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A Decadal, Temporal and Seasonal Variation of Black Carbon Aerosol at High Altitude Region of Ooty, Tamil Nadu, India

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Climate change is accelerating at an unprecedented pace due to escalating greenhouse gas emissions, emphasizing the urgency of understanding its drivers. Aerosols present in the atmosphere, play an significant role in the intricate climate system. In this study, we examine the temporal and seasonal trends of black carbon aerosol, a significant contributor to warming, in the high-altitude locale of Ooty, Tamil Nadu, India. Utilizing the Aethalometer instrument, this research presents a comprehensive analysis of black carbon concentrations over a decade (2013-2023). Observations reveal distinct patterns, with higher concentrations during certain months and seasons. Specifically, April consistently exhibited the highest concentrations, while the monsoon season recorded the lowest. The exceptional decline in 2020, attributed to COVID-19 lockdown measures, highlights the significant role of anthropogenic activities.

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These findings underscore the significance of proactive black carbon monitoring in regions like Ooty. The study contributes valuable insights into the complex interplay between black carbon aerosols and climate systems, especially in high-altitude environments. It underscores the need for continued research to comprehensively understand black carbon's implications on local and global climate dynamics. In conclusion, this research establishes a foundation for grasping the intricate dynamics of black carbon aerosols in Ooty and serves as a stepping stone for broader insights into their role in shaping climate patterns and effects. By addressing these critical knowledge gaps, we can better inform mitigation strategies and policy decisions aimed at tackling climate change.

Keywords: Aerosol; black carbon aerosol; climate change; global warming; seasonal variation; temporal variation.

1. INTRODUCTION

In recent years, climate change is occurring faster than any time in the past 65 million years. It is one of the most notable issues that the world is experiencing nowadays. The main causes are increasing concentration of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), which trap heat in the atmosphere of the Earth and raise global temperatures. The World Meteorological Organization estimated that the average global temperature in 2022 was 1.15°C higher than pre-industrial levels. Although there are other elements that affect the temperature of the Earth, aerosols constitute a significant part of this intricate climate system. Aerosols are very small particles floating in the air, which size ranges from few nanometres to several micrometres [1]. They have both cooling and warming effects on the Earth's climate. A cooling effect results from the production of some aerosols, such as sulphate aerosols, which reflect solar energy back into space, which shows negative radiative forcing. This effect is termed as "Aerosol scattering" or "aerosol albedo effect" [2]. On the other hand, certain aerosols, notably "black carbon" or soot particles created by incomplete burning of fossil fuels and biomass [3,4], can absorb sunlight and contribute to a warming effect (i.e. positive radiative forcing), similar to greenhouse gases [5,6,7].

Black carbon aerosol is a least researched problem even though it is the second contributor to global warming. It has a potential of 2000 times more than carbon dioxide in causing global warming and acts as an excellent indicator for checking air quality and pollution levels [8]. Freshly generated BC aerosols have a hydrophobic character and last between minutes and week in the atmosphere [9], but older particles transform to hygroscopic owing to species mixing [10]. In earlier research, Udayasoorian et al. [11] revealed that burning fossil fuels and biomass dominated the study period, particularly during the summer. Another research, Kompalli et al. [12] identified the possibility of ex-situ particles and gaseous species in the study site and confirmed the maximum concentration of BC during the summer, which was linked to winds primarily from the south and south directions. The purpose of the current study was to comprehend the daily, monthly, and seasonal variations at the study site based on the preamble.

2. STUDY SITE DESCRIPTION

Ooty, situated in the Western Ghats of southern India, is renowned for its calm environment and unique climatic conditions owing to its location in one of the highest mountain ranges. The ISRO ARFI Environmental observatory, located at 2520 meters above sea level, further accentuates its significance in the region (shown in Fig. 1). However, being a popular hill station and tourist destination, Ooty witnesses a substantial influx of vehicles, particularly during peak tourist seasons. The combustion of fossil fuels in these vehicles, along with emissions from diesel generators and industrial activities, contributes to the release of black carbon particles into the atmosphere [13,14]. This phenomenon highlights the importance of monitoring and mitigating black carbon pollution to preserve the elegance and ecological balance of this location.

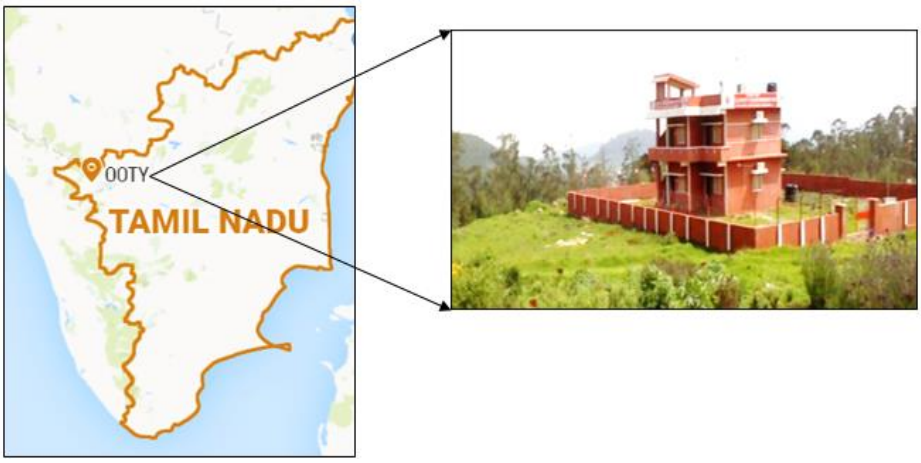


Fig. 1. Study Site at Ooty

3. MATERIALS AND METHODS

3.1 Measurement of Black Carbon Aerosol Using Aethalometer (AE – 31) Instrument

The research involves the collection of continuous real-time data on Black Carbon (BC) aerosol using a seven-channel Aethalometer (model AE-31, Magee Scientific, USA) at the Aerosol Radiative Forcing over India Network (ARFINET) observatory. The measurements were taken at a temporal resolution of 5 minutes over a period of 4 years, from January 2013 to July 2023, excluding the data of 2016, when the instrument was under maintenance. The Aethalometer is a robust and widely used instrument in aerosol research to measure ambient BC mass concentration in various environments, such as remote sites, urban locations, and high-altitude areas. Several studies have utilized this instrument for continuous BC measurements, demonstrating its effectiveness and applicability in understanding aerosol properties [15,16,17,1819,20,21].

In the Aethalometer, air is allowed to pass through a quartz fiber filter paper, which is chosen for its purity, high temperature compatibility, and resistance to humidity. The sample containing aerosol particles is deposited as a spot on the filter paper. When light passes through the quartz filter paper, the intensity of the light beam is reduced due to the presence of the aerosol particles on the filter tape. This reduction in light transmission, known as attenuation, is directly proportional to the amount of Black Carbon (BC) loading in the filter paper.

To calculate the BC concentration, the Aethalometer measures the difference in light transmission through the particle-laden sample spot and a particle-free reference spot on the filter. This measurement helps compute the absorption coefficient, which indicates how much light is absorbed by the BC particles in the sample.

The Aethalometer is equipped to measure the attenuation at seven different wavelengths (350, 470, 520, 590, 660, 880, and 970 nm). Among these wavelengths, the attenuation at 880 nm is considered the standard for BC measurement. This is because at 880 nm, BC becomes the primary absorber of light, and the contribution of other aerosol components is negligible. The instrument uses factory-set wavelength-dependent calibration factors to convert the measured absorption coefficients into "equivalent BC mass" concentration.

Overall, the Aethalometer is a valuable tool for continuously monitoring BC aerosol concentrations and provides valuable data for aerosol research in various environments. By analysing the collected data, the study aims to gain insights into the BC mass concentration trends and variations over time, providing valuable information about the impact of BC aerosols on the atmosphere in the Ooty region of Tamil Nadu, India.

4. RESULTS AND DISCUSSION

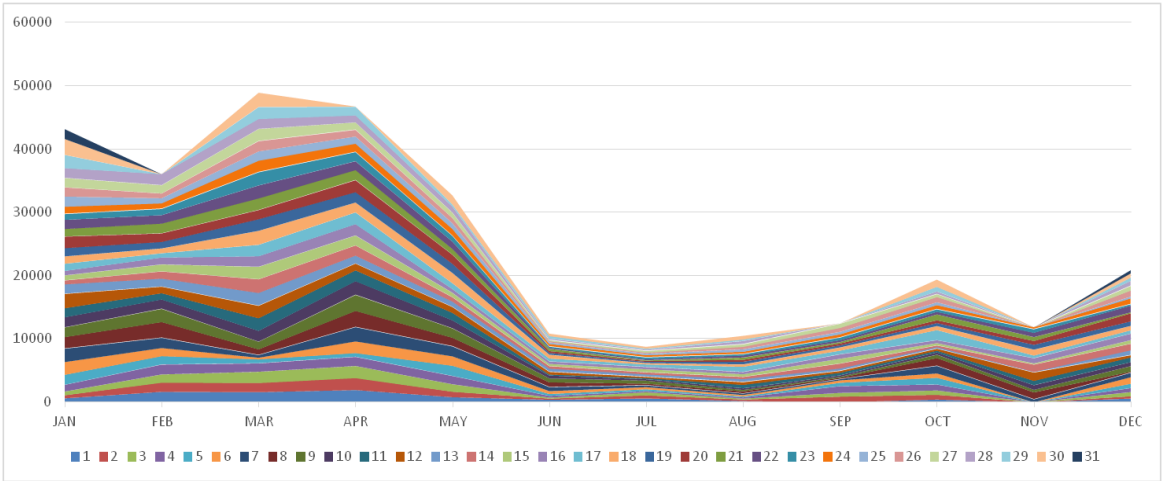
4.1 Temporal Variations of BC Aerosol

The continuous BC concentration measured at 5 min interval using Aethalometer instrument was averaged to hourly intervals. Then, monthly and

seasonal values were computed from hourly interval BC data. The monthly mean values of BC concentration measured at the study site for the observational years of 2013, 2014, 2015, 2017, 2018, 2019, 2020, 2021 & 2023 are shown in Fig. [12] and the temporal variation for those years are shown in Figs. [2 to 11] respectively. Occurrence of high mean BC concentration was observed in the month, April having 1.61 µg m³, 1.87 µg m³, 1.65 µg m³, 1.44 µg m³ & 0.96 µg m³ with their BC maxima of 2.5 µg/m³, 3.0 µg /m³, 2.91µg /m³, 2.53µg/m³ & 1.56µg/m³ during the year of 2013, 2014, 2018, 2019 & 2020 respectively and March having 1.70 µg /m³, 1.58 µg /m³, 1.488 µg/ m³, 1.410 µg/ m³ & 1.42 µg/ m³ with their BC maxima of 3.05 µg/m³, 2.56 µg/ m³, 2.83 µg/ m³, 2.54µg /m³ & 3.33µg/ m³ during the year of 2015, 2017, 2021, 2022 & 2023 respectively. The Annual mean mass concentration of during different years as shown in Fig.13 and overall mean recorded during study period was 0.75 ± 0.26 µg/ m³ during the study period. The annual BC concentration during the year 2020 was lower (shown in Fig.13) compared to other years due to the COVID lockdown period, which likely resulted in reduced vehicular emissions and pollution. The concentration of BC gradually raised from December to April and attained the lowest during June to November with the same trend in the observational year (shown in Figs. 2 to 12). This changes in Bc concentration was also due to the weather parameters over the study site. The reduced BC concentration in the month of June to November is because of rainfall. The black carbon present in the atmosphere will get precipitated when rainfall occurs [22,23]. Since or study site is a tourist spot, people visit this place during the month of March to early June. Thus it may be cause of increase in BC concentration (i.e. due to high vehicular emission).

4.2 Seasonal Variation of BC Aerosol

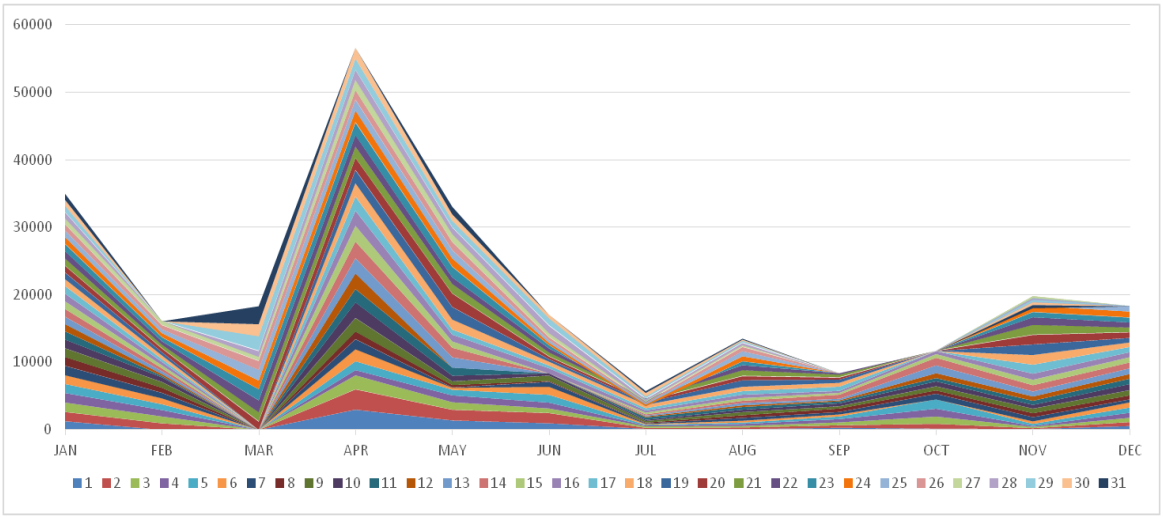
In order to examine the seasonal variation of BC, the mean values of BC mass concentration in each season for all 10 years are presented in Fig. 14. The mean BC concentration showed strong seasonal variation with the highest value (1.24 ± 0.34 µg/m³) during summer (March to May), mid values (0.97 ± 0.21 µg/m³) in winter (January to February) followed by post monsoon (October to December) with the value of (0.55 ± 0.39 µg/m³) and the lowest value (0.32 ± 0.31 µg/m³) were observed in monsoon (June to September) (shown in Fig. 15) with their BC maxima of 1.51 µg/m³, 1.34 µg/m³,0.86 µg/m³,0.46 µg/m³ in 2014, 2013, 2017 & 2015 respectively. The BC minima was observed in winter with 0.58 µg/m³ in 2019, summer with 0.88 µg/m³ in 2020, monsoon with 0.19 µg/m³ in 2021 and post monsoon with 0.27 µg/m³ in 2022.The seasonal mean of BC in monsoon was lesser by a fold of 2, 3 and 4 than post monsoon, winter and summer, respectively (Fig. 14). Monsoon periods are marked by substantial rainfall in various areas. The rain serves as an efficient cleanser by capturing and eliminating aerosol particles, such as black carbon, from the air. As raindrops develop and descend through the atmosphere, they gather aerosols and transport



	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
MIN	491	682	288	601	367	147	105	142	0	254	115	133
MAX	2512	2451	2244	2540	1609	700	599	800	1057	1583	1314	1276

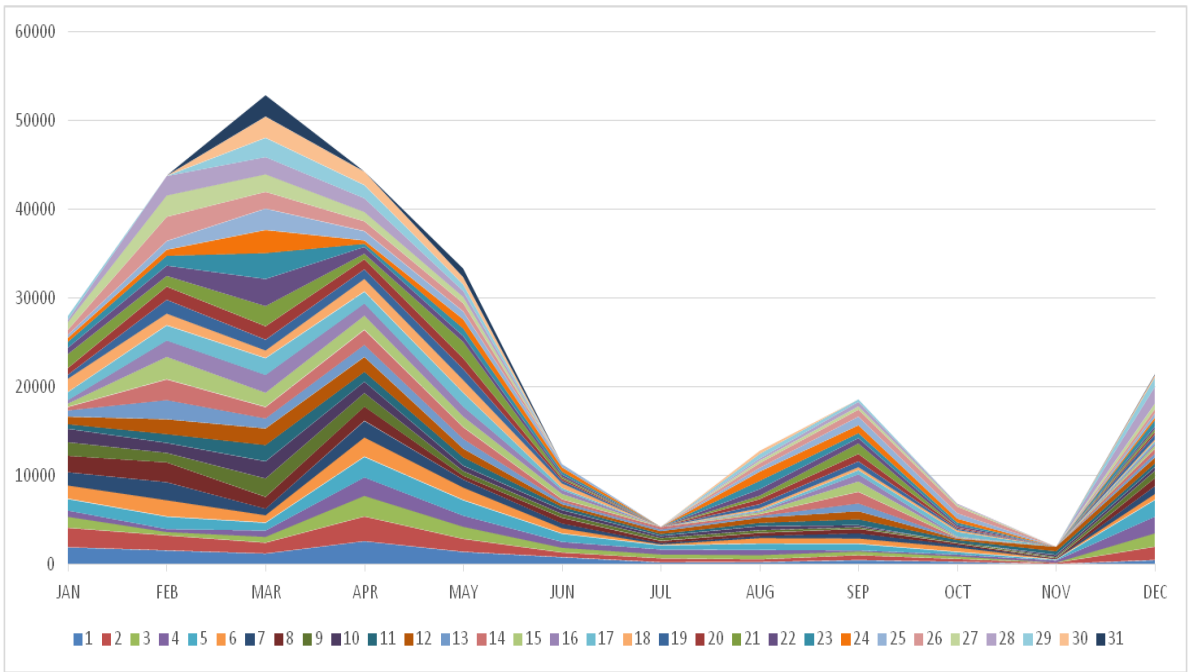
Fig. 2.Temporal variations of monthly mean BC concentration (ng/m³) during 2013

them to the Earth's surface, diminishing their presence in the air. This mechanism is referred as wet deposition [23,7]. Thus due to this process there was a decline in the black carbon concentration in monsoon season compared to other seasons. The seasonal variation of black carbon concentration was showing similar trends in all the years (shown in Fig. 15).



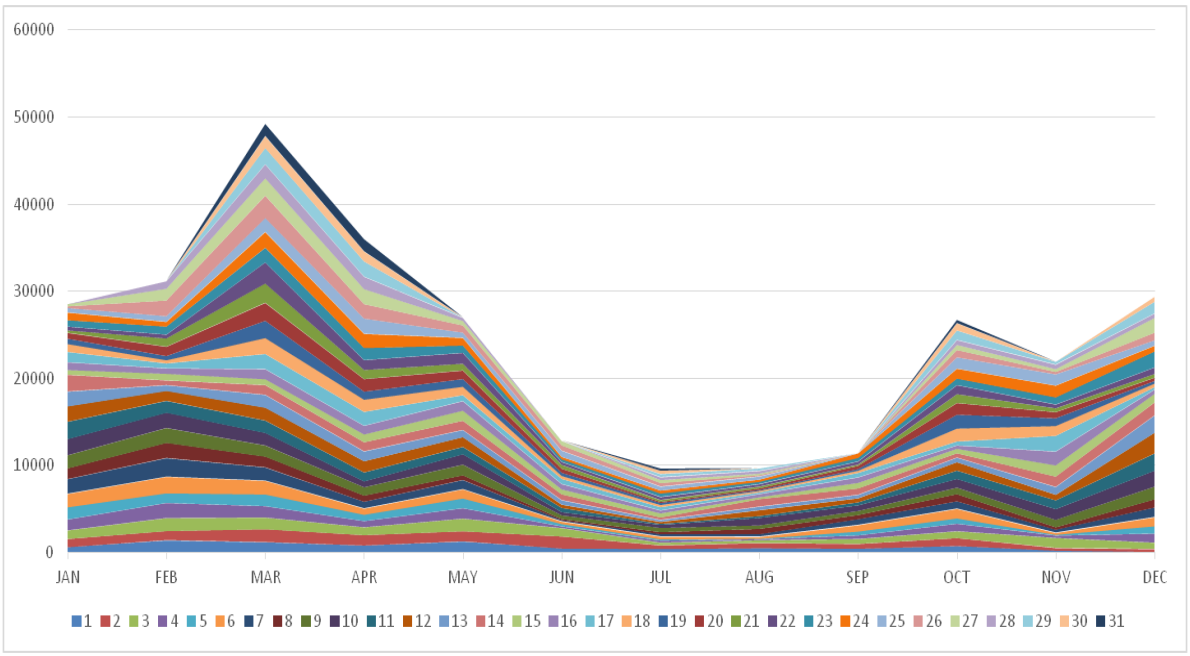
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
MIN	880	224	656	769	48	139	-1108	135	151	187	-449	435
MAX	1403	994	2670	3000	1965	1501	560	969	625	1367	1569	890

Fig. 3.Temporal variations of monthly mean concentration (ng/ m³) during 2014



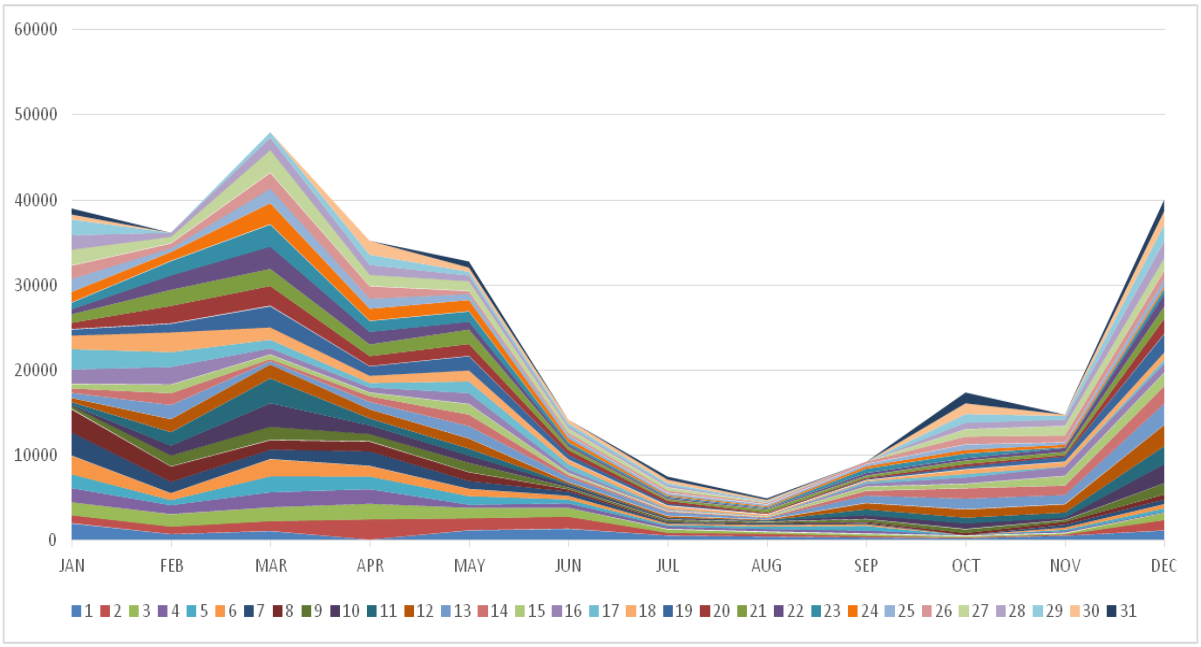
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
MIN	276	343	705	373	424	200	112	108	132	-100	53	95
MAX	2170	2699	3052	2768	1826	909	561	1040	1305	746	534	1888

Fig. 4.Temporal variations of monthly mean concentration (ng/m³) during 2015



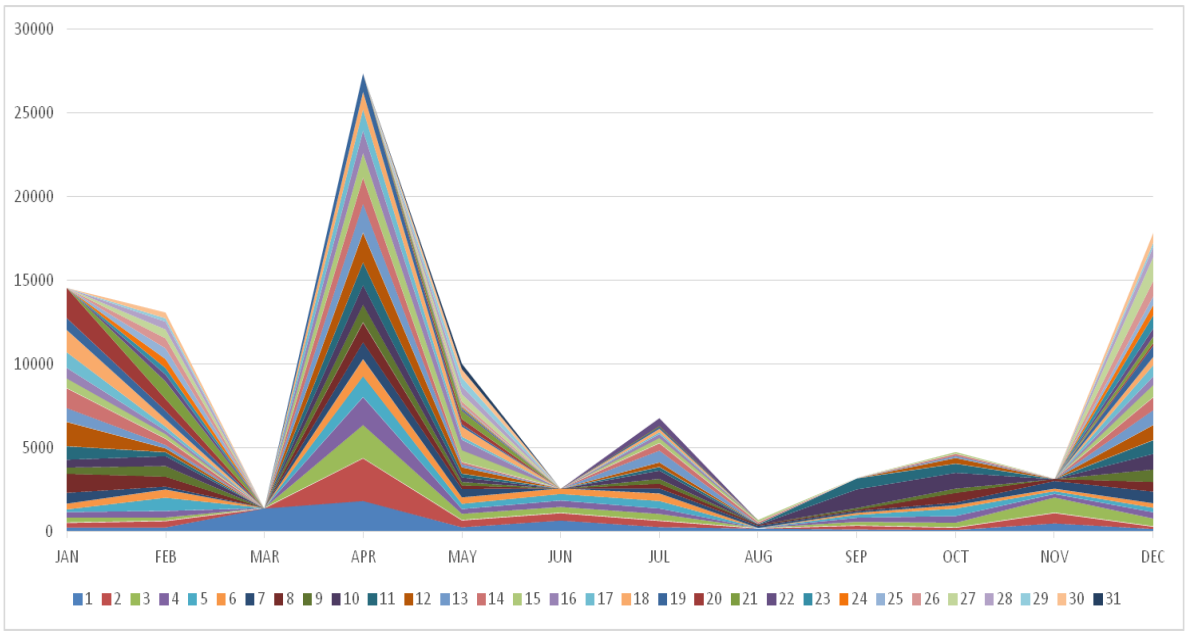
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
MIN	215	421	698	694	342	116	122	106	140	350	158	95
MAX	1989	2110	2564	1747	1450	1348	495	858	726	1613	1778	2374

Fig. 5.Temporal variations of monthly mean concentration (ng/m³) during 2017



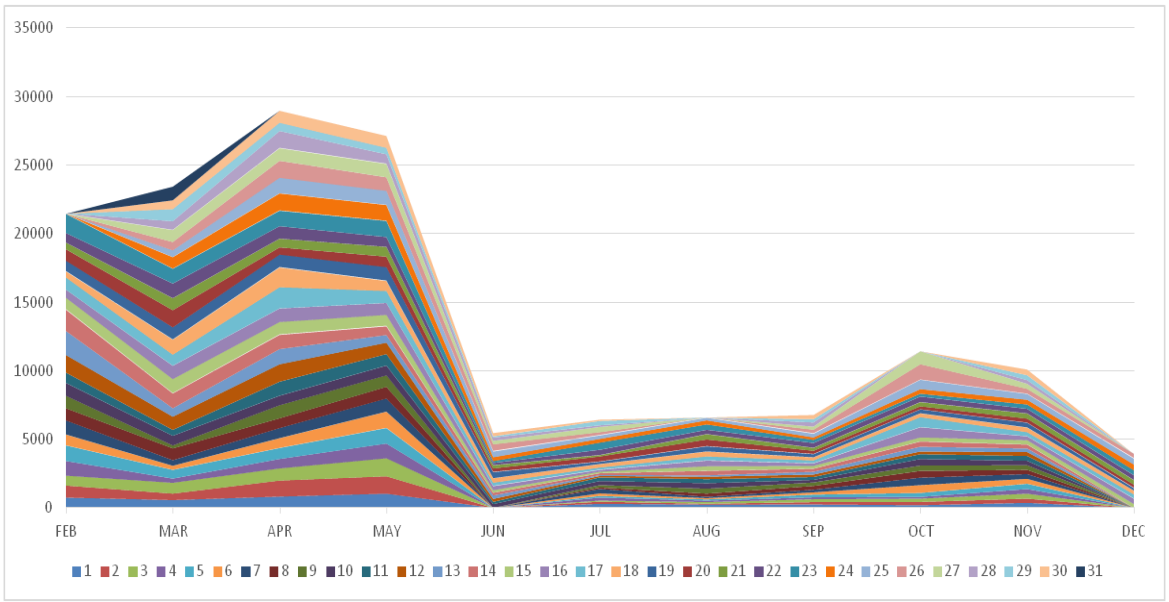
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
MIN	111	479	238	416	354	190	56	58	128	58	79	111
MAX	2741	2377	2916	2404	1702	1417	491	374	853	1272	1114	2506

Fig. 6.Temporal variations of monthly mean concentration (ng/m³) during 2018



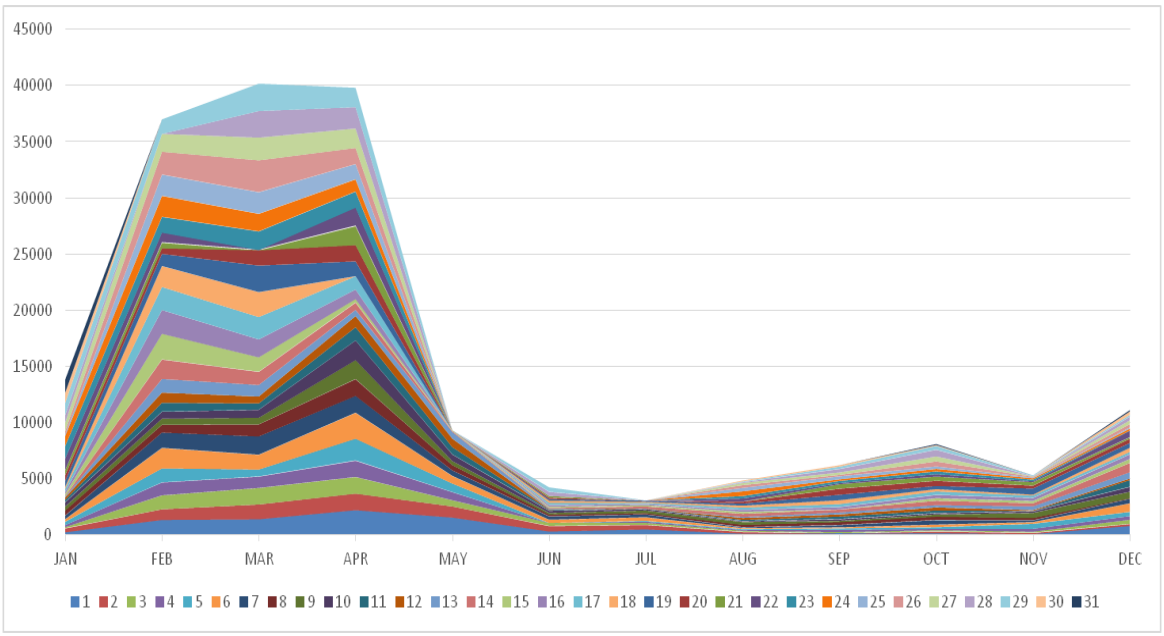
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
MIN	158	179	1401	1012	83	333	-67	45	90	94	135	128
MAX	1800	1043	1401	2536	737	683	703	206	1113	946	900	1412

Fig. 7.Temporal variations of monthly mean concentration (ng/m³) during 2019



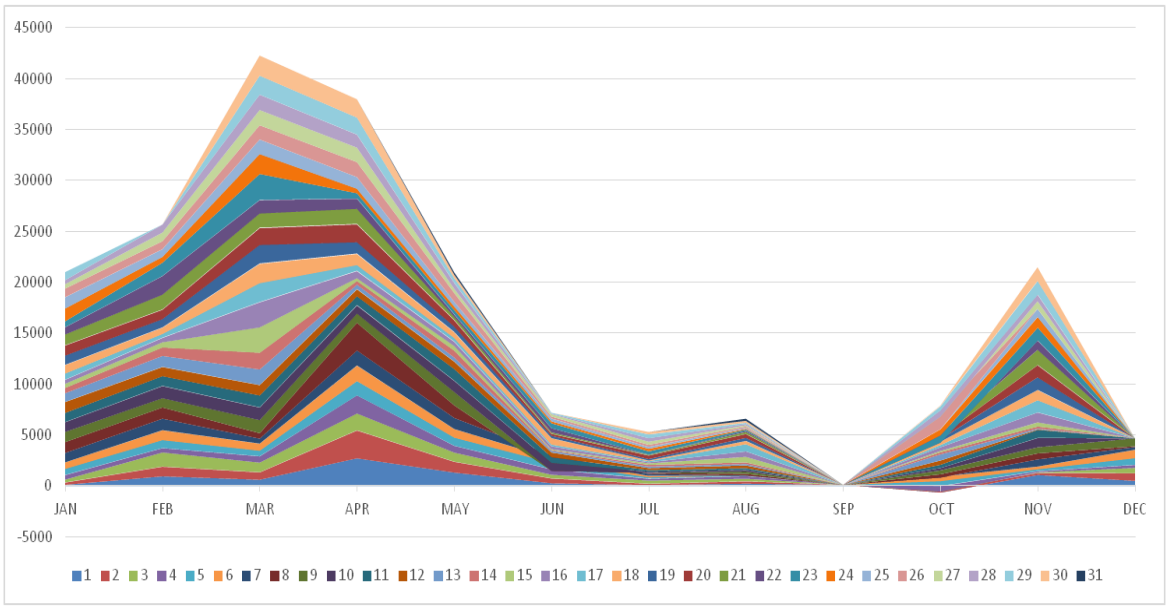
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
MIN	85	436	220	536	495	87	69	62	144	129	263	171
MAX	768	1766	1260	1566	1332	488	532	482	342	1123	422	445

Fig. 8.Temporal variations of monthly mean concentration (ng/m³) during 2020



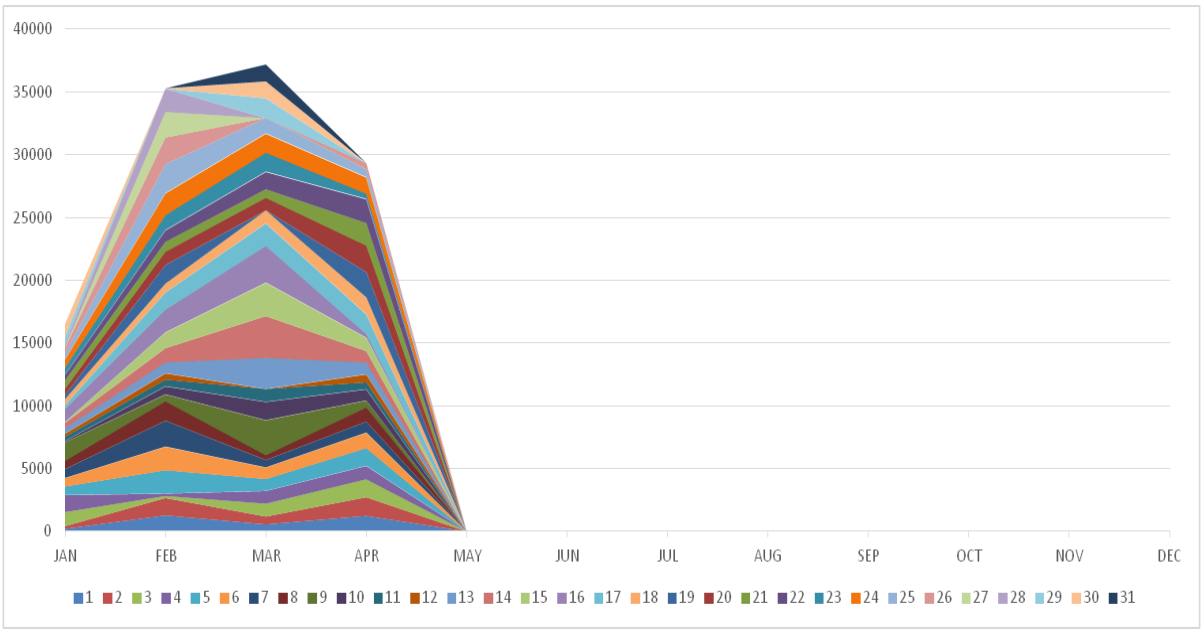
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
MIN	57	494	562	323	64	55	16	58	73	72	24	30
MAX	1173	2292	2839	2307	1522	473	477	417	531	587	552	830

Fig. 9.Temporal variations of monthly mean concentration (ng/m³) during 2021



	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
MIN	121	387	485	317	226	-1501	14	78	119	-872	17	86
MAX	1263	1827	2549	2722	1327	766	368	707	119	1621	1504	825

Fig. 10.Temporal variations of monthly mean concentration (ng/m³) during 2022



	JAN	FEB	MAR	APR
MIN	57	169	418	305
MAX	1476	2292	3335	2138

Fig. 11.Temporal variations of monthly mean concentration (ng/m³) during 2023

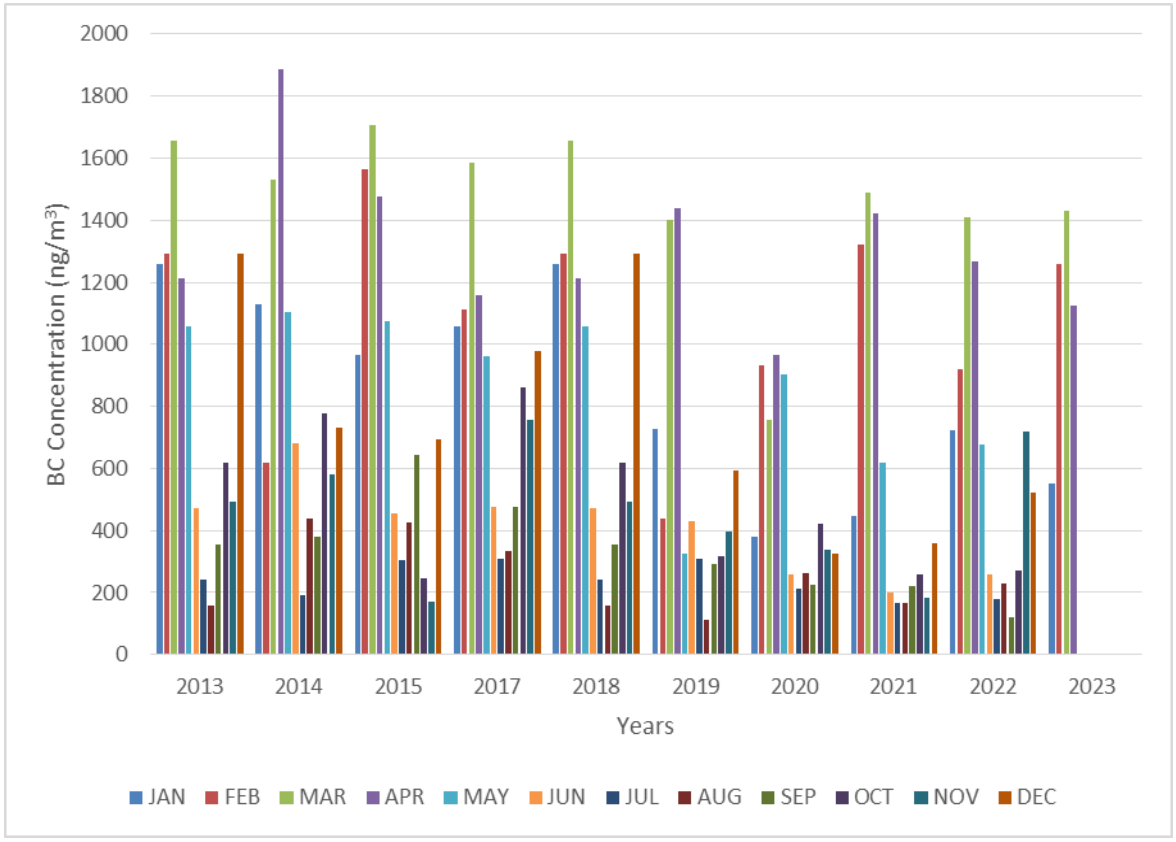


Fig. 12. Monthly Mean BC (ng/m³) concentration during different years

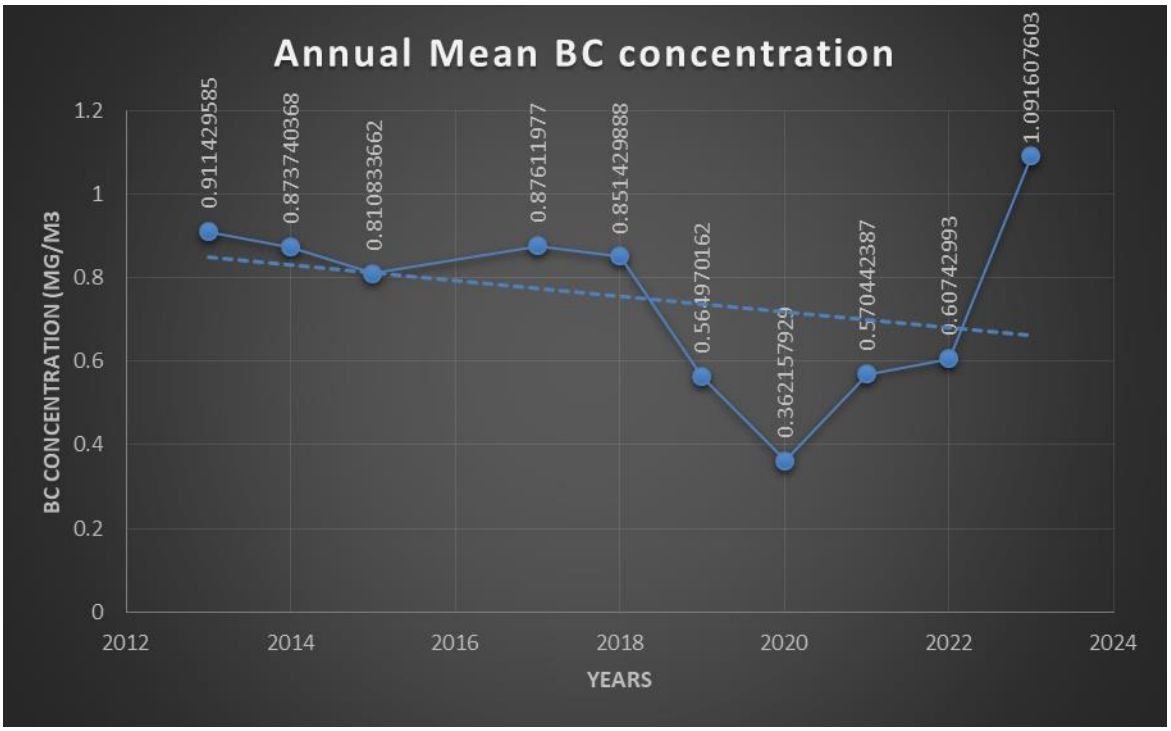


Fig. 13. Annual Mean BC concentration (µg/m^3) during 2013 to 2023

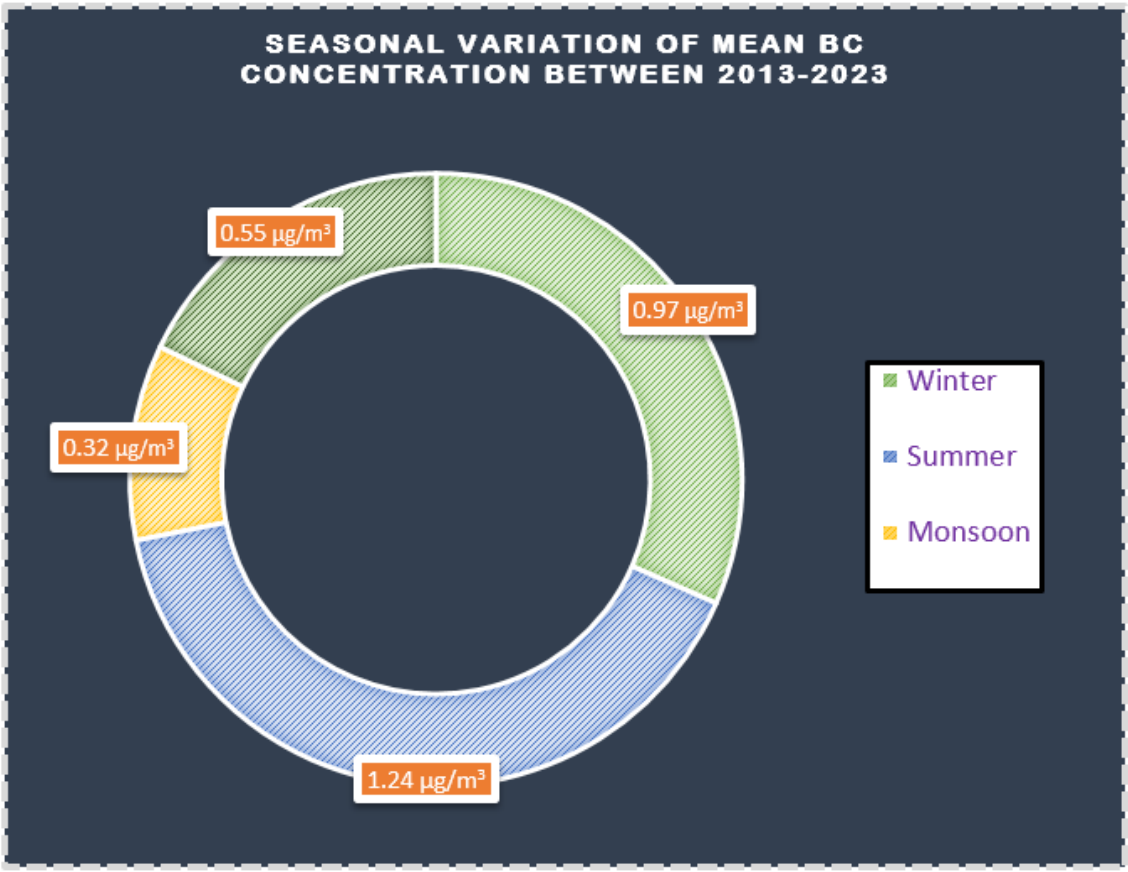
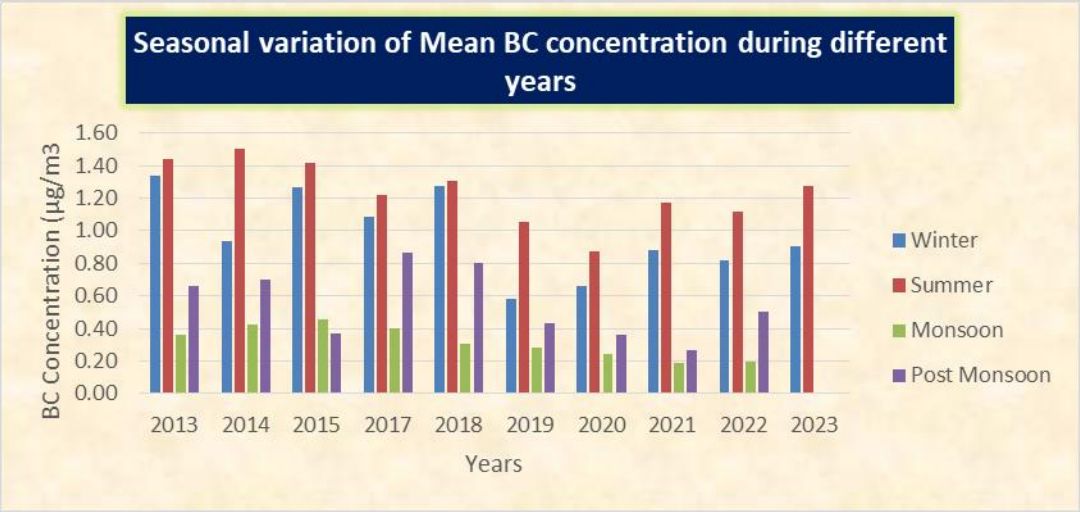


Fig. 14. Overall seasonal variation of mean BC concentration (µg/m^3) between 2013 and 2023



	Winter	Summer	Monsoon	Post monsoon
MIN	0.58	0.88	0.19	0.27
MAX	1.34	1.51	0.46	0.86

Fig. 15. Seasonal variation of mean BC concentration (µg/m^3) between 2013 and 2023

4. CONCLUSION

During the research period, the overall mean mass concentration of black carbon was 0.75 ± 0.26 µg/m3 and the average increase of black carbon concentration was about 0.122 µg/m3. From the paper it is concluded that the increase of black carbon concentration was mainly due to the vehicular emission and biomass burning. It was identified by the BC drop in the lockdown period and we can see further increase of its concentration in the following years. The decrease in black carbon levels during the monsoon season can primarily be attributed to the substantial rain and reduced vehicular emissions resulting from fewer visitors during this period. Although the observation location is clean, there were daily, monthly, and seasonal variations in the BC concentration. To gain a deeper understanding of the role of black carbon aerosols in climate change within this high altitude area, future studies could explore and investigate their specific effects on the climate system. Such research endeavours will contribute to a better comprehension of the significance of aerosols in shaping climate patterns and dynamics in this region. Since BC is the second-largest source of radiative forcing, it is crucial to continually research on the seasonal and diurnal fluctuation and mixing species of BC aerosol in the atmosphere.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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