over a high-altitude Western Ghats location in Southern India. Annales Geophysicae. 2014;32(10):1361–71. https://doi.org/10.5194/angeo-32-1361-2014

26. Bhaskar BV, Rajeshkumar RM, Muthuchelian K, Ramachandran S. Spatial, temporal and source study of black carbon in the atmospheric aerosols over different altitude regions in Southern India. J Atmos Solar Terres Phy. 2018;179:416–24. https://doi.org/10.1016/j.jastp.2018.09.009

27. Jones GS, Christidis N, Stott PA. Detecting the influence of fossil fuel and bio-fuel black carbon aerosols on near-surface temperature changes. Atmos Chem Phy. 2011;11(2):799–816. https://doi.org/10.5194/acp-11-799-2011

28. Rajeshkumar RM, Bhaskar BV, Muthuchelian K. Characteristics of black carbon aerosol at an educational site in Southern India. Environ Asia. 2019;12(1):108–19.