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

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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.

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 at six sites in the southern QDB between 2020 and 2023. We identified the sources of dust-fall during domestic heating (HP) and non-heating periods (NHP) in urban and rural areas and its environmental effects. The results demonstrated that domestic heating increased the concentration of water-soluble ions in rural areas, trace elements in urban areas, 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 (80.44%). Char-EC concentrations were higher in urban areas (85.00%), while secondary organic carbon (68.17%), the main contributor to OC, was more prevalent in rural (73.92%). The OC/EC ratio in urban areas remained stable with an average of 2.16. In contrast, the rural OC/EC ratio was significantly higher during the NHP (7.27 ± 4.66) than during the HP (4.57 ± 3.02). Additionally, the char/soot ratio was elevated in the HP (5.06 ± 4.08) compared to the NHP (4.42 ± 3.09). The OC/EC and char-EC/soot-EC ratios, along with PMF results, indicated that coal combustion (17.28%) and biomass burning (32.50%) were the main contributors to dust deposition in rural areas, strongly influenced by domestic heating, whereas urban dust predominantly originated from ~~vehicle~~ traffic (44.43%) and industrial emissions (16.41%). 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 pollution~~s~~, 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; carbonaceous elements; atmospheric dust deposition.

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., 2016~~a~~; Zhang et al., 2015~~b~~a). PMF analysis of atmospheric dust in urban areas 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 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~~2015b; 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 as a key economic hub in northwest China. It has a high population density~~,~~ and intense human activity, yet it is highly sensitive to climate change. Extensive resource extraction has

rendered 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

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~~ 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 part 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~~Dachaidan, 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 the 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. According to Sow et al (2006), the collection efficiency of the MDCO decreases with increasing wind speed, dropping below 20% when wind speed exceeds 3 m/s, and it preferentially collects fine dust particles ranging from 10 to 31 μm in size (Chow, 1995). This type of collector has been widely used in ~~numerous~~many studies to evaluate local dust conditions (Abdollahi et al., 2021; Barjoee et al., 2021; Alzahrani et al., 2024). Therefore, we consider this collector effective for capturing fine dust particles, and the actual dust deposition flux can be estimated by accounting for its approximately 20% collection efficiency.

In this study, dust samples were collected monthly, with each sampling period lasting 30 or 31 days. The installation height and environment of the samplers are provided in Table S1. 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):

$$M=\frac{m\times 30}{S\times K}, \quad (1)$$

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).

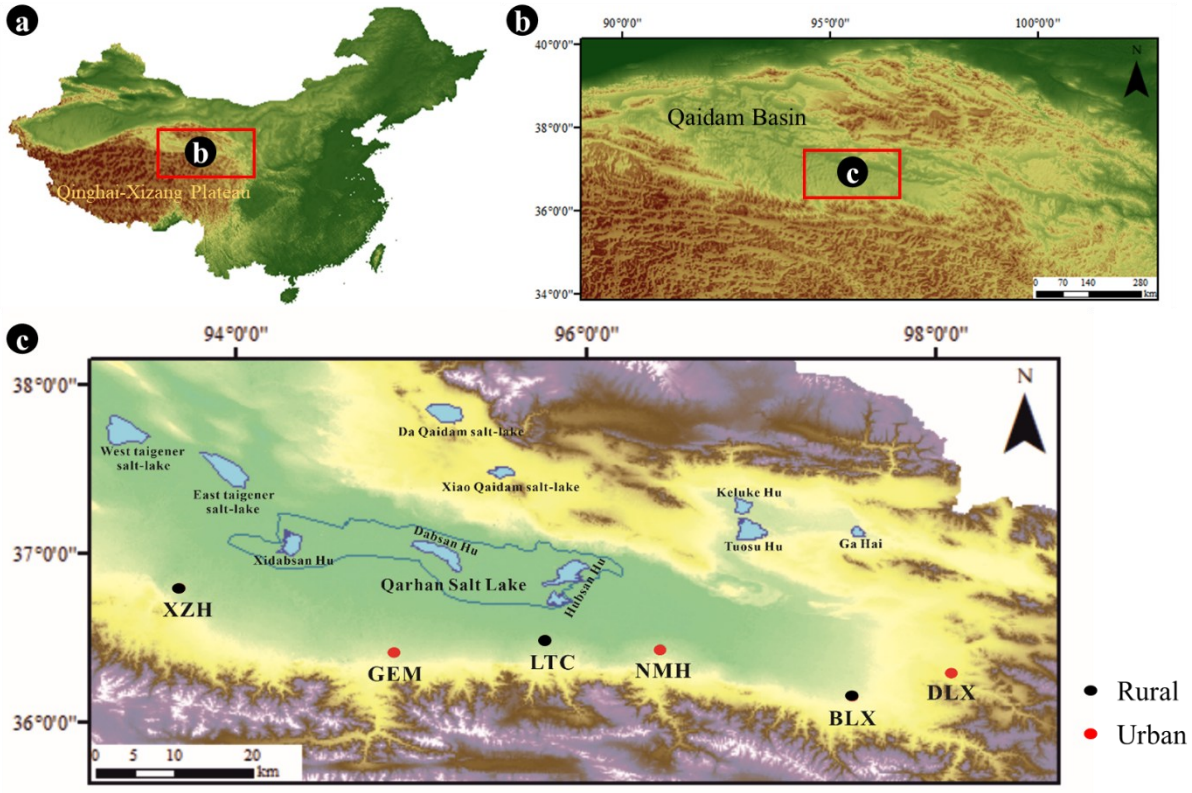


Figure 1. Spatial distribution of monitoring stations in the southern Qaidam Basin. Urban stations (red) and rural stations (black) are labeled as follows: XZH (Xiao Zaohuo), GEM (Golmud), LTC (Da Gele), NMH (Nuo Muhong), BLX (Balong), DLX (Dulan).

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.

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~~ carbon 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). This method has been widely applied to measure OC and EC contents in lake sediments and urban soils (Han et al., 2009; Khan et al., 2009; Han et al., 2011). Studies have shown that the EC collection efficiency of this method is approximately 99.6% (Zhan et al., 2013); however, its OC collection efficiency remains unclear. 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 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 is defined as the sum of EC1, EC2, and EC3, with OPC subtracted~~EC = EC1+EC2+EC3-OPC~~). The method enables differentiation between soot and ~~ash~~char, as determined by the gradual oxidation of these black carbon subtypes in standard reference materials during the EC1 and the EC2 plus EC3 ~~EC2 + EC3~~ steps, where ~~soot~~ char is defined as EC1 minus OPC~~EC1-OPC~~ and ~~ash~~ soot as the sum of EC2 and EC3 ~~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):

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

$$SOC = OC_{total} - POC, \quad (3)$$

where OC_{total} 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 $(OC/EC)_{pri}$. The computational procedure followed the algorithm developed by Wu and Yu (2016) (available at: https://sites.google.com/site/wuchengust), implemented within the Igor Pro environment (WaveMetrics, Inc., Lake Oswego, OR, USA). Due to the limited dataset size and low temporal resolution, the MRS analysis was performed collectively across all sampling sites. In this approach, the R^2 between SOC and EC was calculated iteratively for a range of $(OC/EC)_{pri}$ values spanning 0 to 10. The minimum R^2 value of 1.33 (Figure S2) identified the optimal $(OC/EC)_{pri}$ representative of the true primary ratio.

(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).

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

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

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

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

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

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.

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

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

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

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

(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 the PMF model is to solve the chemical mass balance between measured species concentrations and the respective source profiles, with the purpose of minimizing the objective function Q (Eq. 13) based upon the uncertainties (uij) of measured species (Paatero and Tapper, 1994).

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

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 defined as the sum of two components: the x_{ij} multiplied by an error fraction, and one-third of the method detection limit (MDL).~~calculated to be x_{ij} × 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. The error assessment and uncertainty data for the PMF source apportionment can be found in Tables S2 and S3, respectively.

3. Results and discussion

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~~10.77 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 areas 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~~S3), contributing to the elevated DF levels.

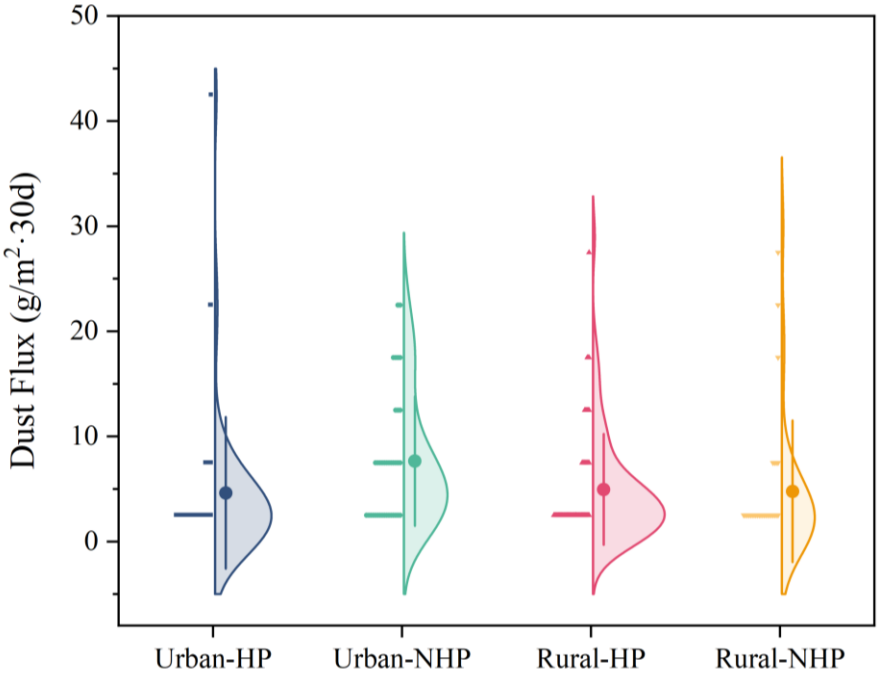


Figure 2 Dust flux distribution in urban and rural. The distribution of dust flux in four contexts: Urban with domestic heating period (Urban-HP), Urban with non-HP (Urban-NHP), Rural with domestic heating period (Rural-HP), and Rural with non-HP (Rural-NHP). Each violin plot illustrates the density 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~~,~~ and ~~S3~~S4). 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% respectively. 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~~,~~ and ~~S5~~S6), 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). The higher nps-SO_4^{2-}/NO_3^- ratio in urban areas compared to rural areas (Figure S7) indicates that during the study period, stationary sources (e.g., industrial emissions, coal, and biomass combustion) contributed more significantly to the ionic composition of urban dust-fall (Pipal et al., 2019). In contrast, the ratio was considerably lower during the NHP than during HP, suggesting that mobile sources likely played a more important role in the dust ionic composition during the NHP. Generally, emissions from coal combustion and biomass burning~~combustion~~ was intensified in northern China during the HP (Liu et al., 2016), while vehicle emissions dominate during the NHP (Xu et al., 2012), supporting the reliability of this analysis. Nevertheless, further investigation integrating atmospheric emission inventories, source tracers, aerosol physicochemical processes, and meteorological conditions is warranted. ~~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.~~

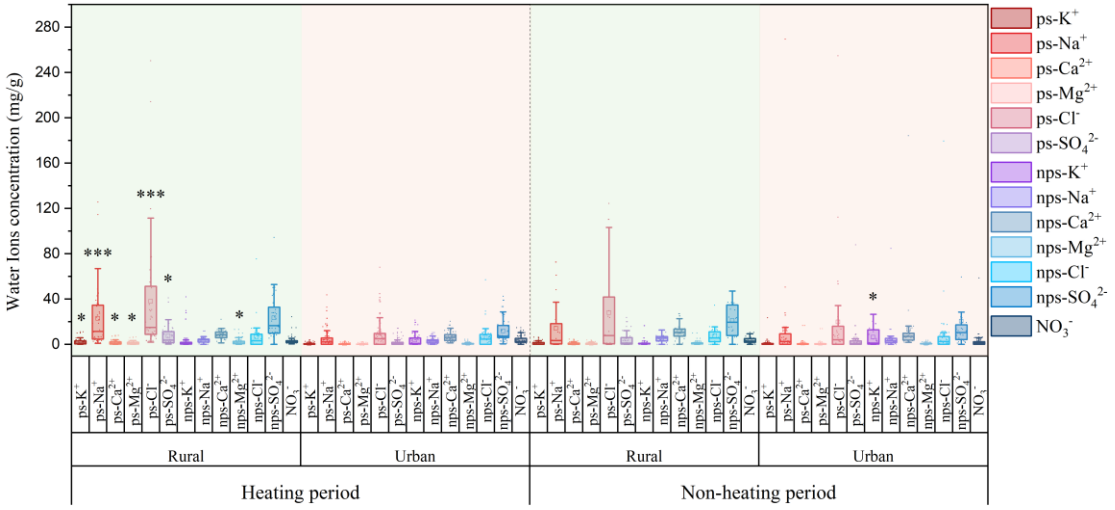


Figure 3 Concentrations of water ions in rural and urban across different seasonal periods (domestic heating and non-domestic heating periods). Asterisks indicate statistically significant differences between sites, with *, P <0.05; **, P <0.01; ***, P < 0.001.

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~~ was marginally lower than the 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~~,~~ and S~~8~~7). 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).

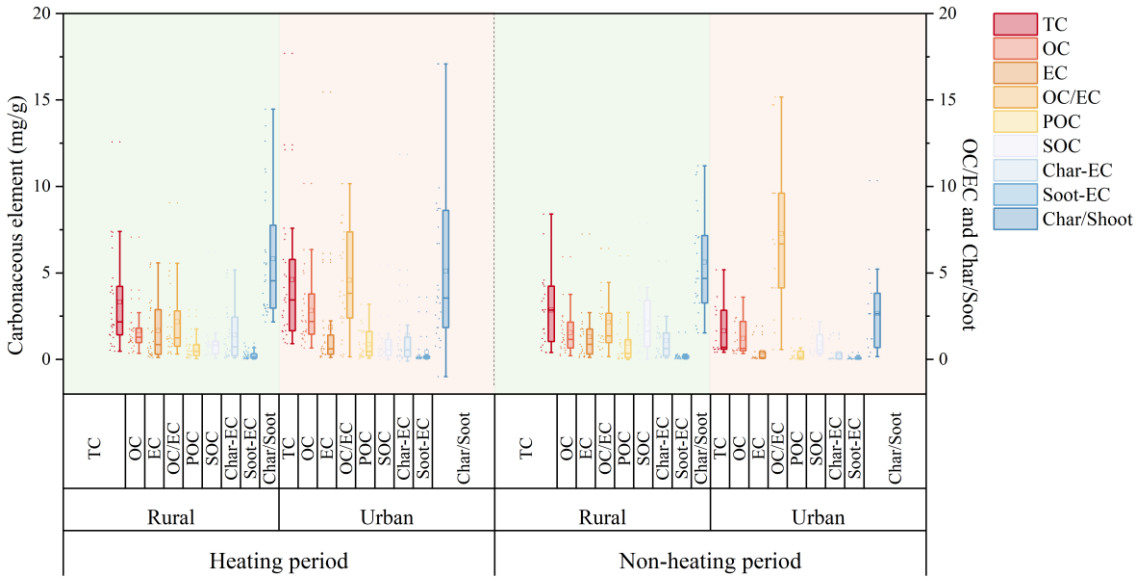
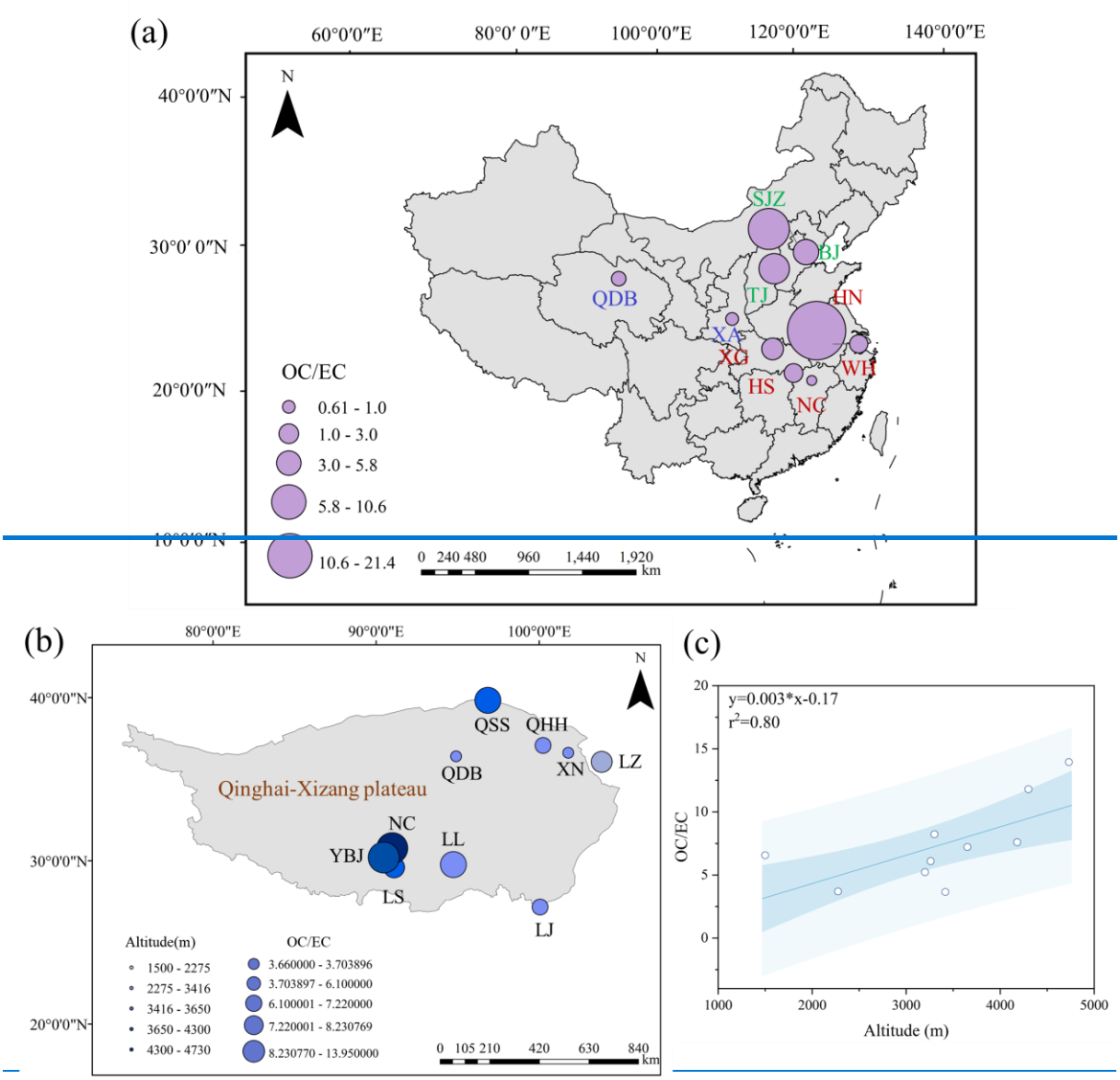


Figure 4 Concentrations of organic carbon (OC), elements carbon (EC), secondary organic carbon (OC), primary organic carbon (POC), char-EC, soot-EC and OC/EC, char/soot ratios in different

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 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 and ~~S9~~S10). 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.~~

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. Furthermore, as the pretreatment used in this study removes impurities such as silicates from the carbonaceous components of dust, and the OC collection efficiency of this treatment is currently unknown, the lower OC/EC ratios observed may also be attributed to a lower OC collection efficiency.~~

~~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) 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 minus OPC and the sum of EC2 and EC3 ~~(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 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~~,~~ and ~~S8~~S9), 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~~,~~ and ~~S9~~S10) 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~~ OC/EC ratio 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 M~~S~~RRS method enables discrimination of OC into POC and SOC (Method 2.7) (Yoo et al., 2022; Liu et al., 2023).~~T~~

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~~,~~ and ~~S10~~S11). 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~~S12), 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.

This study conducted a comparative analysis of carbonaceous element concentrations in atmospheric dust-fall and road dust between the QDB and other global regions (Table S4). To ensure data comparability, the selected road dust samples consisted of directly collected in-situ dust without resuspension treatment. The results revealed that the concentrations of TC, OC, and EC in QDB (3.27, 1.88, and 1.41 mg/g, respectively) were significantly lower than those in industrial or urban

areas such as Bolu, Turkey; New Delhi, India; and Ezhou, China, and were even lower than many other Chinese cities (Table S4). The low concentrations of OC and EC in QDB indicate minimal anthropogenic pollution influence in this region, and the data can represent the regional background values of carbonaceous components in atmospheric dust-fall in the arid inland areas of East Asia (Chen et al., 2019a). This is crucial for global models assessing the emission fluxes of carbonaceous aerosols from dust source regions. In contrast, extremely high values of carbonaceous elements were found primarily in urban road dust from locations like Bolu, Turkey (TC: 605.2 mg/g), Gwangju, South Korea (TC: 31.97 mg/g), and Xi'an, China (TC: 36.53 mg/g), indicating strong influences from traffic emissions (mainly non-exhaust emissions) (Wei et al., 2015; Lee et al., 2018; Demir et al., 2022). For atmospheric dust-fall in major cities like New Delhi, India, and Wuhan, China, the carbonaceous components are affected by the combination of traffic emissions (diesel vehicle emissions being a major source of EC), industrial activities, and emissions from dense populations (Deng et al., 2014; Zhang, 2014; Zhan et al., 2016; Mishra and Kulshrestha, 2017).

The OC/EC ratio in QDB (3.66) is at an intermediate level. It is much lower than that in regions dominated by biomass burning, such as Kumasi, West Africa (17.07) and Huainan, China (21.4), but is relatively close to ratios found in cities like Gwangju, South Korea (5.63) and Ulaanbaatar, Mongolia (5.69), albeit with significantly lower concentrations (Lee et al., 2018; Bandowe et al., 2019; Liu et al., 2020). We primarily analyzed the OC/EC ratios in cities across different regions of China to reveal the influence of varying economic development levels.

Figure 5 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. Furthermore, as the pretreatment used in this study removes impurities such as silicates from the carbonaceous components of dust, and the OC collection efficiency of this treatment is currently unknown, the lower OC/EC ratios observed may also be attributed to a lower OC collection efficiency.

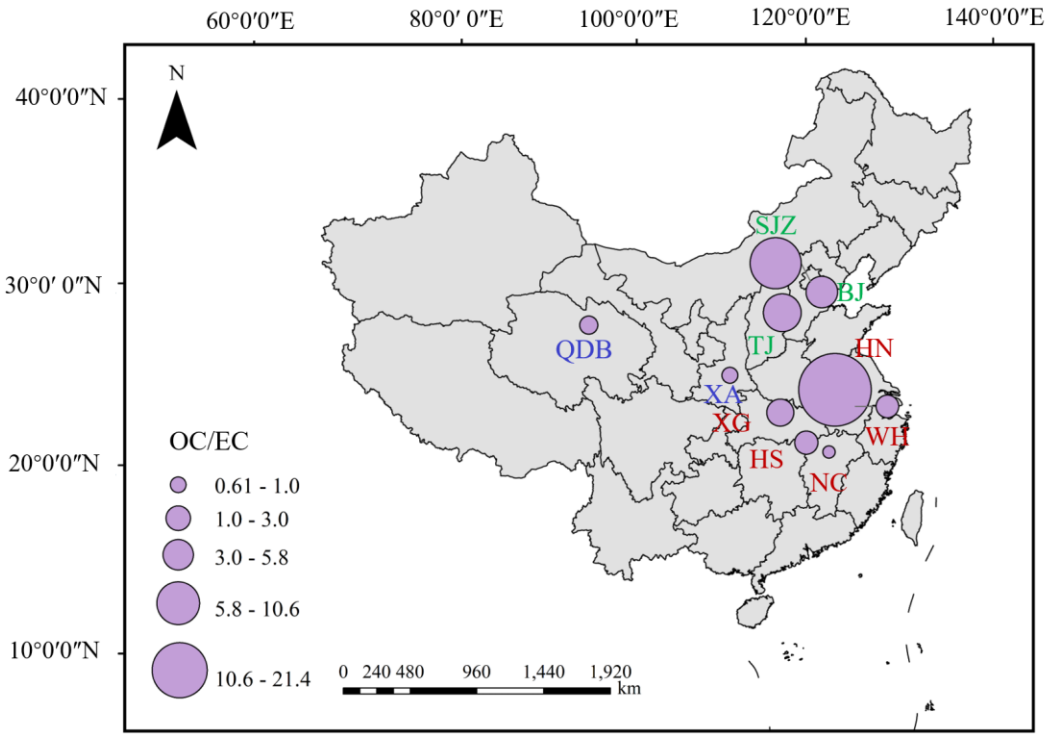


Figure 5 Distribution of OC/EC ratios across various regions of China. ~~(a), at different altitudes on the Qinghai-Xizang Plateau (b), and the relationship between OC/EC ratios and altitude (c).~~ Blue designations represent the Northwest region, red indicates the Central region, and green denotes the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

The Char/Soot ratio in QDB is notably high at 5.04, significantly exceeding that of other regions such as Xi'an (0.99) and Wuhan (0.09) (Wei et al., 2015; Liu et al., 2021). Char-EC primarily originates from incomplete combustion processes like biomass burning and coal combustion. Soot-EC mainly derives from high-temperature combustion sources such as fuel oil and diesel vehicle exhaust (Han et al., 2009). The exceptionally high Char/Soot ratio in QDB strongly indicates that its limited carbonaceous components predominantly originated from relatively inefficient

combustion sources. These potentially included coal or small-scale biomass burning for local residential/expedition activities (e.g., heating, cooking) and possibly long-range transported biomass burning products (e.g., from forest/agricultural fires in South or Southeast Asia) (Han et al., 2009; Han et al., 2006; Han et al., 2016). In contrast, the very low Char/Soot ratios observed in cities like Wuhan and Xi'an clearly point to traffic source emissions as their primary contributor, a finding likely influenced by the specific focus of those studies on road dust.

However, we fully recognize the fundamental differences in sources and composition between road dust and atmospheric dust-fall. Road dust is primarily secondary dust formed from traffic activities, construction dust, soil particles, and resuspended deposited atmospheric particles, with its carbonaceous composition strongly reflecting intense local anthropogenic emissions (Casotti Rienda and Alves, 2021). In contrast, atmospheric dust-fall integrates contributions from local sources, regional transport, and even long-range transport. Therefore, direct comparison between these two may introduce bias when interpreting regional pollution characteristics and the degree of anthropogenic influence, which cannot be overlooked. Building on this analysis, the next phase of this research will focus on the sampling and analysis of fine atmospheric particulate matter ($PM_{2.5}$ and PM_1) to more accurately elucidate the emission levels and environmental and climatic impacts of carbonaceous aerosols in the QDB.

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 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~~S5).

The low heavy metal content in dust deposition within the QDB can be attributed to the following factors. The region has sparse human activity, lacks heavy industrial zones and dense urban clusters, resulting in low total anthropogenic emissions of heavy metals. Furthermore, the

surface soil in the QDB itself has a low background level of heavy metals, primarily derived from natural sources with relatively weak influence from human activities (Nuralykyzy et al., 2021; Chen et al., 2021). F~~or~~rom the meteorological perspectives,~~Meteorologically,~~ the basin's high altitude, strong winds, and arid conditions with minimal precipitation favor the dispersion of atmospheric pollutants. This makes the formation of prolonged stagnant weather conditions unlikely, thereby preventing the accumulation of pollutants and the occurrence of high concentrations near the ground. A particularly unique aspect of the QDB is its role as a significant source of salt dust. The recent study~~Research~~ indicates that salt dust emitted from the playa lakes within the basin contributes substantially to atmospheric dust deposition (Zhu et al., 2025). These salt dust particles, composed mainly of soluble salts like NaCl and gypsum, may dilute the relative concentration of non-salt components, such as heavy metals, when released into the atmosphere in large quantities. The combined effect of these factors leads to the observed low heavy metal content in dust deposition in this region.

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~~,~~ and ~~S12~~S13). 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.

Analysis of the carbonaceous components in QDB dust deposition reveals more intensive coal combustion in rural areas, yet the heavy metal concentrations in atmospheric deposition are lower than in urban area~~s~~. This observation can be explained by the following factors. First, pollution sources in rural areas are relatively singular, whereas urban areas are influenced by more complex heavy metal sources. During the heating period, heavy metals in the rural atmosphere of the QDB mainly originate from coal and biomass combustion. In contrast, urban areas are affected by a wider

range of sources, including industrial activities, traffic emissions, and others (Liu et al., 2021; Huang et al., 2021a). Additionally, the dense building layout in urban areas hinders pollutant dispersion, leading to accumulation, while the open terrain in rural areas facilitates dilution and diffusion. This pattern, where rural heavy metal concentrations (particularly Pb, Cr, Cd, As, and other elements associated with coal combustion) are lower than those in urban areas during the heating season, has also been observed in studies conducted in Northeast China, Shanghai, Taiyuan, the Yangtze River Delta, and Southern Nigeria (Shi et al., 2012; Liu et al., 2021; Huang et al., 2021a; Liu et al., 2023b; Hilary et al., 2025).

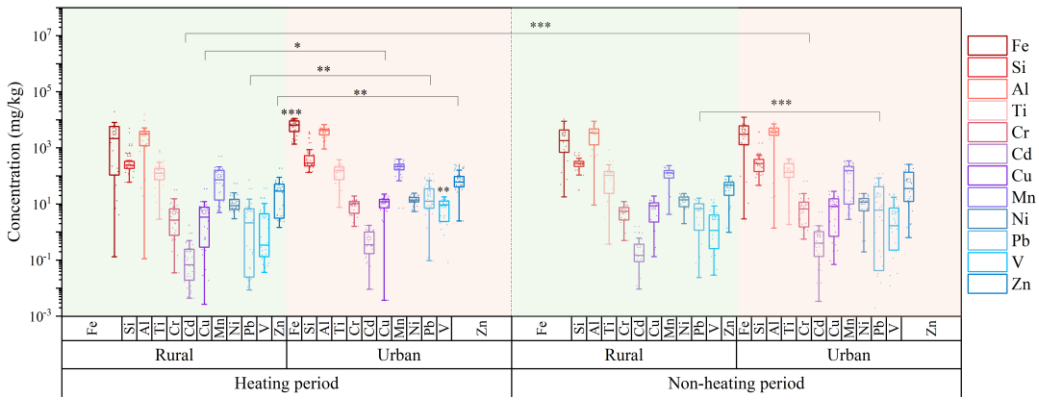


Figure 6 Concentration of heavy metals by rural and urban settings during domestic heating and non-domestic heating periods. Significant differences are indicated by asterisks (*p < 0.05; **p < 0.01; ***p < 0.001).

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+}, 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~~,~~ and ~~S13~~S14). A plot of the time series is provided in Figure S15. The generation of Figure 7a involved extracting factors identified as the same source from the PMF factor profiles of each site (Urban and Rural) and each heating season (HP and NHP) shown in Figure S14. The arithmetic mean of the contributions from characteristic species (elements and ions) corresponding to each factor was

calculated. Species with average contributions exceeding 20% were defined as characteristic species of that source in atmospheric dust over the QDB.

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 uncertainty of the source contributions was calculated directly from the standard error of the multiple regression coefficients between the deposition flux (independent variable) and the source contribution (dependent variable) at different monitoring sites (Belis et al., 2015; Manousakas et al., 2017). The regression method assumes that all factors explaining the mass have been identified; however, if a significant portion of the mass not directly related to the species in the PMF analysis is omitted, the source contributions may be overestimated, which could be an important additional source of uncertainty. The results are shown in Table S6. It must be noted that this method captures only a portion of the total uncertainty, as it does not include errors from profile uncertainty or rotational ambiguity. The low errors calculated by this method indicate a good model fit.

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. Salt lake emissions were most pronounced in rural areas during the HP of 2023 at site LTC and during the NHP of 2020 at site XZH. In urban areas, elevated contributions occurred during the NHP and HP of 2022 at site GEM, and during the HP of 2023 at site DLX. 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, showing opposite seasonal trends. Backward trajectory simulations indicated that during the HP, air~~flows~~ mass in both urban and rural areas mainly originated from the northwestern part of the basin and the eastern Tarim Basin, whereas during the NHP, they were broadly influenced by the salt lake regions within the basin (Figure S6). The minor wind direction differences and the inter-distributed sampling points (Figure 1), suggests no substantial geographical disparity between urban and rural sites. Additionally, the ion content derived from playa salts in dust deposits increased during the NHP in both areas.

Therefore, we propose that the anomalous increase in salt lake contribution during the urban HP may be closely related to human activities. The enhanced Urban Heat Island (UHI) effect~~urban heat island effect~~ and temperature inversion structures during the HP can alter boundary layer height, turbulence, and deposition conditions, thereby increasing the residence time of externally transported particles within the urban boundary layer and elevating their measured contribution (Cichowicz and Bochenek, 2024). Urban heat sources and heating emissions may also modify local transport pathways, leading to more concentrated deposition of dust originating from playa regions over urban areas. Furthermore, dry road surfaces, increased traffic, and construction activities during the HP can promote the ~~repeated~~ resuspension of previously deposited playa dust. The use and subsequent resuspension of road de-icing salts (e.g., NaCl, $CaCl_2$) may further amplify the contribution of tracer ions indicative of playa salts (Gertler et al., 2006; Casotti Rienda and Alves, 2021). ~~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 trace element~~ions~~ such as Si (37.17%) and Al (29.18%), along with ions such as 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. Mg, Al, Si, and Fe are typical tracers for soil dust (Liu et al., 2003; Heo et al., 2009). The temporal variation of soil dust was largely consistent with that of the salt lake source, indicating the fact that they may be influenced by similar factors. 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~~ traffic emissions, which are particularly pronounced in urban areas. Key characteristic elements include Pb (59.52%), V (48.73%), nps-Mg^{2+} (40.78%), Zn (37.47%), nps-Cl^-(33.83%), Cd (32.43%), nps-K^+ (29.64%), Ni (27.01%), $-NO_3^-$ (20.99%)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 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 traffic emission factor in the QDB represents a mixture of vehicle exhaust and non-exhaust sources (e.g., tire and brake wear, and resuspended road dust). Elements and ions including V, NO_3^-, Ni, and carbonaceous components primarily associated with vehicle exhaust (Cong et al., 2011; Zhang et al., 2012). For instance, Ni can be emitted from fuel combustion and vehicle exhaust (Pacyna and Pacyna, 2001). In contrast, elements such as Cu, Zn, nps-Mg^{2+}, and nps-K^+ originate from non-exhaust vehicle emissions, including brake and tire wear, as well as the resuspension of road dust (Amato et al., 2014). For example, Zn may derive from the wear of rubber tires on roads (Rogge et al., 1993), Pb emissions may be related to wear (tires/brakes) (Smichowski et al., 2007), and Cu is associated with brake wear (Lin et al., 2015). Furthermore, the presence of crustal elements and ions such as Fe, Si, and nps-Mg^{2+} in the traffic emission factor for Urban-NHP, Urban-HP, and Rural-NHP suggests an additional contribution from resuspended road dust (Chen et al., 2019). For traffic emissions during the NHP, peaks were observed in both rural and urban areas in 2022, generally concentrated in July, August, and September, coinciding with the tourism high season. During the HP, traffic emissions primarily occurred in 2021 at GEM and in 2023 at DLX. Due to the impact of the COVID-19 pandemic, tourist numbers in the QDB sharply declined in 2020 and 2021. The peak in tourism activity in 2022 (Qinghai Statistical Yearbook, 2022) corresponded with the highest level of traffic emissions during the three-year period, indicating a direct impact of tourism flux on emission levels. However, given the relatively short sampling duration of this study (three years), longer-term data and further research are needed to substantiate this hypothesis. ~~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.~~

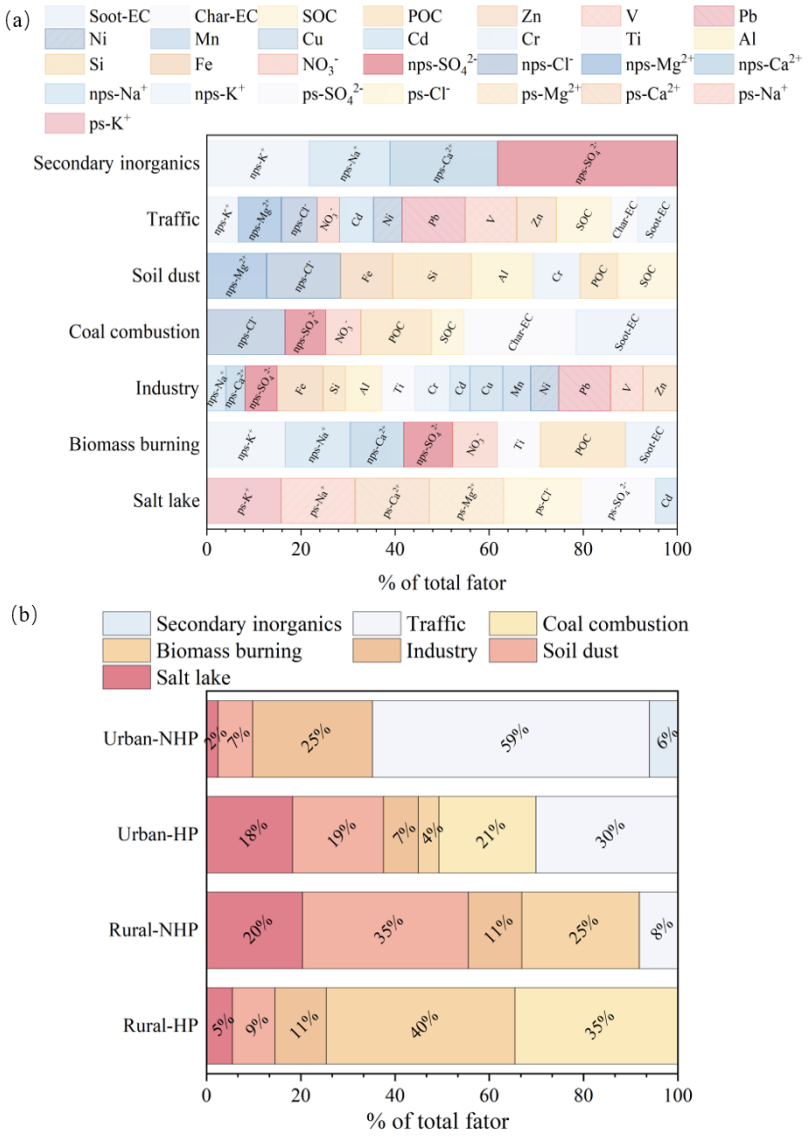


Figure 7 Factor profile and contributions in urban and rural ~~aera~~area. (a) presents the factor profiles, represented as the arithmetic mean of individual elements across various locations, highlighting only those elements that constitute more than 20% of each profile. (b) illustrates the contributions 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). Zhang et al (2023)~~.~~ found that coal combustion emits particles rich in Cl^- ~~(Zhang et al., 2023)~~. Coal combustion was more intense at site LTC in rural areas and at site DLX in urban areas. 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). K^+ serves as an important tracer for biomass burning (Cachier and Ducret, 1991). Biomass burning contributes 32.82% to rural atmospheric dust deposition, with a higher proportion during the HP (39.21%) compared to NHP (26.44%). Biomass burning made significant contributions in urban areas in 2021 and 2022. In rural areas, biomass burning emissions were particularly strong, especially during the HP at LTC and the NHP at XZH. 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., 2016~~b~~). 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 contributions from soil dust. Zn, Cu, Fe, and Mn are major chemical components in industrial emission profiles; Cd is a trace element found in metallurgical industries (Xu et al., 2022), while Zn and Mn emitte from oil combustion, metallurgy, and steel manufacturing processes (You et al., 2017). Pb and Cd are associated with metal smelting and processing (Fang et al., 2021). Industrial emissions showed greater contributions during the HP at XZH and at DLX. 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.~~ Due to the abundance of non-ferrous metal resources (e.g., lead-zinc ores), oil, natural gas, and saline minerals (e.g., potassium, lithium) in the QDB, the primary industrial activities are mining and associated chemical industries. Particularly around the GEM and DLX sites, the presence of numerous lead-zinc, iron, and copper mining enterprises leads to significant contributions from industrial emissions to urban dust fallout, making it one of the major sources of air pollution in the basin.

–The seventh factor is secondary inorganic 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). High mass loadings of NO_3^- and SO_4^{2-} are characteristic of typical secondary inorganic aerosols (Huang et al., 2021). 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 inorganic 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). The secondary inorganic aerosol source was identified only in Urban-NHP, peaking in August 2022 at GEM and in June, July, and August 2022 at NMH. This trend closely followed the distribution of traffic emissions, suggesting that the formation of secondary aerosols is linked to increased traffic activity. Traffic emissions, particularly vehicle exhaust, are a significant source of secondary inorganic aerosols (especially NO_3^-) in urban atmospheres (Ma et al., 2017). Source apportionment studies in Beijing have similarly found that the contribution of secondary inorganic aerosols increases in summer, closely associated with traffic emissions (Zhang et al., 2013).

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~~ traffic 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 burning and coal ~~burning~~combustion, 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 areas. In urban, dust deposition is briefly influenced by anthropogenic activities, including ~~vehicle~~traffic 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).

This study observed that the contribution of biomass burning to atmospheric dust deposition in rural areas of the QDB during the HP was higher than that of soil dust. Given that the collected dust samples had particle sizes >10 μm, while biomass burning typically emits aerosols in the submicron range, we propose several potential explanations. Firstly, during the HP, factors such as increased soil moisture and snow cover significantly suppress soil dust emission, resulting in a lower intensity than in other seasons (An et al., 2018; Yang et al., 2019). Simultaneously, biomass and coal burning for heating increases substantially, leading to intense, short-term emissions of fine particles. Although it was fine initially, these high-concentration ultrafine particles can undergo coagulation or coalescence, aggregating with each other or onto pre-existing coarse particles, thereby increasing their size (Butler and Mulholland, 2004; Kulmala et al., 2004; Li et al., 2020). Furthermore, fine particles from biomass burning (e.g., carbonaceous materials) may mix internally with coarse particles like soil dust or salt dust from the QDB, forming internally mixed particles (Li et al., 2003; Hand et al., 2010). During source apportionment, such coarse particles are more likely to be attributed to the biomass burning source. Additionally, the QDB is a significant source of salt dust (Zhu et al., 2025). Salt dust particles (e.g., halite, gypsum) provide excellent condensation nuclei for soluble substances emitted from biomass burning, greatly promoting hygroscopic growth (Li et al., 2003; Kumar, 2010; Wang, 2013). The basin's topography also favors stable inversion layers, inhibiting pollutant dispersion and allowing particles more time to grow, mix, and age in the atmosphere. Prevailing wintertime winds~~Winter prevailing winds~~ may also transport pollutants from surrounding regions into the basin.

Moreover, the dust in this study was collected using a passive sampler. Over 90% of the collected dust particles were smaller than 100 μm, with approximately 25% less than 10 μm (Figure

S16), indicating the presence of fine particles (<10 μm), albeit in a relatively small proportion. The particle size distribution of atmospheric dust deposition is similar to that of TSP, with both primarily consisting of particles smaller than 100 μm. Using PMF source apportionment, this study identified a notably high contribution from biomass burning in rural areas, particularly during the heating period. Similarly, studies on atmospheric TSP in Iran (Ashrafi et al., 2018), the Qinghai-Xizang Plateau (Lulang) (Zhao et al., 2013), Northeast China (Jia et al., 2024), and Qingdao (Liu et al., 2022) have also reported significant contributions from biomass and coal combustion. This suggests that contributions from biomass and coal combustion can indeed be observed in particles larger than 10 μm. Finally, the PMF model may have uncertainties in resolving sources with similar chemical profiles. If the chemical compositions of local soil dust and biomass burning particles overlap after long-range transport and complex atmospheric reactions, the model might not fully separate them (Cesari et al., 2016).

3.7 Environmental implication

The source apportionment analysis using the 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 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.

In addition to the distinctive energy consumption structure in the rural QDB, which leads to significant contributions from coal and biomass burning during HP, atmospheric dust deposition in the QDB during the NHP primarily originates from traffic and industrial emissions. The contribution from traffic emissions during the NHP was twice that during the HP. Considering the larger particle size of the dust samples collected in this study, the traffic-related dust is likely derived mainly from vehicle non-exhaust emissions, such as road dust (Gondwal and Mandal, 2021). ~~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~~traffic 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 Qaidam Basin from January 2020 to March 2023 and examined DF, soluble ions, ~~metal~~trace, 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 areas exhibited elevated EC levels (1.46 ± 1.60 mg/g), while OC levels were higher in rural (2.25 ± 1.92 mg/g). ~~Both altitude and e~~Economic development increase OC/EC ratios, but they are driven by different intrinsic factors. Char-EC was the dominant contributor to EC (80.44%), with urban Char-EC levels (85.00%) showing a notable increase compared to rural levels (75.88%). SOC was the principal contributor to OC (68.17%), with rural SOC levels surpassing (67%) those in urban areas (57%). 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 combustion (28.44%) and biomass burning (22.14%), while ~~vehicle~~traffic 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~~traffic (45.13%) and industrial emissions (16.41%). 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.

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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).

Reference

Abdollahi, S., Karimi, A., Madadi, M., Eslamian, S., Ostad-Ali-Askari, K., and Singh, V. P.: Lead concentration in dust fall in Zahedan, Sistan and Baluchistan Province, Iran, Journal of Geography and Cartography, 4, 6, 10.24294/jgc.v4i2.601, 2021.

Adeniran, J. A., Yusuf, R. O., and Olajire, A. A.: Exposure to coarse and fine particulate matter at and around major intra-urban traffic intersections of Ilorin metropolis, Nigeria, Atmospheric Environment, 166, 383-392, 10.1016/j.atmosenv.2017.07.041, 2017.

Agarwal, A., Satsangi, A., Lakhani, A., and Kumari, K. M.: Seasonal and spatial variability of secondary inorganic aerosols in $PM_{2.5}$ at Agra: Source apportionment through receptor models, Chemosphere, 242, 125132, https://doi.org/10.1016/j.chemosphere.2019.125132, 2020.

~~Agarwal, T. and Bucheli, T. D.: Is black carbon a better predictor of polycyclic aromatic hydrocarbon distribution in soils than total organic carbon? Environmental Pollution, 159, 64-70, https://doi.org/10.1016/j.envpol.2010.09.016, 2011.~~

Aiken, A. C., DeCarlo, P. F., Kroll, J. H., Worsnop, D. R., Huffman, J. A., Docherty, K. S., Ulbrich, I. M., Mohr, C., Kimmel, J. R., Sueper, D., Sun, Y., Zhang, Q., Trimborn, A., Northway, M., Ziemann, P. J., Canagaratna, M. R., Onasch, T. B., Alfarra, M. R., Prevot, A. S. H., Dommen, J., Duplissy, J., Metzger, A., Baltensperger, U., and Jimenez, J. L.: O/C and OM/OC ratios of primary, secondary, and ambient organic aerosols with High-Resolution Time-of-Flight Aerosol Mass Spectrometry, Environmental Science & Technology, 42, 4478-4485, 10.1021/es703009q, 2008.

Almeida, S. M., Lage, J., Fernández, B., Garcia, S., Reis, M. A., and Chaves, P. C.: Chemical characterization of atmospheric particles and source apportionment in the vicinity of a steelmaking industry, Science of The Total Environment, 521-522, 411-420, https://doi.org/10.1016/j.scitotenv.2015.03.112, 2015.

Alzahrani, A. J., Alghamdi, A. G., and Ibrahim, H. M.: Assessment of soil loss due to wind erosion and dust deposition: Implications for sustainable management in arid regions, Applied Sciences, 14(23), 10822, 10.3390/app142310822, 2024.

Amacher, G. S., Hyde, W. F., and Kanel, K. R.: Nepali fuelwood production and consumption: Regional and household distinctions, substitution and successful intervention, The Journal of Development Studies, 35, 138-163, 10.1080/00220389908422584, 1999.

Ambade, B., Sankar, T. K., Sahu, L. K., and Dumka, U. C.: Understanding sources and composition of

black carbon and $PM_{2.5}$ in urban environments in East India, 10.3390/urbansci6030060, 2022.

Amato, F., Alastuey, A., de la Rosa, J., Gonzalez Castanedo, Y., Sánchez de la Campa, A. M., Pandolfi, M., Lozano, A., Contreras González, J., and Querol, X.: Trends of road dust emissions contributions on ambient air particulate levels at rural, urban and industrial sites in southern Spain, Atmospheric Chemistry and Physics, 14, 3533-3544, 10.5194/acp-14-3533-2014, 2014.

Arimoto, R., Duce, R. A., Savoie, D. L., Prospero, J. M., Talbot, R., Cullen, J. D., Tomza, U., Lewis, N. F., and Ray, B. J.: Relationships among aerosol constituents from Asia and the North Pacific during PEM-West A, Journal of Geophysical Research: Atmospheres, 101, 2011-2023, https://doi.org/10.1029/95JD01071, 1996.

~~Aswini, M. A., Tiwari, S., Singh, U., Kurian, S., Patel, A., Gunthe, S. S., and Kumar, A.: Aeolian dust and sea salt in marine aerosols over the Arabian Sea during the southwest monsoon: Sources and spatial variability, ACS Earth and Space Chemistry, 6, 1044-1058, 10.1021/acsearthspacechem.1c00400, 2022.~~

Arimoto, R., Duce, R. A., Savoie, D. L., Prospero, J. M., Talbot, R., Cullen, J. D., Tomza, U., Lewis, N. F., and Ray, B. J.: Relationships among aerosol constituents from Asia and the North Pacific during PEM-West A, Journal of Geophysical Research: Atmospheres, 101, 2011-2023, https://doi.org/10.1029/95JD01071, 1996.

Ashrafi, K., Fallah, R., Hadei, M., Yarahmadi, M., and Shahsavani, A.: Source apportionment of Total Suspended Particles (TSP) by Positive Matrix Factorization (PMF) and Chemical Mass Balance (CMB) modeling in Ahvaz, Iran, Archives of Environmental Contamination and Toxicology, 75, 278-294, 10.1007/s00244-017-0500-z, 2018.

Bandowe, B. A. M., Nkansah, M. A., Leimer, S., Fischer, D., Lammel, G., and Han, Y.: Chemical (C, N, S, black carbon, soot and char) and stable carbon isotope composition of street dusts from a major West African metropolis: Implications for source apportionment and exposure, Science of The Total Environment, 655, 1468-1478, 10.1016/j.scitotenv.2018.11.089, 2019.

Barjoee, S. S., Abadi, S. Z. M., Elmi, M. R., Varaoon, V. T., and Nikbakht, M.: Evaluation of trace elements pollution in deposited dust on residential areas and agricultural lands around Pb/Zn mineral areas using modified pollution indices, Journal of Environmental Health Science and Engineering, 19, 753-769, 10.1007/s40201-021-00643-8, 2021.

Behera, B., Rahut, D. B., Jeetendra, A., and Ali, A.: Household collection and use of biomass energy

sources in South Asia, Energy, 85, 468-480, 10.1016/j.energy.2015.03.059, 2015.

Belis, C. A., Pernigotti, D., Karagulian, F., Pirovano, G., Larsen, B. R., Gerboles, M., and Hopke, P. K.: A new methodology to assess the performance and uncertainty of source apportionment models in intercomparison exercises, Atmospheric Environment, 119, 35-44, https://doi.org/10.1016/j.atmosenv.2015.08.002, 2015.

Bond, T. C. and and Bergstrom, R. W.: Light absorption by carbonaceous particles: An investigative review, Aerosol Science and Technology, 40, 27-67, 10.1080/02786820500421521, 2006.

Bond, T. C., Streets, D. G., Yarber, K. F., Nelson, S. M., Woo, J.-H., and Klimont, Z.: A technology-based global inventory of black and organic carbon emissions from combustion, Journal of Geophysical Research: Atmospheres, 109, https://doi.org/10.1029/2003JD003697, 2004.

Boreddy, S. K. R., Kawamura, K., Okuzawa, K., Kanaya, Y., and Wang, Z.: Temporal and diurnal variations of carbonaceous aerosols and major ions in biomass burning influenced aerosols over Mt. Tai in the North China Plain during MTX2006, Atmospheric Environment, 154, 106-117, https://doi.org/10.1016/j.atmosenv.2017.01.042, 2017.

Bowen, H.-J-.M.: Environmental chemistry of the elements. Academic Press, 1979.

Brooks, J., Liu, D., Allan, J. D., Williams, P. I., Haywood, J., Highwood, E. J., Kompalli, S. K., Babu, S. S., Satheesh, S. K., Turner, A. G., and Coe, H.: Black carbon physical and optical properties across northern India during pre-monsoon and monsoon seasons, Atmospheric Chemistry and Physics, 19, 13079-13096, 10.5194/acp-19-13079-2019, 2019.

Butler, K. M. and Mulholland, G. W.: Generation and Transport of Smoke Components, Fire Technology, 40, 149-176, 10.1023/B:FIRE.0000016841.07530.64, 2004.

Cachier, H. and Ducret, J.: Influence of biomass burning on equatorial African rains, Nature, 352, 228-230, 10.1038/352228a0, 1991.

Cao, J.-j., Wang, Q.-y., Chow, J. C., Watson, J. G., Tie, X.-x., Shen, Z.-x., Wang, P., and An, Z.-s.: Impacts of aerosol compositions on visibility impairment in Xi'an, China, Atmospheric Environment, 59, 559-566, 10.1016/j.atmosenv.2012.05.036, 2012a.

Cao, J.: Characteristics of carbonaceous aerosol in Pearl River Delta Region, China during 2001 winter period, Atmospheric Environment, 37, 1451-1460, 10.1016/s1352-2310(02)01002-6, 2003.

Cao, J. J., Shen, Z. X., Chow, J. C., Watson, J. G., Lee, S. C., Tie, X. X., Ho, K. F., Wang, G. H., and Han, Y. M.: Winter and summer $PM_{2.5}$ chemical compositions in fourteen Chinese cities, Journal of

Air Waste Manage Association, 62, 1214-1226, 10.1080/10962247.2012.701193, 2012b.

Cao, J. J., Zhu, C. S., Tie, X. X., Geng, F. H., Xu, H. M., Ho, S. S. H., Wang, G. H., Han, Y. M., and Ho, K. F.: Characteristics and sources of carbonaceous aerosols from Shanghai, China, Atmospheric Chemistry and Physics, 13, 803-817, 10.5194/acp-13-803-2013, 2013.

Casotti Rienda, I. and Alves, C. A.: Road dust resuspension: A review, Atmospheric Research, 261, 105740, https://doi.org/10.1016/j.atmosres.2021.105740, 2021.

Cesari, D., Amato, F., Pandolfi, M., Alastuey, A., Querol, X., and Contini, D.: An inter-comparison of PM_{10} source apportionment using PCA and PMF receptor models in three European sites, Environmental Science and Pollution Research, 23, 15133-15148, 10.1007/s11356-016-6599-z, 2016.

Chen, L., Zhang, X. Y., Tang, Q. L., Geng, Y., Wang, E. L., and Li, J. Y.: Heavy metal pollution and source analysis of surface soil in the Qaidam Basin (in Chinese), Environmental Science, 42, 4880–4888, https://doi.org/10.13227/j.hjkx.202101052, 2021.

Chen, M., Li, M.-Y., Zhou, J.-Y., Fu, R.-B., Wang, X.-F., and Shen Z.: Characteristics and source analysis of heavy metal pollution in dust in a heavy industrial area of Northwest China (in Chinese), Environmental Science and Technology, 47(02), 155-164, 10.19672/j.cnki.1003-6504.1004.23.338, 2024.

Chen, P., Kang, S., Bai, J., Sillanpää, M., and Li, C.: Yak dung combustion aerosols in the Tibetan Plateau: Chemical characteristics and influence on the local atmospheric environment, Atmospheric Research, 156, 58-66, 10.1016/j.atmosres.2015.01.001, 2015.

Chen, W., Tong, D. Q., Dan, M., Zhang, S., Zhang, X., and Pan, Y.: Typical atmospheric haze during crop harvest season in northeastern China: A case in the Changchun region, Journal of Environmental Sciences, 54, 101-113, 10.1016/j.jes.2016.03.031, 2017.

~~Cheng, N., Peng, L., Mu, L., Ji, H. D., Liu, X. F., Bai, H. L. and Zhao, Y. K.: Organic carbon and elemental carbon in PM_{10} from coal spontaneous combustion zones in Shanxi (in Chinese), China Environmental Science, 2015, 35: 40-44.~~

Cheng, X and Lin X.: Temporal and spatial distribution characteristics of dust in Shenyang and analysis of influencing factors (in Chinese). Environmental Protection Science 35(06), 1-3 + 58, 10.16803/j.cnki.issn.1004-6216.2009.06.001, 2009.

Chow, J. C.: Measurement methods to determine compliance with ambient air quality standards for

suspended particles, Journal of the Air & Waste Management Association, 45, 320-382, 10.1080/10473289.1995.10467369, 1995.

Chow, J. C., Lowenthal, D. H., Chen, L. W. A., Wang, X., and Watson, J. G.: Mass reconstruction methods for $PM_{2.5}$: a review, Air Quality, Atmosphere & Health, 8, 243-263, 10.1007/s11869-015-0338-3, 2015.

Chow, J. C., Watson, J. G., Kuhns, H., Etyemezian, V., Lowenthal, D. H., Crow, D., Kohl, S. D., Engelbrecht, J. P., and Green, M. C.: Source profiles for industrial, mobile, and area sources in the Big Bend Regional Aerosol Visibility and Observational study, Chemosphere, 54, 185-208, 10.1016/j.chemosphere.2003.07.004, 2004.

Christie, J. A., Elliott, H. E., O'Connell-Lopez, S. M. O., Perry, K., Pratt, K. A., Hallar, A. G., Hrdina, A., Murphy, J. G., Riedel, T. P., Long, R. W., Mitroo, D., Haskins, J. D., and Gaston, C. J.: Halogen production from playa dust emitted from the Great Salt Lake: Implications of the shrinking Great Salt Lake on regional air quality, ACS Earth and Space Chemistry, 9, 480-493, 10.1021/acsearthspacechem.4c00258, 2025.

Chuang, M.-T., Lee, C.-T., Chou, C. C. K., Lin, N.-H., Sheu, G.-R., Wang, J.-L., Chang, S.-C., Wang, S.-H., Chi, K. H., Young, C.-Y., Huang, H., Chen, H.-W., Weng, G.-H., Lai, S.-Y., Hsu, S.-P., Chang, Y.-J., Chang, J.-H., and Wu, X.-C.: Carbonaceous aerosols in the air masses transported from Indochina to Taiwan: Long-term observation at Mt. Lulin, Atmospheric Environment, 89, 507-516, 10.1016/j.atmosenv.2013.11.066, 2014.

Cichowicz, R. and Bochenek, A. D.: Assessing the effects of urban heat islands and air pollution on human quality of life, Anthropocene, 46, 100433, https://doi.org/10.1016/j.ancene.2024.100433, 2024.

Cong, Z., Kang, S., Luo, C., Li, Q., Huang, J., Gao, S., and Li, X.: Trace elements and lead isotopic composition of PM_{10} in Lhasa, Tibet, Atmospheric Environment, 45, 6210-6215, https://doi.org/10.1016/j.atmosenv.2011.07.060, 2011.~~Contini, D., Cesari, D., Conte, M., and Donateo, A.: Application of PMF and CMB receptor models for the evaluation of the contribution of a large coal-fired power plant to PM_{10} concentrations, Science of The Total Environment, 560-561, 131-140, https://doi.org/10.1016/j.scitotenv.2016.04.031, 2016.~~

~~Dan, M.: The characteristics of carbonaceous species and their sources in $PM_{2.5}$ in Beijing, Atmospheric Environment, 38, 3443-3452, 10.1016/j.atmosenv.2004.02.052, 2004.~~

de Oliveira Alves, N., Vessoni, A. T., Quinet, A., Fortunato, R. S., Kajitani, G. S., Peixoto, M. S., Hacon, S. d. S., Artaxo, P., Saldiva, P., Menck, C. F. M., and Batistuzzo de Medeiros, S. R.: Biomass burning in the Amazon region causes DNA damage and cell death in human lung cells, Scientific Reports, 7, 10937, 10.1038/s41598-017-11024-3, 2017.

Deng, Y., Yang, T., Gao, Q., Yang, D., Liu, R., Wu, B., Hu, L., Liu, Y., and He, M.: Cooking with biomass fuels increased the risk for cognitive impairment and cognitive decline among the oldest-old Chinese adults (2011–2018): A prospective cohort study, Environment International, 155, 106593, https://doi.org/10.1016/j.envint.2021.106593, 2021.

Dang, X., Chang, L., and Lu, N.: The impact of climatic warm-wet situation of the Tibetan Plateau on the water resources and environment in Qaidam Basin, Geology of China, 46, 359-368, 2019.

Demir, T., Karakaş, D., and Yenisoy-Karakaş, S.: Source identification of exhaust and non-exhaust traffic emissions through the elemental carbon fractions and Positive Matrix Factorization method, Environmental Research, 204, 112399, https://doi.org/10.1016/j.envres.2021.112399, 2022.

Deng Z.-W., Fang, F. -M., Jiang, P.-L., Zhang J.-Q and Lin Y.-S.: Distribution characteristics of black carbon content in surface dust in Wuhu city (in Chinese), Journal of Anqing Normal University (Natural Science Edition), 37(01), 58-62, 10.14182/j.cnki.1001-2443.2014.01.009, 2014.

Dong, Z., Qin, D., Kang, S., Ren, J., Chen, J., Cui, X., Du, Z., and Qin, X.: Physicochemical characteristics and sources of atmospheric dust deposition in snow packs on the glaciers of western Qilian Mountains, China, Tellus B: Chemical and Physical Meteorology, 66, 20956, 10.3402/tellusb.v66.20956, 2014.

Duan, J. and Tan, J.: Atmospheric heavy metals and Arsenic in China: Situation, sources and control policies, Atmospheric Environment, 74, 93-101, 10.1016/j.atmosenv.2013.03.031, 2013.

Eivazzadeh, M., Hassanvand, M. S., Faridi, S., and Gholampour, A.: Source apportionment and deposition of dustfall-bound trace elements around Tabriz, Iran, Environmental Science and Pollution Research International, 28, 59403-59415, 10.1007/s11356-020-12173-1, 2021.

Fan, Q., Cheng, Y., Chen, T., and Xu, N.: Influence of water replenishment of lakes in the Northern Qaidam Basin on salt lake resources and ecological environment, Journal of Salt Lake Research, 30, 11-18, 2022.

Fang, B., Zeng, H., Zhang, L., Wang, H., Liu, J., Hao, K., Zheng, G., Wang, M., Wang, Q., and Yang, W.: Toxic metals in outdoor/indoor airborne $PM_{2.5}$ in port city of Northern, China: Characteristics,

sources, and personal exposure risk assessment, Environmental Pollution, 279, 116937, https://doi.org/10.1016/j.envpol.2021.116937, 2021.

Fang, H., Lowther, S. D., Zhu, M., Pei, C., Li, S., Fang, Z., Yu, X., Yu, Q., Wang, Y., Zhang, Y., Jones, K. C., and Wang, X.: $PM_{2.5}$-bound unresolved complex mixtures (UCM) in the Pearl River Delta region: Abundance, atmospheric processes and sources, Atmospheric Environment, 226, 10.1016/j.atmosenv.2020.117407, 2020.

Feng, W., Guo, Z., Xiao, X., Peng, C., Shi, L., Ran, H., and Xu, W.: Atmospheric deposition as a source of cadmium and lead to soil-rice system and associated risk assessment, Ecotoxicology and Environmental Safety, 180, 160-167, https://doi.org/10.1016/j.ecoenv.2019.04.090, 2019.

Filonchyk, M., Yan, H., Yang, S., and Lu, X.: Detection of aerosol pollution sources during sandstorms in Northwestern China using remote sensed and model simulated data, Advances in Space Research, 61, 1035-1046, https://doi.org/10.1016/j.asr.2017.11.037, 2018.

Foysal, M., Hossain, M., Rubaiyat, A., Sultana, S., Uddin, M. K., Sayem, M., and Akhter, J.: Household Energy Consumption Pattern in Rural Areas of Bangladesh, Indian Journal of Energy, 1, 72-85, 2012.

Gao, G.-S., Song, L.-M., and Ma, Z.-T.: Temporal and spatial distribution of dust-fall in Qinghai Province and analysis of its influencing factors (in Chinese), Chinese Journal of Desert Research, 33(04), 1124-1130, 2013.

Gao, H. and Washington, R.: Arctic oscillation and the interannual variability of dust emissions from the Tarim Basin: a TOMS AI based study, Climate Dynamics, 35, 511-522, 10.1007/s00382-009-0687-4, 2010.

Gao, Y., Wang, H., Yuan, L., Jing, S., Yuan, B., Shen, G., Zhu, L., Koss, A., Li, Y., Wang, Q., Huang, D. D., Zhu, S., Tao, S., Lou, S., and Huang, C.: Measurement report: Underestimated reactive organic gases from residential combustion – insights from a near-complete speciation, Atmospheric Chemistry and Physics, 23, 6633-6646, 10.5194/acp-23-6633-2023, 2023.

Garaga, R., Gokhale, S., and Kota, S. H.: Source apportionment of size-segregated atmospheric particles and the influence of particles deposition in the human respiratory tract in rural and urban locations of north-east India, Chemosphere, 255, 10.1016/j.chemosphere.2020.126980, 2020.

Gertler, A., Kuhns, H., Abu-Allaban, M., Damm, C., Gillies, J., Etyemezian, V., Clayton, R., and Proffitt, D.: A case study of the impact of Winter road sand/salt and street sweeping on road dust re-

entrainment, Atmospheric Environment, 40, 5976-5985, https://doi.org/10.1016/j.atmosenv.2005.12.047, 2006.

Gholampour, A., Nabizadeh, R., Hassanvand, M. S., Taghipour, H., Nazmara, S., and Mahvi, A. H.: Characterization of saline dust emission resulted from Urmia Lake drying, Journal of Environmental Health Science & Engineering, 13, 82, 10.1186/s40201-015-0238-3, 2015.

~~Gluscic, V., Zuzul, S., Pehnec, G., Jakovljevic, I., Smoljo, I., Godec, R., Beslic, I., Milinkovic, A., Alempijevic, S. B., and Frka, S.: Sources, ionic composition and acidic properties of bulk and wet atmospheric deposition in the Eastern Middle Adriatic region, toxics, 11, 10.3390/toxics11070551, 2023.~~

Gonçalves, C., Alves, C., Evtyugina, M., Mirante, F., Pio, C., Caseiro, A., Schmidl, C., Bauer, H., and Carvalho, F.: Characterisation of PM_{10} emissions from woodstove combustion of common woods grown in Portugal, Atmospheric Environment, 44, 4474-4480, https://doi.org/10.1016/j.atmosenv, 2010.

Gondwal, T. K. and Mandal, P.: Review on classification, sources and management of road dust and determination of uncertainty associated with measurement of particle size of road dust, Mapan, 36, 909-924, 10.1007/s12647-021-00501-w, 2021.

Gong, M., Yin, S., Gu, X., Xu, Y., Jiang, N., and Zhang, R.: Refined 2013-based vehicle emission inventory and its spatial and temporal characteristics in Zhengzhou, China, Science of The Total Environment, 599-600, 1149-1159, https://doi.org/10.1016/j.scitotenv.2017.03.299, 2017.

Gray, H. A., Cass, G. R., Huntzicker, J. J., Heyerdahl, E. K., and Rau, J. A.: Characteristics of atmospheric organic and elemental carbon particle concentrations in Los Angeles, Environmental Science & Technology, 20, 580-589, 10.1021/es00148a006, 1986.

Guo, J., Miao, Y., Zhang, Y., Liu, H., Li, Z., Zhang, W., He, J., Lou, M., Yan, Y., Bian, L., and Zhai, P.: The climatology of planetary boundary layer height in China derived from radiosonde and reanalysis data, Atmosperic Chemistry and Physics, 16, 13309-13319, 10.5194/acp-16-13309-2016, 2016.

Guo, S., Wang, L., Zhou, P., Guo, S., Qin, W., An, S., Xiao, J.-Y., Liu, J., and Ji, Y.: Characteristics and sources of organic carbon and elemental carbon in summer road dust in Shijiazhuang (in Chinese), Environmental Engineering, 36(04), 122-126, 10.13205/j.hjgc.201804025, 2018.

Guo, W.-T., Zhao, F.-Q., and Chang, H.-L.: Analysis of the trend of environmental air quality changes in

the main urban area of Changzhi City (in Chinese), Proceedings of Shanghai, China 3, 2010.

Gupta, A. and Dhir, A.: Assessment of air quality and chemical fingerprints for atmospheric fine aerosols in an Indian smart city, Environmental Pollutants and Bioavailability, 34, 21-33, 10.1080/26395940.2021.2024091, 2022.

Hahnenberger, M. and Nicoll, K.: Meteorological characteristics of dust storm events in the eastern Great Basin of Utah, U.S.A, Atmospheric Environment, 60, 601-612, https://doi.org/10.1016/j.atmosenv, 2012.

Hakanson, L.: An ecological risk index for aquatic pollution control.a sedimentological approach, Water Research, 14, 975-1001, https://doi.org/10.1016/0043-1354(80)90143-8, 1980.

~~Hallquist, M., Wenger, J. C., Baltensperger, U., Rudich, Y., Simpson, D., Claeys, M., Dommen, J., Donahue, N. M., George, C., Goldstein, A. H., Hamilton, J. F., Herrmann, H., Hoffmann, T., Iinuma, Y., Jang, M., Jenkin, M. E., Jimenez, J. L., Kiendler-Scharr, A., Maenhaut, W., McFiggans, G., Mentel, T. F., Monod, A., Prévôt, A. S. H., Seinfeld, J. H., Surratt, J. D., Szmigielski, R., and Wildt, J.: The formation, properties and impact of secondary organic aerosol: current and emerging issues, Atmospheric Chemistry and Physics, 9, 5155-5236, 10.5194/acp-9-5155-2009, 2009.~~

Hama, S., Ouchen, I., Wyche, K. P., Cordell, R. L., and Monks, P. S.: Carbonaceous aerosols in five European cities: Insights into primary emissions and secondary particle formation, Atmospheric Research, 274, 10.1016/j.atmosres, 2022.

Han, Y., Cao, J., An, Z., Chow, J. C., Watson, J. G., Jin, Z., Fung, K., and Liu, S.: Evaluation of the thermal/optical reflectance method for quantification of elemental carbon in sediments, Chemosphere, 69, 526-533, 10.1016/j.chemosphere, 2007a.

Han, Y., Cao, J., Chow, J. C., Watson, J. G., An, Z., Jin, Z., Fung, K., and Liu, S.: Evaluation of the thermal/optical reflectance method for discrimination between char- and soot-EC, Chemosphere, 69, 569-574, 10.1016/j.chemosphere, 2007b.

Han, Y. M., Lee, S. C., Cao, J. J., Ho, K. F., and An, Z. S.: Spatial distribution and seasonal variation of char-EC and soot-EC in the atmosphere over China, Atmospheric Environment, 43, 6066-6073, 10.1016/j.atmosenv, 2009a.

Han, Y. M., Cao, J. J., Chow, J. C., Watson, J. G., An, Z. S., and Liu, S. X.: Elemental carbon in urban soils and road dusts in Xi'an, China and its implication for air pollution, Atmospheric Environment, 43, 2464-2470, 10.1016/j.atmosenv, 2009b.

Han, Y. M., Han, Z. W., Cao, J. J., Chow, J. C., Watson, J. G., An, Z. S., Liu, S. X., and Zhang, R. J.: Distribution and origin of carbonaceous aerosol over a rural high-mountain lake area, Northern China and its transport significance, Atmospheric Environment, 42, 2405-2414, 10.1016/j.atmosenv, 2008.

Han, Y. M., Cao, J. J., Yan, B. Z., Kenna, T. C., Jin, Z. D., Cheng, Y., Chow, J. C., and An, Z. S.: Comparison of elemental carbon in lake sediments measured by three different methods and 150-year pollution history in Eastern China, Environmental Science & Technology, 45, 5287-5293, 10.1021/es103518c, 2011.

Han, Y. M., Chen, L. W. A., Huang, R. J., Chow, J. C., Watson, J. G., Ni, H. Y., Liu, S. X., Fung, K. K., Shen, Z. X., Wei, C., Wang, Q. Y., Tian, J., Zhao, Z. Z., Prévôt, A. S. H., and Cao, J. J.: Carbonaceous aerosols in megacity Xi'an, China: Implications of thermal/optical protocols comparison, Atmospheric Environment, 132, 58-68, 10.1016/j.atmosenv, 2016.

Hand, V. L., Capes, G., Vaughan, D. J., Formenti, P., Haywood, J. M., and Coe, H.: Evidence of internal mixing of African dust and biomass burning particles by individual particle analysis using electron beam techniques, Journal of Geophysical Research: Atmospheres, 115, https://doi.org/10.1029/2009JD012938, 2010.

He, B., Wang, J., Kong, F., Yu, D., Chen, L., Ling, Z., and Hu, J.: Analysis of environmental pollution dissipation capacity of salt lake area in the Qaidam Basin, Journal of Salt Lake Research, 30, 52-60, 2022.

He, L.-Y., Hu, M., Huang, X.-F., Yu, B.-D., Zhang, Y.-H., and Liu, D.-Q.: Measurement of emissions of fine particulate organic matter from Chinese cooking, Atmospheric Environment, 38, 6557-6564, 10.1016/j.atmosenv, 2004.

Heltberg, R., Arndt, T. C., and Sekhar, N. U.: Fuelwood consumption and forest degradation: A household model for domestic energy substitution in rural India, Land Economics, 76, 213-232, 10.2307/3147225, 2000.

Hilary, U., Efeoghene, E. A., Issac, A. O., Sami, R., Baakdah, F., and Pareek, S.: Exposure to airborne pollutants in urban and rural areas: levels of metals and microorganisms in PM_{10} and gaseous pollutants in ambient air, Air Quality, Atmosphere & Health, 18, 317-332, 10.1007/s11869-024-01644-w, 2025.

Hoang, H. G., Chiang, C. F., Lin, C., Wu, C. Y., Lee, C. W., Cheruiyot, N. K., Tran, H. T., and Bui, X. T.:

Human health risk simulation and assessment of heavy metal contamination in a river affected by industrial activities, Environment Pollution, 285, 117414, 10.1016/j.envpol.2021.117414, 2021.

Hoeck, T., Droux, R., Breu, T., Hurni, H., and Maselli, D.: Rural energy consumption and land degradation in a post-Soviet setting – an example from the west Pamir mountains in Tajikistan, Energy for Sustainable Development, 11, 48-57, https://doi.org/10.1016/S0973-0826(08)60563-3, 2007.

~~Hu, X., Yin, Y., Duan, L., Wang, H., Song, W., and Xiu, G.: Temporal and spatial variation of $PM_{2.5}$ in Xining, Northeast of the Qinghai–Xizang (Tibet) Plateau, 10.3390/atmos11090953, 2020.~~

Hu, Y.-N and Liu, Y.-L.: Characteristics and source analysis of heavy metal pollution in indoor dust in Jinan (in Chinese). Environmental Science and Technology 45(06), 179-184, 10.19672/j.cnki.1003-6504.0043.22.338, 2022.

Hua, Y., Wang, S., Jiang, J., Zhou, W., Xu, Q., Li, X., Liu, B., Zhang, D., and Zheng, M.: Characteristics and sources of aerosol pollution at a polluted rural site southwest in Beijing, China, Science of The Total Environment, 626, 519-527, https://doi.org/10.1016/j.scitotenv, 2018.

~~Huss, M. and Hock, R. Global-scale hydrological response to future glacier mass loss. Nature Climate Change 8(2), 135-140, 2018.~~

Huang, H., Xu, Z.-Q., Yan, J.-X., Zhao, X.-G., and Wang, D.-L.: Characteristics of heavy metal pollution and ecological risk evaluation of indoor dust from urban and rural areas in Taiyuan City during the heating season (in Chinese), Journal of Environmrntal Science, 42, 2143-2152, 10.13227/j.hjkx.202008045, 2021a.

Huang, X., Tang, G., Zhang, J., Liu, B., Liu, C., Zhang, J., Cong, L., Cheng, M., Yan, G., Gao, W., Wang, Y., and Wang, Y.: Characteristics of $PM_{2.5}$ pollution in Beijing after the improvement of air quality, Journal of Environmental Sciences, 100, 1-10, https://doi.org/10.1016/j.jes.2020.06.004, 2021b.

Huo, J., Ren, L., Pan, Y., Zhao, J., Xiang, X., Yu, C., Meng, D., Wang, Y., Lu, R., and Huang, Y.: Functional traits of desert plants and their responses to environmental factors in Qaidam Basin,China, Acta Ecologica Sinica, 42, 4494-4503, 2022.

Ji, X., Xu, K., Liao, D., Chen, G., Liu, T., Hong, Y., Dong, S., Choi, S.-D., and Chen, J.: Spatial-temporal characteristics and source apportionment of ambient VOCs in Southeast Mountain Area of China, Aerosol And Air Quality Research, 22, 220016, 10.4209/aaqr.220016, 2022.

Jia, H., Yan, C., and Xing, X.: Evaluation of eco-environmental quality in Qaidam Basin based on the

Ecological Index (MRSEI) and GEE, Remote Sensing, 13, 10.3390/rs13224543, 2021.

Jia, S.-M., Chen, M.-H., Yang, P.-F., Wang, L., Wang, G.-Y., Liu, L.-Y., and Ma, W.-L.: Seasonal variations and sources of atmospheric EPFRs in a megacity in severe cold region: Implications for the influence of strong coal and biomass combustion, Environmental Research, 252, 10.1016/j.envres.2024.119067, 2024.

Jian, X., Guan, P., Fu, S.-T., Zhang, D.-W., Zhang, W., and Zhang, Y.-S.: Miocene sedimentary environment and climate change in the northwestern Qaidam basin, northeastern Tibetan Plateau: Facies, biomarker and stable isotopic evidences, Palaeogeography Palaeoclimatology Palaeoecology, 414, 320-331, 10.1016/j.palaeo.2014.09.011, 2014.

Jiang, L., Xue, B., Xing, R., Chen, X., Song, L., Wang, Y., Coffman, D. M., and Mi, Z.: Rural household energy consumption of farmers and herders in the Qinghai-Tibet Plateau, Energy, 192, 10.1016/j.energy.2019.116649, 2020.

Jiang, Y., Shi, L., Guang, A. l., Mu, Z., Zhan, H., and Wu, Y.: Contamination levels and human health risk assessment of toxic heavy metals in street dust in an industrial city in Northwest China, Environmental Geochemistry and Health, 40, 2007-2020, 10.1007/s10653-017-0028-1, 2018.

Joshi, U. M., Vijayaraghavan, K., and Balasubramanian, R.: Elemental composition of urban street dusts and their dissolution characteristics in various aqueous media, Chemosphere, 77, 526-533, 10.1016/j.chemosphere, 2009.

~~Jun Li, J., Ge, H. W., Xin, M. W., Jun, J. C., Tao, S., Chun, L. C., Jing, J. M., A., F. H. T., and and Xin Liu, s.: Abundance, composition and source of atmospheric $PM_{2.5}$ at a remote site in the Tibetan Plateau, China, Tellus B: Chemical and Physical Meteorology, 65, 20281, 10.3402/tellusb.v65i0.20281, 2013.~~

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

Karimian Torghabeh, A., Jahandari, A., and Jamasb, R.: Concentration, contamination level, source identification of selective trace elements in Shiraz atmospheric dust sediments (Fars Province, SW Iran), Environmental Science and Pollution Research (International), 26, 6424-6435, 10.1007/s11356-018-04100-2, 2019.

Kataki, R., Goswami, K., Bordoloi, N. J., Narzari, R., Saikia, R., Sut, D., and Gogoi, L.: Biomass resources for biofuel production in Northeast India, in: Bioprospecting of indigenous bioresources

of North-East India, edited by: Purkayastha, J., Springer Singapore, Singapore, 127-151, 10.1007/978-981-10-0620-3_8, 2016.

Kerimray, A., Suleimenov, B., De Miglio, R., Rojas-Solórzano, L., Amouei Torkmahalleh, M., and Ó Gallachóir, B. P.: Investigating the energy transition to a coal free residential sector in Kazakhstan using a regionally disaggregated energy systems model, Journal of Cleaner Production, 196, 1532-1548, https://doi.org/10.1016/j.jclepro, 2018.

Khan, A. J., Swami, K., Ahmed, T., Bari, A., Shareef, A., and Husain, L.: Determination of elemental carbon in lake sediments using a thermal–optical transmittance (TOT) method, Atmospheric Environment, 43, 5989-5995, https://doi.org/10.1016/j.atmosenv.2009.08.030, 2009.

Kim, K. H., Sekiguchi, K., Kudo, S., and Sakamoto, K.: Characteristics of atmospheric elemental carbon (Char and Soot) in ultrafine and fine particles in a roadside environment, Japan, Aerosol and Air Quality Research, 11, 1-12, 10.4209/aaqr.2010.07.0061, 2011.

Kulmala, M., Vehkamäki, H., Petäjä, T., Dal Maso, M., Lauri, A., Kerminen, V. M., Birmili, W., and McMurry, P. H.: Formation and growth rates of ultrafine atmospheric particles: a review of observations, Journal of Aerosol Science, 35, 143-176, https://doi.org/10.1016/j.jaerosci.2003.10.003, 2004.

Kumar, A.: Chemical characterization of mineral aerosols: Sources, transport and atmospheric transformations, Mohanlal Sukhadia University Udaipur, 2010.

Kumar, N., Johnson, J., Yarwood, G., Woo, J.-H., Kim, Y., Park, R. J., Jeong, J. I., Kang, S., Chun, S., and Knipping, E.: Contributions of domestic sources to $PM_{2.5}$ in South Korea, Atmospheric Environment, 287, 119273, https://doi.org/10.1016/j.atmosenv.2022.119273, 2022.

~~Kocbach Bølling, A., Pagels, J., Yttri, K. E., Barregard, L., Sallsten, G., Schwarze, P. E., and Boman, C.: Health effects of residential wood smoke particles: the importance of combustion conditions and physicochemical particle properties, Particle and Fibre Toxicology, 6, 29, 10.1186/1743-8977-6-29, 2009.~~

~~Kundu, S. and Stone, E. A.: Composition and sources of fine particulate matter across urban and rural sites in the Midwestern United States, Environmental Science: Processes and Impacts, 16, 1360-1370, 10.1039/c3em00719g, 2014.~~

Lai, S., Zhao, Y., Ding, A., Zhang, Y., Song, T., Zheng, J., Ho, K. F., Lee, S.-c., and Zhong, L.: Characterization of $PM_{2.5}$ and the major chemical components during a 1-year campaign in rural

Guangzhou, Southern China, Atmospheric Research, 167, 208-215, 10.1016/j.atmosres, 2016.

Leavey, A., Patel, S., Martinez, R., Mitroo, D., Fortenberry, C., Walker, M., Williams, B., and Biswas, P.: Organic and inorganic speciation of particulate matter formed during different combustion phases in an improved cookstove, Environmental Research, 158, 33-42, 10.1016/j.envres, 2017.

Lee, K. Y., Batmunkh, T., Joo, H. S., and Park, K.: Comparison of the physical and chemical characteristics of fine road dust at different urban sites, Journal of the Air & Waste Management Association, 68, 812-823, 10.1080/10962247.2018.1443855, 2018.

~~Li, C., Kang, S., Yan, F., Zhang, C., Yang, J. and He, C.: Importance of precipitation and dust storms in regulating black carbon deposition on remote Himalayan glaciers. Environmental Pollution 318, 120885, 2023.~~

~~Li, C., Yan, F., Kang, S., Chen, P., Hu, Z., Gao, S., Qu, B., and Sillanpää, M.: Light absorption characteristics of carbonaceous aerosols in two remote stations of the southern fringe of the Tibetan Plateau, China, Atmospheric Environment, 143, 79-85, https://doi.org/10.1016/j.atmosenv, 2016.~~

Li, J.-K., Liu, X.-F. and Wang, D.-H.: Overview of mineralization laws of lithium deposits in China (in Chinese). Acta Geologica Sinica, 88: 2269-2283. DOI: 10.19762/j.cnki.dizhixuebao, 2014.

Li, L., Ni, W., Cheng, Y., Wang, H., Yuan, K., and Zhou, B.: Evaluation of the eco-geo-environment in the Qaidam Basin, China, Environmental Earth Sciences, 80, 10.1007/s12665-020-09312-9, 2021a.

Li, M., Liu, Z., Chen, J., Huang, X., Liu, J., Xie, Y., Hu, B., Xu, Z., Zhang, Y., and Wang, Y.: Characteristics and source apportionment of metallic elements in $PM_{2.5}$ at urban and suburban sites in Beijing: Implication of emission reduction, Atmosphere, 10, 10.3390/atmos10030105, 2019.

Li, P.-h., Wang, Y., Li, T., Sun, L., Yi, X., Guo, L.-q., and Su, R.-h.: Characterization of carbonaceous aerosols at Mount Lu in South China: implication for secondary organic carbon formation and long-range transport, Environmental Science and Pollution Research, 22, 14189-14199, 10.1007/s11356-015-4654-9, 2015b.

Li, Q.-L and Sha, Z.-J.: Remote sensing monitoring of ecological environment quality in the Qaidam Basin under climate warming (in Chinese), Ecological Science, 41(06), 92-99, 10.14108/j.cnki.1008-8873, 2022.

Li, R., Li, C., Zhuang, J., Zhu, H., Fang, L., and Sun, D.: Mechanistic influence of chemical agglomeration agents on removal of inhalable particles from coal combustion, ACS Omega, 5,

25906-25912, 10.1021/acsomega.0c03263, 2020.

Li, Y., Ma, L., Ge, Y., and Abuduwaili, J.: Health risk of heavy metal exposure from dustfall and source apportionment with the PCA-MLR model: A case study in the Ebinur Lake Basin, China, Atmospheric Environment, 272, 118950, https://doi.org/10.1016/j.atmosenv, 2022.

Li, Z., Liu, J., Zhai, Z., Liu, C., Ren, Z., Yue, Z., Yang, D., Hu, Y., Zheng, H., and Kong, S.: Heterogeneous changes of chemical compositions, sources and health risks of $PM_{2.5}$ with the "Clean Heating" policy at urban/suburban/industrial sites, Science of The Total Environment, 854, 158871, 10.1016/j.scitotenv.2022.158871, 2023.

Li, Z., Yue, Z., Yang, D., Wang, L., Wang, X., Li, Z., Wang, Y., Chen, L., Guo, S., Yao, J., Lou, X., Xu, X., and Wei, J.: Levels, chemical compositions, and sources of $PM_{2.5}$ of rural and urban area under the impact of wheat harvest, Aerosol and Air Quality Research, 21, 10.4209/aaqr.210026, 2021.

~~Lim, H. J. and Turpin, B. J.: Origins of primary and secondary organic aerosol in Atlanta: Results of time resolved measurements during the Atlanta supersite experiment, Environmental Science & Technology, 36, 4489-4496, 10.1021/es0206487, 2002.~~

Lin, Y. C., Tsai, C. J., Wu, Y. C., Zhang, R., Chi, K. H., Huang, Y. T., Lin, S. H., and Hsu, S. C.: Characteristics of trace metals in traffic-derived particles in Hsuehshan Tunnel, Taiwan: size distribution, potential source, and fingerprinting metal ratio, Atmospheric Chemistry and Physics, 15, 4117-4130, 10.5194/acp-15-4117-2015, 2015.

Liu, B., Song, N., Dai, Q., Mei, R., Sui, B., Bi, X., and Feng, Y.: Chemical composition and source apportionment of ambient $PM_{2.5}$ during the non-heating period in Taian, China, Atmospheric Research, 170, 23-33, 10.1016/j.atmosres, 2016a.

Liu, G., Lucas, M., and Shen, L.: Rural household energy consumption and its impacts on eco-environment in Tibet: Taking Taktse county as an example, Renewable and Sustainable Energy Reviews, 12, 1890-1908, https://doi.org/10.1016/j.rser, 2008.

Liu, G., Li, J., Wu, D., and Xu, H.: Chemical composition and source apportionment of the ambient $PM_{2.5}$ in Hangzhou, China, Particuology, 18, 135-143, https://doi.org/10.1016/j.partic, 2015.

Liu, G., Yin, G., Kurban, A., Aishan, T., and You, H.: Spatiotemporal dynamics of land cover and their impacts on potential dust source regions in the Tarim Basin, NW China, Environmental Earth Sciences, 75, 1477, 10.1007/s12665-016-6269-y, 2016b.

Liu, H., Hu, B., Zhang, L., Zhao, X. J., Shang, K. Z., Wang, Y. S., and Wang, J.: Ultraviolet radiation

over China: Spatial distribution and trends, Renewable and Sustainable Energy Reviews, 76, 1371-1383, https://doi.org/10.1016/j.rser, 2017.

Liu, P., Zhou, H., Chun, X., Wan, Z., Liu, T., Sun, B., Wang, J., and Zhang, W.: Characteristics of fine carbonaceous aerosols in Wuhai, a resource-based city in Northern China:Insights from energy efficiency and population density, Environmental Pollution, 292, 118368, https://doi.org/10.1016/j.envpol, 2022.

Liu, T., Zhao, C., Chen, Q., Li, L., Si, G., Li, L., and Guo, B.: Characteristics and health risk assessment of heavy metal pollution in atmospheric particulate matter in different regions of the Yellow River Delta in China, Environmental Geochemistry and Health, 45, 2013-2030, 10.1007/s10653-022-01318-5, 2023b.

Liu, W., Hopke, P. K., Han, Y.-j., Yi, S.-M., Holsen, T. M., Cybart, S., Kozlowski, K., and Milligan, M.: Application of receptor modeling to atmospheric constituents at Potsdam and Stockton, NY, Atmospheric Environment, 37, 4997-5007, https://doi.org/10.1016/j.atmosenv.2003.08.036, 2003.

Liu, X., Wang, Y., Liu, R., Zhang, Y., Shao, L., Han, K., and Zhang, Y.: Pollution characteristics, source identification and potential ecological risk of 50 elements in atmospheric particulate matter during winter in Qingdao, Arabian Journal of Geosciences, 15, 10.1007/s12517-022-09521-5, 2022b.~~Liu, S., Xia, X., Zhai, Y., Wang, R., Liu, T., and Zhang, S.: Black carbon (BC) in urban and surrounding rural soils of Beijing, China: Spatial distribution and relationship with polycyclic aromatic hydrocarbons (PAHs), Chemosphere, 82, 223-228, https://doi.org/10.1016/j.chemosphere, 2011.~~

Liu, Y., Liu, G., Yousaf, B., Zhang, J., and Zhou, L.: Carbon fractionation and stable carbon isotopic fingerprint of road dusts near coal power plant with emphases on coal-related source apportionment, Ecotoxicology and Environmental Safety, 202, 110888, https://doi.org/10.1016/j.ecoenv, 2020a.

Liu, Y., Wu, G., Duan, A and Zhang, Q.: New evidence that climate warming in the Tibetan Plateau is a result of intensified greenhouse gas emissions (in Chinese), Chinese Science Bulletin, 51(8), 989-992, 10.1360/csb2006-51-8-989, 2006.

Liu, Y., Zhu, Q., Huang, J., Hua, S., and Jia, R.: Impact of dust-polluted convective clouds over the Tibetan Plateau on downstream precipitation, Atmospheric Environment, 209, 67-77, https://doi.org/10.1016/j.atmosenv, 2019.

Liu, Y., Zhu, Q., Hua, S., Alam, K., Dai, T., and Cheng, Y.: Tibetan Plateau driven impact of Taklimakan dust on northern rainfall, Atmospheric Environment, 234, 117583,

https://doi.org/10.1016/j.atmosenv, 2020b.

Liu, Z. Y., Cheng, J. L., Li, C. Y., Gao, Y., Zhan, C. L., Liu, S., Zhang, J. Q., and Liu, H. X.: Pollution characteristics and source analysis of carbon components in road dust from Qingshan District, Wuhan (in Chinese), Environmental Chemistry, 40, 772–778, 2021.

Lonati, G., Ozgen, S., and Giugliano, M.: Primary and secondary carbonaceous species in $PM_{2.5}$ samples in Milan (Italy), Atmospheric Environment, 41, 4599-4610, https://doi.org/10.1016/j.atmosenv, 2007.

Löw, F., Navratil, P., Kotte, K., Schöler, H. F., and Bubenzer, O.: Remote-sensing-based analysis of landscape change in the desiccated seabed of the Aral Sea—a potential tool for assessing the hazard degree of dust and salt storms, Environmental Monitoring and Assessment, 185, 8303-8319, 10.1007/s10661-013-3174-7, 2013.

Luo, M., Liu, Y., Zhu, Q., Tang, Y., and Alam, K.: Role and mechanisms of black carbon affecting water vapor transport to Tibet, 10.3390/rs12020231, 2020.

Ma, Q., Wu, Y., Tao, J., Xia, Y., Liu, X., Zhang, D., Han, Z., Zhang, X., and Zhang, R.: Variations of chemical composition and source apportionment of $PM_{2.5}$ during winter haze episodes in Beijing, Aerosol and Air Quality Research, 17, 2791-2803, 10.4209/aaqr.2017.10.0366, 2017.

Ma, Y., Ji, Y.-Q., Guo, J.-J., Zhao, J.-Q., Li, Y.-Y., Wang, S.-B and Zhang L.: Characteristics of carbon components and source analysis of road dust during spring in Tianjin (in Chinese), Acta Scientiae Circumstantiae 40(06), 2540-2545, 10.13227/j.hjkx, 2019.

Manousakas, M., Papaefthymiou, H., Diapouli, E., Migliori, A., Karydas, A. G., Bogdanovic-Radovic, I., and Eleftheriadis, K.: Assessment of $PM_{2.5}$ sources and their corresponding level of uncertainty in a coastal urban area using EPA PMF 5.0 enhanced diagnostics, Science of The Total Environment, 574, 155-164, 10.1016/j.scitotenv.2016.09.047, 2017.

Mbengue, S., Fusek, M., Schwarz, J., Vodička, P., Šmejkalová, A. H., and Holoubek, I.: Four years of highly time resolved measurements of elemental and organic carbon at a rural background site in Central Europe, Atmospheric Environment, 182, 335-346, 10.1016/j.atmosenv, 2018.

Meng, J.-H., Shi, X.-F., Xiang, Y and Ren, Y.-F.: Current status and sources of heavy metal pollution in the atmosphere (in Chinese). Environmental Science and Management 42(08), 51-53, 2017.

Meng, W., Zhong, Q., Chen, Y., Shen, H., Yun, X., Smith, K. R., Li, B., Liu, J., Wang, X., Ma, J., Cheng, H., Zeng, E. Y., Guan, D., Russell, A. G., and Tao, S.: Energy and air pollution benefits of household

fuel policies in northern China, Proceedings of the National Academy of Sciences, 116, 16773-16780, 10.1073/pnas.1904182116, 2019.

Meng, W., Shen, H., Yun, X., Chen, Y., Zhong, Q., Zhang, W., Yu, X., Xu, H., Ren, Y. a., Shen, G., Ma, J., Liu, J., Cheng, H., Wang, X., Zhu, D., and Tao, S.: Differentiated-Rate Clean Heating Strategy with Superior Environmental and Health Benefits in Northern China, Environmental Science & Technology, 54, 13458-13466, 10.1021/acs.est.0c04019, 2020.

Miller, M. B., Fine, R., Pierce, A. M., and Gustin, M. S.: Identifying sources of ozone to three rural locations in Nevada, USA, using ancillary gas pollutants, aerosol chemistry, and mercury, Science of The Total Environment, 530-531, 483-492, https://doi.org/10.1016/j.scitotenv, 2015.

Millet, D. B., Donahue, N. M., Pandis, S. N., Polidori, A., Stanier, C. O., Turpin, B. J., and Goldstein, A. H.: Atmospheric volatile organic compound measurements during the Pittsburgh Air Quality Study: Results, interpretation, and quantification of primary and secondary contributions, Journal of Geophysical Research: Atmospheres, 110, https://doi.org/10.1029/2004JD004601, 2005.

Ming, J., Xiao, C., Sun, J., Kang, S., and Bonasoni, P.: Carbonaceous particles in the atmosphere and precipitation of the Nam Co region, central Tibet, Journal of Environmental Sciences, 22, 1748-1756, https://doi.org/10.1016/S1001-0742(09)60315-6, 2010.

Mishra, M. and Kulshrestha, U.: Chemical characteristics and deposition fluxes of dust-carbon mixed coarse aerosols at three sites of Delhi, NCR, Journal of Atmospheric Chemistry, 74, 399-421, 10.1007/s10874-016-9349-1, 2017.

Moravek, A., Murphy, J. G., Hrdina, A., Lin, J. C., Pennell, C., Franchin, A., Middlebrook, A. M., Fibiger, D. L., Womack, C. C., McDuffie, E. E., Martin, R., Moore, K., Baasandorj, M., and Brown, S. S.: Wintertime spatial distribution of ammonia and its emission sources in the Great Salt Lake region, Atmospheric Chemistry and Physics, 19, 15691-15709, 10.5194/acp-19-15691-2019, 2019.

Muller, G.: Index of geoaccumulation in sediments of the rhine river, GeoJournal, 2, 108-118, 1969.

Munawer, M. E.: Human health and environmental impacts of coal combustion and post-combustion wastes, Journal of Sustainable Mining, 17, 87-96, https://doi.org/10.1016/j.jsm, 2018.

Na, K., Sawant, A. A., Song, C., and Cocker, D. R.: Primary and secondary carbonaceous species in the atmosphere of Western Riverside County, California, Atmospheric Environment, 38, 1345-1355, 10.1016/j.atmosenv, 2004.

Nuralykyzy, B., Wang, P., Deng, X., An, S., and Huang, Y.: Heavy metal contents and assessment of soil

contamination in different land-use types in the Qaidam Basin, Sustainability, 13(21), 12020, 10.3390/su132112020, 2021.

Qi, D.-L, Zhao, Q.-N., Zhao, H.-F., Han, T.-F and Su, W.-J.: Temporal and spatial characteristics and regional differences of dust-fall in Qinghai Province from 2004 to 2017 (in Chinese), Arid Meteorology, 36(06), 927-935, 2018.

Qian, G.-Q and Dong, Z.-B.: Research on methods and related issues of atmospheric dust collection (in Chinese), Chinese Journal of Desert Research, (06), 119-122, 2014.

Oliveira, T., Pio, C., Alves, C., Silvestre, A., Evtyugina, M., Afonso, J., Caseiro, A., and Legrand, M.: Air quality and organic compounds in aerosols from a coastal rural area in the Western Iberian Peninsula over a year long period: Characterisation, loads and seasonal trends, Atmospheric Environment, 41, 3631-3643, 10.1016/j.atmosenv, 2007.

Paatero, P. and Tapper, U.: Positive matrix factorization: A non-negative factor model with optimal utilization of error estimates of data values, Environmetries, 5, 111-126, https://doi.org/10.1002/env.3170050203, 1994.

Pacyna, J. M. and Pacyna, E. G.: An assessment of global and regional emissions of trace metals to the atmosphere from anthropogenic sources worldwide, Environmental Reviews, 9, 269-298, 10.1139/a01-012, 2001.

Pandolfi, M., Gonzalez-Castanedo, Y., Alastuey, A., de la Rosa, J. D., Mantilla, E., de la Campa, A. S., Querol, X., Pey, J., Amato, F., and Moreno, T.: Source apportionment of PM_{10} and $PM_{2.5}$ at multiple sites in the strait of Gibraltar by PMF: impact of shipping emissions, Environmental Science and Pollution Research, 18, 260-269, 10.1007/s11356-010-0373-4, 2010.

Pani, S. K., Wang, S. H., Lin, N. H., Tsay, S. C., Lolli, S., Chuang, M. T., Lee, C. T., Chantara, S., and Yu, J. Y.: Assessment of aerosol optical property and radiative effect for the layer decoupling cases over the northern South China Sea during the 7-SEAS/Dongsha Experiment, Journal of Geophysical Research: Atmospheres, 121, 4894-4906, https://doi.org/10.1002/2015JD024601, 2016.

Patel, A., Rastogi, N., Rangu, S., Dave, J., Borgohain, A., and Kundu, S. S.: Oxidative potential and hydroxyl radical generation capacity of ambient $PM_{2.5}$ over a high altitude site in northeastern Himalaya: Role of long range transport, Atmospheric Environment, 287, 119263, https://doi.org/10.1016/j.atmosenv.2022.119263, 2022.

Pervez, S., Bano, S., Watson, J. G., Chow, J. C., Matawle, J. L., Shrivastava, A., Tiwari, S., and Pervez,

Y. F.: Source profiles for $PM^{10-2.5}$ resuspended dust and vehicle exhaust emissions in Central India, Aerosol and Air Quality Research, 18, 1660-1672, 10.4209/aaqr, 2018.

Phairuang, W., Hongtieab, S., Suwattiga, P., Furuuchi, M., and Hata, M.: Atmospheric Ultrafine Particulate Matter ($PM_{0.1}$)-bound carbon composition in Bangkok, Thailand, Atmosphere, 13, 10.3390/atmos13101676, 2022.

Pio, C., Cerqueira, M., Harrison, R. M., Nunes, T., Mirante, F., Alves, C., Oliveira, C., Sanchez de la Campa, A., Artíñano, B., and Matos, M.: OC/EC ratio observations in Europe: Re-thinking the approach for apportionment between primary and secondary organic carbon, Atmospheric Environment, 45, 6121-6132, 10.1016/j.atmosenv, 2011.

Pipal, A. S., Singh, S., and Satsangi, G. P.: Study on bulk to single particle analysis of atmospheric aerosols at urban region, Urban Climate, 27, 243-258, https://doi.org/10.1016/j.uclim.2018.12.008, 2019.

Popovicheva, O. B., Engling, G., Diapouli, E., Saraga, D., Persiantseva, N. M., Timofeev, M. A., Kireeva, E. D., Shonija, N. K., Chen, S.-H., Nguyen, D. L., Eleftheriadis, K., and Lee, C.-T.: Impact of smoke intensity on size-resolved aerosol composition and microstructure during the biomass burning season in Northwest Vietnam, Aerosol and Air Quality Research, 16, 2635-2654, 10.4209/aaqr, 2016.

~~Qi, S., Zhao, S., Yu, Y., and Yang, L.: Composition, sources and potential source regions of aerosols under contrasting environment conditions of Lanzhou, a valley city of western China: Observations by means of topographic relief, Atmospheric Pollution Research, 15, 102154, https://doi.org/10.1016/j.apr, 2024.~~

Qiao, Q., Huang, B., Zhang, C., Piper, J. D. A., Pan, Y., and Sun, Y.: Assessment of heavy metal contamination of dustfall in northern China from integrated chemical and magnetic investigation, Atmospheric Environment, 74, 182-193, 10.1016/j.atmosenv, 2013.

Rogge, W. F., Hildemann, L. M., Mazurek, M. A., Cass, G. R., and Simoneit, B. R. T.: Sources of fine organic aerosol. 3. Road dust, tire debris, and organometallic brake lining dust: roads as sources and sinks, Environmental Science & Technology, 27, 1892-1904, 10.1021/es00046a019, 1993.~~Ravindra, K., Kaur-Sidhu, M., Mor, S., and John, S.: Trend in household energy consumption pattern in India: A case study on the influence of socio-cultural factors for the choice of clean fuel use, Journal of Cleaner Production, 213, 1024-1034, https://doi.org/10.1016/j.jclepro, 2019.~~

Reff, A., Eberly, S. I., and Bhave, P. V.: Receptor modeling of ambient particulate matter data using Positive Matrix Factorization: Review of existing methods, Journal of the Air & Waste Management Association, 57, 146-154, 10.1080/10473289.2007.

Sandrini, S., Fuzzi, S., Piazzalunga, A., Prati, P., Bonasoni, P., Cavalli, F., Bove, M. C., Calvello, M., Cappelletti, D., Colombi, C., Contini, D., de Gennaro, G., Di Gilio, A., Fermo, P., Ferrero, L., Gianelle, V., Giugliano, M., Ielpo, P., Lonati, G., Marinoni, A., Massabò, D., Molteni, U., Moroni, B., Pavese, G., Perrino, C., Perrone, M. G., Perrone, M. R., Putaud, J. P., Sargolini, T., Vecchi, R., and Gilardoni, S.: Spatial and seasonal variability of carbonaceous aerosol across Italy, Atmospheric Environment, 99, 587-598, https://doi.org/10.1016/j.atmosenv.2014.

Saud, T., Saxena, M., Singh, D. P., Saraswati, Dahiya, M., Sharma, S. K., Datta, A., Gadi, R., and Mandal, T. K.: Spatial variation of chemical constituents from the burning of commonly used biomass fuels in rural areas of the Indo Gangetic Plain (IGP), India, Atmospheric Environment, 71, 158-169, https://doi.org/10.1016/j.atmosenv.2013.

Safai, P. D., Raju, M. P., Rao, P. S. P., and Pandithurai, G.: Characterization of carbonaceous aerosols over the urban tropical location and a new approach to evaluate their climatic importance, Atmospheric Environment, 92, 493-500, 10.1016/j.atmosenv.2014.04.055, 2014.

Schmidl, C., Marr, I. L., Caseiro, A., Kotianová, P., Berner, A., Bauer, H., Kasper-Giebl, A., and Puxbaum, H.: Chemical characterisation of fine particle emissions from wood stove combustion of common woods growing in mid-European Alpine regions, Atmospheric Environment, 42, 126-141, https://doi.org/10.1016/j.atmosenv, 2008.

Secrest, M. H., Schauer, J. J., Carter, E. M., and Baumgartner, J.: Particulate matter chemical component concentrations and sources in settings of household solid fuel use, Indoor Air, 27, 1052-1066, 10.1111/ina.12389, 2017.

Seinfeld, J. H., Pandis, S. N., and Noone, K. J. J. P. T.: Atmospheric chemistry and physics: From air pollution to climate change, 51, 88-90, 1998.

Sheehan, P. E. and Bowman, F. M.: Estimated effects of temperature on secondary organic aerosol concentrations, Environmental Science & Technology, 35, 2129-2135, 10.1021/es001547g, 2001.

Shen, G., Ru, M., Du, W., Zhu, X., Zhong, Q., Chen, Y., Shen, H., Yun, X., Meng, W., Liu, J., Cheng, H., Hu, J., Guan, D., and Tao, S.: Impacts of air pollutants from rural Chinese households under the rapid residential energy transition, Nature Communication, 10, 3405, 10.1038/s41467-019-11453-

~~w, 2019.~~

Shen, J. and Dai, B. L.: Development and utilization of salt lake brine lithium resources and its prospects (in Chinese), Industrial Minerals & Processing, 38, 1 – 4+7, https://doi.org/10.16283/j.cnki.hgkwyjg.2009.04.004, 2009.

Shen, G.-F., Xiong, R., Cheng, H.-F and Tao, S.: Estimation of residential energy structure and primary $PM_{2.5}$ emissions in rural Tibet (in Chinese), Science Bulletin, 66(15), 1900-1911, 2021.

Shen, Z., Arimoto, R., Cao, J., Zhang, R., Li, X., Du, N., Okuda, T., Nakao, S., and Tanaka, S.: Seasonal variations and evidence for the effectiveness of pollution controls on water-soluble inorganic species in total suspended particulates and fine particulate matter from Xi'an, China, Journal of the Air & Waste Management Association, 58, 1560-1570, 10.3155/1047-3289.58.12.1560, 2008.

Shi, G., Chen, Z., Teng, J., Bi, C., Zhou, D., Sun, C., Li, Y., and Xu, S.: Fluxes, variability and sources of cadmium, lead, arsenic and mercury in dry atmospheric depositions in urban, suburban and rural areas, Environmental Research, 113, 28-32, https://doi.org/10.1016/j.envres.2012.01.001, 2012.

Shi, X., Zhao, Y., Dai, S., Xu, L., Li, Y., Jia, H., and Zhang, Q.: Research on climatic change of Qaidam Basin since 1961, Journal of Desert Research, 25, 123-128, 2005.

Shi, Z., Vu, T., Kotthaus, S., Harrison, R. M., Grimmond, S., Yue, S., Zhu, T., Lee, J., Han, Y., Demuzere, M., Dunmore, R. E., Ren, L., Liu, D., Wang, Y., Wild, O., Allan, J., Acton, W. J., Barlow, J., Barratt, B., Beddows, D., Bloss, W. J., Calzolai, G., Carruthers, D., Carslaw, D. C., Chan, Q., Chatzidiakou, L., Chen, Y., Crilley, L., Coe, H., Dai, T., Doherty, R., Duan, F., Fu, P., Ge, B., Ge, M., Guan, D., Hamilton, J. F., He, K., Heal, M., Heard, D., Hewitt, C. N., Hollaway, M., Hu, M., Ji, D., Jiang, X., Jones, R., Kalberer, M., Kelly, F. J., Kramer, L., Langford, B., Lin, C., Lewis, A. C., Li, J., Li, W., Liu, H., Liu, J., Loh, M., Lu, K., Lucarelli, F., Mann, G., McFiggans, G., Miller, M. R., Mills, G., Monk, P., Nemitz, E., O'Connor, F., Ouyang, B., Palmer, P. I., Percival, C., Popoola, O., Reeves, C., Rickard, A. R., Shao, L., Shi, G., Spracklen, D., Stevenson, D., Sun, Y., Sun, Z., Tao, S., Tong, S., Wang, Q., Wang, W., Wang, X., Wang, X., Wang, Z., Wei, L., Whalley, L., Wu, X., Wu, Z., Xie, P., Yang, F., Zhang, Q., Zhang, Y., Zhang, Y., and Zheng, M.: Introduction to the special issue "In-depth study of air pollution sources and processes within Beijing and its surrounding region (APHH-Beijing)", Atmospheric Chemistry and Physics, 19, 7519-7546, 10.5194/acp-19-7519-2019, 2019.

Simoneit, B. R. T.: Biomass burning — a review of organic tracers for smoke from incomplete combustion, Applied Geochemistry, 17, 129-162, https://doi.org/10.1016/S0883-2927(01)00061-0,

2002.

Smichowski, P., Gómez, D., Frazzoli, C., and Caroli, S.: Traffic-related elements in airborne particulate matter, Applied Spectroscopy Reviews, 43, 23-49, 10.1080/05704920701645886, 2007.

Song, P. S., Li, W., Sun, B., Nie, Z., Bu, L. Z., and Wang, Y. S.: Progress in the development and utilization of salt lake resources (in Chinese), Journal of Inorganic Chemistry, 27, 801 – 815, 2011.

Sow, M., Goossens, D., and Rajot, J. L.: Calibration of the MDCO dust collector and of four versions of the inverted frisbee dust deposition sampler, Geomorphology, 82, 360-375, 10.1016/j.geomorph.2006.05.013, 2006.

Strader, R., Lurmann, F., and Pandis, S. N.: Evaluation of secondary organic aerosol formation in winter, Atmospheric Environment, 33, 4849-4863, https://doi.org/10.1016/S1352-2310(99)00310-6, 1999.

Sulong, N. A., Latif, M. T., Sahani, M., Khan, M. F., Fadzil, M. F., Tahir, N. M., Mohamad, N., Sakai, N., Fujii, Y., Othman, M., and Tohno, S.: Distribution, sources and potential health risks of polycyclic aromatic hydrocarbons (PAHs) in $PM_{2.5}$ collected during different monsoon seasons and haze episode in Kuala Lumpur, Chemosphere, 219, 1-14, 10.1016/j.chemosphere, 2019.

Tang, Y., Han, G.-L and Xu, Z.-F.: Characteristics of black carbon content in atmospheric dust in Beijing and its northern regions (in Chinese), Acta Scientiae Circumstantiae, 33(02), 332-338, 10.13671/j.hjkxxb.2013.02.033, 2013.

Tao, J., Cheng, T., Zhang, R., Cao, J., Zhu, L., Wang, Q., Luo, L., and Zhang, L.: Chemical composition of $PM_{2.5}$ at an urban site of Chengdu in southwestern China, Advances in Atmospheric Sciences, 30, 1070-1084, 10.1007/s00376-012-2168-7, 2013.

Tao, S., Ru, M. Y., Du, W., Zhu, X., Zhong, Q. R., Li, B. G., Shen, G. F., Pan, X. L., Meng, W. J., Chen, Y. L., Shen, H. Z., Lin, N., Su, S., Zhuo, S. J., Huang, T. B., Xu, Y., Yun, X., Liu, J. F., Wang, X. L., Liu, W. X., Cheng, H. F., and Zhu, D. Q.: Quantifying the rural residential energy transition in China from 1992 to 2012 through a representative national survey, Nature Energy, 3, 567-573, 10.1038/s41560-018-0158-4, 2018.

Tian, M., Gao, J., Zhang, L., Zhang, H., Feng, C., and Jia, X.: Effects of dust emissions from wind erosion of soil on ambient air quality, Atmospheric Pollution Research, 12, 10.1016/j.apr.2021.101108, 2021.

Tian, S. L., Pan, Y. P., and Wang, Y. S.: Size-resolved source apportionment of particulate matter in urban Beijing during haze and non-haze episodes, Atmospheric Chemistry and Physics, 16, 1-19,

10.5194/acp-16-1-2016, 2016.

~~Turpin, B. J. and Huntzicker, J. J.: Secondary formation of organic aerosol in the Los Angeles basin: A descriptive analysis of organic and elemental carbon concentrations, Atmospheric Environment. Part A. General Topics, 25, 207-215, https://doi.org/10.1016/0960-1686(91)90291-E, 1991.~~

Turpin, B. J. and Huntzicker, J. J.: Identification of secondary organic aerosol episodes and quantitation of primary and secondary organic aerosol concentrations during SCAQS, Atmospheric Environment, 29, 3527-3544, https://doi.org/10.1016/1352-2310(94)00276-Q, 1995.

VanCuren, R. and Gustin, M. S.: Identification of sources contributing to $PM_{2.5}$ and ozone at elevated sites in the western U.S. by receptor analysis: Lassen Volcanic National Park, California, and Great Basin National Park, Nevada, Science of The Total Environment, 530-531, 505-518, https://doi.org/10.1016/j.scitotenv, 2015.

Venkataraman, C., Brauer, M., Tibrewal, K., Sadavarte, P., Ma, Q., Cohen, A., Chaliyakunnel, S., Frostad, J., Klimont, Z., Martin, R. V., Millet, D. B., Philip, S., Walker, K., and Wang, S.: Source influence on emission pathways and ambient $PM_{2.5}$ pollution over India (2015–2050), Atmospheric Chemistry and Physics, 18, 8017-8039, 10.5194/acp-18-8017-2018, 2018.

Wang, F.: The mechanism and timescales of soil formation in the hyper-arid Atacama Desert, Chile, Purdue University, 2013.

Wang, F., Michalski, G., Seo, J.-h., and Ge, W.: Geochemical, isotopic, and mineralogical constraints on atmospheric deposition in the hyper-arid Atacama Desert, Chile, Geochimica et Cosmochimica Acta, 135, 29-48, https://doi.org/10.1016/j.gca, 2014.

Wang, M., Duan, Y., Xu, W., Wang, Q., Zhang, Z., Yuan, Q., Li, X., Han, S., Tong, H., Huo, J., Chen, J., Gao, S., Wu, Z., Cui, L., Huang, Y., Xiu, G., Cao, J., Fu, Q., and Lee, S.: Measurement report: Characterisation and sources of the secondary organic carbon in a Chinese megacity over 5 years from 2016 to 2020, Atmospheric Chemistry and Physics, 22, 12789-12802, 10.5194/acp-22-12789-2022, 2022.~~Wang, J., Yu, A., Yang, L., and Fang, C.: Research on organic carbon and elemental carbon distribution characteristics and their influence on fine particulate matter ($PM_{2.5}$) in Changchun City, 10.3390/environments6020021, 2019.~~

~~Wang, Z. Y., Xue, D., Jia, H. Y., Liu, J., Mao, T. Y., Song, S. J. and Li, H. P.: Characteristics of carbonaceous components in atmospheric fine particulate matter in Binhai New Area, Tianjin (in Chinese), Environmental Chemistry, 40: 1871-1876, 2021.~~

Wei, C., Bandowe, B. A. M., Han, Y., Cao, J., Zhan, C., and Wilcke, W.: Polycyclic aromatic hydrocarbons (PAHs) and their derivatives (alkyl-PAHs, oxygenated-PAHs, nitrated-PAHs and azaarenes) in urban road dusts from Xi'an, Central China, Chemosphere, 134, 512-520, https://doi.org/10.1016/j.chemosphere.2014.11.052, 2015.~~Wei, N., Ma, C., Liu, J., Wang, G., Liu, W., Zhuoga, D., Xiao, D., and Yao, J.: Size segregated characteristics of carbonaceous aerosols during the monsoon and non-monsoon seasons in Lhasa in the Tibetan Plateau, 10.3390/atmos10030157, 2019.~~

Wei, T., Dong, Z., Kang, S., Qin, X., and Guo, Z.: Geochemical evidence for sources of surface dust deposited on the Laohugou glacier, Qilian Mountains, Applied Geochemistry, 79, 1-8, https://doi.org/10.1016/j.apgeochem, 2017.

Wu, C. and Yu, J. Z.: Determination of primary combustion source organic carbon-to-elemental carbon (OC/EC) ratio using ambient OC and EC measurements: secondary OC-EC correlation minimization method, Atmospheric Chemistry and Physics, 16, 5453-5465, 10.5194/acp-16-5453-2016, 2016.

Wu, C., Wu, D., and Yu, J. Z.: Quantifying black carbon light absorption enhancement with a novel statistical approach, Atmospheric Chemistry and Physics, 18, 289-309, 10.5194/acp-18-289-2018, 2018a.

~~Wu, G., Wan, X., Gao, S., Fu, P., Yin, Y., Li, G., Zhang, G., Kang, S., Ram, K., and Cong, Z.: Humic-Like Substances (HULIS) in aerosols of Central Tibetan Plateau (Nam Co, 4730 m asl): Abundance, light absorption properties, and sources, Environmental Science & Technology, 52, 7203-7211, 10.1021/acs.est.8b01251, 2018b.~~

Xia, X., Zong, X., Cong, Z., Chen, H., Kang, S., and Wang, P.: Baseline continental aerosol over the central Tibetan plateau and a case study of aerosol transport from South Asia, Atmospheric Environment, 45, 7370-7378, https://doi.org/10.1016/j.atmosenv.2011.07.067, 2011.

~~Xiang, Y., Li, X., Zhang, T., Cheng, Q., Yan, C., Liu, X., Liu, Y., Wang, Y., Kang, S., Ding, X., and Zheng, M.: Characteristics and sources of organic aerosol in $PM_{2.5}$ at Yangbajing in Tibetan Plateau, Atmospheric Environment, 333, 120662, https://doi.org/10.1016/j.atmosenv, 2024.~~

Xiao, Q., Saikawa, E., Yokelson, R. J., Chen, P., Li, C., and Kang, S.: Indoor air pollution from burning yak dung as a household fuel in Tibet, Atmospheric Environment, 102, 406-412, 10.1016/j.atmosenv, 2015.

Xie, F., Guo, L., Wang, Z., Tian, Y., Yue, C., Zhou, X., Wang, W., Xin, J., and Lu, C.: Geochemical characteristics and socioeconomic associations of carbonaceous aerosols in coal-fueled cities with significant seasonal pollution pattern, Environ Int, 179, 108179, 10.1016/j.envint.2023.108179, 2023.

~~Xu, J., Wang, Q., Deng, C., McNeill, V. F., Fankhauser, A., Wang, F., Zheng, X., Shen, J., Huang, K., and Zhuang, G.: Insights into the characteristics and sources of primary and secondary organic carbon: High time resolution observation in urban Shanghai, Environmental Pollution, 233, 1177-1187, https://doi.org/10.1016/j.envpol.2018a.~~

~~Xu, J. Z., Zhang, Q., Wang, Z. B., Yu, G. M., Ge, X. L., and Qin, X.: Chemical composition and size distribution of summertime $PM_{2.5}$ at a high altitude remote location in the northeast of the Qinghai-Xizang (Tibet) Plateau: insights into aerosol sources and processing in free troposphere, Atmospheric Chemistry and Physics, 15, 5069-5081, 10.5194/acp-15-5069-2015, 2015.~~

Xu, L., Chen, X., Chen, J., Zhang, F., He, C., Zhao, J., and Yin, L.: Seasonal variations and chemical compositions of PM2.5 aerosol in the urban area of Fuzhou, China, Atmospheric Research, 104-105, 264-272, https://doi.org/10.1016/j.atmosres, 2012.

Xu, M., Liu, Z., Hu, B., Yan, G., Zou, J., Zhao, S., Zhou, J., Liu, X., Zheng, X., Zhang, X., Cao, J., Guan, M., Lv, Y., and Zhang, Y.: Chemical characterization and source identification of $PM_{2.5}$ in Luoyang after the clean air actions, Journal of Environmental Sciences, 115, 265-276, https://doi.org/10.1016/j.jes.2021.06.021, 2022.

Xu, R., Tie, X., Li, G., Zhao, S., Cao, J., Feng, T., and Long, X.: Effect of biomass burning on black carbon (BC) in South Asia and Tibetan Plateau: The analysis of WRF-Chem modeling, Science of The Total Environment, 645, 901-912, https://doi.org/10.1016/j.scitotenv.2018.07.165, 2018b.

Xue, W., Wang, L., Yang, Z., Xiong, Z., Li, X., Xu, Q., and Cai, Z.: Can clean heating effectively alleviate air pollution: An empirical study based on the plan for cleaner winter heating in northern China, Applied Energy, 351, 121923, https://doi.org/10.1016/j.apenergy, 2023.

Yan, B., Zheng, M., Hu, Y., Ding, X., Sullivan, A. P., Weber, R. J., Baek, J., Edgerton, E. S., and Russell, A. G.: Roadside, urban, and rural comparison of primary and secondary organic molecular markers in ambient $PM_{2.5}$, Environmental Science & Technology, 43, 4287-4293, 10.1021/es900316g, 2009.

Yang, F., He, K., Ye, B., Chen, X., Cha, L., Cadle, S. H., Chan, T., and Mulawa, P. A.: One-year record of organic and elemental carbon in fine particles in downtown Beijing and Shanghai, Atmospheric

Chemistry and Physics, 5, 1449-1457, 10.5194/acp-5-1449-2005, 2005.

Yang, Q.-L., Wang, J.-X and Zhao, Z.-X.: Temporal and spatial distribution characteristics and source analysis of heavy metals in atmospheric dust in typical industrial cities in Northeast China during winter and spring (in Chinese), Acta Scientiae Circumstantiae, 1-9, 10.13671/j.hjkxxb.2024.0254, 2024.

~~Yang, X. Y.: Analysis of the current status of atmospheric environment in the Northwest China region (Gansu-Qinghai New) (in Chinese), Master's thesis, Lanzhou University, 2014.~~

Yao, L., Yang, L., Yuan, Q., Yan, C., Dong, C., Meng, C., Sui, X., Yang, F., Lu, Y., and Wang, W.: Sources apportionment of $PM_{2.5}$ in a background site in the North China Plain, Science of the Total Environment, 541, 590-598, 10.1016/j.scitotenv, 2016~~a~~.

~~Yao, L., Yang, L., Yuan, Q., Yan, C., Dong, C., Meng, C., Sui, X., Yang, F., Lu, Y., and Wang, W.: Sources apportionment of $PM_{2.5}$ in a background site in the North China Plain, Science of The Total Environment, 541, 590-598, https://doi.org/10.1016/j.scitotenv, 2016b.~~

Ye, W., Saikawa, E., Avramov, A., Cho, S. H., and Chartier, R.: Household air pollution and personal exposure from burning firewood and yak dung in summer in the eastern Tibetan Plateau, Environmental Pollution, 263, 114531, 10.1016/j.envpol, 2020.

Yoo, H. Y., Kim, K. A., Kim, Y. P., Jung, C. H., Shin, H. J., Moon, K. J., Park, S. M., and Lee, J. Y.: Validation of SOC estimation using OC and EC concentration in $PM_{2.5}$ measured at Seoul, Aerosol and Air Quality Research, 22, 210388, 10.4209/aaqr.210388, 2022.

You, S., Yao, Z., Dai, Y., and Wang, C.-H.: A comparison of PM exposure related to emission hotspots in a hot and humid urban environment: Concentrations, compositions, respiratory deposition, and potential health risks, Science of The Total Environment, 599-600, 464-473, https://doi.org/10.1016/j.scitotenv.2017.04.217, 2017.

Yu, H., Yang, W., Wang, X., Yin, B., Zhang, X., Wang, J., Gu, C., Ming, J., Geng, C., and Bai, Z.: A seriously sand storm mixed air-polluted area in the margin of Tarim Basin: Temporal-spatial distribution and potential sources, Science of The Total Environment, 676, 436-446, https://doi.org/10.1016/j.scitotenv, 2019.

Yu, L.-P., Li, D., Meng, L., Du, C.-Y. and Zhao, P.: Observation and data processing methods for atmospheric dust deposition (in Chinese), Anhui Agricultural Sciences, 44: 185-186, 10.13989/j.cnki.0517-6611.2016.31.064, 2016.

Zhan, C., Han, Y., Cao, J., Wei, C., Zhang, J., and An, Z.: Validation and application of a thermal–optical reflectance (TOR) method for measuring black carbon in loess sediments, Chemosphere, 91, 1462-1470, https://doi.org/10.1016/j.chemosphere.2012.12.011, 2013.

Zhan, C.-L., Zhan, J.-W., Ke, Z.-D., Liu, S., Zhang, J.-Q and Liu, H.-X.: Pollution characteristics and source analysis of black carbon in different types of dust in Xiaogan, Hubei (in Chinese), Environmental Pollution and Control 44(01), 14-19 + 26, 10.15985/j.cnki.1001-3865, 2022.

Zhan, C.-L., Zhang, J.-Q., Zheng, J.-G., Yao, R.-Z., Xiao, W.-S and Cao, J.-J.: Pollution characteristics and source analysis of black carbon in atmospheric dust along National Highway 316 (in Chinese), Environmental Science and Technology, 39(04), 154-160, 2016.

Zhang, F.: Study on the dry deposition of organic carbon and elemental carbon in the atmosphere of Nanchang (in Chinese), Master's Thesis, 2014.

~~Zhang, F., Wang, Z. w., Cheng, H. r., Lv, X. p., Gong, W., Wang, X. m., and Zhang, G.: Seasonal variations and chemical characteristics of $PM_{2.5}$ in Wuhan, central China, Science of The Total Environment, 518-519, 97-105, https://doi.org/10.1016/j.scitotenv.2015a.~~

Zhang, F., Wang, Z. W., Cheng, H. R., Lv, X. P., Gong, W., Wang, X. M., and Zhang, G.: Seasonal variations and chemical characteristics of $PM_{2.5}$ in Wuhan, central China, Science of the Total Environment, 518-519, 97-105, 10.1016/j.scitotenv, 2015a~~b~~.

Zhang, H. and Han, F.: The preliminary remote sensing interpretation of salt lake and its environments in the Central Qaidam Basin, Northwest China, Journal of Salt Lake Research, 10, 28-34, 2002.

Zhang, H., Zhang, F., Song, J., Tan, M. L., Kung, H. T., and Johnson, V. C.: Pollutant source, ecological and human health risks assessment of heavy metals in soils from coal mining areas in Xinjiang, China, Environmental Resesrch, 202, 111702, 10.1016/j.envres.2021.111702, 2021a.

Zhang, J., Smith, K. R., Ma, Y., Ye, S., Jiang, F., Qi, W., Liu, P., Khalil, M. A. K., Rasmussen, R. A., and Thorneloe, S. A.: Greenhouse gases and other airborne pollutants from household stoves in China: a database for emission factors, Atmospheric Environment, 34, 4537-4549, https://doi.org/10.1016/S1352-2310(99)00450-1, 2000.

Zhang, J., Huang, X., Li, J., Chen, L., Zhao, R., Wang, R., Sun, W., Chen, C., Su, Y., Wang, F., Huang, Y., and Lin, C.: Chemical composition, sources and evolution of $PM_{2.5}$ during wintertime in the city cluster of southern Sichuan, China, Atmospheric Pollution Research, 14, 101635, https://doi.org/10.1016/j.apr.2022.101635, 2023.

Zhang, K., Shang, X., Herrmann, H., Meng, F., Mo, Z., Chen, J., and Lv, W.: Approaches for identifying PM2.5 source types and source areas at a remote background site of South China in spring, Science of The Total Environment, 691, 1320-1327, https://doi.org/10.1016/j.scitotenv, 2019.

Zhang, N., Cao, J., Liu, S., Zhao, Z., Xu, H., and Xiao, S.: Chemical composition and sources of $PM_{2.5}$ and TSP collected at Qinghai Lake during summertime, Atmospheric Research, 138, 213-222, https://doi.org/10.1016/j.atmosres, 2014.

~~Zhang, N. N., He, Y. Q., Wang, C. F., Pang, H. X., He, X. Z.: The impact of tourism industry development on the chemical characteristics of atmospheric precipitation: a case study of Lijiang, Yunnan (in Chinese), Environmental Science, 32(02), 330-337, 10.13227/j.hjkx, 2011.~~

Zhang, P.-X.: Salt lakes in the Qaidam Basin (in Chinese), Beijing: Science Press, 1987.

~~Zhang, R. J., Cao, J. j., Lee, S. c., Shen, Z. x., and Ho, K. F.: Carbonaceous aerosols in PM10 and pollution gases in winter in Beijing, Journal of Environmental Sciences, 19, 564-571, https://doi.org/10.1016/S1001-0742(07)60094-1, 2007.~~

Zhang, R., Wang, H., Qian, Y., Rasch, P. J., Easter, R. C., Ma, P. L., Singh, B., Huang, J., and Fu, Q.: Quantifying sources, transport, deposition, and radiative forcing of black carbon over the Himalayas and Tibetan Plateau, Atmospheric Chemistry and Physics, 15, 6205-6223, 10.5194/acp-15-6205-2015, ~~2015c~~2015b.

Zhang, X. Y., Wang, Y. Q., Zhang, X. C., Guo, W., and Gong, S. L.: Carbonaceous aerosol composition over various regions of China during 2006, Journal of Geophysical Research: Atmospheres, 113, 10.1029/2007jd009525, 2008.

Zhang, X. Y., Wang, Y. Q., Wang, D., Gong, S. L., Arimoto, R., Mao, L. J., and Li, J.: Characterization and sources of regional-scale transported carbonaceous and dust aerosols from different pathways in coastal and sandy land areas of China, Journal of Geophysical Research: Atmospheres, 110, 10.1029/2004jd005457, 2005.

Zhang, Z., Zhou, Y., Zhao, N., Li, H., Tohniyaz, B., Mperejekumana, P., Hong, Q., Wu, R., Li, G., Sultan, M., Zayan, A. M. I., Cao, J., Ahmad, R., and Dong, R.: Clean heating during winter season in Northern China: A review, Renewable and Sustainable Energy Reviews, 149, 111339, https://doi.org/10.1016/j.rser, 2021b.

Zhang, Z.-C., Xie, Y.-Q., Zhang, Z.-J., Gao, G.-S., Xu, B., Tian, X., Xu, H., Wie, Y.-T., Shi, G.-L. and Feng, Y.-C.: Source analysis and seasonal variation characteristics of atmospheric dust deposition

in Taiyuan City based on two receptor models (in Chinese), China Environmental Science, 42, 2577-2586, 10.3969/j.issn.1000-6923, 2022.

~~Zhao, S., Qi, S., Yu, Y., Kang, S., Dong, L., Chen, J., and Yin, D.: Measurement report: Contrasting elevation-dependent light absorption by black and brown carbon: lessons from in situ measurements from the highly polluted Sichuan Basin to the pristine Tibetan Plateau, Atmospheric Chemistry and Physics, 22, 14693-14708, 10.5194/acp-22-14693-2022, 2022.~~

~~Zhao, Z., Wang, Q., Li, L., Han, Y., Ye, Z., Pongpiachan, S., Zhang, Y., Liu, S., Tian, R., and Cao, J.: Characteristics of $PM_{2.5}$ at a high-altitude remote site in the southeastern margin of the Tibetan Plateau in premonsoon season, 10.3390/atmos10110645, 2019.~~

Zhao, Z., Cao, J., Shen, Z., Xu, B., Zhu, C., Chen, L. W. A., Su, X., Liu, S., Han, Y., Wang, G., and Ho, K.: Aerosol particles at a high-altitude site on the Southeast Tibetan Plateau, China: Implications for pollution transport from South Asia, Journal of Geophysical Research: Atmospheres, 118, 10.1002/jgrd.50599, 2013.

Zheng, J., Hu, M., Du, Z., Shang, D., Gong, Z., Qin, Y., Fang, J., Gu, F., Li, M., Peng, J., Li, J., Zhang, Y., Huang, X., He, L., Wu, Y., and Guo, S.: Influence of biomass burning from South Asia at a high-altitude mountain receptor site in China, Atmospheric Chemistry and Physics, 17, 6853-6864, 10.5194/acp-17-6853-2017, 2017.

Zheng, K., Li, Y., Li, Z., and Huang, J.: Provenance tracing of dust using rare earth elements in recent snow deposited during the pre-monsoon season from mountain glaciers in the central to northern Tibetan Plateau, Environmental Science and Pollution Research, 28, 45765-45779, 10.1007/s11356-021-13561-x, 2021.

Zheng, M.-P.: Geological report on salt lake resources and ecological environment in China (in Chinese), Acta Geologica Sinica, 84: 1613-1622. DOI: 10.19762/j.cnki.dizhixuebao, 2017.

Zhou, Y., Gao, X., and Lei, J.: Characteristics of dust weather in the Tarim Basin from 1989 to 2021 and its impact on the atmospheric environment, 10.3390/rs15071804, 2023.

Zhou, Y., Yang, J., Kang, S., Hu, Y., Chen, X., Xu, M., and Ma, M.: Black carbon aerosols impact snowfall over the Tibetan Plateau, Geoscience Frontiers, 16, 101978, https://doi.org/10.1016/j.gsf, 2025.

Zhu, C.-S., Chen, C.-C., Cao, J.-J., Tsai, C.-J., Chou, C. C. K., Liu, S.-C., and Roam, G.-D.: Characterization of carbon fractions for atmospheric fine particles and nanoparticles in a highway

tunnel, Atmospheric Environment, 44, 2668-2673, 10.1016/j.atmosenv, 2010.

Zhu, H., Li, W., Kong, X., and Zhang, X.: Overlooked contribution of salt lake emissions: A case study of dust deposition from the Qinghai-Xizang Plateau, Journal of Geophysical Research: Atmospheres, 130, e2024JD042693, https://doi.org/10.1029/2024JD042693, 2025.

Zhu, H.-X.: The dust deposition data of the Qaidam Basin [Data set]. Zenodo. https://doi.org/10.5281/zenodo.14382853, 2024.