Thank you very much for your constructive comments and insightful feedback on our work. We have carefully considered your suggestions and made corresponding revisions to the manuscript. We have endeavored to improve the clarity, rigor, and presentation of our study accordingly.

The revised parts of the manuscript, highlighted in red, reflect the changes made in response to your comments. Revision notes, point-by-point, are provided as follows:

(1) I support the comments/suggestions provided by two esteemed reviewers. Addressing those will definitely enhance the quality of this manuscript.

We sincerely appreciate this supportive comment and your acknowledgment of the constructive suggestions provided by the first two reviewers. We fully agree that the revisions made in response to these comments have substantially enhanced the scientific rigor and logical coherence of the manuscript.

In our point-by-point responses, all reviewer comments have been systematically addressed, including:

Clearly highlighting the novelty and regional contributions of the study;

Deepening the physical mechanism explanations, particularly regarding the vertical gradients of radiative forcing and their climatic implications;

Incorporating statistical significance tests for trends and uncertainty analyses to ensure methodological rigor;

Optimizing figure layouts and annotations to improve clarity and interpretability of the results.

We believe that this round of revisions has materially improved both the overall quality and the scholarly value of the manuscript.

(2) The graphical abstract reads crowded. Needs revision.

We sincerely appreciate your valuable suggestion. The original graphical abstract indeed contained an excessive amount of information, which reduced the clarity and emphasis of the main conclusions.

In response, the graphical abstract has been redesigned as follows:

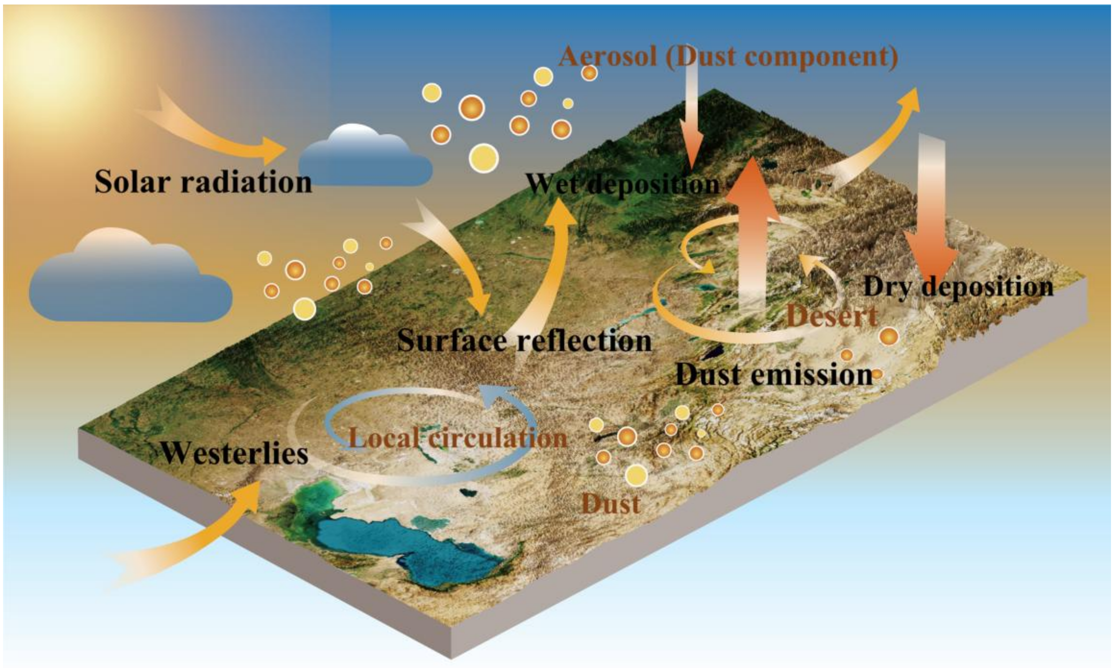
Redundant secondary elements and textual annotations have been removed;

The main storyline—“emissions → deposition → radiation”—has been emphasized to highlight the research logic;

Color schemes and visual hierarchy have been optimized to make the core information more prominent and easily interpretable.

The revised abstract is now more concise and intuitive, effectively conveying the key scientific insights of the study.

Revised Figure:



(3) First-time used abbreviations must be expanded.

We appreciate your reminder to adhere to this academic convention. We have conducted a thorough review of the manuscript to ensure that all abbreviations (e.g., MERRA-2, CMIP6, SBDART, SSPs, MME, ADRF, TOA, SFC, ATM, SARIMA, etc.) are spelled out in full upon their first occurrence.

(4) L71: This sentence reads incomplete; revise.

We appreciate you highlighting this issue. The sentence in line 71 has been revised to ensure grammatical completeness and logical clarity. Additionally, the surrounding paragraph has been optimized to improve contextual flow and enhance accuracy of expression **(Manuscript, pp. 3–4, lines 65–104)**.

Revised related paragraphs:

Model simulations provide information on the temporal and spatial changes of dust aerosols worldwide and facilitate predictions of future trends (Li et al., 2021). Climate models, such as CMIP5 and CMIP6, have enhanced our understanding of the main characteristics of dust aerosols. These models feature increasing resolutions and increasingly complex physical processes and parameterizations, demonstrating their ability to simulate dust events and processes on meso- to global scales (Zhao et al., 2022). In particular, CMIP6 experiments have provided critical support for assessing the climatic effects of dust emissions (Braconnot et al., 2021; Zhao et al., 2024). However, due to insufficient resolution and simplified regional topography, the applicability of these global studies to the arid regions of Central Asia remains limited, underscoring the need for high-resolution analyses at the regional scale.

The arid regions of Central Asia, including Xinjiang in China, constitute the world's second-largest dust source area, with distinctive surface characteristics leading to significant spatiotemporal variations in dust emission fluxes (Shen et al., 2016). However, current research has primarily focused on the spatiotemporal distribution and transport processes of dust (Li et al., 2022b; Tao et al., 2022), while key aspects of the local dust lifecycle in this region—such as the long-term evolution of dust emission–deposition budgets, the strong dependence of direct radiative forcing on dust vertical profiles, and modal differences in dust–climate feedbacks under different carbon emission scenarios—remain poorly understood. These knowledge gaps significantly constrain the reliability of climate models over Central Asia, and uncertainties in radiative forcing estimates primarily stem from the lack of ground-based validation due to the scarcity of observational stations (Brown et al., 2021; Wu & Boor, 2021).

To overcome the above limitations, this study establishes a multi-source data integration framework that systematically incorporates a full-chain analysis of "emission–deposition–radiation," focusing on the regional characteristics of the dust lifecycle over the arid regions of Central Asia. Unlike previous studies that have mainly concentrated on the global scale (Kok et al., 2023; Zhao et al., 2022, 2023, 2024), this work achieves an integrated assessment at the regional scale and emphasizes the role of observations in constraining model uncertainties. The specific innovations are reflected in three aspects: (1) by combining MERRA-2 reanalysis with CMIP6 multi-model ensembles through statistical downscaling, the long-term evolution of dust emission – deposition budgets and their scenario-based differences in Central Asia are systematically characterized, thereby providing regionally refined insights to complement global model results; (2) using the SBDART radiative transfer model together with observational data from the SONET Asian Dust Monitoring Network and the Jinghe CE318 ground-based remote sensing site, the long-term trends of dust shortwave radiative forcing under clear-sky conditions are quantified; and (3) by introducing the SARIMA statistical model, the short-term evolution and risk implications of dust radiative effects are explored. This framework not only deepens the understanding of dust physical mechanisms under the complex topography and local climate of Central Asia but also provides new scientific support for improving regional climate simulations and environmental risk management.

The structure of this paper is as follows. Section 2 presents the data sources, the downscaling method for the CMIP6 dust budget, and the calculation method for clear-sky aerosol radiative forcing. Section 3 examines the detailed characteristics of the dust budget, projections of future changes, and the radiative forcing of dust aerosols. Finally, the main conclusions and a discussion are presented in Section 4.

(5) L109: heliometers or sun-photometers?

We appreciate your precise correction regarding terminology.

The term has been corrected to “sun-photometers.” Accordingly, the relevant text in **line 121 on page 5** has been updated to “ground-based sun-photometers” to ensure consistency and accuracy of professional terminology.

(6) Section 2.2.1: Here, the authors need to mention the station from where the AERONET/SONET data were used. Include the data access link.

We thank the reviewer for this important suggestion. We agree that data transparency and traceability are essential for reproducibility. Accordingly, Section 2.2.1 **(page 6, lines 128 and 135)** has been supplemented to:

Specify the observation sites used: Dushanbe, Issyk-Kul, Kashgar, and Jinghe;

Provide data access links:

AERONET: https://aeronet.gsfc.nasa.gov/

SONET: http://www.sonet.ac.cn/

Revised related paragraphs:

AERONET (AErosol RObotic NETwork) employs a CE-318 solar photometer to measure aerosol optical depth (AOD) across eight bands in the range of 340–1640 nm and to derive microphysical parameters, including single scattering albedo (SSA), refractive index (m), and particle size spectrum (Holben et al., 1998; Holben et al., 2001). The Level 2 data exhibit an uncertainty of less than 5%. As an internationally recognized standard for ground-based aerosol observations, its long-term stability and algorithmic consistency provide reliable input for radiative forcing calculations (García et al., 2012). The data used in this study are available from the AERONET website (https://aeronet.gsfc.nasa.gov/).

The Chinese Academy of Sciences-led SONET (Sun-sky radiometer Observation NETwork) employs the CE318-DP instrument to provide information on the chemical composition and vertical profile of aerosols while adhering to AERONET's stringent quality control procedures. The establishment of SONET sites has effectively addressed gaps in AERONET's spatial coverage in this source region (Li et al., 2018). Cross-validation demonstrates that the correlation coefficient between SONET and AERONET AOD is 0.98 (RMSE < 0.02), confirming a seamless integration of the two datasets (She et al., 2024). The SONET data can be accessed from its official website (http://www.sonet.ac.cn/).

(7) Figure 6 is difficult to understand (overcrowded). Same for Figure 9.

We sincerely thank the reviewer for these valuable comments regarding figure readability. We fully appreciate this concern and have optimized the figures accordingly, including adjustments to line thickness, color contrast, and legend layout to enhance overall clarity.

Figure 6 presents a continuous 120-year time series (1980–2100) spanning multiple regions (northern Xinjiang, southern Xinjiang, Central Asia, etc.) and variables (emissions, dry and wet deposition). Integrating such an extended temporal span and diverse components into a single figure inevitably introduces some visual complexity; however, we believe this format is essential for providing a comprehensive and comparable overview of historical and future dust budget evolution.

Figure 9 depicts site-scale daily data, where high-frequency variability is crucial for capturing the instantaneous characteristics of dust radiative forcing. Thus, excessive smoothing or simplification would obscure these key features.

We apologize for any inconvenience in readability and have included detailed guidance in the figure captions. Despite these visual challenges, we maintain that these figures are indispensable for conveying both the long-term patterns and short-term dynamics of the dust life cycle.

Revised Figure6:

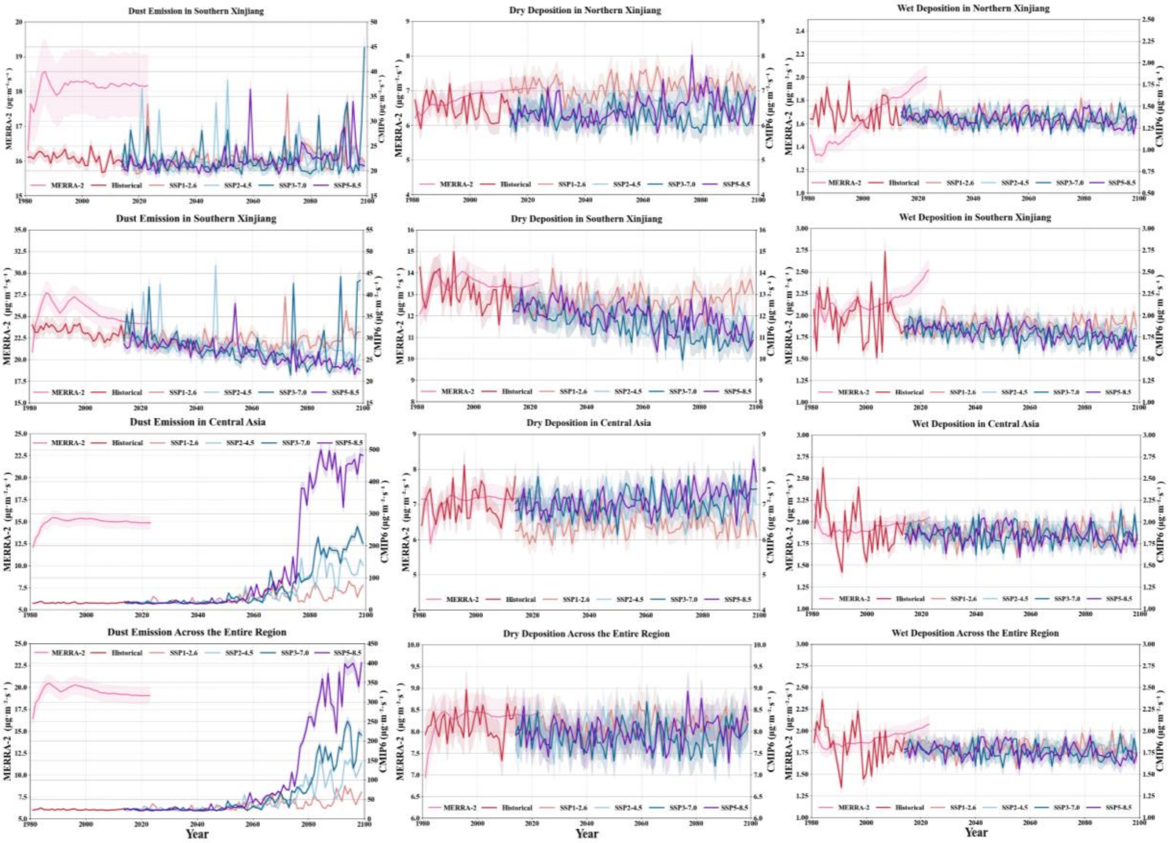


Figure. 6 Time evolution of the dust budget. Dust emissions, dry and wet deposition ($\mu g \cdot m^{-2} \cdot s^{-1}$) for panels (a–c) northern Xinjiang, (d–f) southern Xinjiang, (g–i) Central Asia, and (j–l) the entire study region. Results are from the CMIP6 multi-model ensemble (MME; 1980 – 2100) and MERRA-2 (1980 – 2023).

Finally, we sincerely thank the scholar for highlighting several of their valuable studies on aerosol loading in Central Asia. We have incorporated some of these references into the Introduction to strengthen the scientific context of our work and to better position this study within the regional research framework. These additions further clarify the relevance of our research and demonstrate how it builds upon and complements existing studies in Central Asia.