Thank you for your decision and constructive comments on my manuscript. We have carefully considered the reviewers' suggestions and made corresponding changes. We have tried our best to improve the manuscript accordingly.

In accordance with ACP discussion policies, the full revised manuscript paragraphs are not displayed in these responses. Instead, for each comment, we provide a concise summary of the modifications made and indicate the specific sections, page numbers, and line numbers in the revised manuscript where the changes can be found. We hope that this format allows the reviewers to efficiently assess the revisions while maintaining clarity and compliance with the journal's guidelines.

The parts highlighted in red in the revised manuscript have been updated according to your comments. Revision notes, point-by-point, are given as follows:

RC1:

Major comments:

（1）Some figures are difficult to interpret without clear legends and labels. For instance the unit in figure 6 caption: µg-m-2-s-1, the superscripts should be typeset properly. I recommend change the font size for figures.

We sincerely thank the reviewer for the valuable comments. Due to an oversight, some figure legends, labels, and unit formatting were not sufficiently clear. In response, the entire manuscript—including all figures—has been carefully reviewed. Figure 6, in particular, has been completely redrawn and reformatted, with legends and labels revised or supplemented where necessary. Additionally, the formatting of units, including superscripts and subscripts, has been standardized throughout. We greatly appreciate your careful review and constructive suggestions.(**manuscript pages 17, lines 380)**

Revised Figure:

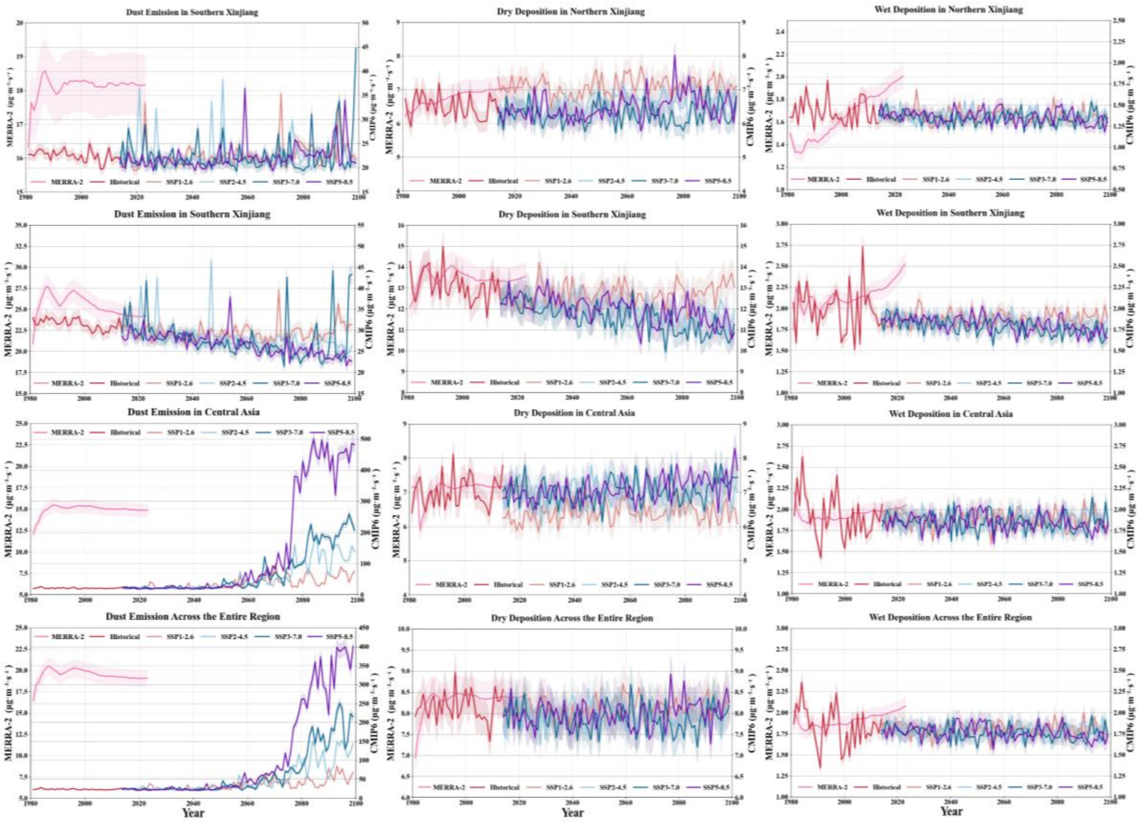


Figure. 6 Time evolution of the dust budget. Dust emissions, dry and wet deposition (μg·m⁻²·s⁻¹) for panels (a–c) northern Xinjiang, (d–f) southern Xinjiang, (g–i) Central Asia, and (j–l) the entire study region. Results are from the CMIP6 multi-model ensemble (MME; 1980–2100) and MERRA-2 (1980–2023).

（2）Please proofread the whole manuscript. There are occasional grammar issues and awkward phrasing. Most of them do not substantially impede understanding, though some do affect the clarity.

We sincerely thank the reviewer for the careful comments. In response to the identified grammatical issues and occasional awkward phrasing, the entire manuscript has been thoroughly reviewed and revised on a sentence-by-sentence basis. Particular attention was given to correcting grammatical errors and improving unclear or awkward expressions, ensuring overall clarity, accuracy, and readability.

（3）This study uses a combination of MERRA-2, CMIP6, and SBDART, but it is not very clear what is genuinely new compared to previous dust studies over Central Asia. The authors should clarify what exactly is new in this work and how this advances beyond previous studies.

We sincerely thank the reviewer for this insightful comment. In the revised manuscript, we have clarified the novelty and advancement of our study in the Introduction section **(see revised version, pp. 3-4, lines 65-104, 1. Introduction)**. The main innovations and contributions of this work are summarized as follows:

Previous pioneering studies (e.g., Kok et al., 2023; Zhao et al., 2022–2024) have greatly enhanced our understanding of the global dust cycle, but their emphasis has been primarily global in scope, where coarse spatial resolution constrains the characterization of regional processes over complex terrains such as Central Asia. Our study introduces a regional-scale multi-source data fusion framework that systematically integrates the full "emission–deposition–radiative forcing" chain. This framework enables a more refined depiction of the dust life cycle in arid Central Asia, effectively bridging the gap between global simulations and regional processes.

Beyond previous regional studies that primarily examined dust distribution and transport (e.g., Li et al., 2022b; Tao et al., 2022), this work advances the field in three key aspects:

(1) By integrating MERRA-2 reanalysis with the CMIP6 multi-model ensemble and applying a statistical downscaling approach, we quantified the long-term evolution and scenario-dependent divergence of dust emission–deposition budgets in Central Asia.

(2) Using the SBDART radiative transfer model constrained by ground-based observations from the SONET network and the Jinghe CE318 site, we obtained refined estimates of clear-sky shortwave dust radiative forcing.

(3) A SARIMA statistical model was further employed to examine short-term variations and potential risks of dust–radiation interactions, offering a novel perspective for near-term environmental prediction.

Importantly, the study also emphasizes reducing model uncertainty through observational constraints, thereby bolstering the credibility of radiative forcing assessments in data-scarce regions. Overall, this work delivers one of the first integrated assessments linking dust emission, deposition, and radiative effects over the complex terrain of Central Asia. The proposed framework not only deepens our understanding of regional dust–climate interactions but also provides scientific support for enhancing climate model performance and environmental risk management in arid regions.

Revised excerpt (pp. 3-4, lines 85-95):

"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... [further details on (2) and (3) as summarized above]."

（4）The results show strong vertical gradients in radiative forcing and surface cooling. However, the physical interpretation in the manuscript is limited. For instance, what are the implications for regional climate? More discussion regarding the broader implication would be beneficial.

We sincerely thank the reviewer for this valuable comment, which highlights a crucial aspect of our study. A thorough elucidation of the physical mechanisms underlying the vertical gradient of radiative forcing and its climatic implications substantially enhances the scientific value of the research. Accordingly, the manuscript has been substantially revised and supplemented **(primarily on pp. 17–18, lines 393–416, 3.3.1 Monthly average changes in direct radiative forcing by dust aerosols)** to strengthen the physical interpretation and expand the discussion of its regional climate significance.

The specific revisions and supplements are summarized as follows:

Enhanced explanation of the "surface cooling–atmospheric heating" mechanism: The results indicate that the pronounced negative surface radiative forcing (with cooling centers reaching –20 W/m²) primarily arises from the combined effects of dust scattering and absorption of solar radiation, significantly reducing net surface radiation. The resultant surface energy deficit further weakens sensible heat flux and evaporation, thereby suppressing the exchange of heat and moisture from the surface to the atmosphere. This provides a clear physical depiction of how dust alters the surface–atmosphere energy balance to establish a vertical radiative gradient.

In-depth discussion of potential regional climate impacts and significance:

Impact on aridity and the water cycle: Surface cooling and reduced evapotranspiration may exacerbate inherent water deficits in the arid regions of Central Asia, posing potential constraints on vegetation growth and agricultural water resources.

Feedback on dust activity: Atmospheric heating enhances the vertical temperature gradient, which may increase the likelihood of deep convection, thereby potentially amplifying the frequency and intensity of spring–summer dust storms. This "dust–

radiation–dynamics” feedback loop represents a key finding of this study.

Implications for weather and ecosystems: Based on observed strong day-to-day fluctuations in ADRF at the measurement sites, such instantaneous radiative perturbations may alter boundary layer stability and convective potential, consequently affecting regional precipitation variability and ecosystem stability.

Revised excerpt (from pp. 17–18, lines 393–416):

"The spatial pattern of surface (SFC) radiative forcing (Figure 7e–h) exhibits stronger negative values, with two pronounced cooling centers over the Tarim Basin and southwestern Central Asia, where shortwave radiation loss peaks at –20 W/m². This arises from the combined scattering and absorption effects of dust particles on incoming solar radiation (Li et al., 2022a), which substantially reduce surface net radiation, thereby diminishing sensible heat flux and evaporation processes and suppressing the transfer of heat and water vapor from the surface to the atmosphere. The atmospheric radiative forcing (ADRF) exhibits a spatial pattern consistent with those at the TOA and SFC but features positive values (10.02 W/m² in spring and 9.89 W/m² in summer), indicating the energy redistribution role of dust aerosols in trapping solar energy within the atmospheric system via shortwave absorption. This vertical gradient of 'surface cooling and atmospheric heating' induces substantial changes in the regional thermodynamic structure (Kok et al., 2017). On one hand, surface cooling diminishes sensible heat flux and evaporation, thereby exacerbating moisture deficits in Central Asia’s arid regions and limiting vegetation growth and agricultural productivity. On the other hand, atmospheric heating strengthens the temperature gradient from the boundary layer to the free troposphere, enhancing the potential for deep convection, which could intensify the frequency and severity of spring–summer dust storms and modify regional precipitation patterns and extreme weather events."

Technical comments:

（1）Please define all the acronyms at their first use.

We sincerely thank the reviewer for the careful reminder. The manuscript has been thoroughly checked to ensure that all abbreviations are fully defined upon their first appearance. The main abbreviations include:

MERRA-2: Modern-Era Retrospective analysis for Research and Applications, Version 2

CMIP6: Coupled Model Intercomparison Project Phase 6

SBDART: Santa Barbara DISORT Atmospheric Radiative Transfer model

ADRF: Aerosol Direct Radiative Forcing

TOA: Top of Atmosphere

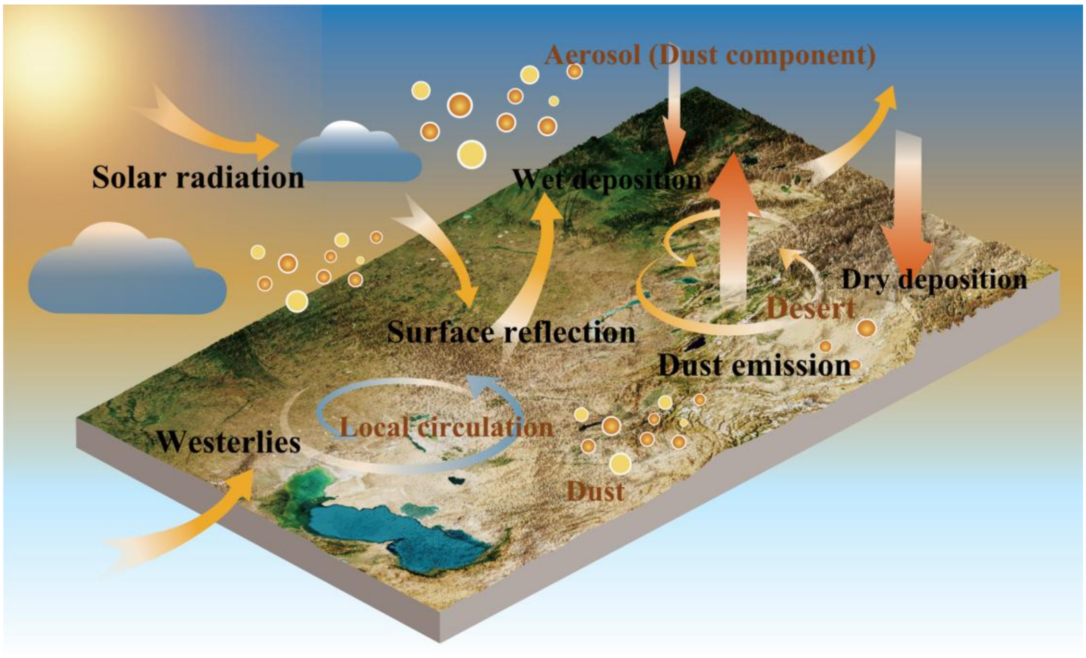
SFC: Surface

SSPs: Shared Socioeconomic Pathways

（2）The graphical abstract is overloaded with text and figures, which makes it difficult to read the key message and results in low readability. The author is encouraged to simplify the graphical abstract by focusing on the main story and remove secondary details.

We sincerely appreciate the reviewer's constructive comment. In response, the graphical abstract has been completely redesigned. The revised version removes redundant text and secondary graphical details, focusing instead on the core research storyline—from dust emission and deposition to radiative forcing and climate feedback. This streamlined design enhances visual clarity, emphasizes the key information, and substantially improves readability.

Revised Figure:



(3) The linear trend analysis was used throughout the manuscript, but it is not clear whether statistical significance was tested. Please clarify the method used to calculate the trends and whether the reported values are statistically significant.

We sincerely thank the reviewer for this important comment, which underscores a critical aspect of our analysis. Evaluating the statistical significance of trends is indeed essential for bolstering the reliability of the study's conclusions.

To address this, we have incorporated detailed information on the trend analysis and significance testing **in Section 2.2.4 ("Linear Trend Method"; revised manuscript, p. 10, lines 240–247).** Specifically:

Trend calculation method: Linear trends were estimated using ordinary least squares (OLS) regression to derive the slope.

Statistical significance testing: All trends were assessed via a two-tailed t-test, with $p < 0.05$ deemed statistically significant.

Visualization of significance: In the spatial trend maps, grid points exhibiting significant trends ($p < 0.05$) are denoted by dots.

Regional average trends: In the time series plots of regional mean trends, both the regression slope and the corresponding p-value are explicitly annotated on the figures.

Revised excerpt (from p. 10, lines 240–247):

2.2.4 Linear Trend Method

In this study, the ordinary least squares (OLS) method was used to perform linear regression on the dust budget time series, with trend significance assessed via a two-tailed t-test. Spatial trends were derived by conducting independent regressions at each grid point, with statistically significant results ($p < 0.05$) indicated by stippling in the figures. Regional mean trends were calculated by regressing the annual averages of grid values within specific regions (Central Asian countries, northern Xinjiang, and southern Xinjiang). The regression slopes and corresponding p-values were annotated directly on the time series plots.

（4）The description of the downscaling method lacks clarity on uncertainties. Please provide more justification for the choice of this method versus dynamic downscaling and quantify potential biases introduced.

We sincerely thank the reviewer for this insightful comment, which has helped substantially enhance the methodological rigor and deepen the discussion of uncertainties. In response, extensive revisions and additions have been made to the manuscript, primarily **in Section 4.2.1 ("Uncertainty Analysis"; revised manuscript, pp. 25–28, lines 570–635)** and the associated methodological descriptions. The specific clarifications are summarized as follows:

Rationale for method selection:

The reasons for adopting statistical downscaling (the Delta method) have been clarified as follows:

Computational efficiency: Dynamic downscaling demands substantial computational resources, whereas the Delta method facilitates efficient analyses across long-term, multi-model, and multi-scenario simulations.

Reduced sensitivity to parameterization uncertainty: Dynamic downscaling outcomes are highly sensitive to internal parameterizations, which can introduce additional, difficult-to-quantify biases in observation-sparse regions such as Central Asia.

Preservation of statistical relationships: The Delta statistical downscaling method effectively accommodates Central Asia’s complex terrain while maintaining the statistical relationships between dust emissions and climate variables, rendering it well-suited for this study.

Quantification of potential biases:

Two primary sources of uncertainty have been systematically evaluated and quantified:

Inter-model uncertainty: Figure 11a and Supplementary Figure 12 spatially illustrate the biases of individual models in the multi-model ensemble (MME) relative to MERRA-2 reanalysis data. Systematic positive/negative biases are evident in key source regions, such as the Taklamakan and Karakum deserts. The inherent dispersion among model simulations is further visualized via the $\pm 1\sigma$ standard deviation of the MME (shaded area in Figure 10b).

Bias introduced by the downscaling procedure:

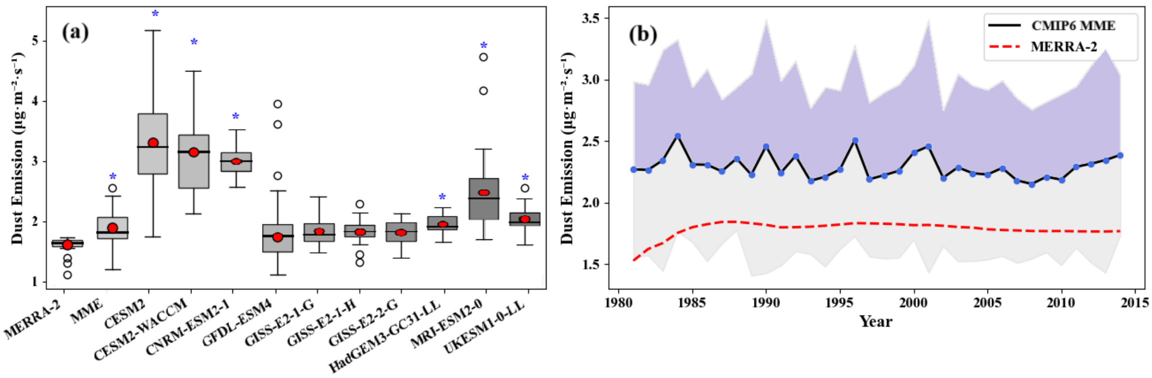
The performance of the statistical downscaling was quantified using spatial root-mean-square error (RMSE) to identify areas of higher uncertainty (e.g., RMSE > 2 μg m^{-2} s^{-1} in complex terrains such as the Tarim Basin; Figure 11b).

Scatterplots (Supplementary Figure 13a) reveal an overall bias of −1.26 and RMSE of 4.31, with a coefficient of determination (R^2 > 0.91), demonstrating high fidelity in capturing spatial patterns despite minor systematic underestimation.

Time series comparisons (Supplementary Figure 13b) confirm that the method reasonably reproduces observed interannual and seasonal variability.

Revised excerpt (from pp. 58–68, lines 570–635, 4.2.1 Uncertainty Analysis):

"The bias-corrected statistical downscaling method employed in this study, which relies on MERRA-2 data, is well-suited to Central Asia's complex terrain and sparse observational networks. It offers low computational costs while preserving the statistical relationships between dust emissions and climate variables—advantages over dynamic downscaling, which is resource-intensive and sensitive to parameterization uncertainties. However, its capacity to simulate extreme events (e.g., intense dust storms) remains limited. To quantify downscaling biases, Figure 11b illustrates the spatial RMSE between CMIP6 downscaled outputs and MERRA-2 data (RMSE > 2 μg·m⁻²·s⁻¹ in the Tarim Basin and Karakum Desert). Supplementary Figure 13a shows a high correlation ($R^2 > 0.91$) with minor underestimation (Bias = –1.26, RMSE = 4.31), and time series (Figure 13b)

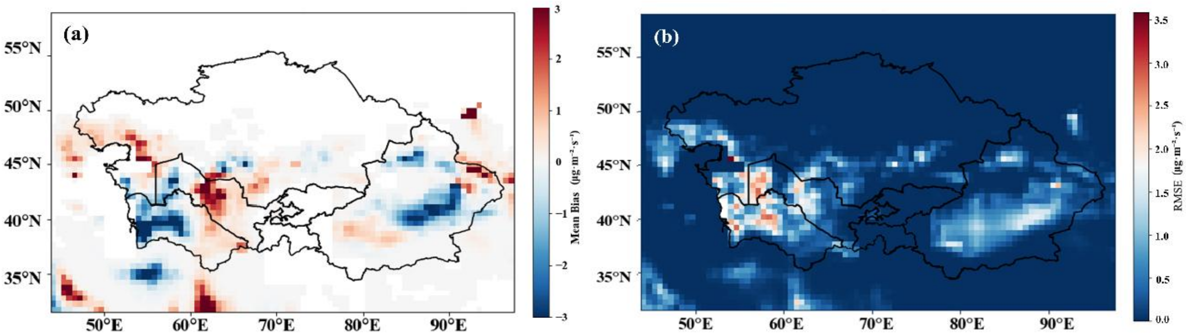


confirm reproduction of variability."

Figure. 11 (a) Dust emission biases of individual models relative to MERRA-2 reanalysis data; (b) time series of dust emissions from the CMIP6 multi-model ensemble, with ±1σ inter-model variability indicated by the shaded area.

Figure. 12 (a) Spatial distribution of biases between individual models in the multi-model ensemble and MERRA-2 reanalysis data; (b) spatial distribution of root-mean-square error (RMSE) between CMIP6 downscaled outputs and MERRA-2 reanalysis data.

（5）For the SBDART simulations, it is not clear how representative the ground-based input data are across such a vast heterogeneous region. How many stations, and how are they weighted? More detail on spatial representativeness and limitations would strengthen the analysis.



We sincerely thank the reviewer for raising this critical point. We fully agree that clarifying the representativeness of ground-based observations is essential for correctly interpreting the SBDART simulation results. In response, we have added a detailed explanation and clarification in the revised manuscript **(p. 19, lines 421–434, Section 3.3.2 "Refinement of Aerosol Direct Radiative Forcing in Dusty Weather")**. The revisions are summarized as follows:

(1) Number, location, and representativeness of observation sites

The SBDART simulations in this study were based on long-term aerosol optical properties observed at five ground-based sites, including:

Dushanbe (AERONET): representing the inland region of Central Asia;

Issyk-Kul (AERONET): representing high-altitude lake environments;

Kashgar (AERONET and SONET): representing the dust source region of the Tarim Basin;

Jinghe (SONET): representing the Gobi–desert transition zone.

These sites encompass the main geomorphological units and typical surface types of Central Asia, enabling spatial representation of the regional diversity in dust aerosol radiative effects. Although the number of sites is limited, their strategic spatial distribution ensures representativeness. Thus, our analysis emphasizes localized radiative responses under distinct environmental conditions rather than spatially averaged regional means.

(2) Weighting strategy and spatial representativeness

No spatial weighting was applied among these sites, primarily for the following reasons:

Long-term, continuous aerosol observations are extremely scarce across Central Asia, and these five sites constitute the full set of available high-quality datasets.

Applying spatial weighting with limited and unevenly distributed sites may introduce misleading regional biases. Therefore, each site was treated as an independent case study to highlight differences and similarities in dust radiative forcing under varying terrain and climatic settings.

(3) Discussion on spatial representativeness and limitations

A new paragraph has been added in the revised manuscript to explicitly address these limitations:

Simulations based on limited sites can only reflect localized radiative responses in representative regions, rather than capturing the full spatial heterogeneity of Central Asia.

As exemplified by Issyk-Kul, high-altitude topography and its shielding effects may weaken springtime dust vertical transport, potentially leading to underestimation of local radiative forcing and underscoring challenges in mountain observations.

Moreover, cross-validation with MERRA-2 reanalysis data (Supplementary Fig. S1) confirms the overall consistency and reliability of the site observations at a regional scale.

Finally, the Conclusion section now explicitly recommends that future research enhance spatial representativeness by expanding ground-based networks and integrating satellite–model synergistic retrievals.

Revised excerpt (from p. 19, lines 421–434):

"These simulations are based on ground-based observations from 2011 to 2023, encompassing AERONET sites at Dushanbe (Tajikistan; representing the Central Asian interior), Issyk-Kul (Kyrgyzstan; representing high-altitude lake regions), and Kashgar (Xinjiang, China; representing the Tarim Basin dust source region), as well as the SONET site at Kashgar and our self-established Jinghe site (Xinjiang, China; representing the Gobi–desert transitional zone). Although the number of sites is limited, their spatial distribution covers the primary dust source regions and representative surface types, thereby achieving a degree of regional representativeness. No spatial weighting was applied, as long-term observations are scarce in Central Asia, and treating sites as independent case studies avoids introducing biases from uneven distribution. Limitations include the inability to fully capture spatial heterogeneity; for instance, Issyk-Kul's topography may underestimate dust transport. Cross-validation with MERRA-2 (Supplementary Fig. S1) confirms site reliability at the regional scale."

(6) The SARIMA model is interesting but feels a bit disconnected, it is not well integrated with the rest of the results. The justification for why a short-term statistical forecast is useful in this context should be expanded. Also please add error metrics to evaluate this forecast skill quantitatively.

We sincerely thank the reviewer for highlighting this important point regarding the integration of the SARIMA model within the overall research framework and its predictive relevance. This comment has greatly assisted us in refining the logical structure and enhancing the scientific rigor of our analysis. In response, we have substantially revised the manuscript to clarify the methodological role, integration, and quantitative validation of the SARIMA model. The main revisions are summarized as follows **(pp. 24–25, lines 536–568, Section 4.2.1 "SARIMA Forecasting"):**

(1) Scientific positioning of the SARIMA model and its integration into the overall framework

The revised manuscript clearly positions the SARIMA model as a methodological supplement rather than an independent analytical module. It is designed to bridge the temporal gap between the historical diagnostic analysis based on MERRA-2 reanalysis and SBDART ground-based simulations, and the long-term projections from CMIP6 scenario experiments. While CMIP6 primarily captures centennial-scale trends, SARIMA effectively characterizes interannual and short-term internal variability in dust radiative forcing, thereby linking long-term climate projections with near-future variations. Consequently, SARIMA serves as a key component of the integrated “emission–deposition–radiation” framework, enabling operational prediction and temporal continuity within the system.

(2) Scientific rationale and practical significance of short-term statistical prediction

In response to the reviewer’s concern about the necessity of short-term forecasting, the revised text elaborates further on its scientific justification and real-world relevance. Dust radiative forcing exhibits strong spatiotemporal non-stationarity and high uncertainty, compounded by limited observational data over Central Asia. Under these conditions, short-term statistical prediction provides actionable insights that complement long-term climate projections. The SARIMA model identifies potential dust-active periods within the next 3–5 years and quantifies the magnitude of interannual fluctuations. These results offer scientific support for regional assessments of agricultural productivity, water resources, renewable energy planning, and ecological risk management, thereby enhancing the operational applicability of the study.

(3) Quantitative validation of model performance

Following the reviewer’s suggestion, we have added quantitative validation metrics for the SARIMA model’s predictive performance (Section 4.2.1 and Supplementary Figure 11). The results demonstrate RMSE = 1.72 W/m^2, MAE = 1.21 W/m^2, MAPE = 8.6%, and R^2 = 0.70, indicating high predictive accuracy in capturing short-term variability. Furthermore, the residual series passed both the Ljung–Box Q test ($p > 0.05$) and the Kolmogorov–Smirnov normality test ($D = 0.12$), confirming the model’s statistical robustness.

Through these revisions, the functional role of the SARIMA model is now clearly delineated. It complements CMIP6-based long-term simulations in the temporal dimension, while its quantitative validation enhances both the scientific reliability and practical value of the results. By integrating SARIMA into the analysis framework, the study provides a more complete representation of dust–climate interactions and offers actionable guidance for regional climate risk management and near-future adaptation planning.

Revised excerpt (from pp. 24–25, lines 536–569):

"This study integrates MERRA-2 reanalysis data, CMIP6 multi-model ensemble (MME) simulations, and ground-based sun photometer observations to develop a fully coupled 'emission–deposition–radiation' framework for the dust cycle in Central Asia, thereby systematically elucidating the radiative regulatory mechanisms of dust aerosols on the land–atmosphere system. To address the pronounced spatiotemporal heterogeneity in aerosol radiative forcing and the limitations of observational data, this study employs a seasonal autoregressive integrated moving average (SARIMA) model as a methodological supplement, bridging the temporal gap between historical diagnostics (MERRA-2/SBDART) and long-term CMIP6 projections by capturing interannual and short-term variability. In contrast to century-scale CMIP6 simulations, SARIMA quantifies short-term internal variability (Kumar et al., 2018), providing actionable near-term forecasts (3–5 years) for dust-active periods, which support regional risk assessments in agriculture, water resources, and ecology. Model validation (Supplementary Figure 11) shows RMSE = 1.72 W/m^2, MAE = 1.21 W/m^2, MAPE = 8.6%, R^2 = 0.70; residuals pass Ljung–Box Q test ($p > 0.05$) and Kolmogorov–Smirnov test (D = 0.12), confirming robustness. Thus, SARIMA complements the framework, enhancing operational applicability for near-future adaptation."

We sincerely appreciate your guidance and suggestions. We will continue to work diligently to improve and refine our research. Thank you, reviewers and editors, for your enthusiastic contributions. We hope the corrections will be approved. In line with ACP guidelines, the full revised manuscript will be submitted separately upon completion of the discussion phase.