https://doi.org/10.5194/egusphere-2025-1561
Preprint. Discussion started: 3 July 2025

Measurement report: Impact of domestic heating on dust deposition sources in hyper-arid Qaidam Basin, northern Qinghai-Xizang Plateau

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https://doi.org/10.5194/egusphere-2025-1561
Preprint. Discussion started: 3 July 2025

Highlights

1. The temporal and spatial distribution of carbonaceous aerosols was analyzed using various carbon indicators.

2. Domestic heating significantly increased atmospheric pollutants in rural areas.

3. The unique energy structure in Qaidam Basin significantly influenced the glaciers of the Qinghai-Xizang Plateau and should not be overlooked.

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Abstract

Given the unique energy profile of the Qaidam Basin (QDB), it is crucial to examine the impacts of domestic heating on, the Qinghai-Xizang Plateau (QXP), and global atmospheric systems. This study collected monthly dust deposition six sites in the southern QDB between2020 and 2023. We identified the sources of dust -fall during domestic heating (HP) and non-heating periods (NHP) in urban and rural and its environmental effects. The results demonstrated that domestic heating increased the concentration of water-soluble ions in rural, trace elements in urban, and carbon emissions in both. Among various carbon indicators, organic carbon (OC) and element carbon (EC) levels rose during the HP, with Char-EC as the primary component of EC. Char-EC concentrations were higher in urban areas, while secondary organic carbon, the main contributor to OC, was more prevalent in rural. The OC/EC and char-EC/soot-EC ratios, along with PMF results, indicated that coal and biomass burning were the main contributors to dust deposition in rural, strongly influenced by domestic heating, whereas urban dust predominantly originated from vehicle and industrial emissions. Coal consumption in QDB was greater during the HP than that of other dust sources in the QXP. This increased consumption leads to higher emissions of atmospheric pollutions, which may accelerate glacier melting in the region. Consequently, integrating QDB carbon aerosols into future environmental policies and climate models for the QXP is essential. This study provides a reference for investigating carbonaceous aerosols in climatically similar hyper-arid basins with intensive human activity and salt lake regions.

Keywords: Qinghai-Xizang Plateau; Qaidam Basin; Biomass burning; carbonous elements; atmospheric deposition.

https://doi.org/10.5194/egusphere-2025-1561
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Short summary

This study collected dust samples from six sites in the Qaidam Basin, over three years to investigate the impact of domestic heating on atmospheric dust in hyper-arid region. Our results indicate that rural dust is significantly influenced by heating, particularly from coal and biomass burning which accounts for over 70% of total sources. The unique energy structure here has resulted in distinct environmental effects from the emitted carbonaceous aerosols and useful for similar dry areas.

1. Introduction

Atmospheric dust, a critical component of particulate matter (PM), serves as both an air quality indicator and environmental stressor, influencing hydrological cycles and soil ecosystems (Feng et al., 2019). Recent advancements in understanding PM characteristics—particularly chemical composition (e.g. water-soluble ions, organic carbon, and elemental carbon) and source apportionment—have been achieved through principal component analysis (PCA), chemical mass balance (CMB), and positive matrix factorization (PMF) models (Lai et al., 2016; Yao et al., 2016a; Zhang et al., 2015b). PMF analysis of atmospheric dust in urban such as Lanzhou, Taiyuan, and Jinan have identified diverse sources, including coal combustion, industrial emissions, construction dust, windblown dust, vehicle emissions, and resuspended road dust. Seasonal variations indicate that coal combustion during the domestic heating period and regional meteorological conditions significantly influence dust deposition (Hu and Liu, 2022; Chen et al., 2024; Yang et al., 2024; Zhang et al., 2022). These findings underscore the urgency of region-specific pollution control strategies.

The Qinghai-Xizang Plateau (QXP) is a key regulator of Northern Hemisphere climate variability and plays a vital role in global ecological and climatic stability, often referred to as the "Asian Water Tower" (Liu et al., 2019; Liu et al., 2020b). However, rapid glacier retreat on the plateau poses risks to the Asian hydrological cycle and the monsoon system, with potential adverse impacts if unchecked (Luo et al., 2020). Beyond climate warming and increased humidity, black carbon (BC) significantly accelerates glacial melt by inducing atmospheric warming and enhancing radiative absorption at the glacier surface (Bond and And Bergstrom, 2006; Chen et al., 2015). Notably, biomass burning in South and Central Asia during winter serves as a major source of BC, further exacerbating glacier decline on the plateau (Zhang et al., 2015c; Zheng et al., 2017; Xu et al., 2018b). However, local sources within the QTP, particularly the Qaidam Basin (QDB) in the northeastern region, should not be underestimated, as QDB is a key dust source for the plateau (Wei et al., 2017; Zheng et al., 2021).

The QDB, known as the "Treasure Bowl" of the QXP, is rich in minerals, coal, oil, and gas, positioning it a key economic hub in northwest China. It has a high population density, and intense human activity, yet is highly sensitive to climate change. Extensive resource extraction has rendered

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its ecosystem fragile (Li and Sha, 2022), exacerbating atmospheric pollution. Unlike South Asia, Central Asia, and Xizang—where biomass fuels dominate—QDB relies primarily on a mixture of coal, yak dung, and firewood for winter domestic heating, reflecting a unique energy structure (Liu et al., 2008; Xiao et al., 2015; Behera et al., 2015; Kerimray et al., 2018; Jiang et al., 2020; Shen et al., 2021). The combustion of coal releases significant pollutants, light-absorbing organic compounds like BC and brown carbon, and hazardous gases such as such as carbon dioxide (CO_2), nitrogen oxides (NO_x) and carbon monoxide (CO). These emissions impact human health and exacerbate climate warming, thereby influencing regional and global climate systems (Munawer, 2018; Ye et al., 2020; Zhou et al., 2025). Consequently, we posit that seasonal carbon emissions in QDB, particularly during winter domestic heating, could exert a unique influence on the climate and ecological stability of the QXP.

Additionally, the QDB as a representative arid region with intensive human activity, exhibits climatic and environmental conditions comparable to the Tarim and Junggar Basins in Xinjiang, the Great Basin in the United States, and other hyper-arid areas. These regions are characterized by low precipitation, rich mineral resources subject to significant anthropogenic impact, and abundant salt lakes. Similarly, salt lakes such as the Uyuni in Bolivia, Atacama in Chile, and Ombre-Muerto in Argentina are located on high plateaus averaging 3,000 m in elevation, with surrounding climates and environments comparable to those of the QDB. Research in the Tarim and Junggar Basins has predominantly focused on dust events, their sources, and associated gas emissions (Gao and Washington, 2010; Liu et al., 2016b; Filonchyk et al., 2018; Yu et al., 2019; Zhou et al., 2023). In the Great Basin, studies largely address ozone and dust sources (Hahnenberger and Nicoll, 2012; Vancuren and Gustin, 2015; Miller et al., 2015). Research on salt lake atmospheres has predominantly focused on high-salinity dust emissions resulting from lakebed desiccation due to resource extraction (Löw et al., 2013; Gholampour et al., 2015; Moravek et al., 2019; Christie et al., 2025), with limited research on atmospheric carbon components, their sources, and environmental impacts. Therefore, this research aims to investigate atmospheric carbonaceous aerosols in arid basins with intensive human activity and climates comparable to the QDB, as well as in salt lakes environments.

This study, conducted from January 2020 to March 2023, involved monthly dust deposition sampling at six urban and rural monitoring sites located in the southern QDB. Samples were

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categorized into two seasonal periods: the domestic heating (HP) and the non-domestic heating (NHP) periods. The HYSPLIT model, and PMF receptor modeling using analyses of dust flux, soluble ions, trace elements, and carbonaceous components, alongside OC/EC and char/soot ratios—the primary sources of dust deposition were identified, with particular emphasis on contributions from domestic heating. The study further evaluated the environmental impacts on the QXP, considering its distinctive energy structure. Furthermore, These findings offer a scientific basis and reference for examining atmospheric carbonaceous aerosols in arid basins with similar climates and human activities to the QDB, as well as in salt lake regions.

2. Materials and methods

2.1 Sampling

The QDB, situated in the northeastern of the QXP, is bordered by the Altyn-Tagh, Kunlun, and Qilian mountains, making it one of China's largest intermontane basins (Zhang, 1987). With an average elevation of 3,000 m, the basin features an extremely arid climate characterized by less than 20 mm of annual precipitation in the northwestern region, while evaporation rates exceed 2,000 mm. The QDB is rich in salt lakes, non-ferrous metals, and hydrocarbon resources, with significant coal deposits. It leads China in reserves of halite, potash, magnesium, lithium, strontium, asbestos, earning it the nickname "Treasure Basin". As a major salt lake resource area, it hosts 33 lakes—including Qarhan, Daqingkan, and Caka Salt Lake—and faces notable conflicts between resource extraction and ecological preservation. Agriculturally, it cultivates crops like goji berries, quinoa, and forage grass, and hosts China's largest resource-rich circular economy pilot zone. The permanent population of basin is approximately 400,000, primarily using coal, yak dung, and firewood for domestic heating (Jiang et al., 2020). Additionally, annual tourism peaks from May to September, attracting around 17 million visitors, which likely amplifies atmospheric pollutant emissions.

From January 2020 to March 2023, monthly dust deposition samples were collected from six monitoring stations in the southern QDB. The stations included Xiao Zaohuo (XZH), Golmud (GEM), Da Gele (LTC), Nuo Muhong (NMH), Balong (BLX), and Dulan station (DLX). Dry deposition collection employed the glass ball method using Marble dust collector (MDCO) designed dust collection cylinders (Sow et al., 2006). The stainless steel collection device (50×30×30 cm) contained a plastic sieve container of identical dimensions, with the sieve base positioned 10 cm above the opening and perforated with 0.5 cm diameter holes (Figure S1). To minimize dust resuspension during high wind events (Qian and Dong, 2004), two layers of 16 mm glass balls were placed within the sieve container. A high-density polyethylene bag was attached to the base for sample collection.

To ensure only dry dust was collected, collection devices were covered during rain or snowfall. A total of 37, 39, 23, 30, 16, and 29 samples were obtained from XZH, GEM, LTC, NMH, BLX, and DLX stations, respectively. Laboratory protocols incorporated biannual analyses with negative controls and appropriate control samples. As continuous dust monitoring commenced in 2020, site blanks were evaluated during initial sampling. Stations were classified as Urban (GEM, NMH, DLX) and Rural (XZH, LTC, BLX) based on location characteristics. Consistent with the cold-arid climate in QDB, the HP was defined as October-April, while the NHP spanned May-September.

Materials such as plant remnants, microfauna, and bird droppings were removed from the sample bags with tweezers. The samples were then measured on a balance (0.0001 g) to determine the dust deposition flux (Eq. 1) (Yu et al., 2016):

$$M = \frac{m \times 30}{S \times K} , \tag{1}$$

where M is dust deposition [g/(m²·30d)]; m is the sample mass (g); S is the area of the dust collection device (m²); and K is the actual number of sampling days per month (d).

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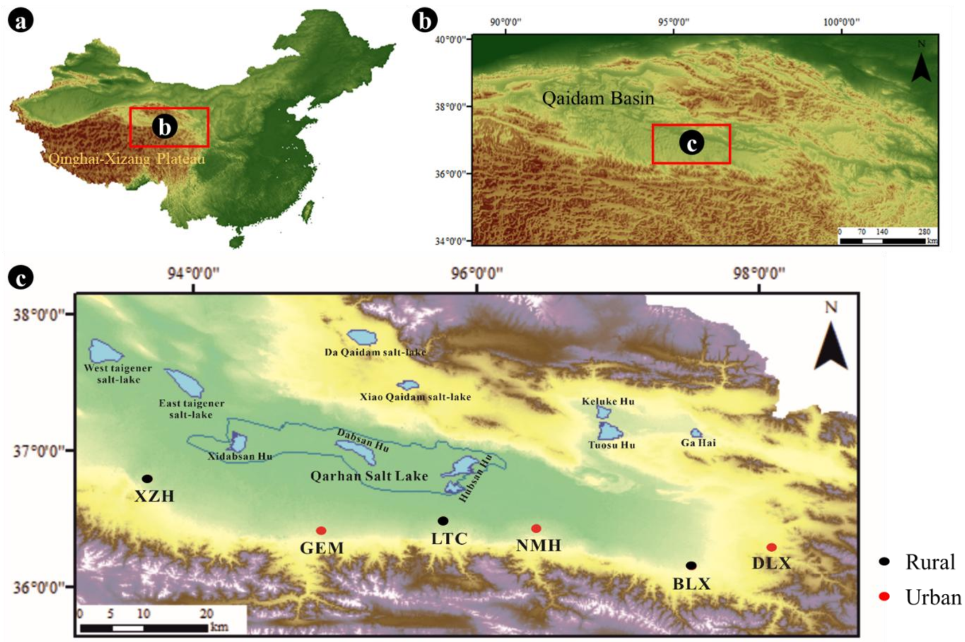

Figure 1. Spatial distribution of monitoring stations in the southern Qaidam Basin. Urban stations (red) and rural stations (black) are labeled as follows: XZH (Xiao Zaohuo), GEM (Golmud), LTC (Da Gele), NMH (Nuo Muhong), BLX (Balong), DLX (Dulan).

2.2 Water-soluble inorganic ions

A 100 mg sample was weighed and transferred into a 250 mL bottle. The mixture underwent ultrasonic extraction for 20 minutes to ensure complete solubilization. The resulting supernatant was then filtered through a 0.45 μm filter for analysis. Based on preliminary experimental results, the concentrations of major ions (K^+, Na^+, Mg^{2+}, and Ca^{2+}) were measured using Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES, NexIon 2000). Anions (Cl^-, SO_4^{2-}, and NO_3^-) were quantified using ion chromatography (IC). To ensure measurement accuracy, samples were organized in sets of twenty, with one randomly selected sample from each group serving as a replicate, achieving an error margin of less than 10%.The detection limits for the various components were as follows: K^+ (0.0560 mg/L), Na^+ (0.0100 mg/L), Ca^{2+} (0.0037 mg/L), Mg^{2+} (0.0390 mg/L), SO_4^{2-} (0.0090 mg/L), NO_3^- (0.0125 mg/L), Cl^- (0.0100 mg/L). All standard solutions employed in the analysis were sourced from the National Standard Material Center.

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2.3 Trace element analysis

According to the Chinese State Standard "Ambient Air and Waste Gas from Stationary Sources Emission - Determination of Metal Elements in Ambient Particles" (HJ 777-2015), the concentrations of elements such as iron (Fe), aluminum (Al), silicon (Si), titanium (Ti), copper (Cu), cadmium (Cd), chromium (Cr), manganese (Mn), nickel (Ni), zinc (Zn), lead (Pb), and vanadium (V) were quantified using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) and ICP-OES. A dust sample weighing 0.100 g was placed in a Teflon cup, to which 20.0 mL of a nitric acid-hydrochloric acid digestion solution was added. The sample was heated to reflux at 100 ± 5°C for 2 h under a watch glass, then cooled. Following this, the inner walls of the cup were rinsed with water, and approximately 10 mL of water was added, allowing the mixture to stand for 30 minutes for extraction. The extract was then filtered into a 100 mL volumetric flask and diluted to volume with distilled water for analysis. In cases where organic matter content was high, an appropriate amount of hydrogen peroxide was introduced during digestion to decompose the organic materials. Prior to sample analysis, the system was flushed with a rinse solution until the blank intensity value reached a minimum, and samples were analyzed only after the signal stabilized. If the concentration of any element exceeded the calibration range, the sample was diluted and reanalyzed.

2.4 Carbon analysis

This study utilized a combination of wet chemical treatment and thermal/optical reflection (TOR) to analyze trace elements in dust deposition (Han et al., 2007b; Han et al., 2007a; Han et al., 2016). Dust samples were treated with hydrochloric and hydrofluoric acids to remove inorganic materials. The residual solution was then filtered through a pre-combusted quartz fiber filter (Whatman, 450 °C for 4 h, diameter 47 mm). The filtered samples were air-dried and analyzed for carbon content using a DRI 2001 thermal/optical carbon analyzer (Atmoslytic Inc., Calabasas, CA) at the Institute of Earth Environment, Chinese Academy of Sciences, adhering to the Interagency Monitoring of Protected Visual Environments (IMPROVE) protocol.

A 0.544 cm^2 disc was extracted from the filter and placed in a quartz boat for analysis. During the carbon analysis, the samples were initially heated in a 100% helium atmosphere, resulting in the

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production of four organic carbon (OC) fractions (OC1, OC2, OC3, and OC4) at four different temperature levels (140, 280, 480, and 580 °C). The atmosphere was subsequently changed to 2% O_2/98% He, generating three elemental carbon (EC) fractions (EC1, EC2, and EC3) at three temperatures (580, 740, and 840 °C). Volatile carbon underwent carbonization in an anaerobic environment, indicated by a decrease in laser reflectance, and is referred to as "pyrolyzed organic carbon" (OPC). In the oxidative atmosphere, OPC was emitted along with the original EC from the filter. The amount of OPC is defined as the carbon evolved until the laser reflectance returned to its baseline value (Han et al., 2007b). According to the IMPROVE protocol, EC is calculated as the total of the three EC subfractions minus OPC (i.e., EC = EC1+EC2+EC3-OPC). The method enables differentiation between soot and ash, as determined by the gradual oxidation of these black carbon subtypes in standard reference materials during the EC1 and EC2 + EC3 steps, where soot is defined as EC1-OPC and ash as EC2+EC3 (Han et al., 2007a; Han et al., 2016).

Please note that in this manuscript, we interchangeably use the terms "EC" and "BC." While these terms do not strictly refer to the same component, they serve as an adequate approximation within the scope of this study (Seinfeld et al., 1998; Bond et al., 2004). We use "EC" when discussing emissions and modeling components, reserving "BC" for climate-related discussions.

2.5 Statistical analysis

(1) Estimation of Secondary Organic Carbon

OC consists of primary organic carbon (POC) and secondary organic carbon (SOC). An OC/EC ratio exceeding 2.0 indicates the possible presence of secondary organic aerosol (SOA) (Castro et al., 1999). Due to the intricate physical and chemical processes involved, SOC in urban atmospheres cannot be directly measured. Therefore, an indirect estimation method, known as the EC tracer method, has been developed (Turpin and Huntzicker, 1991). If the concentrations of OC and EC are available and primary OC from non-combustion sources ($OC_{non\text{-}comb}$) can be disregarded, EC can be utilized as a tracer for POC from combustion sources, facilitating the estimation of SOC (Turpin and Huntzicker, 1995):

$$POC=EC\times(OC/EC)_{pri}\,, \tag{2}$$

$$SOC=OC_{total}-POC\,, \tag{3}$$

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where OC_{tota} represents total organic carbon. Traditional methods for determining $(OC/EC)_{pri}$ involve regressing OC and EC within a fixed percentile range of the lowest (OC/EC) ratio data (typically 5-20%) or relying on sampling days characterized by low photochemical activity and local emissions (Castro et al., 1999; Lim and Turpin, 2002). However, these approaches are limited by their empirical nature, lacking clear quantitative criteria for selecting the data subsets used to establish $(OC/EC)_{pri}$. In this study, we employed the minimum R squared (MRS) method (Millet et al., 2005; Wu and Yu, 2016; Wu et al., 2018a) to determine $(OC/EC)_{pri}$. This method calculates a set of hypothetical $(OC/EC)_{pri}$ and SOC values to identify the minimum correlation coefficient (R^2) between SOC and EC, allowing for the accurate derivation of $(OC/EC)_{pri}$.

(2) Playa salt (ps) and non-playa salt (nps)

To differentiate the contributions of salt lake sources to water-soluble ions in atmospheric deposition, we adopted a methodology similar to that used for marine aerosols. This approach relies on the ratio of water-soluble ions (SO_4^{2-}, Ca^{2+}, K^+, Mg^{2+}, Cl^-) to Na^+ in the salt lakes of the QDB, enabling us to assess the contribution of ps-Na^+ components to nps (Zhang, 1987); details in Zhu (2025).

$$\text{nps-}SO_4^{2-} = [SO_4^{2-}] - 0.333\cdot\text{ps-}Na^+, \quad (4)$$

$$\text{nps-}Ca^{2+} = [Ca^{2+}] - 0.062\cdot\text{ps-}Na^+, \quad (5)$$

$$\text{nps-}K^+ = [K^+] - 0.087\cdot\text{ps-}Na^+, \quad (6)$$

$$\text{nps-}Mg^{2+} = [Mg^{2+}] - 0.051\cdot\text{ps-}Na^+, \quad (7)$$

$$\text{nps-}Cl^- = [Cl^-] - 2.287\cdot\text{ps-}Na^+, \quad (8)$$

This was accomplished using equations that incorporate total Na^+, total Ca^{2+}, the average crustal ratio $(Na^+/Ca^{2+})_{crust}$ = 0.56 w/w (Bowen, 1979), and the average (Ca^{2+}/Na^+) ratio for Qaidam salt lakes, $(Ca^{2+}/Na^+)_{salt\ lake}$= 0.06 w/w (Zhang, 1987). Among these, the mass concentration of $[SO_4^{2-}]$, $[Ca^{2+}]$, $[K^+]$, $[Mg^{2+}]$, $[Na^+]$ and $[Cl^-]$ were identified as constituents of dust-fall.

$$\text{ps-}Na^+ = [Na^+] - \text{nps-}Na^+, \quad (9)$$

$$\text{nps-}Na^+ = \text{nps-}Ca^{2+} \cdot (Na^+/Ca^{2+})_{crust}, \quad (10)$$

$$\text{nps-}Ca^{2+} = [Ca^{2+}] - \text{ps-}Ca^{2+}, \quad (11)$$

$$\text{ps-}Ca^{2+} = \text{ps-}Na^+ \cdot (Ca^{2+}/Na^+)_{salt\ lake}, \quad (12)$$

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(3) HYSPLIT backward trajectory model

Backward trajectory clustering analysis was conducted on sampling points using the TrajStat plugin within Meteoinfo software. Daily backward trajectories for 48 hours were calculated from January 2020 to March 2023 and classified monthly based on differences in the horizontal movement direction and velocity of air masses. The trajectories were initiated at Universal Time (UTC) 00:00, with a 6-hour increment, originating from 500 m above sea level (Yang et al., 2014). Meteorological data utilized in this research were obtained from the Global Data Assimilation System (GDAS) provided by the U.S. National Centers for Environmental Prediction (NCEP), covering the period from December 2019 to February 2023 (Meteoinfo software website: http://meteothink.org).

(4) PMF model

PMF is a multivariate factor analysis tool that decomposes a matrix of speciated sample data into two matrices: factor contributions (G) and factor profiles (F). The goal of PMF model is to solve the chemical mass balance between measured species concentrations and the respective source profiles, with the purpose of minimizing the object function Q (Eq. 13) based upon the uncertainties (uij) of measured species (Paatero and Tapper, 1994).

$$e_{ij} = x_{ij} - \sum_{h=1}^{p} g_{ih} f_{hj}; Q = \sum_{i=1}^{m} \sum_{j=1}^{n} (e_{ij}/h_{ij}s_{ij})^2 \quad , \tag{13}$$

where x_{ij} is the measured concentration of the j^{th} species in the i^{th} sample at receptor sites. f_{kj} is the source profile of the j^{th} species in the k^{th} factor and g_{ik} is the mass contribution of the k^{th} factor in the i^{th} sample. e_{ij} is the difference between modeled concentrations and measured concentrations. The uncertainty for individual species (u_{ij}) was calculated to be $x_{ij} \times$ error fraction + 1/3 MDL, where MDL is the method detection limit. For data below the MDL, concentrations were replaced by 1/2 MDL and the corresponding uncertainty was set to 5/6 MDL (Reff et al., 2007). An extended description of the PMF parameters used in this study and error estimate based on the model's Q value, displacement (DISP), and bootstrapping (BS) tests (DISP-BS) are provided in the Supplementary Information.

3. Results and discussion

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3.1 Atmospheric dust deposition flux and water ions concentration

The total deposition flux (DF) in the southern QDB is 5.41 ± 5.33 g/m²·30d, slightly lower than that of the Lake Aibi Basin (3.32-23.4 g/m²·30d) (Li et al., 2022), but higher than the surrounding areas of Akatama Salt Lake (2.93 g/m²·30d) (Wang et al., 2014). Specifically, DF was 4.67 ± 4.96 g/m²·30d in rural and 5.97 ± 5.73 g/m²·30d in urban areas. During the HP, DF in rural and urban were 4.62 ± 4.15 g/m²·30d and 4.95 ± 5.25 g/m²·30d, respectively. In contrast, NHP showed increased DF values of 4.77 ± 4.42 g/m²·30d (rural) and 7.66 ± 6.09 g/m²·30d (urban) (Figure 2). Notably, Urban DF during NHP demonstrated a 54.6% increase relative to HP, while rural DF rose by 7.1% - contrasting previous findings that associated elevated DF with HP coal combustion (Cheng et al., 2009; Gao et al., 2013; Guo et al., 2010; Qi et al., 2018). We hypothesize that the increase in DF during the NHP is attributed to heightened tourism activity (May to September peaks season) in the QDB (Zhang et al., 2011), attracting approximately 17 million tourists annually, the number continues to grow. This influx likely leads to increased urban emissions, particularly in densely populated areas such as DLX and GEM (Figure S2), contributing to the elevated DF levels.

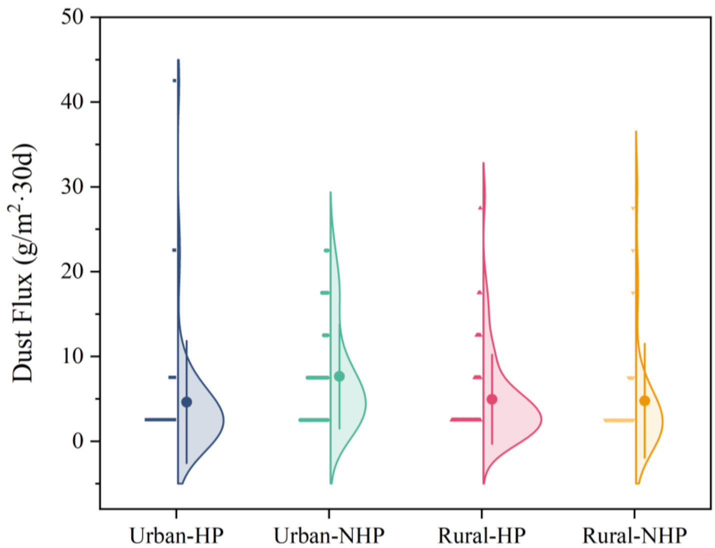

Figure 2 Dust flux distribution in urban and rural. The distribution of dust flux in four contexts: Urban with domestic heating period (Urban-HP), Urban with non-HP (Urban-NHP), Rural with domestic heating period (Rural-HP), and Rural with non-HP (Rural-NHP). Each violin plot

illustrates the density distribution of dust flux values, with the central dot representing the mean, and the vertical lines indicating the interquartile range.

Water-soluble ion concentrations differed significantly between rural (115.31 mg/g) and urban (72.81 mg/g) areas. In rural, water-soluble ion content was greater during the HP than in the NHP, while the opposite trend was observed in urban areas (Figure 3, S3). We categorized the water-soluble ions in dust deposits into playa salt (ps) and non-playa salt (nps) based on their sources, following the model of marine aerosols (Zhu et al., 2025). Playa salt content consistently surpassed nps in rural areas across both periods, while urban areas showed the opposite trend. Notably, during the NHP, ps content in urban and rural increased by 54.46 and 36.86%. Backward trajectory analysis indicated that airflow in both rural and urban areas primarily originated from the northwest QDB and the eastern Tarim Basin during the HP, while during the NHP, it was influenced more broadly by the salt lake of the QDB (Figure S4, S5), aligning with the observed variations in ps content. A similar increase in summer sea salt and non-sea salt ions has been reported in Rajkot, India, attributed to ocean wind direction (Gupta and Dhir, 2022).

The ratio of nps-SO_4^{2-}/NO_3^- in soluble ions is used to differentiate between coal combustion (fixed sources) and vehicular emissions (mobile sources) (Arimoto et al., 1996; Shen et al., 2008). Higher ratios in urban compared to rural areas (Figure S6) suggest a greater influence of fixed sources on urban dust deposition. Additionally, the lower nps-SO_4^{2-}/NO_3^- ratio during the NHP indicates a predominant role of mobile sources in NHP dust-fall. Typically, coal and biomass burning emissions intensify during the HP in northern China (Liu et al., 2016a), while vehicle emissions dominate in the NHP (Xu et al., 2012). These findings support the validity of the analysis, however, further validation using additional indicators is recommended.

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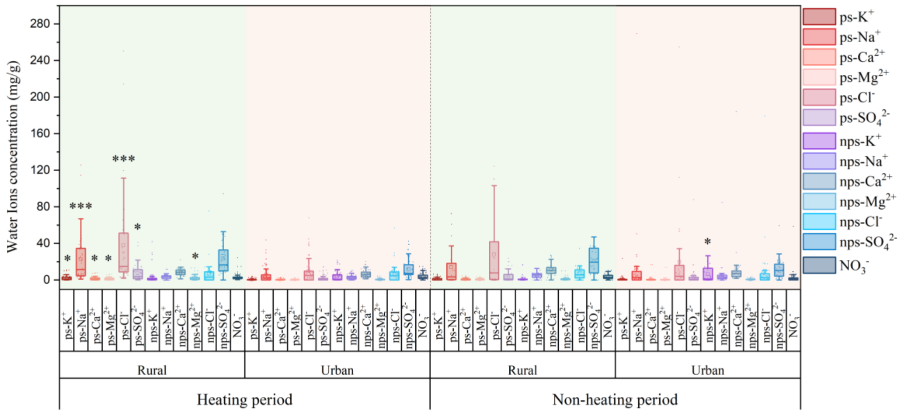

Figure 3 Concentrations of water ions in rural and urban across different seasonal periods (domestic heating and non-domestic heating periods). Asterisks indicate statistically significant differences between sites, with *, P <0.05; **, P <0.01; ***, P < 0.001.

3.2 Organic carbon and element carbon compositions

The average total carbon (TC) concentration in the southern QDB was 3.83 ± 3.2 mg/g, significantly lower than that of Huangshi, Hubei province (25.15 ± 11.79 mg/g) and Washington (157 ± 3.2 mg/g), Kumasi in West Africa (28 mg/g) and Xi'an (14.6 ± 5.8 mg/g) (Han et al., 2007a; Han et al., 2009b; Zhan et al., 2016; Bandowe et al., 2019), suggesting relatively low carbon emissions in the southern QDB. Average OC and EC levels in QDB are markedly lower than those in Xi'an (7.4 and 7.2 mg/g，respectively), Wuhu (33.26and 22.49mg/g，respectively), and Nanchang (25.15 and 11.46 mg/g， respectively) (Han et al., 2009a; Deng et al., 2014; Zhang, 2014), but significantly higher—particularly for EC—than in Nam Co (0.35 mg/g) (Chen et al., 2015).

In urban, TC content (3.05 ± 2.46 mg/g) were marginally lower than rural level (3.55 ± 3.56 mg/g), although this difference was not statistically significant. Contrasting spatial patterns emerged for carbon components: EC dominated urban areas (1.46 ± 1.60 mg/g), while OC prevailed in rural (2.25 ± 1.92 mg/g) (Figure 4, S7). This disparity may be attributed to the long-term combustion of biomass, coal, and wood in rural settings (Na et al., 2004). It may also be associated with meteorological conditions, particularly heightened solar radiation resulting from reduced primary emissions in rural areas, which facilitates the formation of SOC (Xu et al., 2018a; Wang et al., 2019).

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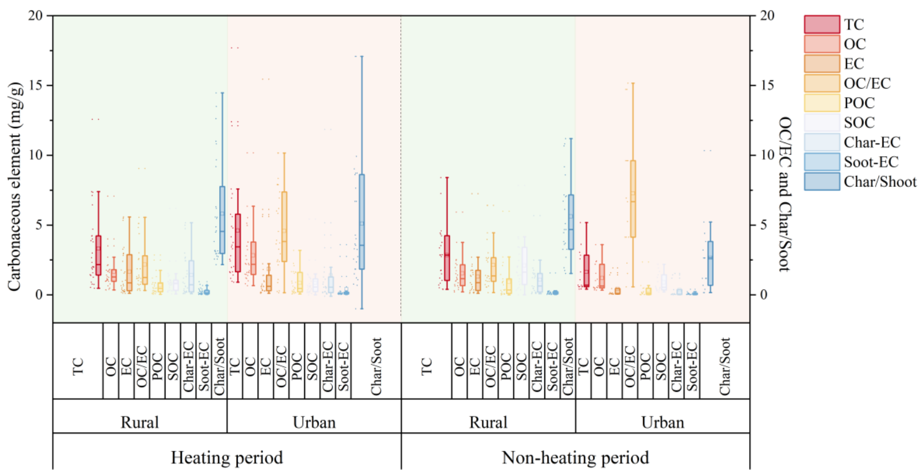

Figure 4 Concentrations of organic carbon (OC), elements carbon (EC), secondary organic carbon (OC), primary organic carbon (POC), char-EC, soot-EC and OC/EC, char/soot ratios in different sites (Rural, Urban) and seasonal variations (domestic heating and non-domestic heating period).

Seasonal analysis revealed elevated carbonaceous compound concentrations, specifically OC and EC, during the HP. This increase is primarily due to local domestic heating activities coupled with adverse meteorological conditions, such as low temperature, weak winds (Oliveira et al., 2007; Gong et al., 2017), weak atmospheric turbulence, and frequent atmospheric inversions (Guo et al., 2016). Rural emissions primarily stem from coal and biomass burning for heating and cooking. (Zhang et al., 2000; He et al., 2004), contributing to reduced OC and EC content in the NHP, whereas elevated EC levels in urban areas are primarily linked to vehicular and industrial sources. Spatiotemporal transport dynamics show EC depletion during rural ward pollutant migration due to atmospheric dispersion, particularly affecting coarse particulate fractions.

Notably, rural carbon emissions exceed urban levels in the southern basin, potentially attributable to extended HP duration (7 months) compelling low-grade fuel (crop residues, wood, raw coal and yak dung) utilization (Na et al., 2004). In contrast, urban areas benefit from solar/wind energy infrastructure and government-led clean heating initiatives (“suitable electricity for electricity” policy), achieving 66.63% clean heating penetration (Statistical Yearbook of Haixi Xizang Autonomous Prefecture of Qinghai Province), leading to a comparatively lower TC content. The OC/EC ratio is a valuable indicator of carbonaceous aerosol sources. In this study, Urban areas

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exhibited stable OC/EC ratios ranging from 0.15 to 15.16 (mean = 2.16), whereas rural areas showed significantly higher ratios during NHP (7.27 ± 4.66) compared to HP (4.57 ± 3.02) (Figure 4, S9). Typically, the OC/EC ratio for vehicle emissions ranges from 0.7 to 2.4, for coal combustion emissions from 0.3 to 7.6, and for biomass burning from 3.8 to 14.5 (Schmidl et al., 2008; Gonçalves et al., 2010; Pio et al., 2011; Popovicheva et al., 2016).

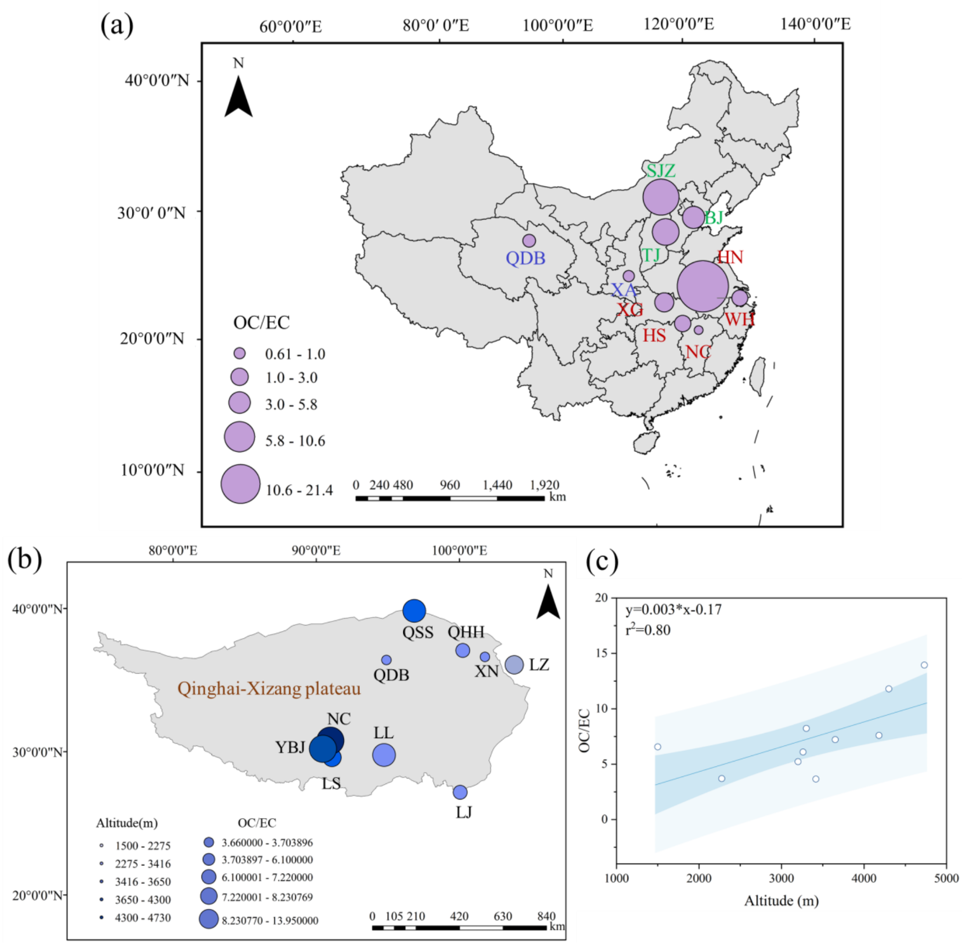

Figure 5 Distribution of OC/EC ratios across various regions of China (a), at different altitudes on the Qinghai-Xizang Plateau (b), and the relationship between OC/EC ratios and altitude (c). Blue designations represent the Northwest region, red indicates the Central region, and green denotes the Eastern region. The color of the circles corresponds to altitude, while circle size reflects the magnitude of the OC/EC ratios.

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These findings suggest that urban OC/EC ratios (0.15-9.05) are primarily associated with vehicle and coal combustion, while rural ratios (0.14-15.16) are predominantly linked to coal and biomass burning. A higher OC/EC ratio typically indicates a greater contribution from biomass combustion; in this study, the OC/EC ratio of rural was 5.56±3.93, which is significantly lower than values recorded in India (8.47) and Nam Co in Xizang (16.3±4.4) (Saud et al., 2013; Chen et al., 2015), yet higher than those observed in Shanxi (0.7-1.6), Beijing (1.9-2.7), and Tianjin rural (2.66) (Zhang et al., 2007; Cheng et al., 2015; Wang et al., 2021). This finding indicates that carbonaceous aerosols in rural QDB derive from both fossil fuel combustion and biomass burning, suggesting source specificity.

Figure 5a presents spatial variations in urban OC/EC ratios across China. The findings reveal that the Northwest region, represented by QDB urban and Xi'an (XA) (Han et al., 2009b), exhibits a significantly lower ratio (1.59 ± 0.56) compared to central regions, including Nanchang (NC) (Zhang, 2014) , Huangshi (HS) (Zhan et al., 2016), Wuhu (WH) (Deng et al. 2014), Xiaogan (XG) (Zhan et al., 2022), and Huainan (HN) (Liu et al., 2020), where the ratio is 5.86 ± 7.81. This ratio is also lower than that observed in eastern cities such as Beijing (BJ) (Tang et al., 2013), Tianjin (TJ) (Ma et al., 2019), and Shijiazhuang (SJZ) (Guo et al., 2018), which have a ratio of 6.83 ± 2.77. This pattern is consistent with the trends in atmospheric PM OC/EC ratios (Xie et al., 2023), suggesting that the carbon in the dust of the QDB urban primarily results from coal combustion and industrial emissions, leading to elevated EC concentrations and lower OC/EC ratios (Liu et al., 2022). Conversely, cities with higher economic development, such as Beijing and Tianjin, characterized by greater population density and income levels, typically experience secondary pollution, resulting in higher OC/EC ratios.

We analyzed the impact of altitude on the OC/EC ratio across various regions of the QXP by comparing aerosol emissions ($PM_{2.5}$, PM_{10}, TSP) from several sites: QDB (this study, altitude 3416 m), Lhasa (LS, altitude 3650 m) (Wei et al., 2019), Nam Co (NC, altitude 4730 m) (Chen et al., 2015; Wu et al., 2018b), Xining (XN, altitude 2275 m) (Hu et al., 2020), Qilian Shan Station of Glaciology and Ecologic Environment (QSS, altitude 4180 m) (Xu et al., 2015), Lijiang (LJ, altitude 3260 m) (Zhao et al., 2019), Qinghai Lake (QHH, altitude 3200 m) (Jun Li et al., 2013; Zhang et al., 2014), Lanzhou (LZ, altitude 1500 m) (Qi et al., 2024), Yangbajing (YBJ, altitude 4300 m) (Xiang et al., 2024), and Lulang (LL, altitude 3330 m) (Li et al., 2016). The findings (Figure 5b, c)

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demonstrated a significant positive correlation between altitude and the OC/EC ratio ($r^2 = 0.80$), indicating an altitude-dependent relationship (Zhao et al., 2022). This relationship may be attributed to the limited sources of EC at higher altitudes and the predominance of aged organic aerosols, which are rich in secondary OC, leading to increased OC/EC ratios (Sandrini et al., 2014; Wu et al., 2018b). The widespread biomass burning in the QXP further contributes to the presence of semi-volatile organic carbon in aerosols, which has a lower light-absorption capacity (Kocbach Bølling et al., 2009), thereby enhancing the OC/EC ratio.

Both increased altitude and economic development elevate OC/EC ratio, though eastern regions exhibit lower values than high-altitude zones. High-altitude areas show depressed OC and EC concentrations overall, with ratio elevation potentially stemming from EC reduction via intensive biomass burning. Conversely, the higher ratios observed in economically developed urban are primarily driven by anthropogenic activities that facilitate the formation of SOA. These scenarios can be differentiated using the WSOC/OC ratio (Patel et al., 2022), though such analyses await experimental validation. Additionally, since this research primarily focused on PM larger than 10 μm, the OC/EC results may be misleading. Further investigation of atmospheric particles smaller than 10 μm is necessary to elucidate the impact of altitude on carbonaceous aerosol emissions.

The elevation of QDB (3416 m) is below the average for QXP (4,000 m), and it exhibits higher economic development and population density. Despite this, some herders still burn yak dung for heating. The OC, EC emissions, and OC/EC ratios indicate that the carbon sources—comprising coal, biomass, and yak dung—are distinct from those in both central and eastern of China economically developed regions and other high-altitude QXP areas, reflecting its unique regional characteristics.

3.3 Char-EC and Soot-EC compositions

EC is classified into soot and char (Han et al., 2009b), with char-EC and soot-EC defined as (EC1-OPC) and (EC2+EC3), respectively (Han et al., 2007). Char-EC is typically produced from biomass burning at relatively low temperatures, whereas soot-EC originates from high-temperature coal combustion and automotive emissions (Zhu et al., 2010; Cao et al., 2013). The char-EC/soot-EC ratio, like the OC/EC ratio, serves as an indicator of carbon aerosol sources. Since char and soot

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are mainly generated through combustion processes, their ratio is typically influenced by two key factors: the primary emission source and the deposition removal efficiency. For localized PM, such as in urban areas, the removal rate is generally negligible (Han et al., 2009a).

Char-EC constitutes 75.88% of rural EC (74.71% HP; 78.84% NHP) and 85.00% of urban EC (85.58% HP; 84.11% NHP) (Figure 4, S8), demonstrating its dominance across spatial and temporal scales. Research suggests that char-EC constitutes a larger proportion of coarse PM, while soot-EC is more predominant in fine particles, resulting in extended atmospheric residence times for soot-EC due to reduced deposition velocities (Han et al., 2009b). The increased levels of char-EC during the urban HP are linked to complex sources, including biomass fuel usage and transportation emissions, resulting in elevated char concentrations in urban areas and along busy roadways (Kim et al., 2011).

The char/soot ratios for automobile emissions, coal combustion, and biomass burning are 0.60, 1.9, and 11.6, respectively (Chow et al., 2004; Chuang et al., 2014). Generally, high-temperature combustion (e.g., vehicle and industrial processes) yields lower char and soot concentrations, while low-temperature combustion (e.g., household cooking and biomass burning) results in higher ratios (Han et al., 2016; Han et al., 2012; Han et al., 2010; Han et al., 2009a). Differences in char/soot ratios between urban and rural areas across seasons may be linked to wheat straw burning, contrasting with minimal vegetation combustion impacts in cities like Xi'an (Cao et al., 2005). The char/soot ratio for dust-fall observed in this study (4.97; Figure 4, S9) is slightly higher than those recorded in Jinchang (3.84) (Han et al., 2009a) and Daheihe, Inner Mongolia (3.2) (Han et al., 2008). The relatively stable concentration of soot-EC in this study, along with the elevated char/soot ratio, suggests a correlation with higher coal consumption among local residents and industries. This indicates that, in comparison to other regions, carbon emissions in the remote QDB are predominantly sourced from coal and biomass burning, supporting previous findings. Furthermore, the char/soot ratio is elevated during HP, highlighting the predominant influence of coal and biomass burning in rural areas during HP, while fossil fuel impacts are more pronounced in NHP.

3.4 POC and SOC compositions

Aerosol samples with low OC/EC ratios typically exhibit low concentrations of POC, which mainly comprises primary carbonaceous compounds. Conversely, OC/EC ratios exceeding 2.0 indicate substantial SOA formation (Chow et al., 1996; Gray et al., 1986). The MSR method enables discrimination of OC into POC and SOC (Method 2.7) (Turpin and Huntzicker, 1995; Cao, 2003).

SOC constitutes a dominant fraction of OC in atmospheric aerosols. Research on carbonaceous aerosols in various Chinese cities indicates that SOC contributes 67% (53-83%) and 57% (48-62%) to rural and urban OC, respectively (Zhang et al., 2008)—marginally higher than the 62.62% observed in this study (Figure 4, S10). Although SOC formation relies on solar radiation, the QDB experiences high levels of solar energy (Liu et al., 2017), which may facilitate photochemical oxidation of VOCs into SOC (Hama et al., 2022). Nevertheless, the consistently low SOC concentrations indicate that VOCs emissions in QDB are significantly lower than the regional averages observed across China, reflecting relatively low pollution levels. This finding is consistent with the previously observed low concentrations of atmospheric carbon emission in the region.

During the NHP, rural areas exhibit the highest SOC/OC ratio of 86.70% (Figure S11), while urban areas record the lowest ratio of 44.32% during the HP. This trend reflects elevated potential for photochemical activity and reduced contributions from POC, likely due to local emission sources, such as traffic and coal combustion (Mbengue et al., 2018). The high SOC/OC ratio suggests that SOC largely displaces OC. Our findings indicate that SOC levels are greater in rural areas (66.52%) compared to urban regions (58.74%), likely attributable to significant coal consumption for domestic heating, which enhances emissions of semi-volatile organic compounds and organic gases (Dan, 2004). As for seasonal variations, studies in California show an increase in SOC levels during warmer months, which is consistent with our results (Na et al., 2004). This contrasts with the broader observation that higher temperatures typically lead to lower SOC concentrations (Strader et al., 1999; Sheehan and Bowman, 2001). This discrepancy may stem from varying sources of SOC emissions throughout the seasons, necessitating further investigation in conjunction with other carbonaceous indicators.

3.5 Trace elements concentration

The total concentration of major (Fe, Si, Al) and trace elements (Ti, Cr, Cd, Cu, Mn, Ni, Pb, V, Zn) was determined to be 8.74 ± 5.82 mg/g, while arsenic (As) remained below the detection limit

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in all analyzed samples. Crustally derived elements—Fe, Al, Si, and Ti—dominated the elemental profile, aligning with dust composition patterns reported in Ira, Singapore, and Beijing-Hebei regions, China (Joshi et al., 2009; Qiao et al., 2013; Eivazzadeh et al., 2021). In comparison to cities such as Beijing, Shanghai, Xi'an, and Lanzhou, and Junggar Basin the levels of heavy metals in dust from the QDB are relatively low (Jiang et al., 2018) (Supplementary Table S1).

Throughout both the HP and NHP, trace elements concentrations in urban areas were consistently higher than in rural areas, with the exception of Ti (Figure 6, S12). During the HP, urban levels of Zn, Pb, and Cu were significantly elevated compared to rural areas, and Pb also demonstrated a significant increase in urban during the NHP. In rural, the differences in metal concentrations between HP and NHP were minimal. In contrast, urban areas exhibited higher concentrations of all elements except for Ti, Cd, and Cr during the HP, with Fe and V showing notably elevated levels compared to other regions. These variations in average concentrations indicate that coal combustion for domestic heating in urban areas contributes to increased atmospheric heavy metal levels (Duan and Tan, 2013; Meng et al., 2017). In contrast, Cd and Cr exhibited mixed anthropogenic sources with limited coal combustion contributions, while Ti concentrations remained stable across seasons, reflecting minimal anthropogenic influence.

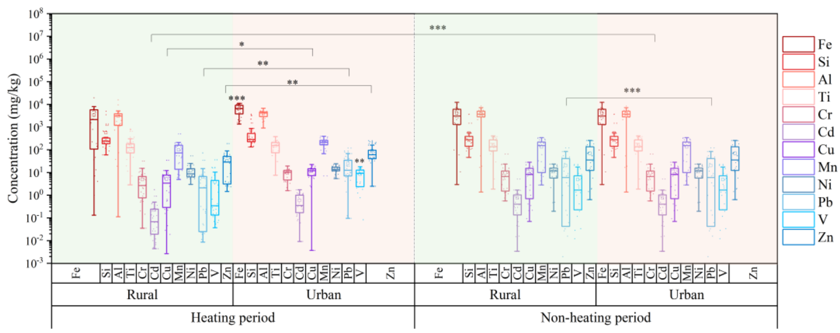

Figure 6 Concentration of heavy metals by rural and urban settings during domestic heating and non-domestic heating periods. Significant differences are indicated by asterisks (*p < 0.05; **p < 0.01; ***p < 0.001).

3.6 Source apportionment

We conducted a PMF source apportionment analysis on soluble ions, trace metals, and carbonaceous elements present in dust, specifically focusing on ps-SO_4^{2-}, ps-Ca^{2+}, ps-K^+, ps-Mg^{2+},

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ps-Cl^-, ps-Na^+, nps-SO_4^{2-}, nps-Ca^{2+}, nps-K^+, nps-Mg^{2+}, nps-Cl^-, nps-Na^+, Fe, Si, Al, Ti, Cr, Cd, Cu, Mn, Ni, Pb, V, Zn, SOC, POC and Char-EC, Soot-EC. Seven source factors were identified based on prior research and an understanding of potential local sources: salt lakes, soil, vehicular emissions, secondary sources, biomass and coal burning, and industrial activities (Figure 7, S13). The factor profiles for each element in these source categories represent the arithmetic mean of profiles from six stations, with detailed operational methods provided in Supplementary Text S1.

The ions ss-Na^+, ss-Cl^-, ss-SO_4^{2-}, ss-Ca^{2+}, ss-K^+, and ss-Mg^{2+} are widely acknowledged as indicators of sea salt (Ambade et al., 2022; Aswini et al., 2022; Gluscic et al., 2023). In this study, we identified ps-Cl^- (82.71%), ps-Mg^{2+} (79.03%), ps-K^+ (79.02%), ps-Na^+ (78.69%), ps-Ca^{2+} (78.70%), and ps-SO_4^{2-} (78.69%) as key markers of salt lake sources. Furthermore, Cd (29.70%) was detected at multiple sampling sites, indicating contributions from both salt lakes and industrial emissions. The contribution of salt lake sources in rural (12.93%) was significantly higher than in urban (10.33%). During the HP, the proportion of salt lake sources in rural areas was 5.49%, compared to 20.37% in the NHP; urban showed contributions of 18.24% during the HP and 2.42% in the NHP. This inverse trend suggests that seasonal variations differentially influence the contribution of salt lake sources in urban and rural, necessitating further research to elucidate the underlying driving factors.

The second factor pertains to soil dust, characterized by ions such as Si (37.17%) and Al (29.18%), along with nps-Cl^- (34.90%), nps-Mg^{2+} (28.21%), and Fe (24.43%) (Pervez et al., 2018; Tian et al., 2021). Additionally, the proportions of elements such as SOC (28.20%) and POC (17.70%) suggest that the dust is likely mixed with fossil fuel emissions. Notably, the contribution of soil dust in rural areas (22.11%) exceeded that in urban areas (13.33%), indicating that soil dust is a major source of atmospheric deposition. In urban areas, the contribution during the NHP was relatively low (7.36%), likely due to higher wind speeds and the effectiveness of frequent summer precipitation (Zhang et al., 2015a).

The third factor is vehicular emissions, which are particularly pronounced in urban areas. Key characteristic elements include Pb (59.52%), V (48.73%), Zn (37.47%), nps-Cl^-(33.83%), Cd (32.43%), Ni (27.01%) and SOC (51.71%), Soot-EC (37.56%), Char-EC (24.94%) (Adeniran et al., 2017). Furthermore, notable concentrations of nps-Mg^{2+} (40.78%), nps-K^+ (29.64%), and NO_3^- (20.99%) were identified. In rural areas, vehicular emissions contributed 8.17% to atmospheric

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deposition during the NHP, whereas in urban areas, the contribution was significantly higher at 45.13%, with 30.07% during the HP and 58.78% in the NHP. These findings correlate with previous studies on OC/EC and char/soot ratios, suggesting that carbonaceous elements in the NHP primarily derive from vehicular emissions. The increase in vehicular emissions during the NHP may be linked to the expanding tourism industry in the QDB, particularly in cities like Golmud, which experience a rise in tourist numbers from May to September, subsequently leading to a surge in population and vehicles, and thus elevating vehicular emissions.

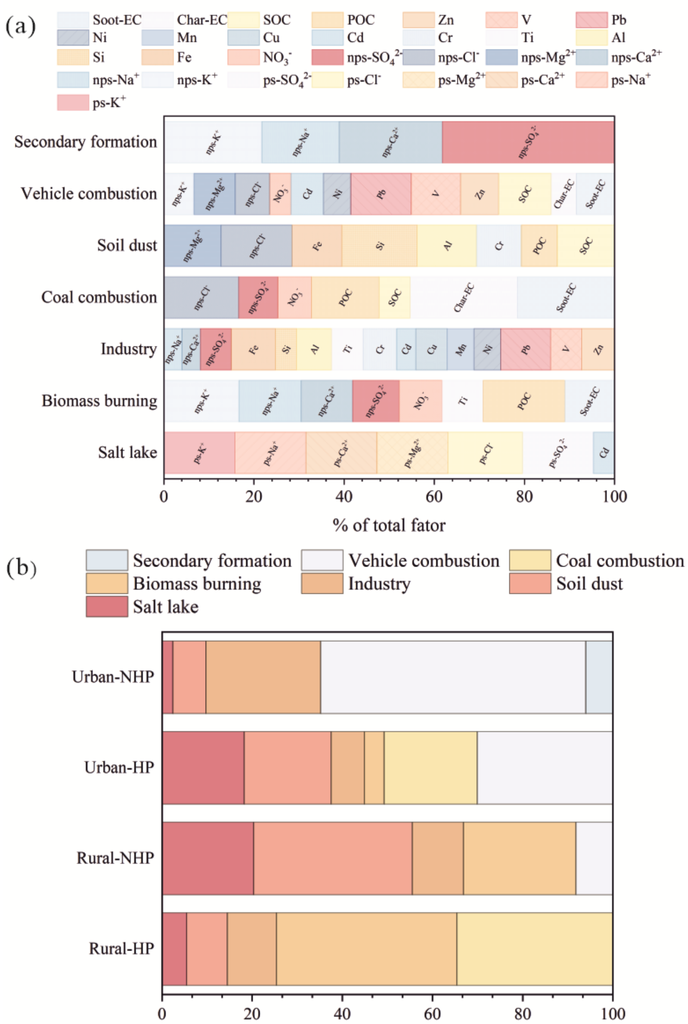

Figure 7 Factor profile and contributions in urban and rural aera. (a) presents the factor profiles,

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represented as the arithmetic mean of individual elements across various locations, highlighting only those elements that constitute more than 20% of each profile. (b) illustrates the contributions of different sources at each location. [HP, domestic heating period; NHP, non-domestic heating period].

The fourth factor is coal combustion, characterized by high concentrations of nps-Cl^- (50.93%), nps-SO_4^{2-} (26.61%), NO_3^- (22.82%), and Char-EC (73.01%), Soot-EC (65.98%), POC (46.04%), SOC (21.12%) (Kundu and Stone, 2014; Contini et al., 2016). Coal combustion occurs exclusively during the HP, contributing 34.57% in rural areas and 20.63% in urban areas. These results align with earlier studies on carbonaceous aerosols, indicating that the carbon content from coal combustion emissions is higher in rural regions than in urban environments. Consistent with northern China, air pollution in QDB urban has declined due to the adoption of clean heating technologies (Zhang et al., 2021; Xue et al., 2023). However, rural coal combustion remains a major source of carbonaceous aerosols during the HP.

The fifth factor, biomass burning, is characterized by significant concentrations of non-precipitating species, including nps-K^+ (42.76%), nps-Na^+ (35.49%), nps-Ca^{2+} (29.23%), nps-SO_4^{2-} (26.56%), NO_3^-(24.46%), Ti (23.41%) and POC (46.48%), Soot-EC (28.33%) (Simoneit, 2002; Sulong et al., 2019). Biomass burning contributes 32.82% to rural atmospheric dust deposition, with a higher proportion during the HP (39.21%) compared to NHP (26.44%). In urban, biomass burning is primarily observed during the HP, contributing only 2.19%. These findings underscore biomass burning as a major source of carbon emissions in rural settings, aligning with the prevalent use of biomass fuels for cooking and domestic heating in Northern China's rural areas (Meng et al., 2019), where 70% to 80% of energy demand are fulfilled by materials such as dung cakes, firewood, charcoal, and crop residues (Tao et al., 2018; Shi et al., 2019). Furthermore, increased biomass burning is also associated with the autumn harvest period (Chen et al., 2017; Li et al., 2021).

The sixth factor pertains to industrial emissions, which are characterized by high concentrations of Pb (55.18%), Fe (48.91%), Cr (37.05%), Zn (36.42%), Ti (35.10%), Cu (34.91%), V (34.44%), Ni (29.69%), Mn (29.59%) and Cd (21.29%) (Almeida et al., 2015; Yao et al., 2016b). These elements were consistently detected across all sampling sites, alongside Al (38.84%), nps-SO_4^{2-} (34.15%), Si (23.39%) and nps-Ca^{2+} (20.48%), nps-Na^+ (20.02%), which indicate potential

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contributions from soil dust. In rural areas, industrial emissions constitute 11.10% of carbon output, with contributions of 10.86% during the HP and 11.33% during the NHP. In urban areas, industrial emissions account for 16.41% overall, with 7.37% during the HP and 25.44% in the NHP. Moreover, industrial emissions are a primary source of atmospheric dust in urban regions, particularly in the QDB, which is rich in mineral resources and hosts numerous mining enterprises, thereby significantly contributing to regional air pollution.

The seventh factor is secondary aerosols, primarily composed of NO_3^-(68.54%), nps-Mg^{2+} (41.04%), nps-Na^+ (39.01%) and nps-Ca^{2+} (30.79%) (Liu et al., 2015; Liu et al., 2016a). Research indicates that NO_3^- and SO_4^{2-} primarily result from the conversion of gaseous precursors, such as SO_2 and NO_x, through photochemical reactions, predominantly sourced from local and regional emission (Liu et al., 2015; Tao et al., 2013). Secondary aerosols are predominantly observed in urban areas during the NHP, where they contribute 6.00% to total aerosol sources. This increase is likely due to elevated temperatures and enhanced solar radiation during this period, which promote photochemical activity (Pandolfi et al., 2010).

Dust deposition sources exhibit significant seasonal and spatial variations. In the QDB, coal combustion (27.60%) and biomass burning (22.21%) dominate during HP, transitioning to vehicular emissions (33.48%), soil dust (21.27%) and industry emission (18.39%) as the primary contributor in NHP. Rural areas predominantly contribute to dust through biomass and coal burning, as well as natural sources like windblown dust and salt lake emissions. This pattern aligns with increased coal usage for winter domestic heating and heightened biomass burning for cooking and heating in rural. In urban, dust deposition is briefly influenced by anthropogenic activities, including vehicle and industrial emissions, with minimal contributions from domestic heating. Such differences can be attributed to varying economic development models, industrial and energy structures, and levels of human activity (Kataki et al., 2016).

3.7 Environmental implication

The source apportionment analysis using PMF model indicates that in the QDB, rural dust-fall predominantly originates from the combustion of solid fuels—including firewood, yak dung, and coal—accounting for approximately 74.61% of the total contribution. This proportion significantly exceeds contributions reported for rural areas in Beijing (41%) (Hua et al., 2018), Agra (54.3%) (Agarwal et al., 2020), and Beihai, Guangxi Province (66.7%) (Zhang et al., 2019).

The higher contribution in this study likely reflects the local energy profile, as the sampling site in Haixi Mongol and Xizang Autonomous Prefecture, Qinghai Province, primarily relies on coal, yak dung, and firewood, constituting 58%, 23.5%, and 13% of rural energy consumption, respectively (Jiang et al., 2020; Shen et al., 2021). In contrast, solid biomass fuels, including wood and yak dung, account for over 70% of rural household energy consumption in Xizang, with yak dung alone representing 53% (Liu et al., 2008; Xiao et al., 2015). Similar patterns emerge in South and Central Asia, where biomass fuels dominate residential heating (firewood: 39%; dung: 29%) (Amacher et al., 1999; Heltberg et al., 2000; Hoeck et al., 2007; Foysal et al., 2012; Behera et al., 2015; Kerimray et al., 2018). In northern China, rural domestic heating primarily relies on coal (46%), firewood (23.8%), and electricity (15.1%) (Tao et al., 2018), further highlighting the unique energy composition of QDB.

Recent studies have shown that South Asia, Central Asia, and Xizang contribute significantly to high concentrations of atmospheric PM, particularly BC, which accelerates glacier melting in the QXP (Ming et al., 2010; Xia et al., 2011; Chen et al., 2015). The QDB is recognized as a significant dust source affecting the glacier surfaces on the QXP, although it is often overlooked (Dong et al., 2014; Wei et al., 2017; Zheng et al., 2021). Compared to other dust sources, the QDB exhibits higher emissions from coal combustion, giving it a unique influence on the QXP. The organic matter and pollutants, such as polycyclic aromatic hydrocarbons (PAHs), released from household solid fuel combustion—particularly coal (98%) and dung (94%)—are substantially higher than those from firewood (Leavey et al., 2017; Secrest et al., 2017; Ye et al., 2020). Consequently, the impact of PM from coal combustion in the QDB on the QXP is significant. Specifically, the presence of BC in PM increases glacier albedo, accelerating the melting of glaciers and snow in the region (Kang et al., 2020), and impacting global freshwater resources (Huss and Hock, 2018). Additionally, BC enhances cloud condensation nuclei (CCN), ice number concentration, and cloud cover (Zhou et al., 2025), thereby influencing global climate change. Furthermore, coal combustion releases harmful emissions, including CO_2, NO_x, CO, SO_2 and sulfur trioxide (SO_3) (Munawer, 2018), adversely affecting local human health and exacerbating climate warming on the QXP (Liu et al., 2006; Li et al., 2023), with broader implications for global climate. Therefore, the atmospheric pollutants

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emission of the QDB deserves considerable attention. However, this study focuses primarily on larger particles, indicating a need for further research on the environmental impacts of carbonaceous aerosols in atmospheric PM within the QDB.

Beyond the unique energy structure of QDB—where coal and biomass dominate during the HP—NHP atmospheric dust primarily stems from vehicle and industrial emissions, with vehicle contributions being twice as high as in the HP. This indicates that NHP atmospheric conditions are significantly influenced by resource development and tourism. Sampling sites, such as Qarhan Salt Lake, along with GEM and LTC stations within approximately 100 km (Figure 1), suggest that salt lake resource extraction has a lower impact on regional aerosols than vehicle emissions, despite salt lakes being the primary resource. This is likely because salt lake development mainly involves solar evaporation and chemical processes like extraction and adsorption, which emit fewer pollutants compared to other mining methods (Zhen, 2010). Consequently, salt lake resource exploitation exerts a relatively minor effect on local atmospheric carbonaceous aerosol.

Similar salt lakes with comparable environments to QDB—such as Salar de Uyuni in Bolivia, the Atacama Salt Lake in Chile, and Ombre Muerto in Argentina—are rich in lithium resources (Li et al., 2014), making them focal points for resource development. Additionally, Salar de Uyuni, the Atacama Salt Lake, Junggar Basin, and the Great Salt Lake are renowned tourist destinations. This suggests that, in arid basin salt lakes with similar climates and intensive human activity, atmospheric carbonaceous aerosols are likely influenced by resource exploitation and tourism, especially tourism. The study's findings can inform policy decisions regarding unexploited salt lakes in South America, such as Ombre Muerto and Salar de Uyuni. However, while QDB also hosts mineral resources such as copper, iron, and tin, this research focused on larger particles (>100 μm), which are more indicative of local sources. Given that sampling was conducted around the salt lakes, potential impacts from other mineral resource developments may have been underestimated. Further research is necessary to fully assess the environmental effects of carbonaceous aerosols in QDB atmospheric particles.

Conclusion

This study analyzed the composition of dust deposition at six sampling sites in the southern

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Qaidam Basin from January 2020 to March 2023 and examined DF, soluble ion, metal, and carbonaceous element content in urban and rural samples during both domestic heating and non-domestic heating periods. Through integrated application of backward trajectory modeling, PMF, and carbon speciation indices, we identified dominant dust sources and evaluated domestic heating impacts on atmospheric processes in remote regions.

The findings revealed that DF and carbon emissions were significantly higher in rural than in urban areas. Among carbon indicators, urban exhibited elevated EC levels, while OC levels were higher in rural. Both altitude and economic development increase OC/EC ratios, but they are driven by different intrinsic factors. Char-EC was the dominant contributor to EC, with urban Char-EC levels showing a notable increase compared to rural levels. SOC was the principal contributor to OC, with rural SOC levels surpassing those in urban areas. The OC/EC and char-EC/soot-EC ratios, along with PMF results, indicated that during HP, dust deposition in the QDB was primarily derived from coal (28.44%) and biomass burning (22.14%), while vehicle emissions accounted for 34.19% of dust during NHP. Coal and biomass burning were the main contributors to rural dust, strongly influenced by domestic heating, whereas urban dust predominantly originated from vehicle and industrial emissions. Compared to other dust sources in the Qinghai-Xizang Plateau, coal consumption in the QDB is higher during the domestic heating period. The resulting emissions of black carbon and greenhouse gases may exacerbate glacier melting in the region, warranting increased attention. Given the distinctive carbonaceous aerosol signatures identified in the Qaidam Basin, we recommend prioritizing their radiative forcing effects in regional environmental policymaking and climate modeling frameworks. Furthermore, findings of this study offer a valuable scientific basis for understanding atmospheric carbonaceous aerosols in arid basins and salt lake regions with climates similar to QDB. They can particularly inform policy decisions regarding unexploited salt lakes in South America, such as Ombre Muerto and Salar de Uyuni.

However, this study primarily focused on larger-scale PM and examined the effects of heating on carbonaceous aerosols in the QDB. It lacks an investigation of aerosols with smaller particle sizes (e.g., PM_{10}, $PM_{2.5}$, PM_1), which is essential for a comprehensive understanding of carbonaceous aerosol characteristics in this unique region. Furthermore, in addition to offline observations, future research should incorporate online observations with high spatiotemporal resolution and utilize numerical air quality models such as CMAQ, CAMx, WRF-CHEM, and

NAQPMS to analyze the spatiotemporal distribution and future trends of carbon aerosols in the QDB.

Author contribution

HZ: Conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, validation, writing – original draft.

LZ: Data curation, formal analysis, methodology.

SZ: funding acquisition, validation, writing – review & edited.

XZ: Supervision, conceptualization, funding acquisition, writing – review & edited.

Acknowledgements

This research was funded by Youth Joint Fund of Lanzhou Branch of Chinese Academy of Sciences (E4400304), and by Qinghai Provincial Innovation Platform Construction Special Program (Project No. 2024-ZJ-J03), and supported by Qinghai Provincial Key Laboratory of Geology and Environment of Salt Lakes (No. The Science and Technology Plan Project of Qinghai Province Incentive Fund 2024).

Declaration of competing interest

The authors declare that there is no conflict of interest.

Data availability

Datasets for this research has been uploaded in Zenodo and is available at https://doi.org/10.5281/zenodo.14382853 (Zhu, 2024).

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