



Research Article

Columnar optical properties of locally emitted light-absorbing carbonaceous aerosols

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ABSTRACT

The vertical distribution of light-absorbing carbonaceous aerosols significantly affects atmospheric radiative forcing properties. A novel method combining HYSPLIT trajectory ensemble and concentration-weighted trajectory (CWT) analysis (Ens-HYSPLIT-CWT) was employed in this study to distinguish local emission events from all air mass sources. The aerosol profile distribution under pollution control measures in Beijing was investigated using continuous and simultaneous measurements at both surface and mountain stations. By applying the wavelength dependence of the absorption Ångström exponent (WDA) method, more accurate brown carbon (BrC) absorption coefficients at 370 and 470 nm were derived, better aligning with the observed wavelengths of the AE33 instrument. We found a larger vertical decrease for BrC compared to black carbon (BC) particles, resulting in an enhanced fraction of BC absorption relative to BrC measured at the mountain station. Furthermore, we investigated the columnar aerosol optical properties at 550 nm by combining BC and BrC absorption, and aerosol scattering properties derived from Mie theory. Peak values of aerosol optical depth (AOD) and absorption aerosol optical depth (AAOD) both occurred at noon during locally emitted pollution events. AOD increased by 1.91 times, and AAOD increased by 1.93. Additionally, due to the higher transport efficiency of BC particles compared to non-BC particles during locally emitted pollution events, the single scattering albedo (SSA) exhibited a valley at noon.

1. Introduction

Light-absorbing carbonaceous aerosols (LACs) consist of black carbon (BC) and brown carbon (BrC) aerosols. Due to the strong light absorption of BC at all visible wavelengths and BrC at short wavelengths, LACs have become one of the most important radiatively active components in the earth system (Liu et al., 2020a). Several studies have reviewed the light absorption of LACs (Bond and Bergstrom, 2006), climate impacts of BC (Bond et al., 2013), and chemistry of BrC (Laskin et al., 2015).

China's rapid and energy-intensive development over several decades has led to severe pollution events and negative public health impacts (Huang et al., 2014). Studies on LACs have primarily focused on high pollution events. For example, Hu et al. (2020) used aircraft-based aerosol measurement instruments to investigate the vertical distribution of BC particles primarily under high pollution levels. Recently, several studies have found a decrease in pollutants after the implementation of the Air Pollution Prevention and Control Action Plan and the Blue-Sky Protection Campaign (Hu et al., 2025; Zhang et al., 2019). Consequently, under these new circumstances, attention on the vertical distribution

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bution of LACs in China should gradually shift towards lower pollution conditions.

To explore the optical properties of carbonaceous aerosols, particularly in the short wavelengths, it is essential to consider the impact of BrC. The absorption Ångström exponent (AAE) method can be used to obtain BrC absorption results. This is because BrC aerosols mainly absorb light at near-ultraviolet (UV) wavelengths, while BC is the sole contributor to absorption at 880 nm (Bahadur et al., 2012; Chung et al., 2012; Russell et al., 2010). Most studies derive the BrC absorption coefficient by assuming a BC AAE of 1. However, the variation of ambient BC absorption results at different wavelengths is influenced by many factors, leading to the fluctuation in BC AAE values. An AAE equal to unity only occurs when BC particle diameter is smaller than 10 nm, while BC particles associated with biomass burning and biofuel sources is typically larger than 70 nm (Bond and Bergstrom, 2006). Moreover, the AAE of particles larger than 20 nm is sensitive to the chosen reference wavelengths. Therefore, the assumption that BC AAE is consistently equal to unity is not supported by either theory or field observations. Consequently, estimates of BrC absorption based on this underlying assumption are subject to large errors.

Most LACs observation experiments are conducted at surface level (Wu et al., 2019; Xu et al., 2020), but surface measurements cannot represent the vertical distribution of aerosols. This is important because the vertical distribution is correlated with columnar optical properties, and varying vertical heights of LACs impact atmospheric thermodynamics. Numerous studies have investigated the vertical profiles of LACs over the East Asian region (Liu et al., 2019; Ran et al., 2016; Zhao et al., 2019), primarily using aerosol measurement instruments on aircraft (Hu et al., 2020) or tethered balloon (Guan et al., 2024) to observe the vertical profiles. However, the limited temporal coverage of these measurement methods prevents continuous monitoring of diurnal variations in the vertical distribution of pollutants.

Accurately determining the concentration or absorption coefficient of BrC is crucial for studying the columnar optical properties LACs. To avoid errors caused by assuming a stable unity value of BC AAE, the wavelength dependence of AAE (WDA) method (Wang et al., 2016) was employed in this study. Wang et al. employed WDA method to calculate the difference in BC AAE between 440/870 and 675/870 nm, while Aethalometer observe the wavelength range of 370, 470, 660, 880 nm, and the influence of wavelength differences on AAE cannot be ignored. By employing a novel method combining HYSPLIT trajectory ensemble with the concentration weighted trajectory (CWT) analysis (Ens-HYSPLIT-CWT), this study identified hourly air mass sources. Integrating this approach with the WDA method enabled more accurate quantification of BrC absorption at 370 and 470 nm and the columnar optical properties of aerosols, such as aerosol optical depth (AOD), absorption aerosol optical depth (AAOD), and single scattering albedo (SSA), during local emission processes.

2. Materials and methods

2.1. Site and instruments

The mountain station (Haituo Mountain, 115.78°E, 40.52°N, 1,344 m a.s.l., white cross in Fig. 1d) is located at the top of the planetary boundary layer (PBL) during winter in Beijing. It receives Beijing surface anthropogenic emissions during convective mixing periods. This phenomenon was previously demonstrated by Liu et al. (2020b) who found that surface-emitted non-volatile BC particles can be effectively elevated to the top of the PBL and measured by the mountain station through convective mixing processes. The surface station, located at the Beijing weather modification center city observation site (116.30°E, 39.94°N, 50 m a.s.l., white star in Fig. 1d), is a typical urban station primarily affected by anthropogenic emission sources. A two-month observation campaign was conducted using these two stations to perform simultaneous measurements from January 1 to February 28, 2021. Plan-

etary boundary layer height (PBLH) data (Fig. 1a) was obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 hourly reanalysis dataset (<https://cds.climate.copernicus.eu/datasets>).

A coordinated GRIMM EDM 180 (Environmental Dust Monitor, GRIMM Aerosol Technik GmbH & Co. KG, Ainring, Germany) particle analyzer was used to monitor the number (Figs. 2d and 3d) and mass (Fig. 1b) concentration of aerosols at surface and mountain stations. The EDM 180 employs a 660 nm diode laser to emit light scattering signals, which are captured by the receiver. The signals are assigned to 31 channels within the range of 0.25–3 µm and converted into mass concentration results with a resolution of 0.1 µg/m³. Nafion tubes were installed before the EDM 180 to remove the influence of water vapor. Due to the PM_{2.5} impactor set in front of the absorbing aerosol measurement instruments, particles greater than 2.5 µm measured by the GRIMM were excluded from further analysis.

2.2. Air mass history

Air mass sources were derived using the Ens-HYSPLIT-CWT method proposed by Hu et al. (2025), which combines HYSPLIT trajectory ensemble with concentration CWT method (Fig. 1d and e). This approach calculates the hourly pollution concentration of each grid and determines the air mass source based on the dominance of integrated concentrations over each grid point in segregated regions (Fig. 1c).

2.3. Absorption properties of carbonaceous aerosols

An Aethalometer AE33 (Magee Scientific Inc., USA) with a PM_{2.5} impactor (BGI SCC1.829) was used to measure the absorption coefficient (σ_{abs} , Mm⁻¹) at both surface and mountain stations (Figs. 2a and 3a). The absorption coefficient at 880 nm ($\sigma_{\text{abs},880}$) was considered to be solely contributed by BC, as BrC aerosols, which strongly absorb at shorter wavelengths, have little impact on measurements at this wavelength. Dual spot measurements at different flow rates automatically calibrate the filter loading effect (Hu et al., 2024). We also compared the absorption coefficient measured by the AE33 with a photoacoustic soot spectrometer (PASS-3, DMT Inc., USA) (Arnott et al., 2005). Multi-scattering is an intrinsic artifact induced by light scattering on the layers of the filter medium, which contributes to light attenuation through the filter but does not result from absorption (Arnott et al., 2003, 2005; Schmid et al., 2006). The multi-scattering correction factor (C-value) was obtained as 3.5, 3.2, and 2.4 at wavelengths of 370, 528, and 880 nm at the surface station, respectively, and a constant value of 2.9 at the mountain station.

The σ_{abs} of BrC can be derived by subtracting the σ_{abs} of BC from the total σ_{abs} , expressed as:

$$\sigma_{\text{abs},\text{BrC}}(\lambda) = \sigma_{\text{abs},\text{total}}(\lambda) - \sigma_{\text{abs},\text{BC}}(\lambda) \quad (1)$$

The σ_{abs} of BC at shorter wavelengths can be derived by using the measured $\sigma_{\text{abs},880}$ and AAE:

$$\text{AAE} = -\frac{\ln\left(\frac{\sigma_{\text{abs}}(\lambda_1)}{\sigma_{\text{abs}}(\lambda_2)}\right)}{\frac{\lambda_1}{\lambda_2}} \quad (2)$$

where, λ_1 and λ_2 are two reference wavelengths, $\text{abs}(\lambda)$ indicates the absorption coefficient at wavelength λ . The ambient BC AAE is not consistently equal to unity, and the AE33 cannot measure the microphysical properties of refractory BC particles. Therefore, the WDA method was employed to derive a more accurate ambient BC AAE.

$$\text{WDA} = \text{AAE}_{\lambda/880} - \text{AAE}_{660/880} \quad (3)$$

According to the WDA method, the σ_{abs} near 880 nm, such as at 660 and 880 nm used in our study, is considered to be dominated by BC particle. The calculated $\text{AAE}_{660/880}$ can be considered as the actual BC AAE between these wavelengths. To explore AAE results at shorter

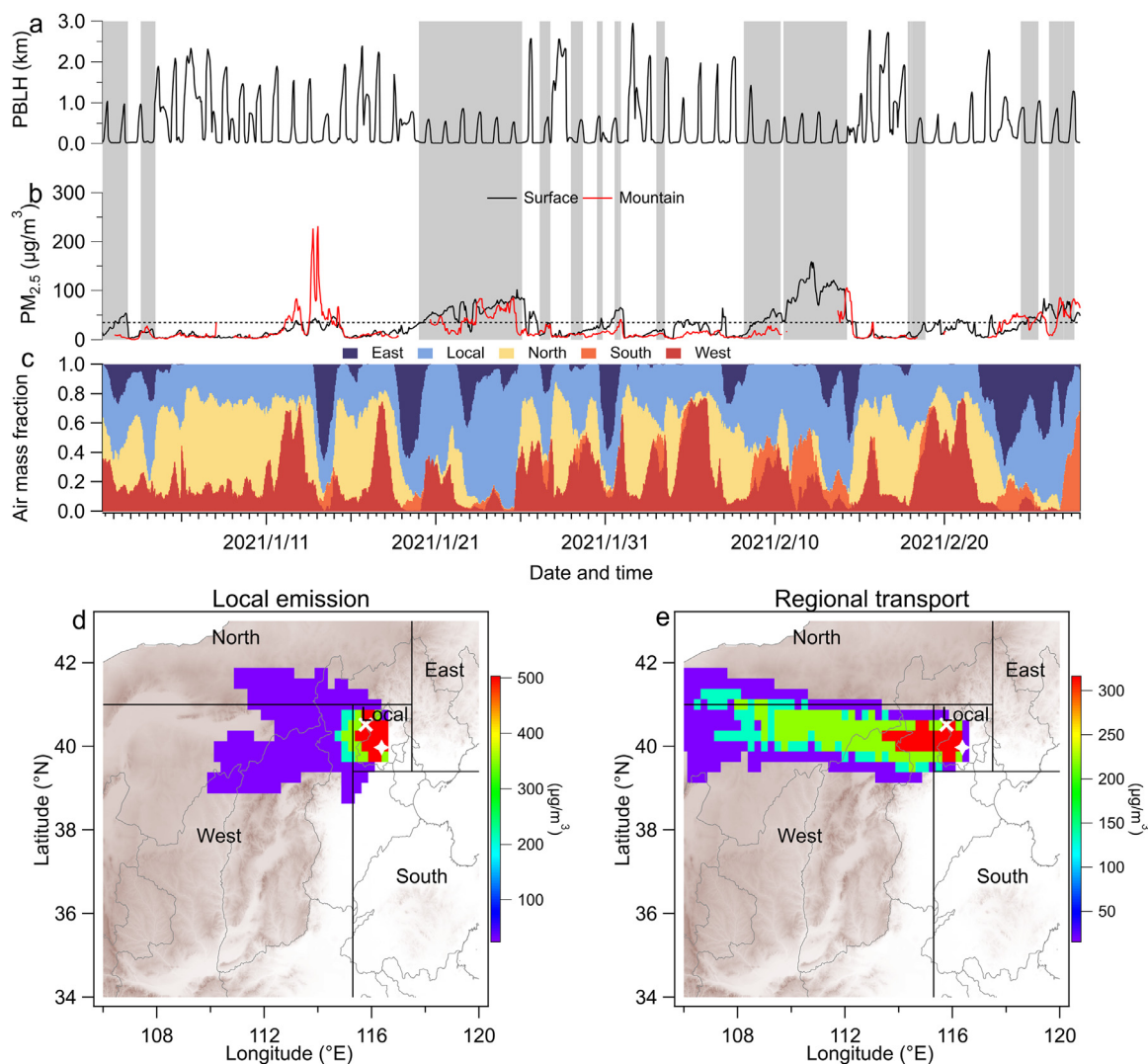


Fig. 1 – Temporal evolution of (a) planetary boundary layer height (PBLH), (b) PM_{2.5} (black and red lines indicate surface and mountain measurement results, respectively.; the black dash line represents the good air quality standard published by Chinese government at 35 $\mu\text{g}/\text{m}^3$ and the grey bar represents local emission events) and (c) air mass fraction in contributing sources. Typical examples of the novel method combining trajectory ensemble and concentration-weighted trajectory (CWT) method (Ens-HYSPLIT-CWT) results are shown for (d) a local emission event (21 January 2021) and (e) a regional transport event (05 February 2021). The star and cross marker indicate the location of surface (116.30°E, 39.94°N, 50 m a.s.l.) and mountain (115.78°E, 40.52°N, 1,344 m a.s.l.) stations, respectively.

wavelength, such as deriving the $\text{AAE}_{370/880}$, we can use Mie theory to calculate a WDA value by assuming the measured particles are spherical. The size distribution of BC typically follows a lognormal distribution, with geometric median diameter (GMD) ranging from 20 to 300 nm and a standard deviation (σ) between 1.4 and 2.2 (Akagi et al., 2012; Dubovik et al., 2002; Knox et al., 2009; Lack et al., 2012; Lewis et al., 2009; Moffet and Prather, 2009; Schwarz et al., 2008; Shamjad et al., 2012). In the Mie theory calculation of the BC absorption coefficient, a refractory index (RI) of 1.95 - 0.79i was employed as suggested by Bond and Bergstrom (2006). The coating thickness was assumed to be 10 %-100 % of the BC core radius, and absorption enhancement results by a factor of 2 were excluded (Bueno et al., 2011; Cappa et al., 2012; Liu et al., 2015; Schwarz et al., 2008; Shiraiwa et al., 2010). The RI of coating material was assumed to be 1.55 - 0.001i, which is a typical value for non-absorbing organic and inorganic compounds (Wang et al., 2016). Fig. 4 shows the WDA results for 370/880 and 470/880 wavelength pairs using this method. By combining the $\text{AAE}_{\lambda/880}$ results with Eq. (4) and the measured $\sigma_{\text{abs},880}$, $\sigma_{\text{abs},\text{BC}}$ result at shorter wavelength can be derived.

$$\text{AAE}_{\lambda/880} = \text{AAE}_{660/880} + \text{WDA}_{\lambda/880} \quad (4)$$

2.4. Aerosol optical size distribution

An exponential decay function, expressed as Eq. (5), is applied to reconstruct the vertical profile distribution based on the simultaneous measurements at surface and mountain stations during local emission events (Liu et al., 2009, 2020b; Zhao et al., 2019).

$$C(h) = C_0 e^{-\frac{h}{h_s}} \quad (5)$$

where C_0 represents the surface observation data at 50 m, and $C(h)$ denotes the mountain measurement results at 1,344 m height, and h_s is gradient index describing the vertical profile trend. This model has been widely used in previous radiative transfer studies (Guleria et al., 2014; Srivastava et al., 2012), effectively capturing the diurnal distribution of vertical profile patterns (Appendix A Fig. S2).

The AAOD_{550} of LACs was derived by summing the AAOD_{550} of BC and BrC by using the following expression, as the light absorption properties of dust aerosols were excluded by the PM_{2.5} impactor.

$$\text{AAOD} = \int_h \sigma_{\text{ab}}(h) d_h \quad (6)$$

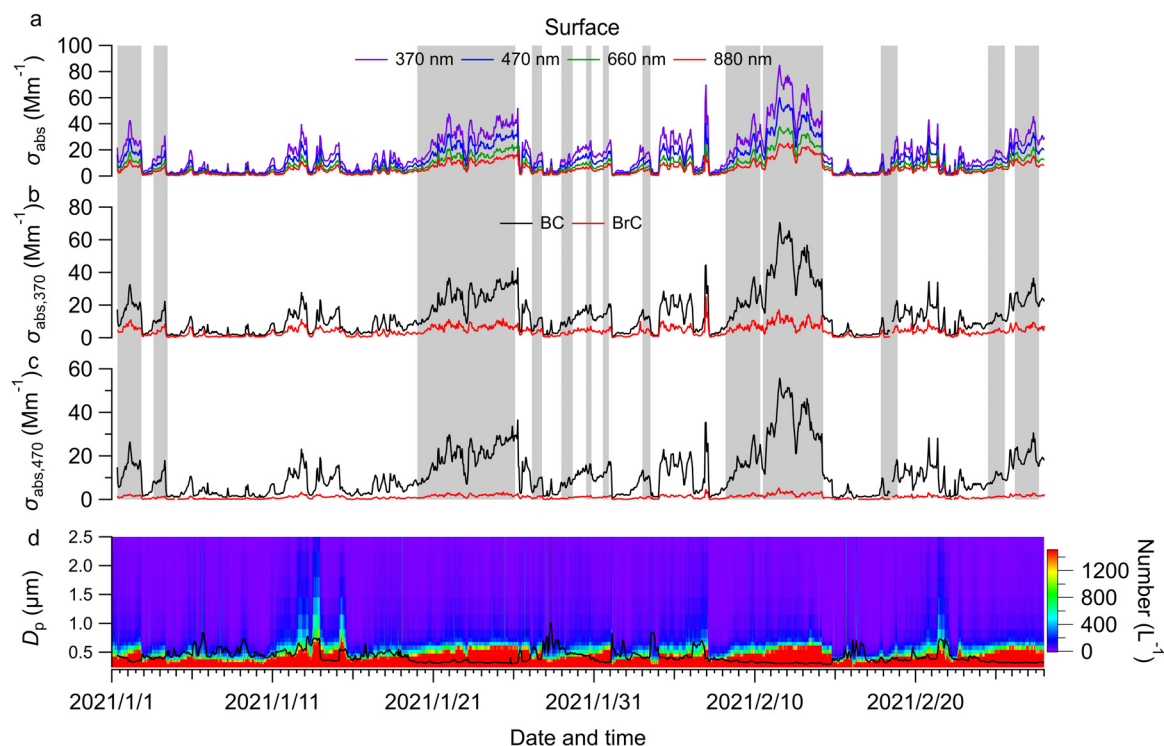


Fig. 2 – Temporal evolution of surface measurements: (a) absorption coefficient (σ_{abs}) at multiple wavelengths measured by AE33; black carbon (BC, black line) and brown carbon (BrC, red line) σ_{abs} at (b) 370 nm and (c) 470 nm; (d) size distribution of particle number concentration measured by GRIMM. The black line indicates the effective diameter. The grey bar represents local emission events.

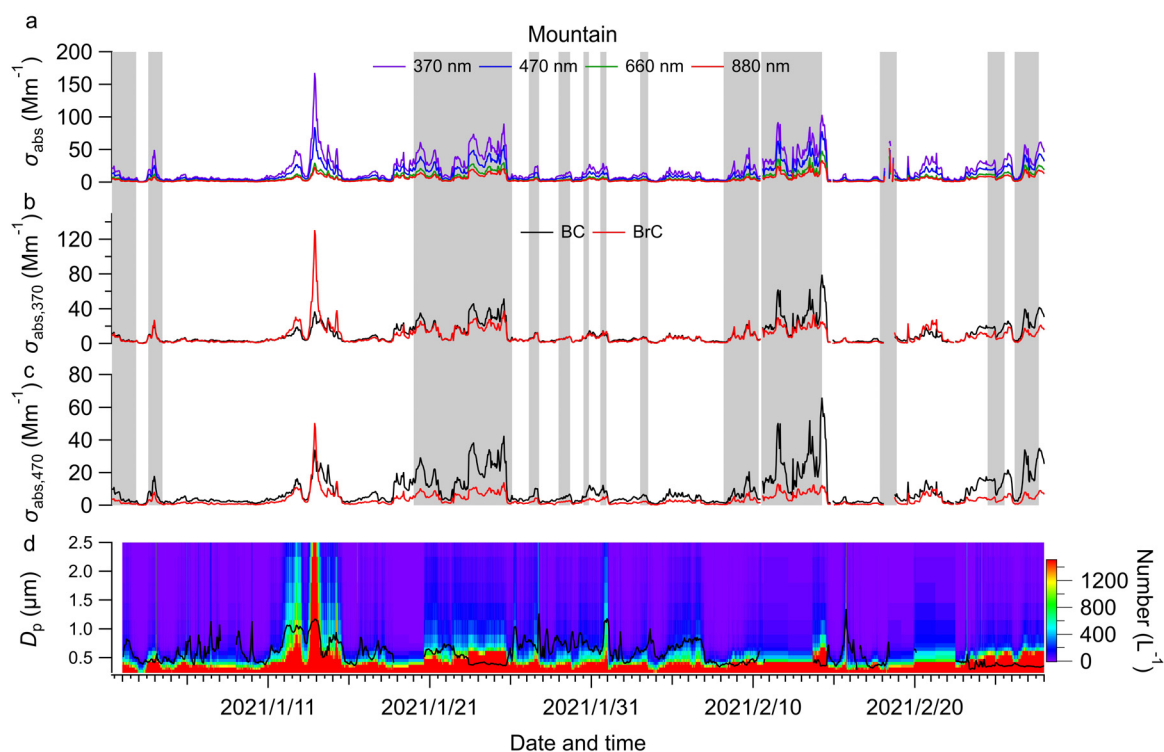


Fig. 3 – Temporal evolution of mountain measurements: (a) σ_{abs} at multiple wavelengths measured by AE33; BC (black line) and BrC (red line) σ_{abs} at (b) 370 nm and (c) 470 nm; (d) size distribution of particle number concentration measured by GRIMM. The black line indicates the effective diameter. The grey bar represents local emission events.

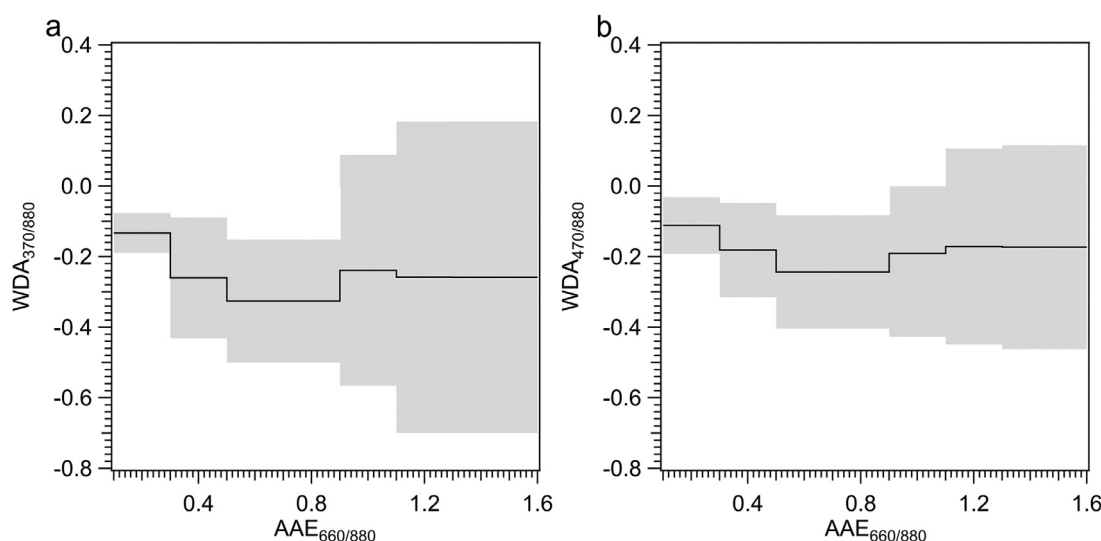


Fig. 4 – The range in the estimated wavelength dependence of AAE (WDA) at (a) 370 nm and (b) 470 nm for BC (shaded region) based on Mie theory calculation. The black lines indicate median WDA values.

where $\sigma_{ab}(h)$ is the absorption coefficient of BC or BrC at each level.

To consider the influence of particle size distribution, Mie theory combined with particle size distribution was employed to derive scattering coefficient results (k_{sc}) (Tian et al., 2023a):

$$k_{sc} = \int Q_s(D_p, m, \lambda) \frac{\pi}{4} D_p^2 n(D_p) dD_p \quad (7)$$

where Q_s indicates the scattering efficiency calculated using the Mie theory by assuming a RI of $1.48 + 0i$ (Liu et al., 2009). D_p and λ are particle diameter and wavelength. $n(D_p)$ is the particle number concentration.

The extinction coefficient k_{ex} was derived by summing the scattering and absorption coefficient. The AOD was obtained by integrating the extinction coefficient over altitudes up to 5 km (Quan et al., 2013), as expressed in Eq. (8):

$$AOD = \int_h^{5 \text{ km}} k_{ex}(h) dh \quad (8)$$

where $k_{ex}(h)$ (Mm^{-1}) is the extinction coefficient at each layer.

3. Results and discussion

3.1. Overview

Recent studies have widely reported the effective decrease in pollution levels due to the successful implementation of emission reduction measures by the Chinese government (Hu et al., 2025). During the study period, the temporal evolution of surface $\text{PM}_{2.5}$ rarely exceeded the mild pollution standard set by the Chinese government, i.e. $\text{PM}_{2.5}$ greater than $75 \mu\text{g}/\text{m}^3$, which was often used to distinguish pollution events. Thus, using previous standards no longer seems appropriate. In this study, $\text{PM}_{2.5}$ greater than $35 \mu\text{g}/\text{m}^3$ was used to distinguish between clean and pollution events.

3.2. Influences of air masses origins on observed characteristics

3.2.1. Identification of source regions of polluted air masses

During the study period, the pollution events accounted for 34 % of the time. To further investigate the sources of polluted air masses, we employed the Ens-HYSPLIT-CWT method. Table 1 shows that local air masses dominated the pollution events, accounting for 69 % of total pollution events and constituting 68 % of all local air masses. In addition to

their high frequency, local polluted air masses also exhibited the highest average $\text{PM}_{2.5}$ concentration among all incoming air masses during pollution events. In addition to local air masses, southern air masses should also be a focus. Although pollution events sourced from the south were the least frequent, this does not imply that southward air masses contained a large number of clean air masses. Instead, the low frequency was due to the meteorological conditions during the study period, which resulted in few air masses coming from the south. Statistics show that the probability of pollution events occurring in southward air masses was 100 %, and the average $\text{PM}_{2.5}$ concentration during these events was second only to that of local emissions. This result emphasizes that the Chinese government should focus not only on local emissions in Beijing but also on anthropogenic emissions originating from the southern region during wintertime.

3.2.2. Identification of source regions of clean air masses

Clean air masses mainly originated from the north, accounting for only 8 % of total pollution events. Notably, under the influence of northward air masses, the average $\text{PM}_{2.5}$ concentration and σ_{abs} of carbonaceous aerosols during clean events were the lowest among all incoming air masses, indicating that northern air masses were the cleanest.

3.3. Vertical transport of light-absorbing carbonaceous aerosols

Given that local emissions were the most frequent source and led to the highest pollution levels, subsequent analysis will focus solely on periods dominated by local air masses (Fig. 1d). Note that the $\text{PM}_{2.5}$ measured at the mountain station presented greater values compared to surface measurement results, e.g., during mid-January 2021, when the air mass was mainly influenced by regional transport. These periods were excluded from our further analysis due to their regional transport nature.

3.3.1. Vertical transport of black carbon particles

Due to the non-volatile characteristics of BC particles, they can be effectively transported to the top of the PBL through convective mixing processes, as demonstrated in our previous study (Liu et al., 2020b). A similar phenomenon was observed during the pollution periods in the current study but for BC absorption results (Fig. 5ai). The surface-observed $\sigma_{abs,880}$ was primarily influenced by the development of PBL. Lower absorption coefficient values were observed during the daytime when the PBL was more developed, with the lowest values occurring at midday. The mountain station can only receive pollutants from the

Table 1 – Fraction of pollution events and mean values of $PM_{2.5}$, $\sigma_{abs,880}$, and $\sigma_{abs,BrC,370}$ during polluted and clean periods dominated by different air mass sources.

Air mass sources	Pollution events	Pollution events fraction (%)	Mean surface $PM_{2.5}$ during pollution / clean events ($\mu g/m^3$)	Mean $\sigma_{abs,880}$ during pollution / clean events (Mm^{-1})	Mean $\sigma_{abs,BrC,370}$ during pollution / clean events (Mm^{-1})
East	38	28	47.41 / 21.75	12.89 / 7.25	19.82 / 11.9
Local	333	68	69.47 / 19.17	9.13 / 4.47	15.66 / 7.28
North	43	8	48.33 / 8.99	2.46 / 1.63	7.74 / 3.13
South	19	100	53.32 / NaN	13.97 / NaN	15.13 / NaN
West	52	23	46.32 / 21.82	3.93 / 3.23	10.41 / 7.86

NaN: no data.

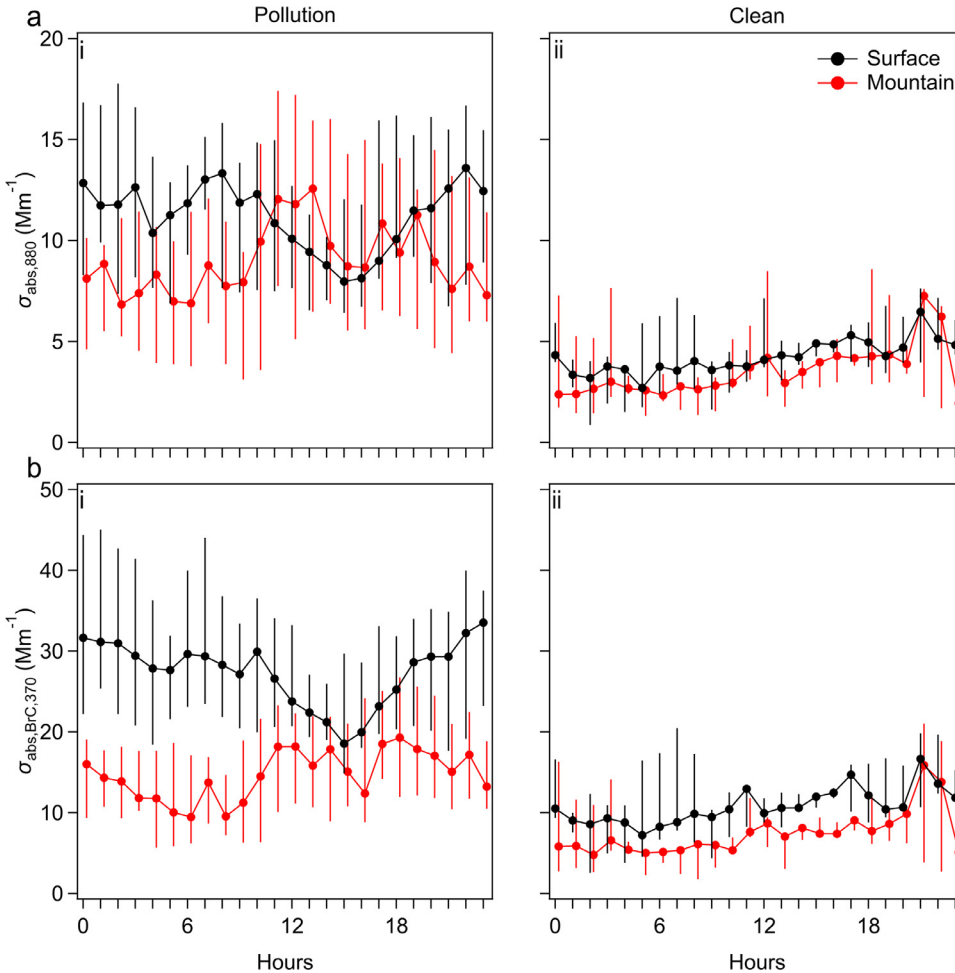


Fig. 5 – Diurnal variations of (a) $\sigma_{abs,880}$, and (b) $\sigma_{abs,BrC,370}$ during local emission events. Black and red lines represent surface and mountain measurement results, respectively. Solid circle and error bars show the median and 75th and 25th percentiles, respectively. Left panels represent pollution periods while the right panels indicate clean periods.

surface, and the comparable $\sigma_{abs,880}$ between the surface and mountain sites at midday emphasizes efficient vertical transport of BC particles and the smallest vertical gradient at noon (Appendix A Fig. S2ai). However, unlike refractory BC (rBC) mass measurement results, where mountain station observed almost the same BC as surface (Liu et al., 2020b), our study found that the mountain $\sigma_{abs,880}$ exhibited a larger observation results than surface. This discrepancy may be attributed to the different measurement targets, as Liu et al. (2020b) measured the rBC by using SP2, while our study measured the absorption coefficient using an AE33. It is noteworthy that the AE33 does not provide rBC absorption results and can be influenced by coating materials. In our study, the surface station was located near fresh BC sources, while the mountain station measured transported BC particles. These transported particles may have been coated in a core-shell structure, enhancing their absorption capabilities after aging. At night, the shallow PBLH led to the accumulation of $\sigma_{abs,880}$ near the surface. BC aging was mainly influenced by photoreactions at BC interfaces, which have been shown to

drive self-aging while simultaneously catalyzing atmospheric NO_2 reduction and SO_2 photooxidation. These reactions can significantly alter the physicochemical properties of BC interfaces, such as hygroscopicity and light absorption (Li et al., 2018; Zhang et al., 2022, 2023, 2024). Recent studies have also demonstrated that BrC photolysis can also drive HONO release, particularly when coexisting pollutants, such as nitrates, accelerate the photolysis process (Liu et al., 2024; Tian et al., 2023b; Wang et al., 2023).

During the clean period (Fig. 5a_{ii}), an increase in $\sigma_{abs,880}$ was observed at mountain station between 11:00 and 12:00, leading to $\sigma_{abs,880}$ results similar to surface measurements due to the effect of convective mixing process. It's noteworthy that the similar $\sigma_{abs,880}$ observed at both mountain and surface stations during clean periods was shorter than during pollution events. This discrepancy is attributed to the aging process during pollution events, which overestimates the $\sigma_{abs,880}$ observed at the mountain station. The surface-observed $\sigma_{abs,880}$ didn't present an obvious diurnal variation, mainly affected by the relative low pollution

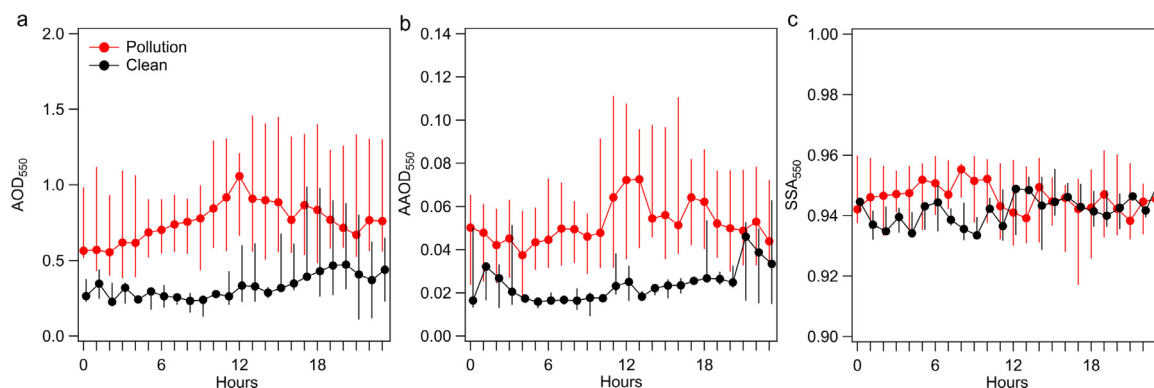


Fig. 6 – Diurnal variations of (a) aerosol optical depth (AOD), (b) absorbing aerosol optical depth (AAOD), and (c) single scattering albedo (SSA) at 550 nm during local emission events. Red and black lines represent pollution and clean periods, solid circle and error bars show the median and 75th and 25th percentiles, respectively.

concentration. The fluctuation in the observed $\sigma_{\text{abs},880}$ were dominated by anthropogenic activities, with meteorological variations also playing a role.

3.3.2. Vertical transport of brown carbon particles

Similar to BC particles, BrC aerosols were still significantly affected by changes in the PBLH during pollution periods (Fig. 5bi). Notably, the increment in mountain-observed $\sigma_{\text{abs},\text{BrC},370}$ was much smaller than that of BC at 880 nm ($\sigma_{\text{abs},880}$). This phenomenon can be attributed to two factors: volatile or semi-volatile properties of BrC, which result in lower transport efficiency compared to BC; and the photolysis of BrC (Forrister et al., 2015; Zhao et al., 2015), which further suppresses its absorption coefficient. This clearly showed that although BC had been efficiently transported upwards to the top of PBL, the volatile or semi-volatile BrC aerosols had not. This led to an enhanced $\sigma_{\text{abs},\text{BrC}}$ compared to $\sigma_{\text{abs},\text{BrC}}$ at 370 nm on the mountain relative to the surface (Appendix A Fig. S1). These factors are also reflected in the vertical transport results, showing a larger vertical decrease for BrC compared to BC particles (Appendix A Fig. S2bi). During clean events, BrC particles exhibited diurnal variations similar to those of BC particles (Fig. 5bii), while no obvious evidence of effective vertical transport of BrC from the surface to the top of PBL during the convective mixing process.

3.4. Column-integrated optical properties of aerosols

Diurnal analysis of AOD₅₅₀ during pollution events (Fig. 6a) reveals a steady increase from morning to midday, with a total improvement of approximately 91 %, followed by an overall decreasing trend. In contrast, during clean periods, the diurnal variation characteristics were not observed, with AOD₅₅₀ exhibiting only a peak around 20:00. AAOD₅₅₀ also showed peak characteristic results at noon (Fig. 6b), and increased by about 93 % compared to early morning. During the Clean period, AAOD₅₅₀ exhibited different diurnal variation characteristics from AOD₅₅₀, with a bimodal distribution and peaks appearing at 1:00 and 21:00.

Although both AOD₅₅₀ and AAOD₅₅₀ increased during pollution periods at noon, SSA₅₅₀ exhibited a valley around 12:00 (Fig. 6c). This decrease in SSA₅₅₀ is likely due to the higher h_s values of absorption aerosols (Appendix A Fig. S3a), primarily caused by BC particles. A higher h_s value for absorption aerosols indicates a less negative vertical gradient or fewer difference between surface and mountain stations and, consequently, higher columnar aerosol absorption. In contrast, secondary semi-volatile particle species contributed to a large portion of surface aerosols in urban Beijing due to high gas emissions from nearby sources (Ianniello et al., 2010; Yang et al., 2018; Zhang et al., 2014). As these species were uplifted, the pollutants were exposed to a larger air volume, leading to dilution and evaporation processes for

all species. These processes were influenced by the mixing state between the gases and the condensed phase, with the partial vapor pressure surrounding the condensed phase being lower than the equilibrium state of each species at that specific temperature (Donahue et al., 2011; Donahue et al., 2006; Simoneit et al., 1993). Consequently, these phenomena caused a significant decrease in the scattering coefficient with increasing height, ultimately resulting in a decrease in the single scattering albedo (SSA₅₅₀) value. During clean events, the high h_s values for both absorbing and scattering aerosols led to an increase in SSA₅₅₀ values at noon.

4. Conclusions

This study employed a novel method combining trajectory ensemble with concentration-weighted trajectory (CWT) analysis (Ens-HYSPLIT-CWT) to distinguish local emission events from all air mass sources. Continuous and simultaneous measurements at both surface and mountain sites were used to reconstruct the vertical distribution of aerosols. The wavelength dependence of the absorption Ångström exponent (WDA) method was applied to derive more accurate brown carbon (BrC) absorption coefficients (σ_{abs}) at 370 and 470 nm.

Under the Chinese government's vigorous promotion and implementation of emission reduction policies, the concentration of pollutants in Beijing has greatly reduced, even during winter. With favorable meteorological conditions, the frequency of clean air events is increasing. During the study period, local emissions contributed for up to 69 % of polluted events (PM_{2.5} greater than 35 $\mu\text{g}/\text{m}^3$), making it the most frequent and second most probable source among all incoming air masses. The air masses originating from the southern region had the highest probability of causing pollution events.

The study of columnar aerosols during local emission periods revealed that the peak values of aerosol optical depth (AOD) and absorption aerosol optical depth (AAOD) occurred around noon during pollution events. AOD increased by a factor of 1.91, while AAOD increased by a factor of 1.93. Black carbon (BC) exhibited higher transmission efficiency and h_s values compared to non-BC particles, resulting in a lower vertical decrease rate of absorption efficiency for light-absorbing carbonaceous aerosols (LACs). At noon, the planetary boundary layer (PBL) development was most vigorous, and the decrease in aerosol scattering with height was more pronounced than the decrease in absorption properties, further promoting the reduction of single scattering albedo (SSA).

CRediT authorship contribution statement

Kang Hu: Writing – review & editing, Writing – original draft, Software, Methodology, Funding acquisition, Data curation. **Hong Liao:** Writing – review & editing, Funding acquisition. **Dantong Liu:** Writing –

review & editing, Methodology, Data curation. **Jianbing Jin**: Writing – review & editing. **Siyan Li**: Writing – review & editing, Methodology, Data curation. **Yangzhou Wu**: Writing – review & editing, Methodology, Funding acquisition, Data curation. **Yuxing Gao**: Data curation. **Xiaotong Jiang**: Writing – review & editing, Methodology. **Shitong Zhao**: Methodology. **Ping Tian**: Writing – review & editing, Data curation. **Fei Wang**: Data curation. **Na Kang**: Methodology. **Weihong Zhang**: Writing – review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A Supplementary data

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.jes.2026.02.005.

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