

**Editor:**

Although the manuscript has been made three revisions, and most comments have been addressed. However, there are still a few critical points being raised by referee and the examination by myself, regarding the structure of the manuscript, the statistical differences including the significance test between groups, the uncertainties of the analytical methods for OC. These information should be carefully included in the main text after further revision. I am also attaching the full comments by the referee for you to make the corresponding revising.

**➤ Response**

Thank you for carefully reviewing our manuscript and providing constructive comments, which are highly valuable for our overall revision. In the revised version, we have made modifications mainly in three key areas:

(1) The Introduction has been restructured to flow logically from the definition of atmospheric dust, environmental impacts, research methods, study area, to research objectives, thereby providing a clearer research background (**Lines 82-223**).

(2) Concerning the lack of description regarding statistical methods and significant relationships in the text, we have added explanations about the analysis of variance (ANOVA) for testing differences and the Pearson correlation analysis in Methods 2.7.5 (**Lines 482-504**). Furthermore, in the figures and text, significant differences are now marked with their significance coefficients (e.g.,  $P < 0.05$ ), while non-significant differences are indicated with the description “not statistically significant”.

(3) Regarding the methodological point on the organic carbon measurement method you mentioned, we acknowledge that water- and acid-soluble organic carbon was not initially accounted for. In response, we have repeated the relevant experimental steps (**Method 2.4**). All supernatant solutions were collected, and their dissolved organic carbon content was quantified using a carbon-nitrogen analyzer. The value was added to the organic carbon measured by the thermal/optical carbon analyzer to determine the total organic carbon (OC) in the dust deposition (**Lines 336-345** and **Lines 376-378**). Consequently, all related findings for POC, SOC, and the OC/EC ratio in the Results and discussion have been updated, and the PMF source apportionment analysis has been re-performed using the updated data.

## **Referee 1:**

### **General comment:**

In this measurement report, the authors collected dust deposition from six urban and rural sites throughout the southern Qaidam Basin, China, between January 2020 to March 2023. The primary objectives of this work were to identify the primary sources of dust emissions in the region and investigate the influence of domestic heating over dust deposition. This investigation offers interesting findings; however, there are several major issues that undermine its conclusions.

**First**, the written structure of the manuscript is somewhat unwieldy and difficult to follow. For example, the introduction is disorganized and does not effectively contextualize the study for the reader. In another instance, the authors discuss the results of particle size analysis without first introducing (or even mentioning) the corresponding methodology earlier in the MS. **Second**, multiple key details critical to scientific rigor of the study are excluded from the MS (or not clearly communicated to the reader). One of the most concerning examples in this case is that the authors do not describe the methods used to test statistical differences between sample groups. **Third**, the analytical methods used in this investigation are not sufficiently described and possibly introduce unconstrained analytical error, particularly in the case of organic carbon measurements.

Given the abundance and severity of issues present, I unfortunately recommend that the editor reject the manuscript. After significant revisions and satisfactory QA/QC analysis, this measurement report could be re-submitted to ACP to undergo the peer review processes a second time.

### **➤ Response**

Thank you for carefully reviewing the manuscript and pointing out the issues, which are highly valuable for revising our manuscript. Here, we briefly respond to your main comments:

(1) Regarding the Introduction, guided by your detailed comments, we have refined it accordingly. The structure of the Introduction has been reorganized in the order of definition of atmospheric dust, environmental impacts, research methods, study area, and research objectives to effectively present the research background (**Lines 82-223**).

(2) As suggested, the methodological description of particle size analysis, previously provided in the supplementary material, has been incorporated into the main manuscript (**Lines 381-389**).

(3) To address the need for clarification on statistical methods and significant relationships in the text, we have added explanations about the analysis of variance (ANOVA) for testing differences and the Pearson correlation analysis in Methods 2.7.5 (**Lines 482-504**). Furthermore, in the figures and text, significant differences are now marked with their significance coefficients (e.g.,  $P < 0.05$ ), while non-significant differences are indicated with the description “not statistically significant”.

(4) Regarding the methodological point in the organic carbon measurement method you mentioned, we acknowledge that water-/acid-soluble organic carbon was not initially accounted for. In response, we repeated the experiments according to Method 2.4, recollected all supernatant solutions from each step, and measured the water-/acid-soluble organic carbon content using a carbon-nitrogen analyzer. The dissolved organic carbon was added to the organic carbon value obtained from the thermal/optical carbon analyzer to determine the total organic carbon (OC) content in the dust deposition (**Lines 336-345** and **Lines 376-378**). Consequently, all related results for POC, SOC, and OC/EC in the Results and discussion have been updated, and the PMF source apportionment has been re-performed using the updated data.

#### **Specific comments:**

Line 62: The introduction would benefit from a general restructuring as its current form would be somewhat confusing for the reader. For example, the brief discussion regarding PM source characterization (e.g., PMF) is misleading when located in the opening paragraph – as it is not evident at that point why these methods matter. I would suggest starting the introduction more broadly by focusing on atmospheric dust deposition and its human / environmental impacts (e.g., glacier melt) – and then lead into sources / source characterization methods, study area, and study objectives.

#### **➤ Response**

Thank you for your suggestion. We have restructured the Introduction section to follow the logical sequence of: definition of atmospheric dust, environmental impacts, source apportionment methods, study area, and research objectives. The revised content is presented in **Lines 82-223**:

“Atmospheric dust comprises solid particles, typically ranging in size from below 1  $\mu\text{m}$  to 100  $\mu\text{m}$ , which may become airborne, depending on their origin, physical characteristics and ambient conditions (Xu, 2014). It is a key component of particulate matter (PM). Within this size spectrum, larger particles (10-100  $\mu\text{m}$ ) that settle under gravity are defined as atmospheric dust deposition. Notably, during long-distance transport, these coarse particles can undergo fragmentation into fine

particles ( $PM_{2.5}$ ) and subsequently actively participate in atmospheric chemical and climatic processes (Noll and Fang, 1989). As the dominant natural component of PM, atmospheric dust deposition serves not only a crucial indicator of regional air quality but also a key biogeochemical process linking the atmosphere, cryosphere, hydrosphere, and biosphere, with global-scale influences that significantly shape environmental and climate systems (Feng et al., 2019).

Arid and semi-arid regions are the primary global sources of atmospheric dust (Griffin et al., 2002; Schepanski, 2018). Long-distance transport of this dust via wind currents exerts multi-faceted impacts on the environment and human society. A particularly critical effect is the alteration of the cryosphere: dust deposition on snow and ice lowers surface albedo and modifies ice crystal structure, thereby accelerating glacier and snowpack melt (Tuzet et al., 2017). This process disrupts regional snow energy balance, which is directly linked to glacier retreat and water resource security. Dust deposition also influences the atmospheric energy budget by attenuating solar radiation reaching the surface and participates in the global carbon cycle through biogeochemical pathways, such as delivering nutrients to oceans and affecting marine primary productivity (Mahowald et al., 2009; Parajuli et al., 2022). For human health, harmful components associated with dust can induce respiratory and cardiovascular diseases and even damage cellular DNA (Shahram et al., 2016). For terrestrial ecosystems, the shading effect of dust on leaves can inhibit plant photosynthesis and reduce biological productivity.

Given the complexity and regional variability of atmospheric dust impacts, identifying dust sources (source apportionment) is fundamental for understanding its environmental behavior and effects. Recent advancements in understanding PM characteristics, particularly chemical composition (e.g. water-soluble ions, carbonaceous components, and trace elements) and source apportionment, have been driven by the integrated application of methodological tools. These receptor models, such as principal component analysis (PCA), chemical mass balance (CMB), and positive matrix factorization (PMF), are used to quantify source contributions. Specifically, the PMF model mathematically deconstructs the chemical composition matrix of ambient samples to achieve this. Additionally, multivariate statistical approaches like backward trajectory simulations (e.g., the HYSPLIT model) trace air mass transport pathways to identify potential source regions (Lai et al., 2016; Yao et al., 2016; Zhang et al., 2015a). This multi-method approach has greatly enhanced the precision of PM source analysis. For instance, 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. When considering the global scale, arid and semi-arid regions are unequivocally the dominant sources, contributing over 60% of the global atmospheric dust flux (Zan et al., 2025). Therefore, a comprehensive investigation of atmospheric dust processes in these key regions, encompassing emission intensity, physicochemical properties, transport pathways, and environmental effects, is indispensable for elucidating global dust cycle mechanisms and assessing their profound impacts on the cryosphere (e.g., glacial melting) and regional climate.

The Qinghai-Xizang Plateau (QXP) is often referred to as the “Roof of the World” due to its immense elevation, plays a crucial role in regulating the regional and global climate by altering large-scale atmospheric circulation. Its vast glaciers and snow cover influence regional energy balance through the albedo effect, and as the source of many major Asian rivers, it is known 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 moistening, black carbon (BC), a light-absorbing carbonaceous aerosol component emitted from incomplete combustion processes such as household cooking, heating, and coke production (Bond et al., 2013), significantly accelerates glacial melt. By depositing on ice, BC reduces surface albedo, enhances radiative absorption and thus raises its temperatures, promoting glacial melt (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., 2015b; Zheng et al., 2017; Xu et al., 2018b). In addition to these external sources, local dust sources within the QXP itself remain significant. Among these, the Qaidam Basin (QDB) in the northeastern plateau is a particularly important contributor, identified as a key dust source for the plateau (Wei et al., 2017; Zheng et al., 2021) and a critical, unique arid dust source area.

The QDB, known as the “Treasure Basin” of the QXP, is rich in mineral resources (e.g., copper, iron, and tin) as well as abundant oil and gas reserves. It serves as a key economic development zone in northwest China, accounting for approximately 30% of the plateau's industrial and agricultural output despite comprising only about 8% of its registered population (Fu, 2023). The region is also highly sensitive and vulnerable to climate change, with severe and extreme vulnerability zones covering 45.98% of its area (Xu et al., 2024). Extensive resource extraction has rendered its ecosystem fragile (Li and Sha, 2022), exacerbating the impact of atmospheric pollution. Unlike South Asia, Central Asia, and Xizang, where biomass fuels dominate, the QDB relies

primarily on distinct mix of coal (about 60%) and biomass fuels like yak dung, firewood (about 35%) 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, including light-absorbing aerosols like BC and brown carbon (BrC) (Munawar, 2018; Ye et al., 2020; Zhou et al., 2025). Brown carbon refers to organic compounds that can absorb light, particularly at shorter wavelengths, resulting in a reddish orange or brown appearance (Donahue, 2018). Both BC and BrC can influence solar radiation absorption and cloud properties, exerting a positive radiative forcing on climate (Ramanathan and Carmichael, 2008; Bond et al., 2013). When deposited on snow and ice, they further accelerate glacial melt (Qian et al., 2015; Kang et al., 2020a). Additionally, BC and BrC are significant contributors to global warming and can exacerbate adverse health effects by carrying toxic components (Ramanathan and Carmichael, 2008; Shrivastava et al., 2017). Notably, QDB's widespread use of yak dung as a fuel, a practice less common in other coal-intensive heating regions of northern China, releases pollutants like carbon monoxide (CO), volatile organic compounds (VOCs), and polycyclic aromatic hydrocarbons (PAHs), further affecting local air quality and health (Zhang et al., 2022). 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.

The QDB, as a representative arid region with intensive human activity, exhibits climatic and environmental conditions comparable to other hyper-arid basins (e.g., the Tarim and Junggar Basins in Xinjiang, the Great Basin in the United States) and high-altitude salt lake regions (e.g., Uyuni in Bolivia, Atacama in Chile). These regions are characterized by low precipitation, rich mineral resources subject to significant anthropogenic impact, and abundant salt lakes. 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 (L w 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.

From January 2020 to March 2023, monthly dust deposition samples were collected at six urban and rural monitoring sites in the southern QDB. Samples were categorized into two seasonal periods: the domestic heating period (HP) and the non-domestic heating period (NHP). Measured parameters included dust deposition flux, soluble ions, trace elements, and key carbonaceous components. The objectives of this study were: (1) to clarify the variation trends of carbonaceous components in atmospheric dust deposition under the unique energy structure of the QDB, and to quantify the contribution of domestic heating; and (2) to identify the major sources of atmospheric dust deposition in the basin and to evaluate their associated environmental impacts. To achieve these aims, we applied OC/EC and char/soot ratios, the HYSPLIT trajectory, and PMF model for source apportionment. Furthermore, these findings offer a scientific basis and reference for examining atmospheric carbonaceous aerosols in arid basins with similar climates and human activities to the QDB, as well as in salt lake regions.”

Line 63: The authors need to more effectively define atmospheric dust and clarify how it relates to PM.

➤ **Response**

Thank you for your insightful suggestions. We have redefined atmospheric dust at the beginning of the Introduction and clarified its relationship with atmospheric particulate matter.

**Lines 82-91:**

“Atmospheric dust comprises solid particles, typically ranging in size from below 1  $\mu\text{m}$  to 100  $\mu\text{m}$ , which may become airborne, depending on their origin, physical characteristics and ambient conditions (Xu, 2014). It is a key component of particulate matter (PM). Within this size spectrum, larger particles (10-100  $\mu\text{m}$ ) that settle under gravity are defined as atmospheric dust deposition. Notably, during long-distance transport, these coarse particles can undergo fragmentation into fine particles ( $\text{PM}_{2.5}$ ) and subsequently actively participate in atmospheric chemical and climatic processes (Noll and Fang, 1989). As the dominant natural component of PM, atmospheric dust deposition serves not only a crucial indicator of regional air quality but also a key biogeochemical process linking the atmosphere, cryosphere, hydrosphere, and biosphere, with global-scale influences that significantly shape environmental and climate systems (Feng et al., 2019).”

Lines 76-78: Further elaboration is needed here. Why is the QXP an important climate regulator? What are the features/mechanisms responsible for this influence? I assume it relates to the

abundance of freshwater sources and glaciers in the region – but this should be made clear for the reader.

➤ **Response**

Thank you for your valuable suggestions and feedback. We have added an elaboration on the climatic characteristics of the Qinghai-Xizang Plateau (QXP), which is located in the core arid zone of Asia. Due to its immense elevation, the plateau modifies large-scale atmospheric circulation patterns. Its vast glaciers and snow cover influence regional energy balance through the albedo effect, and as the source of many major Asian rivers, it is known as the “Asian Water Tower,” playing a crucial regulatory role in regional and even global climate(Liu et al., 2019a; Liu et al., 2020b). The relevant content has been added in **Lines 131-136**.

Lines 80-81: Please describe what black carbon is.

➤ **Response**

Thank you for your insightful suggestions. A description defining black carbon has been added in **Lines 139-141** of the manuscript.

“Black carbon (BC), a light-absorbing carbonaceous aerosol component emitted from incomplete combustion processes of solid and liquid fuels during household cooking, heating, and coke production (Bond et al., 2013)”

Lines 80-82: Make sure it is clear to the reader that BC enhances glacier surface temperatures through atmospheric deposition.

➤ **Response**

We greatly appreciate your feedback. Black carbon deposited on glacier surfaces via atmospheric deposition reduces their albedo, enhances the absorption of radiation, raises surface temperatures, and consequently accelerates glacier melt. We have added relevant content in **Lines 142-143** of the manuscript.

Line 85: I think this should be “QXP”.

➤ **Response**

Thank you for pointing this out. We confirm that the correct abbreviation is “QXP (Qinghai–Xizang Plateau)” We apologize for the oversight and have double-checked the entire manuscript to ensure this error does not occur elsewhere.

Lines 89 – 90: “It has a high population density and intense human activity, yet it is highly sensitive to climate change” - Could the authors provide some data or statistics to contextualize these statements? Additionally, I do not think the use of “yet” in this sentence is needed – I would also suggest merging this sentence with the following one.

➤ **Response**

We really appreciate your review and suggestions. We have rewritten the following sentence: “It serves as a key economic development zone in northwest China, accounting for approximately 30% of the plateau's industrial and agricultural output despite comprising only about 8% of its registered population (Fu, 2023). Extensive resource extraction has rendered its ecosystem fragile (Li and Sha, 2022), exacerbating the impact of atmospheric pollution. The region is also highly sensitive and vulnerable to climate change, with severe and extreme vulnerability zones covering 45.98% of its area (Xu et al., 2024).” (Lines 155-160)

Line 91: Did the authors mean to say “...exacerbating the impacts of atmospheric pollution.”?

➤ **Response**

We apologize for the misunderstanding here. It is meant to express that resource exploitation in the Qaidam Basin exacerbates the impact of atmospheric pollution. We have revised the statement in Lines 157-158 accordingly.

“Extensive resource extraction has rendered its ecosystem fragile (Li and Sha, 2022), exacerbating the impact of atmospheric pollution.”

Lines 91-94: I am confused by this sentence. The authors state that the QDB relies on coal, yak, dung, and firewood. Three of the fuels listed are biomass, as such, this statement contradicts the previous phrase “Unlike South Asia....where biomass fuels dominate...”. Some clarification is needed here.

➤ **Response**

We apologize for the ambiguity. Our intended meaning was to highlight the diversity of the energy structure, which relies not only on coal but also extensively on locally available biomass fuels (such as dung and firewood). This differs from some regions in South Asia that depend almost entirely on biomass. The relevant text in the manuscript (**Lines 162-165**) has been revised accordingly.

“Unlike South Asia, Central Asia, and Xizang, where biomass fuels dominate, the QDB relies primarily on distinct mix of coal (about 60%) and biomass fuels like yak dung, firewood (about 35%) 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)”

Lines 95-98: The structure of this section is somewhat confusing. I would suggest reworking the discussion here so that there is a more direct emphasis on carbon emissions.

➤ **Response**

Thank you for your valuable suggestions and feedback. We have explicitly emphasized that the combustion of fossil fuels (coal) emits substantial amounts of carbonaceous components such as black carbon (BC) and brown carbon (BrC) into the atmosphere. Black carbon is a light-absorbing carbonaceous aerosol component emitted from incomplete combustion processes of solid and liquid fuels during household cooking, heating, and coke production (Bond et al., 2013). Brown carbon refers to organic compounds that can absorb light, particularly at shorter wavelengths, resulting in a reddish orange or brown appearance (Donahue, 2018). Both BC and BrC can influence solar radiation absorption and cloud properties, exerting a positive radiative forcing on climate (Ramanathan and Carmichael, 2008; Bond et al., 2013). When deposited on snow and ice, they further accelerate glacial melt (Qian et al., 2015; Kang et al., 2020a). Additionally, BC and BrC are significant contributors to global warming and can exacerbate adverse health effects by carrying toxic components (Ramanathan and Carmichael, 2008; Shrivastava et al., 2017). The relevant content has been added in **Lines 167-178** of the manuscript.

Lines 102-106: It should be made clear to the reader why the authors are interested in arid climates (i.e., this could be established in the introduction while discussing dust sources).

➤ **Response**

We really appreciate your review and suggestions. We have included content emphasizing that arid and semi-arid regions are unequivocally the dominant sources, contributing over 60% of the global atmospheric dust flux (Zan et al., 2025). Therefore, a thorough investigation of atmospheric dust

processes in these key regions, encompassing emission intensity, material properties, transport pathways, and environmental effects, is indispensable for unraveling global dust cycle mechanisms and assessing their profound impacts on the cryosphere (e.g., glacial melting) and regional climate. The relevant content has been added to the manuscript in **Lines 125-130**.

Line 119: The study objectives should be clearly outlined at the beginning of this final paragraph.

➤ **Response**

Thank you for your insightful suggestion. The objectives of this study were: (1) to clarify the variation trends of carbonaceous components in atmospheric dust deposition under the unique energy structure of the QDB, and to quantify the contribution of domestic heating; and (2) to identify the major sources of atmospheric dust deposition in the basin and to evaluate their associated environmental impacts. The relevant text has been added to the manuscript in **Lines 209-212**.

Line 122: The HYSPLIT model and PMF models need a brief description in the introduction.

➤ **Response**

Thank you for your suggestion. We have added the relevant introduction and description in **Lines 114-118**:

“Specifically, the PMF model mathematically deconstructs the chemical composition matrix of ambient samples to achieve this. Additionally, multivariate statistical approaches like backward trajectory simulations (e.g., the HYSPLIT model) trace air mass transport pathways to identify potential source regions (Lai et al., 2016; Yao et al., 2016; Zhang et al., 2015a).”

Lines 122-125: This passage is difficult to follow. Please re-phrase.

➤ **Response**

Thank you for the opportunity to clarify. Monthly dust deposition samples were collected at six urban and rural sites in the southern Qaidam Basin. Samples were categorized into two seasonal periods: the domestic heating period and the non-heating period. Measured parameters included deposition flux, soluble ions, trace elements, and key carbonaceous components. To assess the influence of domestic heating, we applied OC/EC ratios, char/soot ratios, HYSPLIT trajectory modeling, and Positive Matrix Factorization analysis. The related description has been revised in **Lines 205-209 and Lines 212-214** of the manuscript.

Lines 119-128: As it is written, the introduction suggests that this study will be largely interested in carbon deposition; however, there is relatively limited discussion here describing carbonaceous PM (e.g., BC and brown carbon) and its impacts. The authors should expand on these concepts in the introduction.

➤ **Response**

We really appreciate your review and suggestions. An introduction to the environmental effects of black carbon and brown carbon has been included in **Lines 167-178**, as follows:

“The combustion of coal releases significant pollutants, including light-absorbing aerosols like BC and brown carbon (BrC) (Munawer, 2018; Ye et al., 2020; Zhou et al., 2025). Brown carbon refers to organic compounds that can absorb light, particularly at shorter wavelengths, resulting in a reddish orange or brown appearance (Donahue, 2018). Both BC and BrC can influence solar radiation absorption and cloud properties, exerting a positive radiative forcing on climate (Ramanathan and Carmichael, 2008; Bond et al., 2013). When deposited on snow and ice, they further accelerate glacial melt (Qian et al., 2015; Kang et al., 2020a). Additionally, BC and BrC are significant contributors to global warming and can exacerbate adverse health effects by carrying toxic components (Ramanathan and Carmichael, 2008; Shrivastava et al., 2017).”

Lines 133-135: Provide a data source or reference.

➤ **Response**

Thank you for your valuable suggestions and feedback. The corresponding references have been included in the manuscript (**Lines 228-231**), as detailed below:

“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 (Feng et al., 2022).”

Line 138: The authors have referred to the QDB as a “treasure bowl” (line 88) and “treasure basin” (line 138); one of these is the correct name I assume.

➤ **Response**

Thank you for noting this. The term has been corrected to “treasure basin” (lowercase) throughout the manuscript, and we have verified its consistency across the entire manuscript.

Line 144-145: Are there any studies / reports that could support this claim?

➤ **Response**

The data cited here are from the Qinghai Statistical Yearbook, 2023. The corresponding reference has been added in **Lines 238-240** of the article, as follows:

“Additionally, annual tourism peaks from May to September, attracting around 17 million visitors (Qinghai Statistical Yearbook, 2023), which likely amplifies atmospheric pollutant emissions.”

Lines 146-147: Were these stations part of a network? Could the authors provide a link or reference for this resource?

➤ **Response**

Among the six atmospheric monitoring stations established in the southern Qaidam Basin, four (XZH, GEM, DLX, and NMH) are state-standard meteorological observatories with comprehensive monitoring capabilities. We installed atmospheric dust deposition samplers at these sites; their information is available in the Qinghai surface meteorological observation dataset from China’s National Meteorological Science Data Center (<https://data.cma.cn>). In contrast, the LTC and BLX atmospheric dust deposition sites were established independently by our research team and do not belong to any other monitoring network.

Lines 147-148: This would be a good place to reference Fig. 1.

➤ **Response**

We greatly appreciate your feedback. We have added a citation for Figure 1 following the site description.

Lines 149-150: Can the authors provide additional information on the operating principles of the MDCO methodology?

➤ **Response**

The MDCO sampler operates on the principle of gravitational settling. It uses a collection vessel with a known opening to capture particulate matter that settles naturally from the air. In field

measurements, surrogate surfaces or deposition traps are commonly employed to better quantify atmospheric deposition. These surfaces mimic the original ground surface, are easy to deploy, and can be integrated without significantly disturbing airflow. Examples include glass beads (Ganor, 1975; Offer et al., 1992), moist filter paper (Goossens and Offer, 1993), plastic surfaces (Gregory, 1961), and water or antifreeze solutions (Smith and Twiss, 1965). The MDCO deposition vessel is based on the original concept of Ganor (1975), using glass beads as a surrogate collection surface. Due to their very low microscopic roughness, the beads help prevent the resuspension of particles once they have been captured (Goossens and Offer, 1993). Relative content has been added in **Lines 245-254**.

Lines 155-157: Without immediate context, this discussion around collection efficiency is more confusing than helpful. If wind speed impacts efficiency, what were the wind speeds during the study (at each site)? How might variable particle-size collection efficiencies impact your observations? How did you account for collection efficiency if it varies as a function of wind and particle size? How confident are you that your sample is representative of real-world deposition?

➤ **Response**

This study calculated the average wind speed during the sampling period (2020-2023) at each sampling site, as shown in Table 1. According to Sow et al. (2006), the collection efficiency of the MDCO sampler is relatively high under low wind speeds but decreases rapidly as wind speed increases. Additionally, the collection efficiency declines significantly with increasing particle size of atmospheric dust (Figure 1). Based on our findings, more than 50% of the collected dust particles are below 40  $\mu\text{m}$  (Figure S2), whereas the mean particle size of atmospheric dust deposition reported in other studies is approximately 80  $\mu\text{m}$  (Lin et al., 2022a; Lin et al., 2022b). This confirms that the MDCO sampler preferentially collects relatively finer particles. Consequently, this study may place greater emphasis on analyzing the chemical activity of the finer fraction of atmospheric dust, thereby enhancing the detection sensitivity for components such as secondary ions and carbonaceous species in deposited dust. However, this method introduces a particle-size selectivity bias, which can amplify differences in deposition flux between sites, increase the difficulty of local source apportionment, strengthen the signal from distant sources (e.g., combustion and vehicle emissions), and weaken the contribution from local coarse-particle-dominated sources (e.g., resuspended dust and construction dust). These factors may affect the accuracy of both deposition flux estimates and source apportionment. Future research should enhance data comparability and the reliability of ecological assessments through efficiency correction and the combined application of multiple methods.

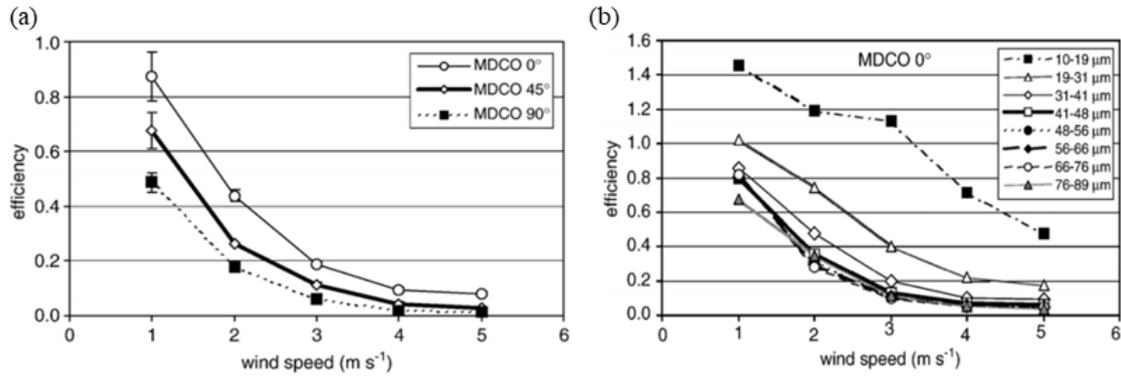


Figure 1 Efficiency curve of the MDCO sampler for atmospheric dust (including all particle-size fractions) (a), and the relationship between efficiency and particle size (b) (Adapted from Sow et al., 2006)

In this study, the sampling efficiency was calculated using Eq (1):

$$E=p[\cos(2H)+q\cos(4H)]+r \quad (1)$$

where: E is efficiency; H is MDCO orientation (in radians).  $H=0$  when the MDCO is parallel to the airflow, and  $H=\pi/2$  when perpendicular. This formula accurately computes efficiency values measured in wind tunnel experiments.

The coefficients p, q, and r are determined based on local dust particle size and wind speed. Since the mean size of dust particles at all monitoring sites in this study ranged from 20 to 40 μm, coefficients were uniformly calculated using Eqs. (2-4):

$$p=-0.0001487u^6+0.0039875u^5-0.0430022u^4+0.2363859u^3-0.6819261u^2+0.8975262u-0.19002 \quad (2)$$

$$q=0.0011874u^6-0.0267361u^5+0.2292733u^4-0.9326238u^3+1.827994u^2-1.5175786u+0.5077858 \quad (3)$$

$$r=0.0000704u^6-0.0011765u^5+0.004459u^4+0.0178979u^3-0.113394u^2-0.0988192u+0.9562646 \quad (4)$$

Table 1 Wind speed and sampling efficiency at atmospheric dust deposition monitoring stations

Sites	Wind speed(m·s <sup>-1</sup> )	Efficiency (%)
Xiao Zaohuo (XZH)	3.34	9.98
Golmud (GEM)	1.91	34.85
Da Gele (LTC)	3.73	7.09
Nuo Muhong (NMH)	1.46	44.55
Balong (BLX)	3.38	9.46
Dulan (DLX)	2.35	25.82

Based on the wind speed and particle size conditions at each monitoring site, the calculated sampling efficiencies are presented in the table below. Relative content has been added in the manuscript (Lines 263-278) and Supplementary Text S1.

Line 157: Fine particles are <2.5 µm in diameter.

➤ **Response**

We appreciate the opportunity to clarify. Here, we refer to the collected particles in the dust deposition with a size range of 10-31 µm, which represent the finer fraction of atmospheric dust but are not equivalent to fine particles (PM<sub>2.5</sub>). Accordingly, the relevant descriptions in the manuscript (like **line 261 and 267**) have been revised to “the finer fraction of atmospheric dust particles” or “relatively finer particles”.

Lines 163-164: Where the samplers covered manually or automatically?

➤ **Response:**

The sampler was manually covered. During rainy or snowy weather, the sampling inlet was covered with its matching lid to prevent interference from dry deposition. Corresponding content has been added in **Line 284**:

“To ensure only dry dust was collected, collection devices were manually-operated covered during rain or snowfall.”

Lines 167-168: Were any replicate samples collected during the study?

➤ **Response**

This study did not collect duplicate samples for atmospheric dust deposition. Relevant content has been added in **Lines 285-287** of the manuscript.

“A total of 37, 39, 23, 30, 16, and 29 samples were obtained from XZH, GEM, LTC, NMH, BLX, and DLX stations, respectively, and no duplicate samples were collected during the sampling period.”

Line 160: Are you measuring fine or total dust deposition? Make sure this is clearly stated.

➤ **Response**

We acknowledge the lack of precision. To clarify, we measured total dust deposition, and this has been checked and verified throughout the manuscript.

Lines 215-220: More detail regarding sample treatment is needed here. For instance, what concentration of HCl and HF were used? What was the extraction temperature and length? etc.

➤ **Response**

Thank you for your valuable suggestions and feedback. We have added details of the sample treatment (**Lines 336-345**), as detailed above:

“Dust samples were digested stepwise to remove inorganic materials: first samples were treated with 10 mL of 2 N hydrochloric acid (HCl) for 24 h at room temperature to dissolve carbonates and partial metals, followed by centrifugation (4500 rpm, 12 min) to separate the residue; then with 15 mL of a 1:2 (v/v) mixture of 6 N HCl and 48% hydrofluoric acid (HF) for 24 h at room temperature to dissolve silicates and residual metals; and finally with 15 mL of 4 N HCl for 24 h at 60 °C to remove minerals such as fluorite formed during demineralization. After each step, the mixture was centrifuged, and the supernatant was collected. The solid residue was diluted with 200mL of deionized water and filtered through a pre-combusted quartz fiber filter (Whatman, 450°C for 4 h, diameter 47 mm) (Han et al., 2007a).”

Lines 215 - 224: I have some serious concerns regarding this methodology. The authors state that they treated the dust samples with HCl and HF and analysed the filtered solids for EC and OC; they further state that this method has a high EC recovery, but are unable to provide similar assurance for OC. Organic carbon within atmospheric PM often contains polar, basic, and mineral-bound compounds – these can be soluble in HCl / HF solution and would be lost during the filtration process. Without accounting for this loss, I suspect that the authors are underestimating OC by an unknown factor. Erroneous values would impact the accuracy of subsequent metrics derived from OC, including OC/EC ratios, POC, and SOC.

➤ **Response**

Thank you for your highly constructive suggestion. We initially did not account for the loss of water-/acid-soluble organic carbon in our initial study. In response, the experiments were repeated following Method 2.4. All supernatant solutions from each step were recovered, and the dissolved organic carbon (DOC) content was determined using a carbon-nitrogen analyzer (Shimadzu, TOCN-4200, Japan). This DOC value was then added to the OC value obtained from the thermal/optical carbon analyzer to derive the total organic carbon content in the dust deposition.

Based on this revised data, the results related to POC, SOC, and OC/EC in the Results and discussion sections have been re-analyzed and the PMF source apportionment has been updated. The updated results show that the average total carbon (TC) in atmospheric dust deposition from the Qaidam Basin increased to  $5.70 \pm 3.2$  mg/g, with OC averaging 3.48 mg/g. Compared to urban sites, rural areas exhibited relatively higher OC content ( $3.73 \pm 2.61$  mg/g), although the difference was not statistically significant. Nevertheless, the content of carbonaceous components in the Qaidam Basin remains lower than that in other developed cities and regions. For the OC/EC ratio, urban areas remained relatively stable with an average of 3.97, whereas the average in rural areas increased significantly from 5.56 to 10.99. This marked change indicates a more pronounced influence from biomass burning and coal combustion in rural areas. Corresponding changes were also observed in POC and SOC. Specifically, when DOC was taken into account, the SOC/OC ratio increased notably from 68.17% to 72.61%. However, the overall trends between urban and rural areas remained consistent.

**Lines 349-353:**

“However, because OC includes polar, basic, and mineral-bound compounds that may dissolve in HCl/HF and be lost during filtration, the supernatant from all three acid-digestion steps was collected and analyzed for water-soluble OC using a carbon-nitrogen analyzer (Shimadzu, TOCN-4200, Japan). Total OC was obtained by summing the dissolved OC and the particulate OC measured by TOR.”

**Lines 376-378:**

“Throughout this manuscript, the term “OC” refers to the total organic carbon (sum of the dissolved OC and the particulate OC)”

Line 247: It is best not to start a sentence with an acronym/abbreviation.

➤ **Response**

Thank you for your insightful suggestions. We have revised this sentence (**Line 405**) and have thoroughly reviewed the entire manuscript to avoid similar issues.

“Organic carbon consists of primary organic carbon (POC) and secondary organic carbon (SOC).”

Lines 247-271: Previously, I identified my concerns regarding the accuracy of the OC measured from the dust samples due to the acid treatment method. As such, I have reservations regarding the accuracy of the SOC values, as these are estimated using the OC concentrations.

➤ **Response**

We greatly appreciate your feedback. We have repeated the experiments to measure the water-/acid-soluble organic carbon content. By combining the DOC results with the organic carbon values obtained from the thermal/optical carbon analyzer, we derived the total organic carbon (OC) content in the dust deposition. Based on this updated OC data, we have recalculated the values for SOC and POC.

Line 257: What does  $(OC/EC)_{pri}$  theoretically represent? This detail will help the reader understand the purpose of the MRS method.

➤ **Response**

We really appreciate your review and suggestions. The  $(OC/EC)_{pri}$  represents the characteristic OC/EC ratio of primary emission sources and serves as a key parameter for estimating SOC using the MRS approach. These data are provided in Supplementary Figure S2, and a detailed explanation has also been added in the manuscript (**Lines 418-420**).

“However, these approaches are limited by their empirical nature, lacking clear quantitative criteria for selecting the data subsets used to establish  $(OC/EC)_{pri}$ , defined as the hypothetical primary OC/EC ratio.”

Line 324: Are the values reported here (and throughout) the average of total deposition flux during the study period,  $\pm 1$  standard deviation? Please clarify.

➤ **Response**

We sincerely apologize for the lack of clarity. All data presented here and throughout the manuscript are expressed as the mean  $\pm 1$  standard deviation (Mean  $\pm 1$  SD). The corresponding clarification has been added to the Methods section (**Lines 495**).

“Data in this study are presented as mean  $\pm 1$  standard deviation (Mean  $\pm 1$  SD).”

Lines 324-336: In this section, the authors note that deposition flux was elevated during the heating period and suggest that this difference was due to increased tourism in the region. Perhaps this is true, but I don't think the authors can make this assertion before considering the influence of other factors like seasonal meteorology (variable wind speeds could easily explain differences in dust

deposition; see Yang et al., 2024, DOI: 10.1016/j.rcar.2024.12.007). Now that I am thinking about it, there is very limited analysis and discussion regarding regional meteorology during the study period. I would strongly encourage the authors to include this in the manuscript.

➤ **Response**

Thank you for your insightful suggestions. Our previous research indeed overlooked the influence of seasonal variations in meteorological factors. Accordingly, we have rewritten **lines 518-527** to include an analysis of the effects of wind speed and other meteorological parameters. Furthermore, a dedicated section (**3.5 Influence of meteorological factors**) has been added to the manuscript to specifically describe the influence of meteorological factors in the Qaidam Basin on atmospheric dust deposition during the sampling period, as below:

**Lines 518-527**

“We hypothesize that the increase in DF during the NHP is attributed to seasonal meteorological variations such as wind speed (Yang et al., 2024), and heightened anthropogenic emissions associated with tourism (Zhang et al., 2011). The NHP coincides with the peak tourist season (May-September) in the QDB, which receives about 17 million visitors annually, a number that continues to rise (Qinghai Statistical Yearbook, 2023). This elevated human activity likely enhances local emissions, contributing to increased dust deposition during this period. The influence of meteorological factors on dust deposition will be further examined in Section 3.5.”

**3.5 Influence of meteorological factors (Lines 1086-1156)**

“Meteorological parameters critically influence the accumulation and dispersion of airborne pollutants. To examine their impact on the chemical composition of dust deposition in this study, monthly data for temperature, humidity, precipitation, wind speed and direction, sunshine duration, frequency of visibility  $\leq 10$  km were obtained from four monitoring stations (XZH, GEM, NMH, DLX) during the study period (Table 1 and Figure S17). Data from the LTC and BLX sites were excluded from this analysis due to a lack of on-site meteorological instrumentation.

Based on ANOVA results, wind speed and temperature were significantly higher during the NHP ( $P < 0.05$ ), promoting dust emission and consequently increasing atmospheric dust flux (Jiménez et al., 2018; Li et al., 2019b; Yang et al., 2024). However, at DLX, wind speed showed no significant seasonal difference, while precipitation and relative humidity were significantly higher in the NHP ( $P < 0.05$ ). Since precipitation is a known suppressor of dust deposition (Li et al., 2019b), meteorological factors were not the primary driver of the elevated dust flux at DLX during the NHP

(Figure S18); other factors, such as increased tourism, likely played a more important role. Additionally, correlation analysis revealed that dust and salt dust flux were positively correlated with the frequency of visibility  $\leq 10$  km and wind speed ( $P < 0.05$ ) and negatively correlated with relative humidity ( $P < 0.05$ ), consistent with previous findings (Wei et al., 2023).

Pearson correlation analysis further elucidated the relationships between dust chemical components and meteorological parameters. Ions derived from salt lake (ps ions) and crustal elements (e.g., Al) showed significant correlations with wind direction and speed ( $P < 0.05$ , Figure S19), indicating the dominant control of wind on the emission and transport of both playa salt and soil dust. During the HP in both rural and urban areas, relative humidity was negatively correlated with ps ions and crustal elements ( $P < 0.05$ ), suggesting that higher humidity promotes the removal of airborne particles (Deshmukh et al., 2011). Playa salt ions are hygroscopic, so higher relative humidity facilitates their deliquescence (Rörig-Dalgaard, 2021). The mean annual relative humidity in the QDB (about 34 %RH) is notably lower than Wuhan (75.4 %RH) (Zang et al., 2021), Handan (63.35 %RH) (Meng et al., 2016), Pearl River Delta region (67.05 %RH) (Yue et al., 2015), Jorhat, India (80.29 %RH) (Rabha et al., 2021) and other regions, providing favorable conditions for the long-range transport of salt-lake-derived particles.

**Table 1** Summary of meteorological conditions at the monitoring stations during the sampling period

Site	Period	Temperature (°C)	Relative humidity (%)	Precipitation (mm·d <sup>-1</sup> )	Wind speed (m·s <sup>-1</sup> )	Wind direction	Sunshine duration (h·m <sup>-1</sup> )	Frequency of visibility $\leq 10$ km
	Whole	4.27 ± 10.58	33.56 ± 5.74	2.63 ± 3.64	3.29 ± 0.63	WNW	237.73 ± 26.86	36.52 ± 15.27
XZH	HP	-3.16 ± 6.30	33.57 ± 6.36	1.47 ± 2.95	2.93 ± 0.49	WNW	240.58 ± 25.04	41.19 ± 16.61
	NHP	15.65 ± 2.86	33.54 ± 4.63	4.41 ± 3.97	3.83 ± 0.40	W	233.55 ± 28.82	29.36 ± 9.10
	Whole	5.76 ± 9.80	31.22 ± 5.39	3.07 ± 4.03	1.94 ± 0.43	W	237.44 ± 30.10	65.89 ± 26.78
GEM	HP	-0.91 ± 5.94	30.38 ± 5.58	1.78 ± 1.69	1.75 ± 0.35	W	233.03 ± 30.95	83.54 ± 14.18
	NHP	16.45 ± 2.83	32.57 ± 4.38	6.1 ± 4.77	2.24 ± 0.36	W	244.21 ± 27.40	37.65 ± 15.71
	Whole	5.42 ± 10.01	33.03 ± 6.99	2.93 ± 4.05	1.53 ± 0.39	WNW	221.93 ± 23.79	78.58 ± 16.21
NMH	HP	-1.57 ± 6.08	30.23 ± 6.09	0.54 ± 1.14	1.70 ± 0.37	W	218.58 ± 20.84	88.75 ± 8.04
	NHP	16.13 ± 2.77	37.32 ± 6.04	6.59 ± 4.17	1.29 ± 0.30	WNW	226.84 ± 26.79	62.99 ± 12.84
	Whole	3.32 ± 9.07	38.24 ± 8.48	18.45 ± 23.90	2.40 ± 0.35	WNW	254.63 ± 56.83	33.69 ± 12.3
DLX	HP	-3.08 ± 5.39	34.04 ± 6.26	7.12 ± 8.89	2.42 ± 0.33	WNW	260.09 ± 49.28	34.5 ± 11.45

Site	Period	Temperature (°C)	Relative humidity (%)	Precipitation (mm·d <sup>-1</sup> )	Wind speed (m·s <sup>-1</sup> )	Wind direction	Sunshine duration (h·m <sup>-1</sup> )	Frequency of visibility ≤10 km
	NHP	13.12 ± 2.78	44.68 ± 5.95	35.83 ± 29.34	2.38 ± 0.35	W	230.33 ± 32.44	32.45 ± 11.98

Note: HP = heating period; NHP = non-heating period.

For nps ions, nps-Cl<sup>-</sup> (a tracer of coal combustion) during the HP was positively correlated with wind direction ( $P < 0.05$ , Figure S19), indicating downwind transport. In contrast, nps-K<sup>+</sup> (a tracer of biomass burning) was negatively correlated with wind speed and solar radiation ( $P < 0.05$ ), consistent with the observed peak in combustion contributions during winter when solar radiation is the lowest. Increased wind speed may suppress biomass-burning intensity (Zhang, 2024), while higher solar radiation can reduce smoldering-phase nps-K<sup>+</sup> emissions and enhance photochemical removal of aerosols (Kuang et al., 2020; Huang and Gao, 2021).

For carbonaceous components (Figure S20), in the rural NHP, soot-EC, OC, and the char/soot ratio were positively correlated with precipitation and negatively with the frequency of visibility ≤10 km ( $P < 0.05$ ). In the rural HP, the char/soot ratio was positively correlated with precipitation. In the urban NHP, char-EC, soot-EC, and their ratios showed positive correlations with humidity and precipitation ( $P < 0.01$ ), while POC was positively correlated with the frequency of visibility ≤10 km ( $P < 0.01$ ). Total carbon, OC, and SOC were negatively correlated with wind speed ( $P < 0.05$ ). In the urban HP, EC and char-EC were negatively correlated with the frequency of visibility ≤10 km; POC was positively correlated with wind speed and solar radiation but negatively with the frequency of visibility ≤10 km ( $P < 0.05$ ); and the char/soot ratio was positively correlated with wind speed and negatively with the frequency of visibility ≤10 km ( $P < 0.01$ ).

Overall, wind speed was negatively correlated with TC, OC, SOC, POC, and the char/soot ratio ( $P < 0.05$ ). This pattern aligns with findings from Xi'an (Cao et al., 2009), New Delhi (Tiwari et al., 2015), and Karachi (Bibi et al., 2017), although it was not observed in rural areas (Sharma et al., 2002). Increased wind speed enhances ventilation, promoting aerosol dispersion and reducing carbonaceous aerosol concentrations (Saha and Despiaiu, 2009). The low mean wind speed (about 2.30 m/s) may also indicate that carbon emissions are predominantly local rather than distant sources (Shen et al., 2021). Positive correlations of precipitation and relative humidity with soot-EC, char-EC, OC, and the char/soot ratio likely reflect the hygroscopic nature of carbonaceous aerosols: under humid conditions, particles absorb water, increase in mass, and undergo accelerated dry deposition. For instance, PM<sub>2.5</sub> deposition rates can increase 2-3 fold as relative humidity rises from 30% to 70%, thereby shortening their atmospheric residence time (Wu et al., 2016). The negative

correlations of EC, char-EC, and POC with the frequency of visibility  $\leq 10$  km align with findings in cities such as Suzhou (Zhang et al., 2010) and Beijing (Kong et al., 2021), attributable to the strong light-absorbing (EC) and light-scattering (OC) properties of these components, which jointly enhance atmospheric extinction and reduce visibility (Zhang et al., 2010; Kong et al., 2021). Weaker correlations in rural areas indicate that carbonaceous components are less influenced by local meteorological dilution and removal processes, pointing to more complex source influences.

In summary, seasonal variations in atmospheric dust deposition result from the combined effects of meteorological conditions and anthropogenic emissions. In urban areas, meteorological factors, especially wind speed and relative humidity, play a dominant role in the dispersion and removal of local anthropogenic pollutants. In rural areas, dust composition is more strongly influenced by large-scale wind-driven dust transport and regional combustion activities.”

Lines 326-331: This discussion compares deposition flux between different periods and stations; however, there is no mention of statistical tests here. How can we be confident that these observations are significantly different, especially when mean values are relatively close (e.g., 7.1% on line 331).

➤ **Response**

Thank you for your valuable suggestions and feedback. We acknowledge that the discussion in this section may not have been sufficiently clear regarding the significance of differences in deposition flux across different periods and monitoring stations. To avoid potential misunderstanding, we clarify that statistically significant differences are typically indicated in the figures with asterisk (\*) markers and accompanied by explicit statements of significance level (e.g.,  $P < 0.05$ ) in the text. The differences referred to here are not significant. Accordingly, we have added the notation “(not statistically significant)” to the relevant descriptions in the text (e.g., **Lines 515 and 536**).

Line 344-345: If you state that sample groups are significantly different, you must describe how this was determined (i.e., what tests were used). I have noticed that discussion regarding statistical analysis is generally vague throughout the entire manuscript (see Figures 3 & 6, lines 383-384). This must be addressed.

➤ **Response**

We apologize for the lack of clarity regarding this issue. In this study, one-way analysis of variance (One-Way ANOVA) was used to examine the differences in deposition flux, soluble ions,

carbonaceous components, and trace elements across different monitoring stations and periods. All statistical analyses were performed in SPSS (IBM SPSS Statistics 26.0.0), with the significance level ( $P$ ) set at 0.05. Prior to conducting ANOVA, normality and homogeneity of variance were tested for each dataset. When the assumptions of ANOVA were met and the overall test result was significant ( $P < 0.05$ ), it indicated that there were statistically significant differences between at least two group means. To further identify which specific groups differed, post-hoc tests were performed using Tukey's Honestly Significant Difference (HSD) method to analyze the significance of differences between groups. The description of the statistical analysis has been added to the Methods section of the manuscript (**Lines 482-495**). Furthermore, we have carefully reviewed all statements related to significant differences throughout the text. For results that were not statistically significant, the notation "not statistically significant" has been added, while statistically significant differences are now explicitly marked with their corresponding significance level (e.g.,  $P < 0.05$ ).

"A one-way analysis of variance (One-Way ANOVA) was performed to examine the differences in dust deposition flux, soluble ions, carbonaceous components, and trace elements among various monitoring sites and periods. All statistical analyses were conducted in SPSS (IBM SPSS Statistics 26.0.0), with the significance level ( $P$ ) set at 0.05. Prior to ANOVA, the normality and homogeneity of variance were tested for each dataset. The Shapiro-Wilk test was used to assess normality. If the data met the normality assumption ( $P > 0.05$ ), parametric ANOVA was applied directly. If not, the data were log-transformed and retested; if the transformed data still violated this assumption, the non-parametric Kruskal-Wallis H test was used instead. In this study, all datasets were confirmed to follow a normal distribution. Homogeneity of variance was verified using Levene's test; meeting this assumption ( $P < 0.05$ ) is a prerequisite for conducting ANOVA. When the overall ANOVA result was significant ( $P < 0.05$ ), indicating that at least two group means differed statistically, a post-hoc test was performed. Given the potentially unequal sample sizes among groups, Tukey's Honestly Significant Difference test was used for pairwise comparisons to identify specific inter-group differences."

Lines 375-382: This is where my concerns regarding the accuracy of the OC measurement data come up again. Without any knowledge regarding the collection efficiency of the OC method how can we be confident that the values reported here are actually low, and not instead a result of OC loss due to the HCl/HF treatment and filtration?

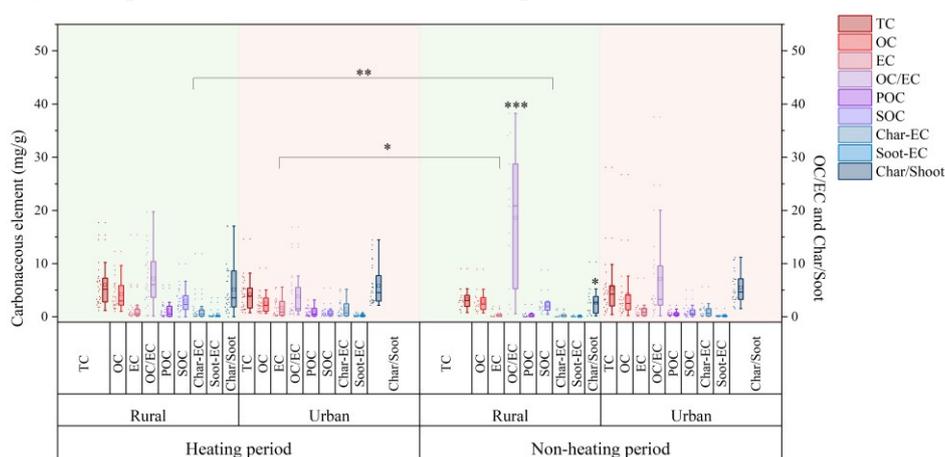
➤ **Response**

We greatly appreciate your constructive feedback. We have measured water-/acid-soluble organic carbon content in the dust deposition and calculated the total OC content by summing the soluble OC and particulate OC. Consequently, we have re-analyzed the results for OC, POC, SOC, and the OC/EC ratio throughout the manuscript. The revised results indicate that carbonaceous components levels in atmospheric dust deposition in the Qaidam Basin are lower than that in more developed urban regions.

Figure 4: Elements of this figure are difficult to interpret. The colour of certain bar and whisker plots are too light and/or similar to the background colour (e.g., SOC).

➤ **Response**

We really appreciate your review and suggestions. We have revised **Figure 4** according to the new OC findings and updated the color scheme of the boxplots to increase visual contrast.



**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).

Lines 396-397: How large of a difference in OC and EC was observed between these periods? Were these significant differences? Based on my visual inspection of Fig. 4., it looks like OC and EC at the rural sites are somewhat comparable between HP and NHP periods.

➤ **Response:**

Compared with the non-heating period (NHP), OC and EC increased by 60.26% and 87.75%, respectively, during the heating period (HP); however, these differences were not statistically significant. Except for EC in urban areas during HP being significantly higher than that in rural areas during NHP ( $P < 0.05$ ), no other statistically significant differences were identified. We have carefully reviewed all statements related to significant differences throughout the manuscript.

Descriptions of non-significant differences have been supplemented with the notation “not statistically significant”, while statistically significant differences are marked with their corresponding significance level (e.g.,  $P < 0.05$ ).

Line 797-801: This discussion regarding particle size distribution was somewhat confusing, as there is no mention of this analysis in the primary methods section.

➤ **Response**

In line with your suggestion, the description of the particle size analysis method, which was originally provided in the Supplementary material, has been incorporated into the Methods section.

2.5 The particle size analysis (Lines 381-389)

The grain size of dust-fall samples was measured using a laser particle analyzer (Malvern Mastersizer 2000, UK). The particle size distribution was calculated for 100 grain size classes within a range of 0.02-2000  $\mu\text{m}$ . Sample preparation for grain size analysis included wet oxidation of organic matter by adding 10 mL of 30% hydrogen peroxide ( $\text{H}_2\text{O}_2$ ) per 1.5 g dry sample. Carbonates were dissolved by boiling with 10 mL (10% HCl) over 10 min. The glass beakers were filled with 150 mL distilled water and suspended particles were left to deposit. After siphoning the supernatant water, 10 mL of 0.05 N sodium hexametaphosphat [ $(\text{NaPO}_3)_6$ ] were added, and the residue was dispersed for 5 min in an ultrasonic bath before measurement (Lu and An, 1997). And the results are expressed as volume percentages.

Line 843: There is no need to introduce the abbreviation, “SO<sub>3</sub>”, if it is not mentioned again in the manuscript.

➤ **Response**

We have made the modifications accordingly and conducted a full review of the manuscript.

Line 933: Please check all references for formatting consistency.

➤ **Response**

Thank you for your suggestion. We have double-checked the reference list to ensure formatting consistency.

**Reference**

- Bond, T. C., Doherty, S. J., Fahey, D. W., Forster, P. M., Berntsen, T., DeAngelo, B. J., Flanner, M. G., Ghan, S., Kärcher, B., Koch, D., Kinne, S., Kondo, Y., Quinn, P. K., Sarofim, M. C., Schultz, M. G., Schulz, M., Venkataraman, C., Zhang, H., Zhang, S., Bellouin, N., Guttikunda, S. K., Hopke, P. K., Jacobson, M. Z., Kaiser, J. W., Klimont, Z., Lohmann, U., Schwarz, J. P., Shindell, D., Storelvmo, T., Warren, S. G., and Zender, C. S.: Bounding the role of black carbon in the climate system: A scientific assessment, *Journal of Geophysical Research: Atmospheres*, 118, 5380-5552, <https://doi.org/10.1002/jgrd.50171>, 2013.
- Donahue, N. M.: Chapter 3.2 - Air pollution and air quality, in: *Green chemistry*, Elsevier, 151-176, <https://doi.org/10.1016/B978-0-12-809270-5.00007-8>, 2018.
- Feng, Y., Du, S., Fraedrich, K., and Zhang, X.: Fine-grained climate classification for the Qaidam Basin, *Atmosphere*, 13(6), 913, <https://doi.org/10.3390/atmos13060913>, 2022.
- Fu, B.: Socio-economic data set of Qinghai-Tibet Plateau (1982-2018). National Tibetan Plateau / Third Pole Environment Data Center, <http://data.tpsc.ac.cn>, 2023.
- Goossens, D. and Offer, Z. Y. J. Z. F. G.: Eolian deposition of dust over symmetrical hills: an evaluation of wind-tunnel data by means of terrain measurement, *Zeitschrift für Geomorphologie*, 37, 103-111, <https://doi.org/10.1127/zfg/37/1993/103>, 1993.
- Jiménez, L., Rühland, K. M., Jeziorski, A., Smol, J. P., and Pérez-Martínez, C.: Climate change and Saharan dust drive recent cladoceran and primary production changes in remote alpine lakes of Sierra Nevada, Spain, *Global Change Biology*, 24, e139-e158, <https://doi.org/10.1111/gcb.13878>, 2018.
- 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, 103346, <https://doi.org/10.1016/j.earscirev.2020.103346>, 2020.
- Li, Y., Song, Y., Kaskaoutis, D. G., Chen, X., Mamadjanov, Y., and Tan, L.: Atmospheric dust dynamics in southern Central Asia: Implications for buildup of Tajikistan loess sediments, *Atmospheric Research*, 229, 74-85, <https://doi.org/10.1016/j.atmosres.2019.06.013>, 2019.
- Li, Q. and Sha, Z.: Remote sensing monitoring of ecological environment quality in the Qaidam Basin under climate warming, *Ecological Science*, 41, 92-99, <https://doi.org/10.14108/j.cnki.1008-8873.2022.06.011>, 2022.
- Li, Y., Song, Y., Kaskaoutis, D. G., Chen, X., Mamadjanov, Y., and Tan, L.: Atmospheric dust dynamics in southern Central Asia: Implications for buildup of Tajikistan loess sediments, *Atmospheric Research*, 229, 74-85, <https://doi.org/10.1016/j.atmosres.2019.06.013>, 2019.
- Lin, Y., Mu, G., Chen, L., Wu, C., and Xu, L.: Sorting characteristics and implications indicated by the grain size of near-surface atmospheric dust fall in the Qira Oasis, *Journal of Desert Research*, 42, 139-146, <https://doi.org/10.7522/j.issn.1000-694X>, 2022a.

- Lin, Y., Mu, G., and Xu, L.: Grain size and sedimentary sorting characteristics of atmospheric dust in the Cele Oasis, Southern Margin of Taklimakan Desert, 14 (13), 8093 <https://doi.org/10.3390/su14138093>, 2022b.
- 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.2019.04.001>, 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.2020.117583>, 2020.
- Offer, Z. Y., Goossens, D., and Shachak, M.: Aeolian deposition of nitrogen to sandy and loessial ecosystems in the Negev Desert, *Journal of Arid Environments*, 23, 355-363, [https://doi.org/10.1016/S0140-1963\(18\)30609-8](https://doi.org/10.1016/S0140-1963(18)30609-8), 1992.
- Qian, Y., Yasunari, T. J., Doherty, S. J., Flanner, M. G., Lau, W. K. M., Ming, J., Wang, H., Wang, M., Warren, S. G., and Zhang, R.: Light-absorbing particles in snow and ice: Measurement and modeling of climatic and hydrological impact, *Advances in Atmospheric Sciences*, 32, 64-91, <https://doi.org/10.1007/s00376-014-0010-0>, 2015.
- Ramanathan, V. and Carmichael, G.: Global and regional climate changes due to black carbon, *Nature Geoscience*, 1, 221-227, <https://doi.org/10.1038/ngeo156>, 2008.
- Shrivastava, M., Lou, S., Zelenyuk, A., Easter, R. C., Corley, R. A., Thrall, B. D., Rasch, P. J., Fast, J. D., Massey Simonich, S. L., Shen, H., and Tao, S.: Global long-range transport and lung cancer risk from polycyclic aromatic hydrocarbons shielded by coatings of organic aerosol, *Proceedings of the National Academy of Sciences*, 114, 1246-1251, <https://doi.org/10.1073/pnas.1618475114>, 2017.
- Smith, R. M. and Twiss, P. C.: Extensive gaging of dust deposition rates, *Kansas Acad*, 68:2, <https://doi.org/10.2307/3626489>, 1965.
- 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, <https://doi.org/10.1016/j.geomorph.2006.05.013>, 2006.
- Wei, Y., Xie, Y., Dang, X., Guo, J., Liu, M., and Wu, H.: Characteristics of atmospheric dust deposition and influencing factors in different protection functional areas of the Jilantai Salt Lake Protection system, *Research of Soil and Water Conservation*, 30, 201-208, <https://doi.org/10.13869/j.cnki.rswc.2023.05.027>, 2023.
- Xu, Z., Wang, J., and Han, J.: Ecological vulnerability assessment of the Qaidam Basin based on the SRP Model, *Salt Lake Research*, 32, 53-60, <https://doi.org/10.3724/j.yhyj.2024009>, 2024.

- Xu, Z.: Airborne particles in outdoor air: Atmospheric dust, in: Fundamentals of air cleaning technology and its application in cleanrooms, Springer Berlin Heidelberg, 47-132, [https://doi.org/10.1007/978-3-642-39374-7\\_2](https://doi.org/10.1007/978-3-642-39374-7_2), 2014.
- Yang, S., Du, H., and Fan, Y.: Spatiotemporal variations of dust emission in Qaidam basin during the past 40 years, Research in Cold and Arid Regions, <https://doi.org/10.1016/j.rcar.2024.12.007>, 2024.
- Zan, J., Maher, B. A., Fang, X., Stevens, T., Ning, W., Wu, F., Yang, Y., Kang, J., and Hu, Z.: Global dust impacts on biogeochemical cycles and climate, Nature Reviews Earth & Environment, 6, 789-807, <https://doi.org/10.1038/s43017-025-00734-2>, 2025.

## Referee 2:

The manuscript titled "*Measurement report: Impact of domestic heating on dust deposition sources in hyper-arid Qaidam Basin, northern Qinghai-Xizang Plateau*" provides a thorough analysis of atmospheric dust deposition, focusing on the influence of domestic heating during both the heating and non-heating periods. The study integrates field observations, chemical analyses, and advanced statistical models like PMF to identify the sources of dust and its chemical composition, including carbonaceous elements, ions, and trace metals. The authors provide insight into how domestic heating, primarily through coal and biomass burning, exacerbates air pollution in rural areas, while urban areas see different contributions from industrial emissions and traffic. Additionally, the study explores the environmental impacts of these emissions on the Qinghai-Xizang Plateau, notably the accelerated glacier melting due to black carbon emissions.

1. The title and abstract are clear, precise, and effectively summarize the study. However, I would suggest slightly modifying the abstract to better emphasize the novel contributions of this research, especially the spatiotemporal variability observed and the specific findings related to coal and biomass combustion.

### ➤ Response

Thank you for your valuable suggestions and feedback. To better highlight the novelty and spatiotemporal variation characteristics of our research, we have revised the abstract (Lines 53-71) as follows:

“Given the unique energy structure of the Qaidam Basin (QDB), this study systematically reveals the spatiotemporal variations in the chemical composition of atmospheric dust deposition and clarifies the key contributions of coal and biomass burning to carbonaceous aerosols, as well as their potential impacts on the Qinghai-Xizang Plateau (QXP) and global atmospheric systems. Monthly dust deposition samples were collected at six sites in the southern QDB between 2020 and 2023. Results indicated heightened carbon emissions and the higher char/soot ratio during the heating period (HP,  $5.06 \pm 4.08$ ) than the non-heating period (NHP,  $4.42 \pm 3.09$ ), indicating intensified seasonal solid fuel consumption. Spatially, the organic carbon (OC) and elemental carbon (EC) ratio was significantly lower in urban ( $3.97 \pm 2.04$ ) than that in rural areas ( $10.99 \pm 10.00$ ). Char-EC dominated EC (80.44%), especially in urban areas (85.00%), while secondary organic carbon (SOC) dominated OC (72.61%), particularly in rural areas (87.32%). The coal combustion (15.19%) and biomass burning (33.55%) as major contributors in rural areas, strongly associated with domestic heating, whereas urban dust predominantly originated from traffic (46.83%) and industrial

emissions (16.41%). Coal consumption in QDB was greater during the HP relative to other dust sources on the QXP leads to increased atmospheric pollutant emissions, which may accelerate regional glacier melting. Consequently, integrating QDB carbonaceous 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.”

2. The introduction provides a solid background on the importance of atmospheric dust, its impact on the hydrological and ecological systems, and the specific context of the Qaidam Basin. It could benefit from a more explicit discussion of how this study fills existing research gaps, especially in terms of the unique energy use profile in Qaidam compared to other regions.

➤ **Response**

We greatly appreciate your feedback. We have emphasized that unlike South Asia, Central Asia, and Xizang, where biomass fuels dominate, the Qaidam Basin (QDB) relies primarily on distinct mix of coal (about 60%) and biomass fuels like yak dung, firewood (about 35%) 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, including light-absorbing aerosols like black carbon (BC) and brown carbon (BrC) (Munawar, 2018; Ye et al., 2020; Zhou et al., 2025). Both BC and BrC can influence solar radiation absorption and cloud properties, exerting a positive radiative forcing on climate (Ramanathan and Carmichael, 2008; Bond et al., 2013). When deposited on snow and ice, they further accelerate glacial melt (Qian et al., 2015; Kang et al., 2020a). Additionally, BC and BrC are significant contributors to global warming and can exacerbate adverse health effects by carrying toxic components (Ramanathan and Carmichael, 2008; Shrivastava et al., 2017). Notably, QDB’s widespread use of yak dung as a fuel, a practice less common in other coal-intensive heating regions of northern China, releases pollutants like carbon monoxide (CO), volatile organic compounds (VOCs), and polycyclic aromatic hydrocarbons (PAHs), further affecting local air quality and health (Zhang et al., 2022). 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 Qinghai-Xizang Plateau. This content has been added in **Lines 162-184**.

3. The methods section is robust and well-explained. The use of advanced analytical tools, including PMF and HYSPLIT modeling, is commendable. However, there is a slight issue with the description of the uncertainty analysis for PMF (e.g., not using bootstrapping due to the small sample size).

This limitation should be acknowledged more explicitly in the discussion, and the authors should consider a future exploration using a larger dataset for increased reliability.

➤ **Response**

We really appreciate your review and suggestions. We acknowledge that the sample numbers used for PMF source apportionment in this study were indeed relatively limited, with 690, 780, 480, and 750 samples for the Urban-NHP, Urban-HP, Rural-NHP, and Rural-HP, respectively. In our uncertainty analysis, we employed the Bootstrap method to help evaluate the basic robustness of the data volume and the reliability of the source apportionment results (Supplementary Text S2 and Table S2, S3). Nevertheless, we fully recognize that such limited sample size can increase the risk of model overfitting, reduce the representativeness of source profiles, and potentially lead to the merging of multiple sources into a mixed factor (Norris et al., 2014). We acknowledge this as a limitation of our study. Consequently, we have added a discussion regarding this limitation in section 3.4 (**Lines 862-868**)

“In this study, the sample sizes used for PMF source apportionment were 690, 780, 480, and 750 for the Urban-NHP, Urban-HP, Rural-NHP, and Rural-HP groups, respectively. Limited sample number can increase the risk of model overfitting, reduce the representativeness of source profiles, and potentially lead to the merging of multiple sources into a mixed factor (Norris et al., 2014). Future research will extend the observation period and increase the sample number to further enhance the reliability of the source apportionment results.”

4. The study employs the PMF model to identify major dust sources. While the results are insightful, the paper could delve deeper into the temporal trends observed in the rural versus urban areas. The authors should also discuss more on how the seasonal variations affect the accuracy of their source apportionment.

➤ **Response**

Thank you for your insightful suggestions. Based on the temporal trends derived from the PMF model, we conducted an in-depth analysis of the differences between rural and urban areas. Time series analysis (Figure S16) indicates that atmospheric dust deposition in rural areas primarily originates from natural processes and dispersed anthropogenic combustion due to sparse human activities. During the NHP, the contribution of salt-lake emissions increases in May and June. Strong winds in spring and summer in southern QDB transport saline soil particles, making them a key source of dust deposition (Zhu et al., 2025). Soil-derived dust shows variations highly synchronized

with the salt-lake source, with elevated contributions also occurring in May and June, reflecting the natural erosion of exposed surfaces under high wind conditions (Zhang, 2010). Traffic contributions rise noticeably in July and August, likely linked to increased summer tourism and transportation. During the HP, contributions from biomass and coal combustion increase, peaking from November to January. This peak is attributed to the widespread use of biomass fuels such as livestock dung for decentralized heating in rural areas, leading to increased particulate matter emissions (Chen et al., 2023). In contrast, contributions from salt lakes and wind-blown dust decrease significantly, likely due to lower wind speeds and reduced natural source emissions in winter (Jiménez et al., 2018; Li et al., 2019b; Yang et al., 2024).

In urban areas, where human activities are more concentrated, pollution sources are dominated by centralized anthropogenic emissions (industry, traffic, and centralized heating), with temporal trends driven by both industrial activity and the heating cycle. During the NHP, industrial contributions increase, especially in towns such as GEM and DLX, where surrounding mining operations constitute a major anthropogenic source (Zhu et al., 2016). Traffic-related contributions follow a trend similar to that in rural NHP, also peaking in July and August, reflecting the common influence of increased vehicle flow during the tourism season. Meanwhile, precursors such as SO<sub>2</sub> and NO<sub>x</sub> from industrial and traffic emissions undergo photochemical and gas-to-particle conversion under summer sunlight, enhancing the formation of secondary inorganic aerosols (e.g., sulfates, nitrates) (Zhang et al., 2013; Ma et al., 2017). During the HP, trends in salt-lake emissions, soil dust, and coal/biomass combustion are generally similar to those in rural areas. However, unlike in rural regions, traffic contributions in urban areas continue to increase during the HP, highlighting the higher intensity and less seasonally-variable nature of human activities in towns (Peng et al., 2021). The corresponding content has been added to the manuscript in **Lines 1023-1049**.

In addition, bivariate polar plots were generated for the concentrations of POC, SOC, char-EC, soot-EC, water soluble ions and trace elements during the sampling period (Figure S21-S24), as well as for the source contributions of dust deposition from the PMF model (Figure 8 and 9), to visually illustrate their directional characteristics. The results showed that the polar plots of several tracer ions and elements exhibited patterns consistent with those of the PMF-resolved factors, confirming the reliability of the PMF source apportionment. Furthermore, pronounced spatiotemporal variations were identified in the sources of atmospheric dust components in the Qaidam Basin, primarily influenced by urban–rural differences, seasonal variations, and transport pathways. The corresponding content has been added to the manuscript in **Lines 1167-1207**.

“Wind direction analysis provides a valuable supplement to the PMF model (Watson et al., 2008). Studies have shown that emissions from sources such as traffic, biomass burning, coal combustion, and salt lakes exhibit significant directional patterns, which can be effectively visualized using polar plots (Saraga et al., 2021). In this study, bivariate polar plots were generated for the concentrations of POC, SOC, char-EC, soot-EC, and selected ions/elements (Figure S21-S24), as well as for the source contributions resolved by the PMF model (Figure 8 and 9), to illustrate their directional provenance. Notably, the directional patterns of the various aerosol components exhibited distinct differences and did not fully align with the local prevailing wind directions.

The polar plots of key tracer ions and elements (Figure S21-S24) showed patterns consistent with the corresponding PMF-resolved source factors (Figure 8 and 9), supporting the validity of the source apportionment. Specifically, the following pairs showed similar directional distributions: Total-ps and the salt-lake source; nps-K<sup>+</sup>, POC, and char-EC with biomass burning; nps-Ca<sup>2+</sup> and Si with soil dust; nps-SO<sub>4</sub><sup>2-</sup>, nps-Cl<sup>-</sup>, and SOC with coal combustion; Fe and Cd with industry; Ni and Zn with vehicle combustion; Fe and Al with industry; and nps-SO<sub>4</sub><sup>2-</sup> together with NO<sub>3</sub><sup>-</sup> with secondary formation. These spatial consistencies reinforce that the selected chemical tracers are associated with their respective PMF-identified sources.

Wind speeds in rural areas are generally higher than those in urban environments, with predominant wind directions between west (W) and north (N), indicating the potential long-distance transport of pollutants. Specifically, emissions from saline lakes primarily originate from the west-northwest (WNW) direction. Back trajectory modeling suggests that HP levels are mainly attributed to salt lake emissions from the northwestern QDB, while in NHP, sources include long-distance transport from salt lakes in the Tarim Basin (Figure S6, S7). For industrial emissions during the HP, sources primarily originate from medium- to short-distance transport in the W direction, with NHP periods showing contributions from both the west (W) and northwest-northwest (NNW) directions. In contrast, soil dust in HP is predominantly sourced from long-distance transport from the W direction, whereas in NHP, it is largely of local origin. Biomass burning during HP mainly arises from local sources, while its contribution during NHP is minimal and comes from both local and long-distance transport, consistent with PMF results.

In urban areas, lower wind speeds and varying dominant wind directions between the HP and NHP lead to different sources of pollutants. During HP, emissions from saline lakes and coal combustion primarily originate from short-distance transport in the WNW direction, while biomass burning is sourced from the W. In contrast, industrial emissions, soil dust, and vehicle combustion are

predominantly attributed to local sources. In NHP, pollutants demonstrate a dispersion trend from their sources to urban areas. Industrial emissions primarily come from the WNW to north-northeast (NNE) directions, soil dust from the southwest (SW), and vehicle emissions from the W direction. Notably, both salt lake and secondary formation sources exhibit similar directional patterns, indicating a common origin from the SW direction. The presence of processing enterprises near salt lakes suggests that secondary aerosols may form from emitted SO<sub>2</sub> and NO<sub>2</sub> (Hewitt, 2001). These findings align with previous analyses showing that urban industrial and traffic emissions mainly derive from local sources, while coal and biomass burning predominantly originate from surrounding rural areas, corroborating the role of nearby soil sources in salt lake and soil emissions.”

5. The comparison of OC/EC ratios across regions is valuable, though the authors should discuss potential limitations regarding the collection efficiency of OC, especially considering the variability of OC collection in different environments.

➤ **Response**

We really appreciate your review and suggestions. We agree that the collection efficiency of OC and EC is closely related to the sampling methodology and local environmental conditions. Accordingly, we have added a discussion regarding collection efficiency in **Lines 735-753** of the manuscript, as detailed below:

“While the MDCO sampler effectively captures dry deposition flux, the reported OC and EC values must be interpreted with specific limitations in mind. First, passive sampling is governed by aerodynamic drag and gravitational settling; therefore, the collected OC is likely skewed toward the coarse fraction (e.g., re-suspended soil, biological debris) while potentially under-representing fine-mode anthropogenic combustion aerosols which have negligible settling velocities. This implies that the OC fluxes reported here should be interpreted as fluxes of deposited particulate OC, not as a direct surrogate for total atmospheric OC. Second, the extended exposure period inherent to passive sampling may lead to negative artifacts due to volatilization. Semi-volatile organic compounds may partition from the particulate to the gas phase, a process accelerated in environments with high solar radiation and ambient temperatures (Turpin et al., 1994). Consequently, the OC fluxes reported here likely represent a conservative lower limit. Finally, environmental factors such as wind speed and humidity affect collection efficiency. High wind speeds can induce turbulence leading to the resuspension of lighter organic particles from the collector, while high humidity may facilitate chemical or biological degradation of the organic fraction prior to laboratory analysis (Chow et al., 2011). Taken together, these processes imply that

the OC collection efficiency of the MDCO sampler is not constant but varies with temperature, humidity, precipitation, wind speed and other environmental factors. The role of these meteorological factors in atmospheric dust deposition is examined in detail in Section 3.5.”

6. The environmental implications of increased carbonaceous emissions from domestic heating are well-addressed. It would be beneficial to expand on the potential policy implications in light of the findings, particularly in terms of integrating findings into climate models and developing local mitigation strategies.

➤ **Response**

Thank you for your valuable suggestions and feedback. In modeling applications, the localized source profiles developed in this study, such as OC/EC ratios for heating-period emissions and key heavy-metal tracers, provide critical input parameters for regional climate and air quality models. This enables more accurate simulation of the emission, transport, and deposition of carbonaceous aerosols in the Qaidam Basin (QDB) and supports quantitative assessment of their contribution to glacier retreat on the Qinghai-Xizang Plateau (QXP). Regarding policy implications, based on the finding that rural areas in arid and semi-arid basins such as QDB rely heavily on solid fuels for heating, with associated environmental impacts, we recommend that local governments implement targeted clean-energy transition policies. These should prioritize promoting clean heating alternatives (e.g., solar and electric heating) in rural regions, supported by financial subsidies and technical assistance. Simultaneously, the adoption of clean stoves and upgraded biomass fuels should be encouraged to reduce emissions from traditional biomass and coal combustion (Dickinson et al., 2015; Li et al., 2011; Shen et al., 2017). Given the close climatic and environmental linkage between QDB and QXP, we further propose integrating air pollution control in QDB into the broader environmental protection framework of QXP. Establishing a joint regional air pollution prevention and control mechanism for the “QDB–QXP” system would help align emission reduction in the basin with glacier protection goals on the plateau. To strengthen the scientific foundation of such a mechanism, future studies should focus on clarifying the key transport pathways, transformation processes, and quantitative impacts of air pollutants from QDB to QXP glaciers. The relevant content has been added to the manuscript in **Lines 1273-1290**.

**Reference**

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, <https://doi.org/10.1016/j.energy.2015.03.059>,

2015.

- Bond, T. C., Doherty, S. J., Fahey, D. W., Forster, P. M., Bernsten, T., DeAngelo, B. J., Flanner, M. G., Ghan, S., Kärcher, B., Koch, D., Kinne, S., Kondo, Y., Quinn, P. K., Sarofim, M. C., Schultz, M. G., Schulz, M., Venkataraman, C., Zhang, H., Zhang, S., Bellouin, N., Guttikunda, S. K., Hopke, P. K., Jacobson, M. Z., Kaiser, J. W., Klimont, Z., Lohmann, U., Schwarz, J. P., Shindell, D., Storelvmo, T., Warren, S. G., and Zender, C. S.: Bounding the role of black carbon in the climate system: A scientific assessment, *Journal of Geophysical Research: Atmospheres*, 118, 5380-5552, <https://doi.org/10.1002/jgrd.50171>, 2013.
- Chen, P., Li, Y., Zhang, Y., Xue, C., Hopke, P. K., and Li, X.: Dynamic changes of composition of particulate matter emissions during residential biomass combustion, *Environmental Science & Technology*, 57, 15193-15202, <https://doi.org/10.1021/acs.est.3c05412>, 2023.
- Chow, J. C., Watson, J. G., Robles, J., Wang, X., Chen, L. W. A., Trimble, D. L., Kohl, S. D., Tropp, R. J., and Fung, K. K.: Quality assurance and quality control for thermal/optical analysis of aerosol samples for organic and elemental carbon, *Analytical and Bioanalytical Chemistry*, 401, 3141-3152, <https://doi.org/10.1007/s00216-011-5103-3>, 2011.
- Dickinson, K. L., Kanyomse, E., Piedrahita, R., Coffey, E., Rivera, I. J., Adoctor, J., Alirigia, R., Muvandimwe, D., Dove, M., Dukic, V., Hayden, M. H., Diaz-Sanchez, D., Abisiba, A. V., Anaseba, D., Hagar, Y., Masson, N., Monaghan, A., Titiati, A., Steinhoff, D. F., Hsu, Y.-Y., Kaspar, R., Brooks, B. A., Hodgson, A., Hannigan, M., Oduro, A. R., and Wiedinmyer, C.: Research on emissions, air quality, climate, and cooking technologies in Northern Ghana (Reaccting): study rationale and protocol, *BMC Public Health*, 15, 126, <https://doi.org/10.1186/s12889-015-1414-1>, 2015.
- Hewitt, C. N.: The atmospheric chemistry of sulphur and nitrogen in power station plumes, *Atmospheric Environment*, 35, 1155-1170, [https://doi.org/10.1016/S1352-2310\(00\)00463-5](https://doi.org/10.1016/S1352-2310(00)00463-5), 2001.
- 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, <https://doi.org/10.1016/j.energy.2019.116649>, 2020.
- Jiménez, L., Rühland, K. M., Jeziorski, A., Smol, J. P., and Pérez-Martínez, C.: Climate change and Saharan dust drive recent cladoceran and primary production changes in remote alpine lakes of Sierra Nevada, Spain, *Global Change Biology*, 24, e139-e158, <https://doi.org/10.1111/gcb.13878>, 2018.
- 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, 103346, <https://doi.org/10.1016/j.earscirev.2020.103346>, 2020.

- 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.2018.06.158>, 2018.
- Li, Y., Song, Y., Kaskaoutis, D. G., Chen, X., Mamadjanov, Y., and Tan, L.: Atmospheric dust dynamics in southern Central Asia: Implications for buildup of Tajikistan loess sediments, *Atmospheric Research*, 229, 74-85, <https://doi.org/10.1016/j.atmosres.2019.06.013>, 2019.
- Li, Z., Sjödin, A., Romanoff, L. C., Horton, K., Fitzgerald, C. L., Eppler, A., Aguilar-Villalobos, M., and Naeher, L. P.: Evaluation of exposure reduction to indoor air pollution in stove intervention projects in Peru by urinary biomonitoring of polycyclic aromatic hydrocarbon metabolites, *Environment International*, 37, 1157-1163, <https://doi.org/10.1016/j.envint.2011.03.024>, 2011.
- 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.2007.03.008>, 2008.
- 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<sub>2.5</sub> during Winter Haze Episodes in Beijing, *Aerosol and Air Quality Research*, 17, 2791-2803, <https://doi.org/10.4209/aaqr.2017.10.0366>, 2017.
- 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.2017.12.007>, 2018.
- Norris, G., Duvall, R., Brown, S., and Bai, S.: EPA Positive Matrix Factorization (PMF) 5.0 fundamentals and user guide, The United States Environmental Protection Agency, <https://www.epa.gov>, 2014.
- Qian, Y., Yasunari, T. J., Doherty, S. J., Flanner, M. G., Lau, W. K. M., Ming, J., Wang, H., Wang, M., Warren, S. G., and Zhang, R.: Light-absorbing particles in snow and ice: Measurement and modeling of climatic and hydrological impact, *Advances in Atmospheric Sciences*, 32, 64-91, <https://doi.org/10.1007/s00376-014-0010-0>, 2015.
- Ramanathan, V. and Carmichael, G.: Global and regional climate changes due to black carbon, *Nature Geoscience*, 1, 221-227, <https://doi.org/10.1038/ngeo156>, 2008.
- Peng, T., Sun, C., Zhang, Y., and Fan, F.: Spatiotemporal variation of anthropogenic heat emission landscape pattern in the central urban area of Guangzhou, *Journal of South China Normal University (Natural Science Edition)*, 53, 92-102, <https://doi.org/10.6054/j.jscnun.2021080>, 2021.
- Saraga, D., Maggos, T., Degrendele, C., Klánová, J., Horvat, M., Kocman, D., Kanduč, T., Garcia

- Dos Santos, S., Franco, R., Gómez, P. M., Manousakas, M., Bairachtari, K., Eleftheriadis, K., Kermenidou, M., Karakitsios, S., Gotti, A., and Sarigiannis, D.: Multi-city comparative PM<sub>2.5</sub> source apportionment for fifteen sites in Europe: The ICARUS project, *Science of The Total Environment*, 751, 141855, <https://doi.org/10.1016/j.scitotenv.2020.141855>, 2021.
- Shen, Z., Zhang, Q., Cao, J., Zhang, L., Lei, Y., Huang, Y., Huang, R. J., Gao, J., Zhao, Z., Zhu, C., Yin, X., Zheng, C., Xu, H., and Liu, S.: Optical properties and possible sources of brown carbon in PM<sub>2.5</sub> over Xi'an, China, *Atmospheric Environment*, 150, 322-330, <https://doi.org/10.1016/j.atmosenv.2016.11.024>, 2017.
- Shrivastava, M., Lou, S., Zelenyuk, A., Easter, R. C., Corley, R. A., Thrall, B. D., Rasch, P. J., Fast, J. D., Massey Simonich, S. L., Shen, H., and Tao, S.: Global long-range transport and lung cancer risk from polycyclic aromatic hydrocarbons shielded by coatings of organic aerosol, *Proceedings of the National Academy of Sciences*, 114, 1246-1251, <https://doi.org/10.1073/pnas.1618475114>, 2017.
- Turpin, B. J., Huntzicker, J. J., and Hering, S. V.: Investigation of organic aerosol sampling artifacts in the los angeles basin, *Atmospheric Environment*, 28, 3061-3071, [https://doi.org/10.1016/1352-2310\(94\)00133-6](https://doi.org/10.1016/1352-2310(94)00133-6), 1994.
- Watson, J. G., Antony Chen, L. W., Chow, J. C., Doraiswamy, P., and Lowenthal, D. H.: Source apportionment: Findings from the U.S. supersites program, *Journal of the Air & Waste Management Association*, 58, 265-288, <https://doi.org/10.3155/1047-3289.58.2.265>, 2008.
- 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, <https://doi.org/10.1016/j.atmosenv.2014.11.060>, 2015.
- Yang, S., Du, H., and Fan, Y.: Spatiotemporal variations of dust emission in Qaidam basin during the past 40 years, *Research in Cold and Arid Regions*, <https://doi.org/10.1016/j.rcar.2024.12.007>, 2024.
- 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, *Environ Pollut*, 263, 114531, <https://doi.org/10.1016/j.envpol.2020.114531>, 2020.
- Zhang, B., Shen, Z., Sun, J., He, K., Zou, H., Zhang, Q., Li, J., Xu, H., Liu, S., Ho, K.-F., and Cao, J.: County-level of particle and gases emission inventory for animal dung burning in the Qinghai-Tibetan Plateau, China, *Journal of Cleaner Production*, 367, <https://doi.org/10.1016/j.jclepro.2022.133051>, 2022.
- Zhang, R., Jing, J., Tao, J., Hsu, S. C., Wang, G., Cao, J., Lee, C. S. L., Zhu, L., Chen, Z., Zhao, Y., and Shen, Z.: Chemical characterization and source apportionment of PM<sub>2.5</sub> in Beijing: seasonal perspective, *Atmospheric Chemistry and Physics*, 13, 7053-7074,

<https://doi.org/10.5194/acp-13-7053-2013>, 2013.

Zhang, S.: Spatial and temporal variation characteristics of atmospheric dust deposition flux in Hebei Province over the recent 20 Years, Master's thesis, Hebei Normal University, 2010.

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.2024.101978>, 2025.

Zhou, Y., Xing, X., Lang, J., Chen, D., Cheng, S., Wei, L., Wei, X., and Liu, C.: A comprehensive biomass burning emission inventory with high spatial and temporal resolution in China, *Atmospheric Chemistry and Physics*, 17, 2839-2864, <https://doi.org/10.5194/acp-17-2839-2017>, 2017.

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, X., Zhu, K., Xie, M., Huang, A., Ouyang, Y., Chen, F., and Zhao, W.: Analysis of current situation and future trend of anthropogenic heat emissions in Jiangsu Province, *Climatic and Environmental Research*, 21, 306–312, <https://doi.org/10.3878/j.issn.1006-9585.2016.15171>, 2016.