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Spatiotemporal variations in black carbon aerosol concentration and its correlation with meteorological parameters and other pollutants in India

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सार – ब्लैक कार्बन (BC), जो कणिकीय पदार्थ (PM) का एक प्रमुख घटक है, अपूर्ण दहन से उत्सर्जित होता है और वायु गुणवत्ता, जलवायु तथा मानव स्वास्थ्य पर महत्वपूर्ण प्रभाव डालता है। यह अध्ययन 2018-2021 के दौरान सात भारतीय शहरों में BC और सह-उत्सर्जित प्रदूषकों (PM10, PM2.5, NOx, CO, SO_2, ओज़ोन और VOCs) के बीच स्थानिक एवं कालिक संबंधों की जाँच करता है, जिसमें प्रदूषण आँकड़ों को वायुमंडलीय सीमा-परत की गतिकी के साथ समेकित किया गया है। प्रमुख निष्कर्षों में BC और PM (PM2.5-BC: नागपुर में r = 0.92 तक) तथा NOx (कोलकाता में r = 0.90) के बीच प्रबल सहसंबंध पाए गए, जो वाहनीय और औद्योगिक दहन स्रोतों के प्रमुख योगदान को दर्शाते हैं।BC और VOCs के बीच कमजोर सहसंबंध (जैसे बेंज़ीन-BC, r = 0.12-0.60) विभिन्न उत्सर्जन स्रोतों–जैसे विलायक और गैर-दहन प्रक्रियाओं–की ओर संकेत करते हैं। मौसमी रूप से, सर्दियों में BC (8-10 µg/m³) और PM का स्तर सर्वाधिक पाया गया, जिसका कारण कम वेंटिलेशन गुणांक (<6000 m²/s) और कम मिश्रण ऊँचाई (<1200 m) रहा, जबकि मानसूनी वर्षा ने सांद्रताओं को 50-70% तक कम कर दिया। ग्रीष्म ऋतु में प्रकाश-रासायनिक अभिक्रियाओं के कारण ओज़ोन का स्तर अधिक (60-80 µg/m³) रहा। शहर-विशिष्ट प्रवृत्तियाँ भी सामने आईं: इंडो-गंगेटिक शहरों (दिल्ली, कोलकाता) में BC-NOx-PM का तीव्र युग्मन देखा गया, जबकि तटीय तिरुवनंतपुरम में समुद्री प्रभावों के कारण BC-NOx संबंध नगण्य (r = 0.014) रहा। ये निष्कर्ष BC-प्रेरित प्रदूषण को कम करने हेतु ऋतु- और शहर-विशिष्ट शमन रणनीतियों की आवश्यकता को रेखांकित करते हैं। यह अध्ययन भारत में शहरी वायु प्रदूषण की गतिकी की समझ को आगे बढ़ाता है और नीति-निर्माताओं को लक्षित हस्तक्षेपों की रूपरेखा प्रदान करता है।

ABSTRACT. Black Carbon (BC), a key component of particulate matter (PM), is emitted from incomplete combustion and significantly impacts air quality, climate, and human health. This study investigates the spatial and temporal relationships between BC and co-emitted pollutants (PM10, PM2.5, NOx, CO, SO_2, ozone, and VOCs) across seven Indian cities (2018-2021), integrating pollution data with atmospheric boundary layer dynamics. Key findings reveal strong correlations between BC and PM (PM2.5-BC: up to r = 0.92 in Nagpur) and NO_x (r = 0.90 in Kolkata), highlighting dominant contributions from vehicular and industrial combustion. Weak BC-VOC correlations (e.g., Benzene-BC, r = 0.12–0.60) suggest divergent emission sources, such as solvents and non-combustion processes. Seasonally, winter exhibited the highest BC (8–10 µg/m³) and PM levels due to low ventilation coefficients (<6,000 m²/s) and mixing heights (<1,200 m), while monsoon rains reduced concentrations by 50–70%. Summer saw elevated ozone (60–80 µg/m³) from photochemical reactions. City-specific trends emerged: Indo-Gangetic cities (Delhi, Kolkata) faced severe BC-NOx-PM coupling, whereas coastal Thiruvananthapuram showed minimal BC-NOx links (r = 0.014) due to marine influences. These findings underscore the need for season- and city-specific mitigation strategies to curb BC-driven pollution. The study advances the understanding of urban air pollution dynamics in India, providing a framework for policymakers to design targeted interventions for improved air quality and public health.

Key words – Carbonaceous aerosols, Black carbon, Particulate matter, Surface ozone, Air pollution.

1. Introduction

Air pollution is a pressing global environmental issue that poses a significant threat to both human health and the natural ecosystem (Al-Delaimy *et al.*, 2020; Amann *et al.*, 2011; Singh *et al.*, 2020). It involves the presence of harmful substances in the air, which can cause various health problems, such as respiratory issues, reproductive, cardiovascular diseases, and even premature death. This pollution results from a range of factors including industrial activities, vehicular emissions, burning of fossil fuels and natural phenomena such as dust storms and wildfires (Kampa and Castanas, 2008; Manisalidis *et al.*, 2020).

The types of air pollutants can be divided into two categories: primary and secondary pollutants. Primary pollutants include carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen oxides (NOx), and particulate matter (PM), volatile organic compounds (VOCs) and heavy metals (Kampa and Castanas, 2008; Manisalidis *et al.*, 2020; Saxena and Sonwani, 2019) which come from a variety of sources including the production and use of fossil fuels, power generation, and transportation (Năstase *et al.*, 2018).The secondary pollutants are formed when primary pollutants undergo chemical reactions in the atmosphere (Sitaras and Siskos, 2008; Xu *et al.*, 2022). One example of a secondary pollutant is ozone, which is formed by the reaction of NOx and VOCs in the presence of sunlight (Garzón *et al.*, 2015; Jenkin and Clemitshaw, 2000). Particulate matter of diameter size of 2.5 and 10µm can go deep into the lungs and cause respiratory and cardiovascular diseases (Grahame and Schlesinger, 2010). The prevalence of obesity among adults globally has increased 1.5 times since 2000 as impacted by the PM2.5 and PM10 (WHO, 2021).

Black carbon (BC) is a primary pollutant and a significant component of PM and air pollution. BC is produced by the incomplete combustion of fossil fuels, wood, cow dung, and other organic matter. Complete combustion would turn all carbon present in the fuel into carbon dioxide (CO_2), but combustion is never complete and CO_2, carbon monoxide, volatile organic compounds, organic carbon and BC aerosols are all formed in the process. These aerosols absorb solar radiation over a wide spectral band from UV to IR and contribute to the atmospheric warming (Bond *et al.*, 2013; Bond and Bergstrom, 2006; Jacobson, 2001; Ramanathan and Carmichael, 2008). BC contributes to climate change by absorbing sunlight, heating up the atmosphere, and causing the melting of ice caps and glaciers (Flanner *et al.*, 2009; Kang *et al.*, 2020; Shahgedanova, 2021). BC diurnal variation shows two sharp peaks indicating the traffic rush hours in most of the cities (Kumar, 2020; Kumar *et al.*, 2023; Şahin *et al.*, 2020).

A ventilation coefficient (VC) is an essential parameter and plays an important role in the dispersion of air pollutants and is one of the factors that determine the pollution potential over a region (Lu *et al.*, 2012; Saha *et al.*, 2019). High ventilation coefficient values can effectively dilute air pollutants, while low values tend to exacerbate pollution levels (Lu *et al.*, 2012; Saha *et al.*, 2019; Sujatha *et al.*, 2016). The ventilation coefficient in India varies significantly across different regions and seasons. The ventilation coefficient is high during the monsoon period and low in winter, with daily and seasonal variations (Iyer and Raj, 2013; Krishnan and Kunhikrishnan, 2004). Iyer and Raj, (2013) observed a decreasing trend in the ventilation coefficient in major Indian cities, leading to increased pollution potential.

The atmospheric boundary layer (ABL) exerts a significant impact on pollution dispersion and concentration levels (Liu *et al.*, 2020; Nair *et al.*, 2018; Singh *et al.*, 2021; Yan *et al.*, 2019). The height and stability of the ABL play a crucial role in the vertical mixing of pollutants, impacting their dispersion and dilution. In the daytime, solar heating typically leads to a higher ABL, facilitating efficient vertical dispersion of pollutants emitted near the surface and resulting in lower ground-level concentrations. During stable nighttime conditions characterized by a decrease in ABL height, pollutants get trapped near the surface, leading to elevated concentrations and deteriorating air quality (Kumar *et al.*, 2023; Murthy *et al.*, 2020; Nair *et al.*, 2018; Yassin *et al.*, 2018). Changes in the height of the ABL during the day and across seasons can affect pollution levels by changing how pollutants are dispersed and transported.

The studies by Allabakash *et al.* (2022), Kim *et al.* (2017), Safai *et al.* (2013), Sandeep *et al.* (2013) and Tiwari *et al.* (2009) all found a correlation between BC and PM. Sandeep *et al.* (2013) and Tiwari *et al.* (2009) both observed a significant presence of BC in PM2.5, with later also noting a strong correlation between BC and PM2.5. Kim *et al*. (2017) found a strong relationship between PM2.5 and BC concentrations, particularly in urban diesel engine emission hotspots. Research on the correlation between BC and SO_2 has yielded mixed results. Wang *et al*. (2011) found a weak correlation between BC and SO_2 in Beijing, China. Wang *et al.* (2021) conducted an observation campaign in Shanghai, China, revealing correlations between BC and VOCs in different time periods showing a strong positive correlation between the two in the Northern Region of Hangzhou Bay in Shanghai, China. Safai *et al*., (2013) and

Raju *et al*., (2011) both identified a strong correlation between BC and other anthropogenically originated chemical components, such as sulphur dioxide, in urban and high altitude regions of India. Latha and Badarinath (2004) further supported this correlation, demonstrating a positive relationship between BC and carbon monoxide, as well as a negative relationship between BC and tropospheric ozone in an urban environment. Ambade *et al*. (2021) compared the emission profile of BC and carbon monoxide in eastern India, showing a strong positive correlation between BC and PM. Swamy *et al*., (2012) investigated surface-level ozone (Surface Ozone), nitrogen oxides (NOx, NO2, NO), VOCs and BC through continuous monitoring at an urban site in Hyderabad over the course of one year.

The research gap identified lies in the limited scope of existing studies, which predominantly focus on short-term correlations between BC and meteorology or other pollutants, often within a single city. To address this gap, the present study aims to investigate the correlation coefficients between BC concentrations and other air pollutants, along with local meteorological parameters, across seven monitoring stations: Jodhpur, Kolkata, Nagpur, New Delhi, Pune, Thiruvananthapuram, and Varanasi. This research spans the years 2018 to 2021 and seeks to provide a comprehensive understanding of the relationships between pollutants and meteorological factors within the Indian atmosphere.

2. Data and methodology

2.1. *Data*

The BC aerosol monitoring network of India Meteorological Department (IMD) employs Aethalometer- model AE-33 installed at various geographical locations having different environmental conditions. The data for the period 2018-2021 are used in this study. The pollutant concentration data of PM10 ($\mu g/m^3$), PM2.5 ($\mu g/m^3$), CO (mg/m^3), NO ($\mu g/m^3$), NO2 ($\mu g/m^3$), NOx ($\mu g/m^3$), SO2 ($\mu g/m^3$), ozone($\mu g/m^3$) and Volatile organic compounds(VOCs) ($\mu g/m^3$) from Central Pollution Control Board (CPCB) and State Pollution Control Boards for the same period is used the study. Hourly BC and pollutant data were averaged to obtain daily mean values. Synoptic meteorological data utilized in this study were obtained from IMD stations corresponding to BC monitoring stations. The analysis was conducted using RStudio, an open-source software.

2.2. *Study area*

The study area encompasses seven Indian cities (Fig. 1) which is a part of a larger network of IMD

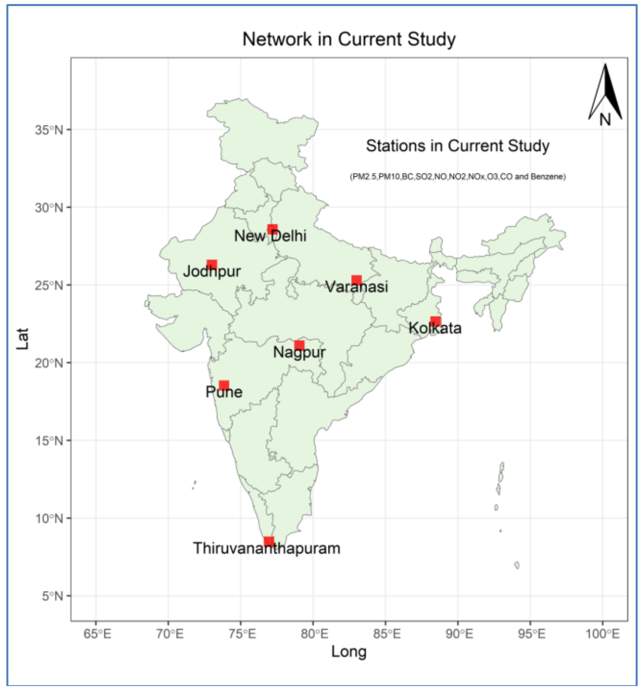


Fig. 1. Map of study locations across India showing the seven monitoring stations (Jodhpur, Kolkata, Nagpur, New Delhi, Pune, Thiruvananthapuram, and Varanasi).

(Ramesh *et al*., 2025). Jodhpur in Rajasthan experiences a semi-arid climate with hot, dry conditions, prone to dust storms due to its proximity to the Thar Desert. Kolkata in West Bengal has a tropical wet-and-dry climate, with hot, humid summers and milder winters influenced by its coastal location near the Bay of Bengal. Nagpur in Maharashtra has tropical savanna climate brings hot summers, mild winters, and significant temperature variations throughout the year. New Delhi is the capital territory experiences a semi-arid climate, with scorching summers, heavy monsoon rains, and cool winters. Its location in the Indo-Gangetic Plain exacerbates air pollution during winter. Pune in Maharashtra enjoys a tropical wet-and-dry climate with hot summers, moderate monsoons, and cool winters. Its elevation and proximity to the Western Ghats contribute to its pleasant weather. Thiruvananthapuram in Kerala has a tropical climate with hot, humid weather year-round, punctuated by heavy monsoon rains and coastal breezes. Varanasi in Uttar Pradesh along the Ganges River, Varanasi experiences a humid subtropical climate with hot summers, cool winters, and notable air pollution, particularly in winter due to its location in the Indo-Gangetic Plain.

3. Results and discussion

BC is a primary component of PM and is a key contributor to air pollution in India. The relationship between BC and other characteristic pollutants (*e.g*. sulfur dioxide, nitrogen oxides) in India is complex and depends on a variety of factors such as local emissions sources, meteorological conditions, and regional transport patterns.

3.1. *Pollutant correlation with local meteorology*

The variability in BC aerosol and other pollutant concentration exhibit distinct relation with meteorological parameters such as Temperature, wind, rainfall, relative humidity, boundary layer height (BLH) and VC. The daily and monthly averaged data were employed to explore the influence of meteorological conditions on pollutant concentrations. The correlation coefficient of pollutant concentrations with local meteorology for seven cities is shown in Table 1. This analysis examines the relationship between key air pollutants, such as PM10, PM2.5, BC, CO, NO, NO_2, NO_x, SO_2, ozone, and benzene, and meteorological parameters. PM and BC concentration is predominantly influenced by rainfall exhibiting a significant impact. Meteorological conditions significantly influence pollutant dispersion, transformation, and removal processes, making them critical in understanding air quality dynamics.

The relationship between BC and Tav shows a predominantly negative correlation across most cities, indicating that higher temperatures lead to lower BC concentrations. This trend is strongest in Kolkata (−0.89), followed by New Delhi (−0.65) and Jodhpur (−0.61), suggesting that warmer conditions enhance atmospheric mixing and boundary layer expansion, facilitating pollutant dispersion. However, Thiruvananthapuram exhibits a weak positive correlation (0.16), which may be attributed to local factors such as increased emissions from traffic or biomass burning during warmer periods, outweighing the dispersion effect.

Wind speed consistently demonstrates negative correlations with BC in all studied cities, reinforcing that higher wind speeds reduce BC levels by enhancing dispersion and dilution. The strongest influence is observed in Pune (−0.77), indicating efficient pollutant scattering under windy conditions. Similarly, Kolkata (−0.72) and Thiruvananthapuram (−0.61) show significant negative correlations, confirming that wind plays a crucial role in mitigating BC pollution. This pattern holds across both inland and coastal cities, suggesting that wind-driven dispersion is a key factor in reducing ambient BC concentrations.

The impact of relative humidity on BC varies across cities, though most locations exhibit weak to moderate negative correlations, implying that higher humidity may contribute to BC removal through wet deposition or particle growth. The strongest negative correlations are seen in Thiruvananthapuram (−0.62) and Kolkata (−0.59), likely due to frequent high-humidity conditions enhancing aerosol scavenging. In contrast, New Delhi shows a slight positive correlation (0.12), possibly because humid conditions favor secondary aerosol formation or because local emission sources dominate over wet removal processes. These differences highlight the role of regional climate and pollution sources in modulating BC-humidity relationships.

TABLE 1

Overall correlation coefficients with local meteorology 2018-21

Station / Parameter		BC
Jodhpur	Tav	-0.61
	WS	-0.46
	RH	-0.29
	RF	-0.42
Kolkata	Tav	-0.89
	WS	-0.72
	RH	-0.59
	RF	-0.48
Nagpur	Tav	-0.36
	WS	-0.53
	RH	-0.37
	RF	-0.59
New Delhi	Tav	-0.65
	WS	-0.62
	RH	0.12
	RF	-0.51
Pune	Tav	-0.58
	WS	-0.77
	RH	-0.15
	RF	-0.46
Thiruvananthapuram	Tav	0.16
	WS	-0.61
	RH	-0.62
	RF	-0.56
Varanasi	Tav	-0.54
	WS	-0.53
	RH	-0.24
	RF	-0.74

Rainfall exhibits strong negative correlations with BC in all cities, confirming that precipitation effectively removes BC particles from the atmosphere through wet deposition. The most pronounced effect is observed in Varanasi (−0.74), where heavy monsoon rains likely contribute to efficient BC washout. Similarly, Nagpur

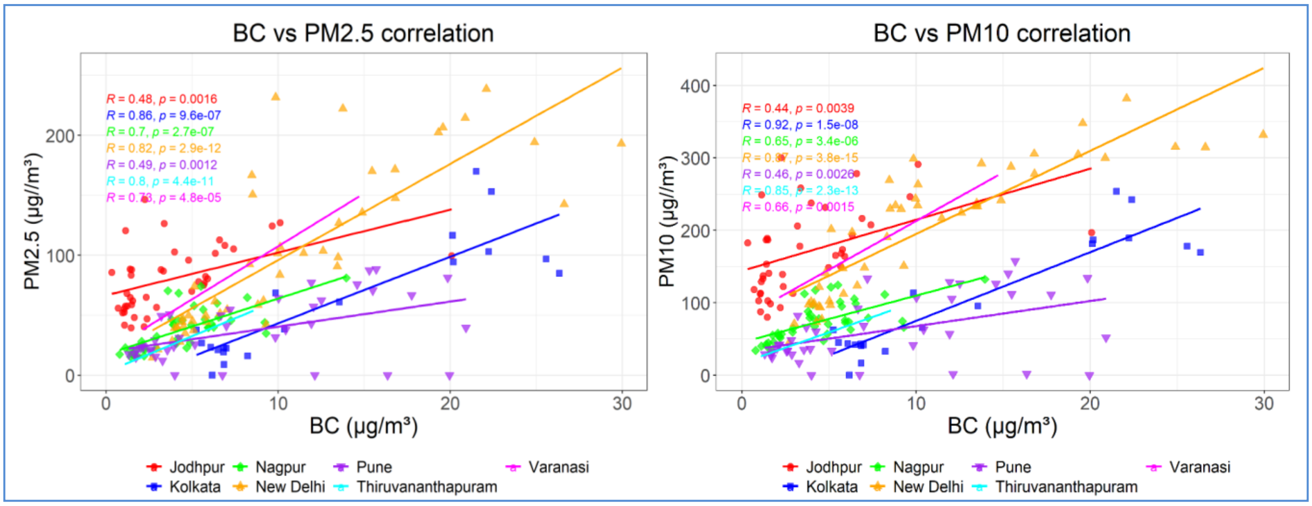


Fig. 2. Monthly data scatter plot for BC of study area with (a) PM2.5 and (b) PM10 for the study period

TABLE 2

Monthly Correlation of pollutants with BC concentration 2018-21

City	NO	NO2	NOx	SO2	CO	Ozone	PM10	PM2.5	Benzene	Toluene
Jodhpur	0.76	0.52	0.78	0.31	0.56	0.27	0.44	0.48	0.21	0.31
Kolkata	0.90	0.90	0.90	0.85	0.77	0.46	0.85	0.80	0.60	0.26
Nagpur	0.45	0.56	0.42	0.42	0.41	0.30	0.92	0.86	0.41	0.12
New Delhi	0.82	0.68	0.76	0.16	0.54	0.06	0.87	0.82	0.58	0.55
Pune	0.36	0.28	0.54	0.27	0.36	0.04	0.65	0.70	-0.07	-0.02
Thiruvananthapuram	-0.20	0.18	0.014	0.14	0.56	0.76	0.85	0.80	NA	NA
Varanasi	0.69	0.78	0.76	0.36	0.66	-0.29	0.66	0.73	0.38	0.49

*Pearson correlation with $p<0.05$

(-0.59) and Kolkata (-0.48) show notable reductions in BC with increased rainfall. This consistent pattern across diverse climatic regions underscores rainfall as a critical natural cleansing mechanism for BC pollution. This negative correlation indicates that rain effectively washes out pollutants from the atmosphere, resulting in cleaner air.

3.2. *BC correlation with other pollutants*

3.2.1. *Correlation of BC with particulate matter*

BC is a primary component of PM and is strongly correlated with PM levels. PM is a complex mixture of small particles and liquid droplets in the air and can include a variety of substances, such as dust, pollen, and chemicals. When BC is emitted into the atmosphere, it can combine with other pollutants to form PM, which can have negative impacts on human health and the environment. The correlation between BC and PM levels is strong because BC is a major contributor to PM levels, and as BC levels increase, PM levels also tend to increase (Ambade *et al.*, 2021; Janssen *et al.*, 2011). As BC concentration levels significant positive correlation at all the monitoring stations (Table 2). Although, BC is part of PM2.5 and PM10, its spatial distribution can be more localized because of specific emission sources, consequently high BC concentration values may not always coincide with higher PM concentration.

Jodhpur showed a positive correlation between PM2.5-BC (0.48) and PM10-BC (0.44), suggesting that vehicular traffic and agricultural activities play a role in the levels of both pollutants Figs. 2 (a and b). These correlations imply that BC emissions, often from incomplete combustion of fossil fuels, contribute to PM concentrations in Jodhpur's atmosphere. Kolkata exhibited strong correlations between PM2.5-BC (0.80) and PM10-BC (0.85), indicating substantial contributions from vehicular emissions and industrial processes to both pollutants. This high correlation suggests that BC sources, likely including diesel engines, biomass burning (especially coal), and industrial sources, are significant contributors to PM in Kolkata's atmosphere. Nagpur showed a correlation between PM2.5-BC (0.86) and PM10-BC (0.92), suggesting that both pollutants are strongly influenced by common sources, likely including vehicular emissions and industrial activities. New Delhi demonstrated correlations between PM2.5-BC (0.82) and PM10-BC (0.87), indicating that major contributors to both pollutants are vehicular emissions, industrial activities, and construction dust. These strong correlations highlight that BC emissions, especially from vehicle exhaust and industrial sources, significantly influence PM2.5 and PM10 levels in New Delhi's atmosphere. Pune exhibited correlations between PM2.5-BC (0.70) and PM10-BC (0.65), suggesting that vehicular emissions and industrial activities are potential sources of both pollutants. The correlation implies that BC emissions from local traffic and industrial processes contribute to PM concentrations in Pune. Thiruvananthapuram showed correlations between PM2.5-BC (0.80) and PM10-BC (0.85), indicating the influence of vehicular emissions, biomass burning, and industrial activities on air quality. These correlations suggest that BC emissions significantly contribute to PM concentrations in this city. Varanasi exhibited correlations between PM2.5-BC (0.73) and PM10-BC (0.66), suggesting that vehicular emissions and industrial sources are significant contributors to both pollutants in Varanasi’s atmosphere.

3.2.2. *Correlation of BC with Nitrogen oxide (NO, NO_2, NOx)*

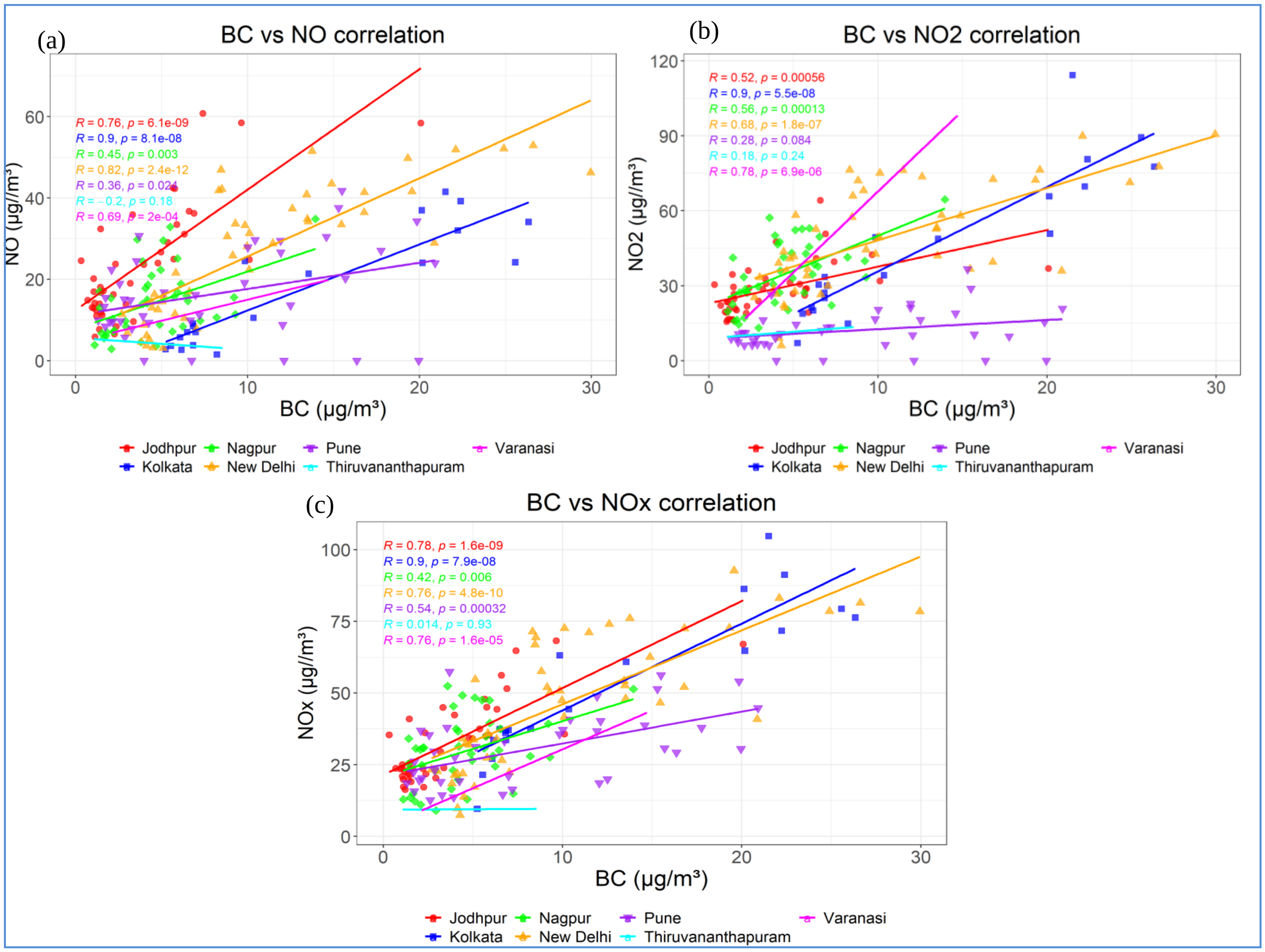
NOx is a group of gases that are produced during combustion of fossil fuels and can contribute to the formation of secondary pollutants, such as PM and ozone. NOx can interact with BC in the atmosphere and contribute to the formation of secondary pollutants, such as nitrates (Yang *et al*., 2022; Zhang *et al*., 2015). The formation of nitrates from the reaction between NOx and BC can enhance the ability of BC to absorb sunlight, leading to warming of the atmosphere. the presence of NOx can enhance the formation of secondary pollutants from BC, leading to increased levels of PM and warming of the atmosphere. In other cases, the interaction between NOx and BC can reduce the warming effects of BC through the formation of nitrates. The formation of nitrates from the reaction between NOx and BC can enhance the ability of BC to absorb sunlight, leading to warming of the atmosphere. This process contributes to radiative forcing and can exacerbate the effects of climate change.

Figs. 3(a, b and c), reflects the correlations of BC with nitrogen oxides (NO, NO_2, and NO_x) across different cities. For Jodhpur, BC shows positive correlations with NO (0.76), NO_2 (0.52), and NO_x (0.78), indicating that emissions from sources like vehicular traffic and industrial activities contribute significantly to both BC and nitrogen oxide levels. For Kolkata, BC shows positive correlations with NO (0.90), NO_2 (0.90), and NO_x (0.90), suggesting that heavy traffic congestion and industrial activities are major sources of both BC and nitrogen oxides, reflecting a strong interdependence between these pollutants. For Nagpur, BC exhibits a positive correlation with NO (0.45), NO_2 (0.56), and NO_x (0.42). This suggests a relatively smaller contribution from vehicular and industrial emissions to BC and nitrogen oxides compared to other cities, but still indicating some common sources. For New Delhi, BC shows positive correlations with NO (0.82), NO_2 (0.68), and NO_x (0.76). This points to significant contributions from vehicular emissions and industrial activities, which are likely the main sources of both BC and nitrogen oxides in the city. For Pune, BC displays positive correlations with NO (0.36), NO_2 (0.28), and with NO_x (0.54). This suggests that vehicular emissions and industrial activities might contribute to BC and NOx, but their influence is weaker in comparison to other cities. For Thiruvananthapuram, BC shows a correlation with NO (-0.20), NO_2 (0.18), and NO_x (0.014). The differing strengths and directions of these correlations suggest that BC concentrations are not strongly influenced by nitrogen oxide emissions, possibly due to varying emission sources or atmospheric conditions. For Varanasi, BC shows strong positive correlations with NO (0.69), NO_2 (0.78), and NO_x (0.76), indicating that vehicular emissions and industrial activities are significant sources of both BC and nitrogen oxides, similar to the patterns observed in other heavily polluted urban areas.

Cities like Kolkata and New Delhi exhibit very strong correlations between BC and nitrogen oxides, suggesting that major pollution sources such as traffic and industry are shared. In contrast, Thiruvananthapuram shows minimal correlation, indicating different influencing factors (coastal city) or distinct sources of BC and NOx.

3.2.3. *Correlation of BC with surface ozone*

Surface Ozone or Ground Ozone is a reactive gas formed (mostly from anthropogenic sources) near the ground in the presence of sunlight, VOCs, and nitrogen



Figs. 3(a-c). Monthly data scatter plot for BC of study area with (a) NO, (b)NO_2 and (c) NO_x for the study period

oxides (NOx). Owing to its highly reactive chemical properties, ozone is harmful to vegetation, materials and human health. In the troposphere, ozone is also an efficient greenhouse gas and is one of the most important air pollutants associated with health in Europe (Amann, 2008). Higher temperatures can increase the production of Surface Ozone near the ground, as elevated temperatures can enhance the reaction rates of the photochemical processes that produce Ozone (Coates *et al*., 2016; Ueno and Tsunematsu, 2019). Surface Ozone can affect the radiative properties of BC and PM, leading to warming of the atmosphere. Humidity can also affect the formation of Surface Ozone, as higher humidity levels can reduce the formation of Surface Ozone by suppressing the photochemical reactions that lead to its formation (Li *et al*., 2021). The relationship between Surface Ozone and BC can be influenced by wind speed, as changes in wind speed can affect the transport and dispersion of pollutants in the atmosphere. Higher wind speeds can lead to increased mixing of pollutants and a reduction in Surface Ozone concentrations near the surface, while lower wind speeds can lead to increased accumulation of pollutants, including Surface Ozone and PM, near the surface.

The correlation of Ozone-BC (0.27) (see Table 2) in Jodhpur suggests a potential contribution from common emission sources like industrial activities and biomass burning to both pollutants. Their limited relationship indicates that other factors, such as meteorological conditions, might also influence ozone formation in this region. The correlation between Ozone and BC (0.46) in Kolkata indicates a potential contributions from vehicular emissions and industrial processes to both pollutants. The urban setting and high pollution levels in Kolkata likely facilitate photochemical reactions that produce ozone. The correlation between Ozone and BC (0.30) in Nagpur suggests that vehicular emissions, agricultural activities, and industrial processes could contribute to both Ozone and BC levels in the city. The correlation between Ozone and BC in New Delhi (0.06) does not provide a clear

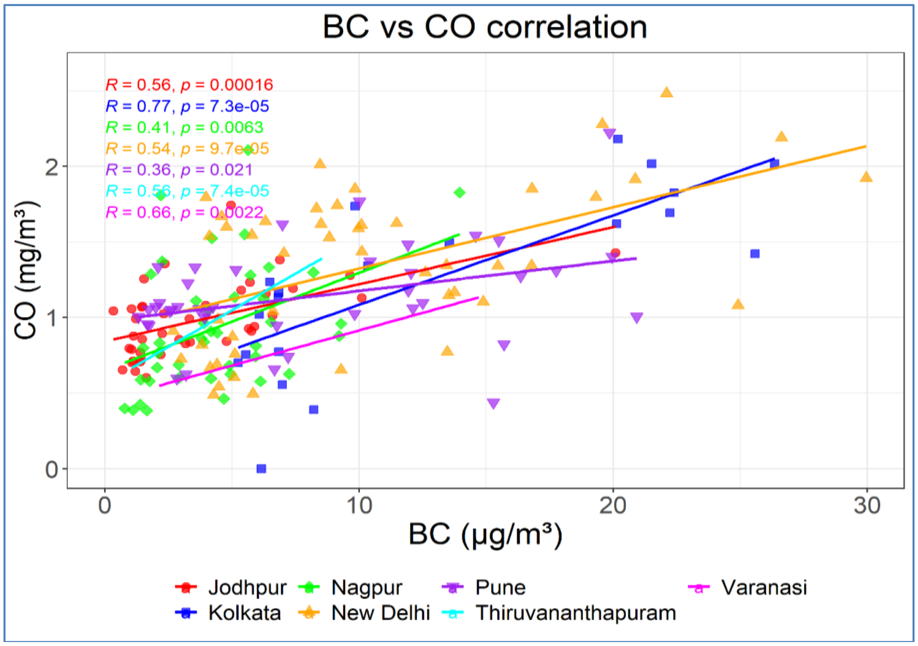


Fig. 4. Monthly data scatter plot for BC with Carbon Monoxide for the study period

indication of their relationship based on the provided data. The correlation does not establish a clear relationship between Ozone and BC in New Delhi. Despite high pollution levels, ozone formation might be suppressed due to processes like NO titration, where NO reacts with ozone to reduce its concentration. The correlation between Ozone and BC in Pune (0.04) suggests a limited relationship between the two pollutants in the city. This could be attributed to lower precursor emissions or atmospheric conditions less conducive to ozone formation. The correlation between Ozone and BC (0.76) in Thiruvananthapuram suggests that photochemical reactions involving precursors such as NOx and VOCs contribute to both Ozone and BC levels in the city. These precursors likely contribute to the simultaneous presence of Ozone and BC in the atmosphere. The negative correlation between Ozone and BC (-0.29) in Varanasi indicates an inverse relationship between the two pollutants, which could be influenced by different emission sources or atmospheric conditions. High NO emissions in Varanasi may lead to ozone suppression through titration processes, while BC originates from other sources like biomass burning and vehicular emissions.

3.2.4. *Correlation of BC with carbon monoxide (CO)*

BC and CO are by-products of the incomplete combustion of fossil fuels and biomass such as gasoline, natural gas, coal, wood, and oil.

Temperature can also influence the relationship between CO and BC, as higher temperatures can enhance the formation of both pollutants. In general, elevated temperatures can increase the likelihood of incomplete combustion, leading to increased emissions of CO and BC. Conversely, lower temperatures can reduce emissions of these pollutants. The correlation between CO and BC is strong (Fig. 4), as they are both produced by the same sources and can be co-emitted.

The positive correlation between CO and BC (0.56) in Jodhpur suggests common emission sources like vehicular traffic and industrial activities contributing to both pollutants. The positive correlation between CO and BC (0.77) in Kolkata indicates significant contributions from vehicular emissions and industrial processes to both pollutants. Kolkata's dense traffic and reliance on coal for industrial energy are key contributors, while the city's humid conditions and lower wind speeds may facilitate the co-accumulation of CO and BC in the atmosphere. The positive correlation between CO and BC (0.41) in Nagpur suggests potential sources such as vehicular emissions and industrial activities contributing to both pollutants. The positive correlation between CO and BC (0.54) in New Delhi suggests vehicular emissions as significant sources of both pollutants. New Delhi's high traffic density and frequent temperature inversions during certain seasons trap pollutants near the surface, enhancing their association. The positive correlation between CO and BC (0.36) in Pune indicates vehicular emissions and industrial activities as potential sources of both pollutants.

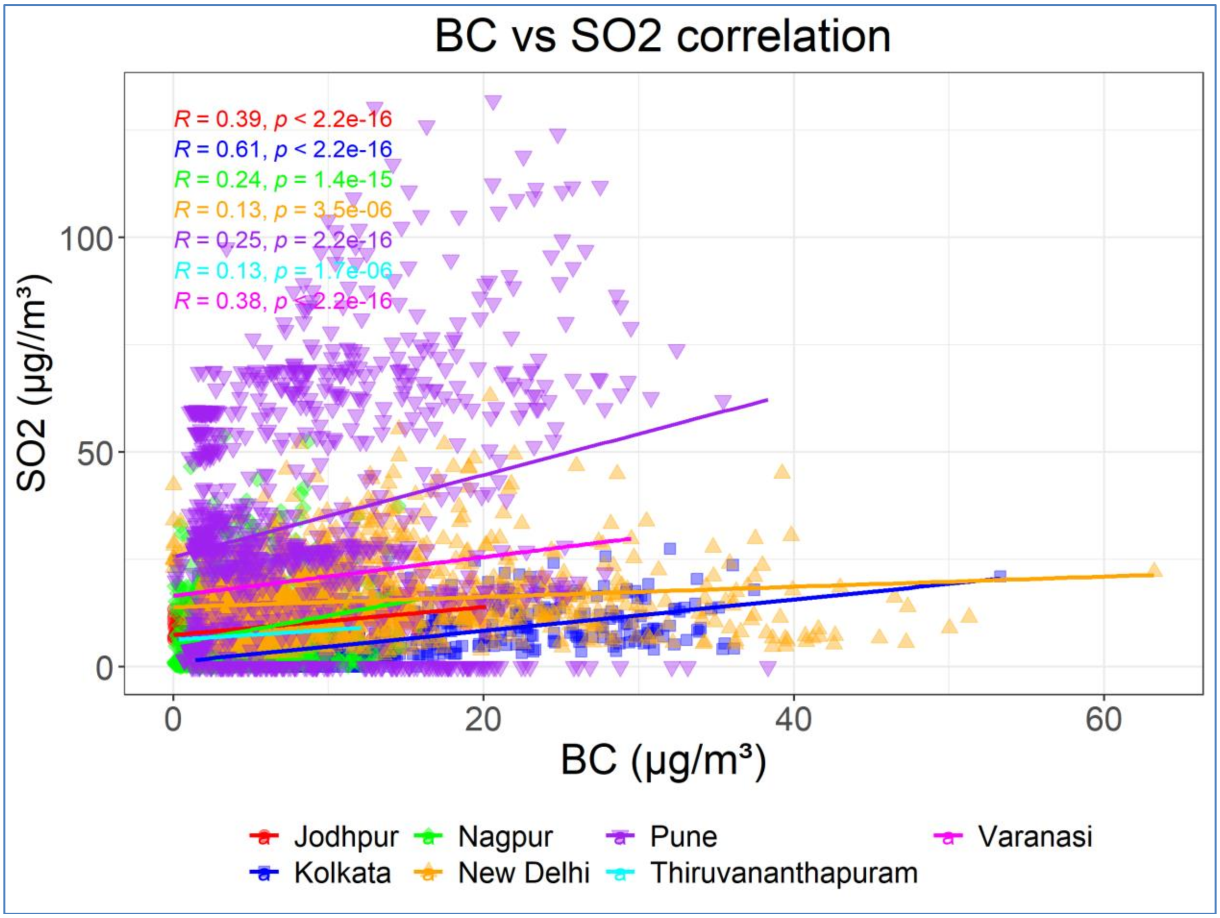


Fig. 5. Monthly data scatter plot for BC with sulphur Dioxide for the study period

Pune's better ventilation conditions due to favorable wind patterns, which may disperse CO and BC more effectively, reducing their co-accumulation. The positive correlation between CO and BC (0.56) in Thiruvananthapuram suggests potential contributions from vehicular emissions, biomass burning, and industrial activities to both pollutants. The positive correlation between CO and BC (0.66) in Varanasi indicates vehicular emissions and industrial activities as major sources of both pollutants. Varanasi's stagnant atmospheric conditions, particularly during winter, likely facilitate the co-accumulation of CO and BC. Biomass burning along the Gangetic plains may also enhance their levels, strengthening the correlation. Humidity can also have an impact on the relationship between CO and BC. High humidity levels can enhance the formation of secondary pollutants, such as PM, from primary pollutants like CO and BC. As humidity levels increase, the formation of PM can also increase, leading to higher levels of air pollution.CO can enhance the ability of BC to absorb sunlight, leading to warming of the atmosphere and potentially affecting rainfall patterns.

3.2.5. *Correlation of BC with sulphur dioxide*

It is a short-lived, colorless, and foul-smelling toxic gas that is produced when fossil fuels such as coal and oil are burned, and it can contribute to the formation of secondary pollutants, such as PM and acid rain. In some cases, SO_2 can interact with BC in the atmosphere and contribute to the formation of secondary pollutants, such as sulfates. The formation of sulfates from the reaction between SO_2 and BC can enhance the ability of BC to absorb sunlight, leading to warming of the atmosphere (Şahin *et al*., 2020; Zhang *et al*., 2022). BC-SO_2 showed positive correlation with varying magnitudes for the cities during the study period (Fig. 5).

Jodhpur exhibited a positive correlation between SO_2 and BC (0.31), suggesting contributions from common emission sources such as vehicular traffic and industrial activities. This mild correlation could also reflect the dispersed nature of emissions in Jodhpur, where localized sources might not strongly dominate pollutant levels due to wind patterns and semi-arid climatic conditions.

Kolkata showed a positive correlation between SO_2 and BC (0.85), highlighting the significant role of coal combustion, vehicular emissions, and industrial processes in contributing to BC levels. The high correlation likely results from the city's reliance on coal for industrial energy, dense traffic emissions, and limited dispersion due to high population density and lower ventilation in the atmospheric boundary layer. The association suggests that BC emissions, particularly from biomass burning, diesel engines, and industrial sources, are closely linked to SO_2 levels in Kolkata's atmosphere. In Nagpur, a positive correlation of 0.42 was observed between SO_2 and BC, indicating common sources such as vehicular traffic and industrial activities. This moderate correlation might be influenced by seasonal factors, including agricultural residue burning in surrounding areas, which could contribute to both BC and SO_2 emissions. New Delhi exhibited a positive correlation between SO_2 and BC (0.16), implying potential differences in the emission sources for these pollutants. The weak correlation may arise from significant contributions to SO_2 levels from coal-fired power plants and industrial processes, while BC levels are more strongly influenced by vehicular emissions and biomass burning. Additionally, atmospheric processes like photochemical reactions could affect the levels of SO_2 independently of BC.

Pune showed a positive correlation of 0.27 between SO_2 and BC. This reflects the influence of vehicular and industrial emissions, although Pune's relatively better air dispersion due to favorable wind speeds and its moderate industrial activity might reduce the correlation strength. Thiruvananthapuram exhibited a similar positive correlation between SO_2 and BC (0.14), reflecting the influence of vehicular emissions and industrial activities. The low correlation can also be attributed to the coastal location, where sea breezes dilute pollutants, and the predominance of natural sources, such as marine aerosols, which may not contribute to BC or SO_2 levels. Varanasi demonstrated a positive correlation between SO_2 and BC (0.36), suggesting common sources such as vehicular exhaust and industrial processes. The correlation may also be influenced by biomass burning in surrounding rural areas, a significant seasonal contributor to both BC and SO_2. Additionally, the relatively stagnant atmospheric conditions in Varanasi during certain seasons could enhance the accumulation of both pollutants.

3.2.6. *Correlation of BC with benzene and toluene*

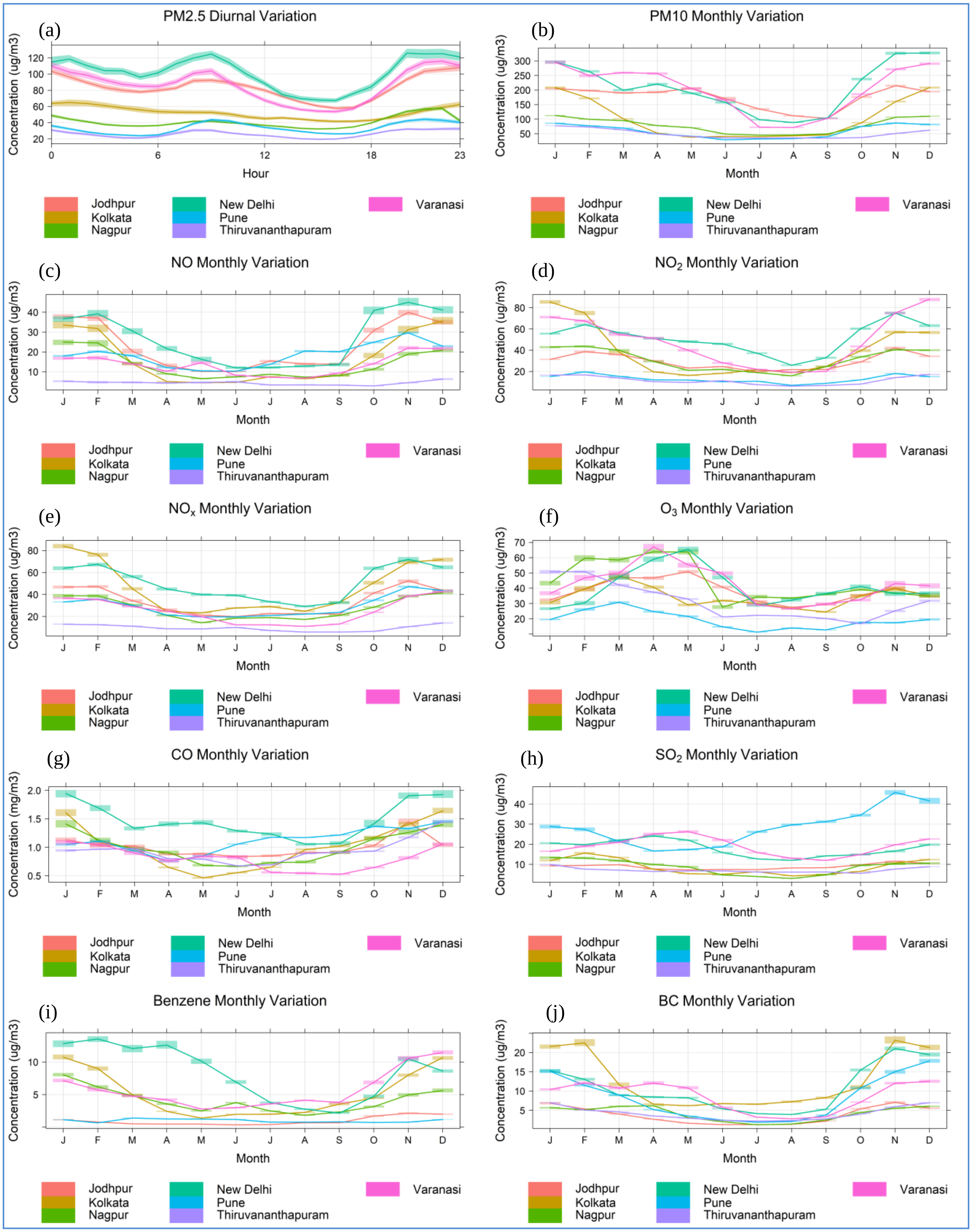
In Jodhpur, the correlation coefficients for Benzene (0.21) and Toluene (0.31) suggest a weaker association between BC concentrations and these VOCs compared to other pollutants such as NO, NOx, CO, PM10, and PM2.5. This weaker association may be due to the relatively lower contribution of traffic emissions and industrial activities involving VOCs in Jodhpur, where BC levels are more influenced by combustion-related sources. Additionally, the semi-arid climate may facilitate the rapid dispersion of VOCs, further reducing the observed correlation. In Kolkata, the correlation coefficients for benzene (0.60) and toluene (0.26) indicate a slightly weaker association between BC concentration and these VOCs compared to pollutants such as NO_2, NOx, CO, PM10, and PM2.5. The moderate correlation for benzene suggests its significant contribution from traffic and industrial sources, while the weaker correlation for toluene may reflect its emissions from non-combustion activities, such as solvent use and paint industries, which are less associated with BC. In Nagpur, the correlation coefficients for Benzene (0.41) and Toluene (0.12) suggest a weaker association between BC concentration and these VOCs compared to pollutants like NO_2, PM10, and PM2.5. This disparity may result from differences in the emission sources, with BC primarily originating from traffic and industrial combustion, whereas VOCs like toluene may have substantial contributions from solvent evaporation and other non-combustion processes. Seasonal factors, such as agricultural burning, might also differentially affect these correlations. In New Delhi, the correlation coefficients for Benzene (0.58) and Toluene (0.55) were slightly lower than for pollutants such as NO, NO_2, NOx, CO, PM10, and PM2.5 but still indicate a notable association between BC concentration and these VOCs. The relatively higher correlation for both VOCs compared to other cities suggests their significant emission from traffic-related activities, particularly due to the combustion of petrol and diesel, which emit both BC and VOCs in substantial quantities. However, the presence of other VOC sources, such as industrial solvent use, may lower the overall association. In Varanasi, the correlation coefficients for Benzene (0.38) and Toluene (0.49) suggest a weaker association between BC concentration and these VOCs compared to pollutants like NO_2, NOx, CO, PM10, and PM2.5. This weaker association may reflect the mixed contributions to VOC emissions in Varanasi, including vehicular exhaust, industrial activities, and biomass burning, with some of these sources (e.g., solvent use) contributing less to BC emissions. Additionally, atmospheric processes like photochemical reactions may alter VOC concentrations independently of BC levels.

3.3. *Atmospheric boundary layer and ventilation coefficients*

During the post-monsoon and winter seasons, the mixing height and ventilation coefficients play a crucial role in determining the dispersion and dilution of pollutants in the atmosphere across various cities. The maximum mixing height (MMH) and maximum ventilation coefficient (MVC) have been determined using radiosonde data. Stations categorized by MVC have been classified based on their pollution potential: low pollution potential (VC > 12000 m^2/sec), medium pollution potential (VC ≈ 6000-12000 m^2/sec), and high pollution potential (VC < 6000 m^2/sec) (Attri *et al*., 2008). The MVC values indicate the atmosphere's ability to disperse pollutants effectively.

Both PM2.5 and PM10 Figs. 6(a & b) exhibit distinct seasonal trends, with the highest concentrations observed during winter (December–January), driven by increased emissions and atmospheric stability. PM2.5 levels peak at 150–200 µg/m³, while PM10 reaches 250–300 µg/m³ in highly polluted cities like New Delhi and Varanasi. In contrast, during the monsoon season (June–September), concentrations drop significantly due to wet deposition, with PM2.5 ranging between 20–40 µg/m³ and PM10 between 50–100 µg/m³ in relatively cleaner cities like Pune and Thiruvananthapuram. The concentrations of nitrogen oxides (NO, NO_2, and NO_x) follow a similar pattern Figs. 6(c-e), with wintertime peaks due to enhanced vehicular and industrial emissions combined with atmospheric stagnation. NO levels reach 50–60 µg/m³, NO_2 peaks at 40–50 µg/m³, and total NO_x levels exceed 70–80 µg/m³ in cities such as New Delhi and Kolkata. During the monsoon months, these pollutants drop significantly, with NO falling below 5–10 µg/m³, NO_2 to 10–15 µg/m³, and NO_x below 20 µg/m³, particularly in coastal cities like Thiruvananthapuram, where precipitation and wind patterns help dilute pollution. Ozone exhibits a different seasonal trend (Fig. 6(f)) compared to primary pollutants, with peak levels occurring in summer (April–June) due to strong solar radiation and enhanced photochemical activity. Concentrations reach 60–80 µg/m³ in cities like Pune and Jodhpur. Winter months see the lowest ozone levels, around 20–30 µg/m³, due to reduced sunlight and higher NO_x concentrations, which promote ozone depletion. CO concentrations are highest in winter, reaching 2.0-2.5 mg/m³ in densely populated cities like New Delhi (Fig. 6(g)), where combustion sources dominate. Summer and monsoon months show a decline, with concentrations dropping to 0.5–1.0 mg/m³ due to improved dispersion and atmospheric mixing. SO_2 levels peak in winter, exceeding 40–50 µg/m³ in industrial cities such as Kolkata and Jodhpur (Fig. 6(h). During the monsoon, concentrations drop to 10–15 µg/m³, mainly due to washout effects and reduced coal combustion in some regions. Benzene, primarily from vehicular emissions, shows maximum concentrations in winter, reaching 5–7 µg/m³ in cities like Delhi and Kolkata (Fig. 6(i)). The levels drop to 1–3 µg/m³ in summer and monsoon seasons due to atmospheric dilution and changes in emission patterns. BC exhibits strong seasonal variation, with winter concentrations exceeding 8–10 µg/m³ in northern cities like New Delhi and Kolkata (Fig. 6(i) due to biomass burning and heating emissions. In summer, concentrations moderate to 3–5 µg/m³, while monsoon months register the lowest levels (1–3 µg/m³) due to wet deposition.

In Jodhpur, where positive correlations with BC - are observed, atmospheric boundary layer (see Fig. 7) dynamics and ventilation coefficients likely contribute to the efficient dispersion of pollutants. The high ventilation coefficients facilitate the mixing of pollutants within the boundary layer, leading to elevated concentrations of BC and other pollutants. In New Delhi, Kolkata, and Varanasi, where robust correlations with BC are evident, the atmospheric boundary layer and ventilation coefficients likely play a significant role in dispersing pollutants emitted from vehicular traffic and industrial activities. The efficient mixing within the boundary layer may contribute to the accumulation of BC and other pollutants, exacerbating air quality issues in these urban centers. In Nagpur and Thiruvananthapuram, where weaker associations between pollutants and BC are observed, the atmospheric boundary layer and ventilation coefficients may contribute to the dispersion and dilution of pollutants, resulting in lower concentrations of BC compared to other cities. However, local emission sources and meteorological conditions likely play a more significant role in influencing BC levels in these regions. For New Delhi, the MVC ranges from 19264 m^2/s (pre-monsoon) to 6127 m^2/s (winter). In Nagpur, the range is from 17964 m^2/s (pre-monsoon) to 5413 m2/s (winter). Jodhpur shows values ranging from 10860 m^2/s (pre-monsoon) to 5328 m2/s (winter). Meanwhile, Kolkata exhibits a variation from 17513 m^2/s (pre-monsoon) to 4948 m2/s (winter). Thiruvananthapuram's MVC varies from 4451 m^2/s (pre-monsoon) to 2899 m^2/s (winter). Cities like New Delhi and Kolkata exhibit substantial fluctuations in MVC between seasons, reflecting significant changes in atmospheric conditions and are also having maximum BC concentrations. Regarding the MMH, for New Delhi, it varies from 2701 meters (pre-monsoon) to 1106 meters (winter). In Kolkata, the range is from 2975 meters (pre-monsoon) to 1029 meters (winter). Jodhpur shows a variation from 1773 meters (pre-monsoon) to 997 meters (winter). In Nagpur, the MMH ranges from 3009 meters (pre-monsoon) to 1226 meters (winter). Thiruvananthapuram's MMH varies from 1305 meters (pre-monsoon) to 1367 meters (winter). MMH values represent the vertical extent within which pollutants are well-mixed by atmospheric turbulence. Higher MMH values indicate greater potential for vertical dispersion of pollutants. The observed variations in MMH



Figs. 6(a-j). Monthly variation of pollutants (a) $PM_{2.5}$, (b) PM_{10}, (c) NO, (d) NO_2, (e) NOx, (f) Surface Ozone, (g) CO, (h) SO2 (i) Benzene &(j) BC for the study period

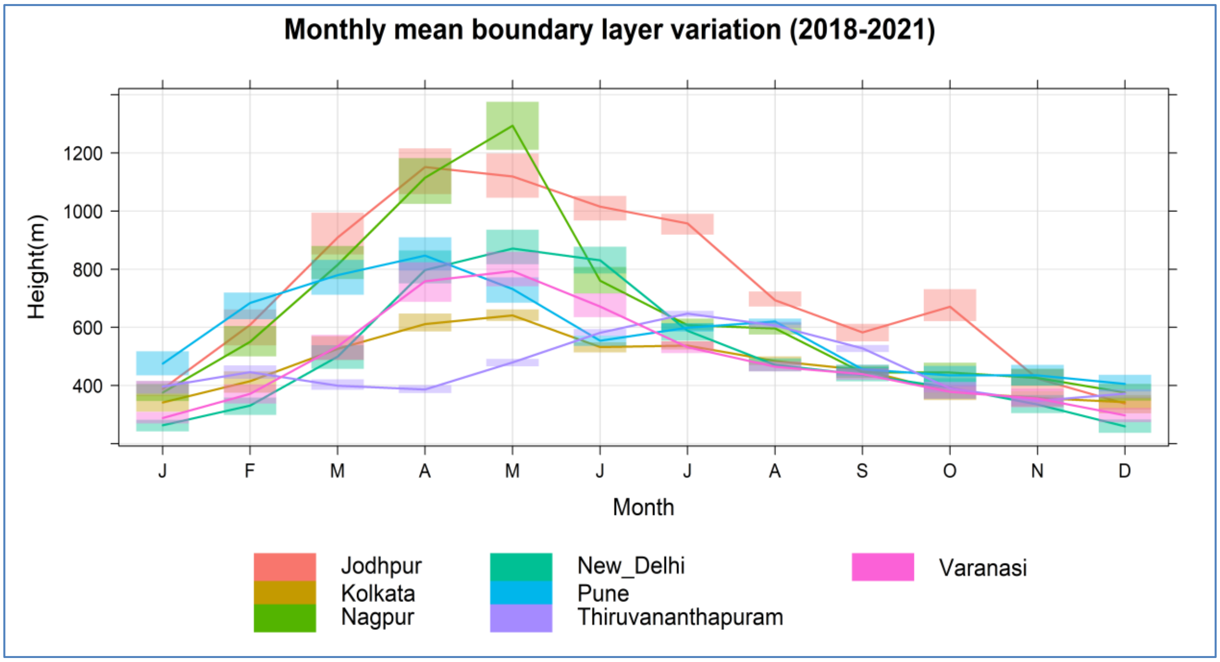


Fig. 7. Monthly mean boundary layer variation for the study period

across seasons highlight seasonal differences in atmospheric stability and turbulence. Higher MVC and MMH values during pre-monsoon seasons suggest favorable conditions for pollutant dispersion, potentially leading to better air quality. Lower MVC and MMH values during winter indicate stagnant atmospheric conditions, which may lead to poor dispersion and higher pollution levels. The observed fluctuations in MVC and MMH across seasons are indicative of the variability in the structure and dynamics of the atmospheric boundary layer. During pre-monsoon seasons, the atmospheric boundary layer tends to be more turbulent and well-mixed, allowing for efficient pollutant dispersion and dilution. During winter, the atmospheric boundary layer becomes more stable, characterized by reduced vertical mixing and increased pollutant concentration near the surface. The changes we see in MVC and MMH show how the atmosphere behaves differently throughout the year. This shows that the stability of the air, its turbulence, and the spread of pollutants are linked. It's important to adapt our strategies depending on the season to tackle pollution in cities better.

4. Conclusions

This study examines the complex factors influencing air pollution in Indian cities. Key pollutants like BC, carbon monoxide (CO), nitrogen oxides (NOx), and volatile organic compounds (VOCs) were analyzed to identify emission sources and their impact on air quality. Most cities (except New Delhi) showed a negative correlation between temperature and pollutants, indicating lower pollution at higher temperatures. New Delhi exhibited an interesting anomaly with higher humidity led to increased ozone levels, while other pollutants showed a decrease with humidity. Higher wind speeds, humidity, and rainfall were generally associated with lower pollutant concentrations across most cities. Pollution levels fluctuated with seasons due to changes in emission patterns and weather conditions. Monsoon rains helped reduce pollutant concentrations through washout. Winter and post-monsoon seasons showed city-specific variations. Traffic, industry, and construction dust were major contributors to BC and air pollution, especially during the pre-monsoon season (as shown by strong positive correlations with NO_x and SO_2). Benzene and toluene, while showing weaker correlations with BC compared to other pollutants, still exhibited significant associations, indicating potential contributions from these volatile organic compounds. The study highlights the importance of local atmospheric conditions like MVC and MMH in pollutant dispersion. These factors vary across seasons, necessitating season-specific pollution management strategies. The study provides valuable insights for policymakers to develop targeted interventions to mitigate air pollution. By adopting season-specific approaches, enabling staggered responses to activities, and considering local atmospheric dynamics, effective strategies can be implemented to achieve cleaner air and safeguard public health.

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Authors' contributions

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Panuganti CS Devara: Supervision, Writing – review and editing, Visualization
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References

Al-Delaimy, W.K., Ramanathan, V., Sánchez Sorondo, M. (Eds.), 2020, "Health of People, Health of Planet and Our Responsibility: Climate Change, Air Pollution and Health", *Springer International Publishing, Cham*. doi: https://doi.org/10.1007/978-3-030-31125-4.

Allabakash, S., Lim, S., Chong, K.-S., Yamada, T., 2022, "Particulate Matter Concentrations over South Korea: Impact of Meteorology and Other Pollutants", *Remote Sensing* **14**, 4849. doi : https://doi.org/10.3390/rs14194849.

Amann, M., 2008. Health risks of ozone from long-range transboundary air pollution. World Health Organization, Regional Office for Europe, Copenhagen.

Amann, M., Bertok, I., Borken-Kleefeld, J., Cofala, J., Heyes, C., Höglund-Isaksson, L., Klimont, Z., Nguyen, B., Posch, M., Rafaj, P., Sandler, R., Schöpp, W., Wagner, F. and Winiwarter, W., 2011, "Cost-effective control of air quality and greenhouse gases in Europe: Modeling and policy applications", *Environmental Modelling & Software* **26**, 1489–1501. https://doi.org/10.1016/j.envsoft.2011.07.012.

Ambade, B., Sankar, T.K., Panicker, A.S., Gautam, A.S., Gautam, S., 2021, "Characterization, seasonal variation, source apportionment and health risk assessment of black carbon over an urban region of East India", *Urban Climate* **38**, 100896. https://doi.org/10.1016/j.uclim.2021.100896.

Attri, S.D., Singh, S., Mukhopadhyay, B. and Bhatnagar, A.K., 2008, "Atlas Of Hourly Mixing Height And Assimilative Capacity Of Atmosphere In India" EMRC IMD, New Delhi.

Bond, T.C. and Bergstrom, R.W., 2006, "Light Absorption by Carbonaceous Particles: An Investigative Review", *Aerosol Science and Technology* **40**, 27–67. https://doi.org/10.1080/02786820500421521.

Bond, T.C., Doherty, S.J., Fahey, D.W., Forster, P.M., Berntsen, T., DeAngelo, B.J., Flanner, M.G., Ghan, S., Kärcher, B., Koch, D., Kinne, S., Kondo, Y., Quinn, P.K., Sarofim, M.C., Schultz, M.G., Schulz, M., Venkataraman, C., Zhang, H., Zhang, S., Bellouin, N., Guttikunda, S.K., Hopke, P.K., Jacobson, M.Z., Kaiser, J.W., Klimont, Z., Lohmann, U., Schwarz, J.P., Shindell, D., Storelvmo, T., Warren, S.G. and Zender, C.S., 2013, "Bounding the role of black carbon in the climate system: A scientific assessment: BLACK CARBON IN THE CLIMATE SYSTEM", *J. Geophys. Res. Atmos*. **118**, 5380–5552. https://doi.org/10.1002/jgrd.50171.

Coates, J., Mar, K.A., Ojha, N. and Butler, T.M., 2016, "The influence of temperature on ozone production under varying NO_{<i>x</i>} conditions – a modelling study", *Atmos. Chem. Phys*. **16**, 11601–11615. https://doi.org/10.5194/acp-16-11601-2016.

Flanner, M.G., Zender, C.S., Hess, P.G., Mahowald, N.M., Painter, T.H., Ramanathan, V. and Rasch, P.J., 2009, "Springtime warming and reduced snow cover from carbonaceous particles", *Atmos. Chem. Phys.* **17**.

Garzón, J.P., Huertas, J.I., Magaña, M., Huertas, M.E., Cárdenas, B., Watanabe, T., Maeda, T., Wakamatsu, S. and Blanco, S., 2015, "Volatile organic compounds in the atmosphere of Mexico City", *Atmospheric Environment* **119**, 415–429. https://doi.org/10.1016/j.atmosenv.2015.08.014.

Grahame, T.J. and Schlesinger, R.B., 2010, "Cardiovascular health and particulate vehicular emissions: a critical evaluation of the evidence", *Air QualAtmos Health* **3**, 3–27. https://doi.org/10.1007/s11869-009-0047-x.

Iyer, U.S. and Raj, P.E., 2013, "Ventilation coefficient trends in the recent decades over four major Indian metropolitan cities", *J Earth SystSci* **122**, 537–549, https://doi.org/10.1007/s12040-013-0270-6.

Jacobson, M.Z., 2001, "Strong radiative heating due to the mixing state of black carbon in atmospheric aerosols", *Nature* **409**, 695–697. https://doi.org/10.1038/35055518.

Janssen, N.A.H., Hoek, G., Simic-Lawson, M., Fischer, P., van Bree, L., ten Brink, H., Keuken, M., Atkinson, R.W., Anderson, H.R., Brunekreef, B. and Cassee, F.R., 2011, "Black Carbon as an Additional Indicator of the Adverse Health Effects of Airborne Particles Compared with PM_{10} and $PM_{2.5}$.", *Environmental Health Perspectives* **119**, 1691–1699. https://doi.org/10.1289/ehp.1003369.

Jenkin, M.E., Clemitshaw, K.C., 2000, "Ozone and other secondary photochemical pollutants: chemical processes governing their formation in the planetary boundary layer", *Atmospheric Environment* **34**, 2499–2527. https://doi.org/10.1016/S1352-2310(99)00478-1.

Kampa, M. and Castanas, E., 2008, "Human health effects of air pollution", *Environmental Pollution* **151**, 362–367. https://doi.org/10.1016/j.envpol.2007.06.012.

Kang, S., Zhang, Y., Qian, Y. and Wang, H., 2020, "A review of black carbon in snow and ice and its impact on the cryosphere", *Earth-Science Reviews* **210**, 103346. https://doi.org/10.1016/ j.earscirev.2020.103346.

Kim, S., Yu, S. and Yun, D., 2017, "Spatiotemporal Association of Real-Time Concentrations of Black Carbon (BC) with Fine Particulate Matters (PM2.5) in Urban Hotspots of South Korea", *IJERPH* **14**, 1350. https://doi.org/10.3390/ijerph 14111350.

Krishnan, P. and Kunhikrishnan, P.K., 2004, "Temporal variations of ventilation coefficient at a tropical Indian station using UHF wind profiler", *Current Science,* **86**.

Kumar, R.R., 2020, "Evaluation of spatial and temporal heterogeneity of black carbon aerosol mass concentration over India using three year measurements from IMD BC observation network", *Science of the Total Environment*, **12**.

Kumar, V., Devara, P.C.S., Soni, V.K., 2023, « Multisite Scenarios of Black Carbon and Biomass Burning Aerosol Characteristics in India", *Aerosol Air Qual. Res*. **23**, 220435. https://doi.org/ 10.4209/aaqr.220435.

Latha, K.M., Badarinath, K.V.S., 2004, "Correlation between black carbon aerosols, carbon monoxide and tropospheric ozone over a tropical urban site", *Atmospheric Research* **71**, 265–274. https://doi.org/10.1016/j.atmosres.2004.06.004.

Li, M., Yu, S., Chen, X., Li, Z., Zhang, Y., Wang, L., Liu, W., Li, P., Lichtfouse, E., Rosenfeld, D., Seinfeld, J.H., 2021, "Large scale control of surface ozone by relative humidity observed during warm seasons in China", *Environ ChemLett* **19**, 3981–3989. https://doi.org/10.1007/s10311-021-01265-0.

Liu, C., Huang, J., Wang, Y., Tao, X., Hu, C., Deng, L., Xu, J., Xiao, H.-W., Luo, L., Xiao, H.-Y., Xiao, W., 2020, "Vertical distribution of PM2.5 and interactions with the atmospheric boundary layer during the development stage of a heavy haze pollution event", *Science of The Total Environment* **704**, 135329. https://doi.org /10.1016/j.scitotenv.2019.135329.

Lu, C., Deng, Q., Liu, W., Huang, B., Shi, L., 2012, "Characteristics of ventilation coefficient and its impact on urban air pollution", *J. Cent. South Univ. Technol*. **19**, 615–622. https://doi.org/10. 1007/s11771-012-1047-9.

Manisalidis, I., Stavropoulou, E., Stavropoulos, A., Bezirtzoglou, E., 2020, "Environmental and Health Impacts of Air Pollution: A Review", *Front. Public Health* **8**, 14. https://doi.org/10.3389/ fpubh.2020.00014.

Murthy, B.S., Latha, R., Tiwari, A., Rathod, A., Singh, S., Beig, G., 2020, "Impact of mixing layer height on air quality in winter", *Journal of Atmospheric and Solar-Terrestrial Physics* **197**, 105157. https://doi.org/10.1016/j.jastp.2019.105157.

Nair, S.K., Madhusoodanan, M.S., Mehajan, R.K., 2018, "The role of Boundary Layer Height (BLH) variations on pollution dispersion over a coastal station in the Southwest Peninsular India", *Journal of Atmospheric and Solar-Terrestrial Physics* **179**, 273–280. https://doi.org/10.1016/j.jastp.2018.07.011.

Năstase, G., Șerban, A., Năstase, A.F., Dragomir, G., Brezeanu, A.I., 2018, "Air quality, primary air pollutants and ambient concentrations inventory for Romania", *Atmospheric Environment,* **184**, 292–303. https://doi.org/10.1016/j.atmosenv .2018.04.034.

Raju, M.P., Safai, P.D., Rao, P.S.P., Devara, P.C.S. and Budhavant, K.B., 2011, "Seasonal characteristics of black carbon aerosols over a high altitude station in Southwest India", *Atmospheric Research* **100**, 103–110. https://doi.org/10.1016/j.atmosres. 2011.01.006.

Ramanathan, V. and Carmichael, G., 2008, "Global and regional climate changes due to black carbon", *Nature Geosci* **1**, 221–227. https://doi.org/10.1038/ngeo156.

Ramesh, K.J., Jena, C., Kumar, A., Kumar, V., Soni, V.K., 2025, "Advances in Environmental Meteorology and Air Quality Early Warning", *Mausam* **76**, 185–214. https://doi.org/10. 54302/mausam.v76i1.6941.

Safai, P.D., Raju, M.P., Budhavant, K.B., Rao, P.S.P. and Devara, P.C.S., 2013, "Long term studies on characteristics of black carbon aerosols over a tropical urban station Pune, India', *Atmospheric Research* 132–133, 173–184. https://doi.org/10. 1016/j.atmosres.2013.05.002.

Saha, D., Soni, K., Mohanan, M.N. and Singh, M., 2019, "Long-term trend of ventilation coefficient over Delhi and its potential impacts on air quality", *Remote Sensing Applications: Society and Environment* **15**, 100234. https://doi.org/10.1016/j.rsase. 2019.05.003.

Şahin, Ü.A., Onat, B., Akın, Ö., Ayvaz, C., Uzun, B., Mangır, N., Doğan, M. and Harrison, R.M., 2020, "Temporal variations of atmospheric black carbon and its relation to other pollutants and meteorological factors at an urban traffic site in Istanbul", *Atmospheric Pollution Research* **11**, 1051–1062. https://doi.org/ 10.1016/j.apr.2020.03.009.

Sandeep, P., Saradhi, I.V., Pandit, G.G., 2013, "Seasonal Variation of Black Carbon in Fine Particulate Matter (PM2.5) at the Tropical Coastal City of Mumbai, India", *Bull Environ ContamToxicol* **91**, 605–610. https://doi.org/10.1007/s00128-013-1108-2.

Saxena, P. and Sonwani, S., 2019, "Criteria Air Pollutants: Chemistry, Sources and Sinks, in: Criteria Air Pollutants and Their Impact on Environmental Health", *Springer Singapore, Singapore*, 7–48. https://doi.org/10.1007/978-981-13-9992-3_2.

Shahgedanova, M., 2021, "Climate change and melting glaciers, in: The Impacts of Climate Change", *Elsevier*, 53–84. https://doi.org/10.1016/B978-0-12-822373-4.00007-0.

Singh, J., Srikanth, R. and Ramasesha, S.K., 2021, "Dispersion of Particulate Matter and Sulphur Oxides from Thermal Power Plant: a Case Study", *Environ Model Assess* **26**, 763–778. https://doi.org/10.1007/s10666-021-09790-6.

Singh, N., Singh, S. and Mall, R.K., 2020, "Urban ecology and human health: implications of urban heat island, air pollution and climate change nexus, in: Urban Ecology", *Elsevier*, 317–334. https://doi.org/10.1016/B978-0-12-820730-7.00017-3.

Sitaras, I.E., Siskos, P.A., 2008, "The role of primary and secondary air pollutants in atmospheric pollution: Athens urban area as a case study", *Environ ChemLett* **6**, 59–69. https://doi.org/10.1007/ s10311-007-0123-0.

Sujatha, P., Mahalakshmi, D.V., Ramiz, A., Rao, P.V.N. and Naidu, C.V., 2016, "Ventilation coefficient and boundary layer height impact on urban air quality", *Cogent Environmental Science* **2**, 1125284, doi: https://doi.org/10.1080/23311843.2015.1125284.

Swamy, Y.V., Venkanna, R., Nikhil, G.N., Chitanya, D.N.S.K., Sinha, P.R., Ramakrishna, M., Rao and A.G., 2012, "Impact of Nitrogen Oxides, Volatile Organic Compounds and Black Carbon on Atmospheric Ozone Levels at a Semi Arid Urban Site in Hyderabad", *Aerosol Air Qual. Res*. **12**, 662–671. https://doi.org/10.4209/aaqr.2012.01.0019.

Tiwari, S., Srivastava, A.K., Bisht, D.S., Bano, T., Singh, S., Behura, S., Srivastava, M.K., Chate, D.M. and Padmanabhamurty, B., 2009, "Black carbon and chemical characteristics of PM10 and PM2.5

at an urban site of North India” *J. AtmosChem,* **62**, 193–209. https://doi.org/10.1007/s10874-010-9148-z.

Ueno, H. and Tsunematsu, N., 2019, “Sensitivity of ozone production to increasing temperature and reduction of precursors estimated from observation data”, *Atmospheric Environment* **214**, 116818. https://doi.org/10.1016/j.atmosenv.2019.116818.

Wang, F., Xu, J., Huang, Y. and Xiu, G., 2021, “Characterization of Black Carbon and Its Correlations with VOCs in the Northern Region of Hangzhou Bay in Shanghai, China” *Atmosphere* **12**, 870. https://doi.org/10.3390/atmos12070870.

Wang, Y., Wang, X., Kondo, Y., Kajino, M., Munger, J.W., Hao, J., 2011, “Black carbon and its correlation with trace gases at a rural site in Beijing: Top-down constraints from ambient measurements on bottom-up emissions: BC AND CO CORRELATION NEAR BEIJING”, *J. Geophys. Res.* **116**, n/a-n/a. https://doi.org/10.1029/2011JD016575.

WHO, 2021. WHO global air quality guidelines: particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. WHO, Geneva.

Xu, J., Hu, W., Liang, D. and Gao, P., 2022, “Photochemical impacts on the toxicity of $PM_{2.5}$. Critical Reviews in Environmental Science and Technology **52**, 130–156. https://doi.org/10.1080/10643389.2020.1816126.

Yan, S., Xiang, J., Du, H., 2019, “Determining Atmospheric Boundary Layer Height with the Numerical Differentiation Method Using Bending Angle Data from COSMIC”, *Adv. Atmos. Sci*. **36**, 303–312, https://doi.org/10.1007/s00376-018-7308-2.

Yang, S., Yuan, B., Peng, Y., Huang, S., Chen, W., Hu, W., Pei, C., Zhou, J., Parrish, D.D., Wang, W., He, X., Cheng, C., Li, X.-B., Yang, X., Song, Y., Wang, H., Qi, J., Wang, B., Wang, Chen, Wang, Chaomin, Wang, Z., Li, T., Zheng, E., Wang, S., Wu, C., Cai, M., Ye, C., Song, W., Cheng, P., Chen, D., Wang, Xinming, Zhang, Z., Wang, Xuemei, Zheng, J., Shao, M., 2022, “The formation and mitigation of nitrate pollution: comparison between urban and suburban environments”, *Atmos. Chem. Phys.* **22**, 4539–4556. https://doi.org/10.5194/acp-22-4539-2022.

Yassin, M.F., Al-Shatti, L.A., Al Rashidi, M.S., 2018, “Assessment of the atmospheric mixing layer height and its effects on pollutant dispersion”, *Environ Monit Assess* **190**, 372. https://doi.org/10.1007/s10661-018-6737-9.

Zhang, F., Peng, J., Chen, L., Collins, D., Li, Y., Jiang, S., Liu, J., Zhang, R., 2022, “The effect of black carbon aging from NO2 oxidation of SO2 on its morphology, optical and hygroscopic properties,” *Environmental Research* **212**, 113238. https://doi.org/10.1016/j.envres.2022.113238.

Zhang, Q., Shen, Z., Cao, J., Zhang, R., Zhang, L., Huang, R.-J., Zheng, Chenjia, Wang, L., Liu, S., Xu, H., Zheng, Chunli, Liu, P., 2015.Variations in PM2.5, TSP, BC, and trace gases (NO2, SO2, and O3) between haze and non-haze episodes in winter over Xi’an, China. *Atmospheric Environment* **112**, 64–71. https://doi.org/10.1016/j.atmosenv.2015.04.033.