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:

RC2:

Major comments:

(1) The claim of presenting the first "closed-loop emission-deposition-radiation analysis" should be moderated. Several previous studies (e.g., Kok et al., 2023; Zhao et al., 2022, 2023, 2024) have examined the dust life cycle, particularly at the global scale. While the proposed "closed-loop" framework is conceptually interesting, its interpretation and scientific depth remain somewhat superficial. A more detailed discussion of how this framework advances understanding beyond prior studies would strengthen the contribution of the manuscript.

We sincerely thank the reviewer for this constructive comment. The concern regarding the originality and scientific depth of the "closed-loop emission–deposition–radiation analysis" framework is highly valuable for refining the scientific positioning and rigor of our study. In response, we have carefully revised the manuscript to systematically clarify the research scope, its relationship to previous studies, and the innovative aspects of the framework. The main revisions are summarized as follows: **(pp. 3–4, lines 65–104, Section 1. "1.introduction"):**

(1) Removal of overemphasized claims of novelty

All statements in the original manuscript referring to the "first" or "first-ever closed-loop analysis" have been completely removed to avoid overstating the innovation. The revised core discussion now focuses on presenting a multi-source data integration framework that systematically quantifies dust emission–deposition–radiation processes at the regional scale, thereby enabling a full-chain diagnosis of the dust lifecycle. This revision more accurately reflects the study’s contribution and positioning.

(2) Relationship to and distinction from existing global-scale studies

In the Introduction, we have added a systematic review and clarification regarding previous work. We explicitly state that this study does not replicate global-scale analyses such as those by Kok et al. (2023) or Zhao et al. (2022, 2023, 2024), but rather deepens and extends their findings at the regional scale. While global studies primarily focus on the overall dust budget in the climate system and its impact on radiative balance, our work emphasizes the regional variability of dust emission, deposition, and radiative effects under the complex topography of arid Central Asia. By integrating multi-source observations with model simulations, we reveal region-specific interactions and mechanisms, thereby addressing the limitations of global models in capturing local-scale processes.

(3) Scientific deepening and innovative contributions of the framework

To address the reviewer’s comments on “scientific depth,” the revised manuscript further elaborates the theoretical significance and methodological innovations of the framework in the Discussion:

Regional refinement: By combining CMIP6 global model outputs with MERRA-2 reanalysis and ground-based observations, the framework reveals the long-term evolution and scenario-dependent differences of dust emission–deposition budgets in Central Asia, bridging the scale gap between global models and regional realities.

Observation-constrained modeling: SBDART radiative simulations are constrained using ground-based observations from SONET and AERONET, significantly reducing uncertainty in clear-sky aerosol direct radiative forcing estimates.

Temporal scale complementarity: The incorporation of the SARIMA statistical model captures short-term variability in dust radiative forcing, complementing CMIP6 long-term climate scenarios and providing actionable insights for risk assessment and climate adaptation.

The revised manuscript no longer frames the framework as a “first-of-its-kind” theory, but clearly emphasizes its applied innovation and methodological integration at the regional scale. Through the synergistic fusion of multi-source data and cross-scale analysis, this framework offers new scientific perspectives and empirical support for understanding regional dust lifecycle responses in arid Central Asia, validating climate model simulations, and supporting regional climate risk management.

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].”

（2）The manuscript presents ensemble mean maps and time series for future projections, but the inter-model spread is not shown or sufficiently discussed. Given the known diversity in dust emission schemes and particle size assumptions across CMIP6 models, the robustness of the results cannot be fully assessed from the ensemble mean alone. For example, the large differences in emission trajectories between the Aral Sea and Tarim Basin under SSP585 may depend heavily on the dust emission parameterizations of specific models. To strengthen confidence in the findings, it would be helpful to include an explicit representation of the inter-model spread and a more thorough discussion of how much weight should be placed on the ensemble mean versus the range of individual model outcomes.

We sincerely thank the reviewer for this important comment. As noted, fully assessing inter-model uncertainties is essential for evaluating the robustness of multi-model ensemble (MME) results. Given the substantial differences among CMIP6 models in dust emission schemes, particle sizes, and surface parameterizations, relying solely on ensemble means is insufficient. In response, the revised manuscript adds a new section, “**4.2.1 Uncertainty Analysis” (pp. 25–28, lines 571–635)**, with figures and quantitative results illustrating spatial patterns of inter-model differences and their influence on ensemble mean reliability.

(1) Visualization of inter-model variability:

Figures 10a–b quantitatively illustrate model differences and variability. Figure 10a depicts the emission bias of each model relative to MERRA-2 reanalysis, with statistical significance assessed using two-tailed t-tests ($p < 0.05$). The results reveal significant biases in CESM2, CESM2-WACCM, CNRM-ESM2-1, and MRI-ESM2-1, suggesting that their dust parameterizations may introduce additional uncertainties. Figure 10b presents time series of dust emissions along with the ±1σ inter-model variability range (shaded), providing a quantitative measure of ensemble uncertainty. Notably, MERRA-2 observations consistently fall within the historical model range, demonstrating that the ensemble mean reasonably represents the climatological mean state.

(2) Regional differences and spatial distribution of model biases:

Figure 11a and Supplementary Figure 12 reveal the spatial distribution of model biases. All models exhibit biases in key dust source regions, including the Taklamakan Desert, Kumtag Desert, areas surrounding the Aral Sea, Karakum Desert, and the eastern Caspian region. Positive biases predominate in the southeastern Tarim Basin, whereas negative biases dominate the western Karakum and Aral Sea regions. These regional differences confirm the reviewer's concern regarding model dependence, as dust emission trajectories strongly depend on specific emission parameterizations and particle size assumptions.

(3) Bias correction and downscaling evaluation:

To further mitigate systematic model errors, a bias-corrected statistical downscaling approach based on MERRA-2 was applied to improve simulations under Central Asia's complex topography. Figure 11b shows the spatial distribution of root-mean-square error (RMSE) between downscaled results and MERRA-2, highlighting elevated RMSE (>2 μg m^{-2} s^{-1}) in topographically complex regions such as the Tarim Basin and Karakum Desert, suggesting caution in interpreting predictions for these areas. Supplementary Figure 13 scatterplots indicate high correlation between downscaled MME anomalies (ΔMME) and MERRA-2 ($R^2 > 0.91$), with slight underestimation (Bias = –1.26, RMSE = 4.31). Time series comparisons (Supplementary Figure 11b) also demonstrate that downscaled results effectively capture seasonal and interannual variability.

(4) Representativeness of ensemble mean and discussion of weighting:

The revised manuscript further clarifies the physical meaning of the ensemble mean and the rationale for weighting. Despite inter-model variability, the ensemble mean consistently captures the core spatial structure of dust emissions, reflecting the major emission patterns of the "Tarim Basin–Aral Sea–Karakum" source regions. The ±1σ variability range and spatial bias maps (Figures 10b and 11a) together constitute an essential component of uncertainty assessment, identifying low-confidence and high-RMSE areas, thereby enhancing the interpretability and practical utility of the results.

(5) Comprehensive assessment and limitations:

While the above analyses significantly improve understanding of model distributions and ensemble robustness, some limitations remain. Differences in dust particle size assumptions and parameterizations remain the primary sources of inter-model variability. Additionally, the SBDART model does not explicitly include aerosol–cloud interactions in radiative transfer calculations, which may bias radiative forcing estimates in high-dust regions. The limited number of ground-based observation sites also constrains representativeness in Central Asia's complex topography. Future studies should integrate higher-resolution models and multi-source observational data, while systematically considering aerosol vertical structure and cloud-phase processes, to further improve the accuracy and reliability of regional radiative forcing assessments.

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 $\mu g \cdot m^{-2} \cdot s^{-1}$ 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."

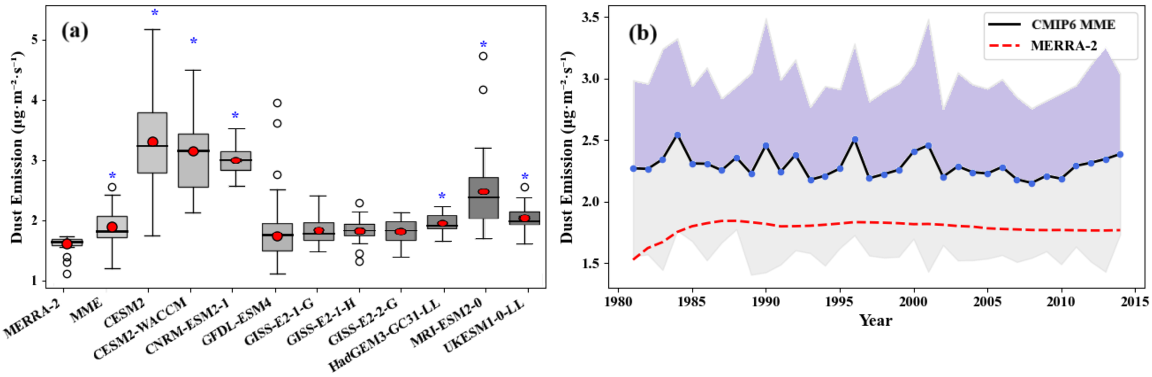


Figure. 11 (a) Dust emission biases of individual models relative to MERRA-2 reanalysis data; (b) time series of dust emissions from the CMIP6 multi-model ensemble, with ±1σ inter-model variability indicated by the shaded area.

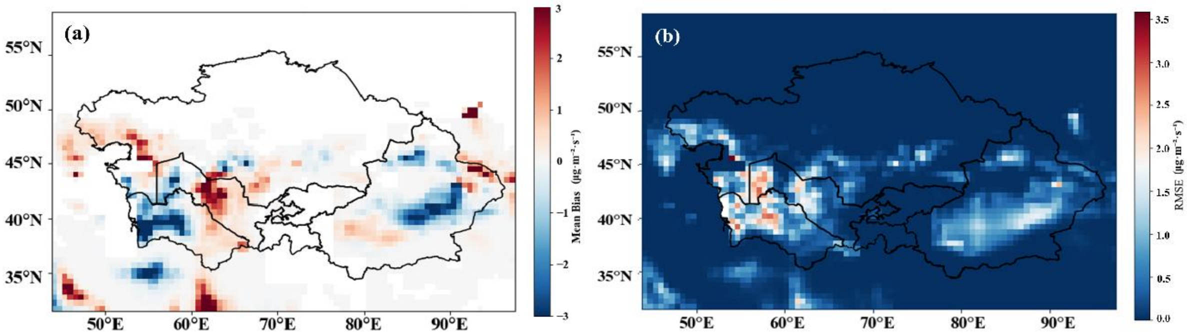


Figure. 12 (a) Spatial distribution of biases between individual models in the multi-model ensemble and MERRA-2 reanalysis data; (b) spatial distribution of root-mean-square error (RMSE) between CMIP6 downscaled outputs and MERRA-2 reanalysis data.

（3）The SARIMA analysis is an interesting addition, but its role in the manuscript is unclear. The projected period (2024-2029) is short compared to the centennial-scale projections in CMIP6, and it is unclear how these two approaches complement each other. The authors should clarify the purpose: Is SARIMA intended as an operational tool (e.g. for regional dust risk management) or as a methodological complement to CMIP6? Without clearer framing, this analysis risks looking tangential.

We sincerely thank the reviewer for these constructive comments. As correctly pointed out, without a clear methodological positioning, the connection between the SARIMA model and CMIP6 long-term projections would appear insufficient. In response, the revised manuscript provides a systematic clarification of the model's scientific rationale, complementary role, and practical value in both the Methods and Results sections **(pp. 24–25, lines 536–568, Section 4.2.1 "SARIMA Forecasting")**, thereby making its function within the overall framework more explicit and coherent.

(1) Clarification of the SARIMA model's role

At the methodological level, SARIMA is applied to identify and quantify short-term interannual and internal variability in dust radiative forcing across Central Asia. This approach validates natural fluctuation signals in the reanalysis records and enhances understanding of the multi-timescale behavior of the dust–climate system. At the applied level, its short-term forecasting capability (3–5 years ahead) provides quantitative support for regional dust hazard early warning, agricultural planning, and public health protection, underscoring its relevance to climate risk management.

(2) Establishing a multi-timescale analytical framework

The revised manuscript further explains the complementary relationship between SARIMA and CMIP6: The CMIP6 multi-model ensemble (MME) primarily captures century-scale, externally forced trends, addressing “How will the overall dust cycle evolve by the end of the century under different emission scenarios?” In contrast, the SARIMA model focuses on decadal and interannual variability, answering “Superimposed on the long-term background, what short-term fluctuations and risk levels can be expected in the near future?” Together, these approaches form a cross-timescale analytical framework that integrates the scientific depth of long-term climate evolution with the practical value of near-term projections, bridging the gap between “long-term climate change” and “regional adaptation needs.”

(3) Empirical results and model validation

Section 4.2.1 of the revised manuscript adds full model diagnostics and predictive performance evaluation. The SARIMA$(1,1,0)\times(1,0,2)_{12}$ model residuals passed the white-noise (Ljung–Box Q, $p > 0.05$) and normality (K–S, D = 0.12) tests, demonstrating strong predictive skill (RMSE = 1.72 W/m², MAE = 1.21 W/m², MAPE = 8.6%, R^2 = 0.70). The forecasts indicate quasi-stationary fluctuations in dust radiative forcing (1.6–9.8 W/m²) over 2024–2029, with southern Xinjiang identified as a strong-response region, while northern Xinjiang exhibits a non-stationary trend related to snow-cover variability.

In summary, the SARIMA analysis is not a supplementary add-on but a key methodological bridge connecting long-term climate simulations with short-term regional responses. It strengthens the interpretability of reanalysis and observational records and enhances the practical applicability of the study’s findings for regional climate risk assessment and 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."

Minor comments

(1)Please specify the units for all figures.

We thank the reviewer for this careful reminder. In accordance with the suggestion, all figures and tables in the manuscript have been thoroughly reviewed, and explicit units have been provided for every physical quantity.

(2) Be cautious when using the term “significant” throughout the manuscript. If you intend to use it in a statistical sense, please provide the corresponding statistical values.

We sincerely thank the reviewer for this rigorous and constructive comment. Following the suggestion, we have systematically reviewed all instances of the term “significant” throughout the manuscript and made the following revisions:

(1) Statistical usage: For all statements referring to statistical significance, we have added the corresponding statistical indicators (e.g., p-values such as $p < 0.05$) or confidence intervals to ensure that the results are reported in accordance with statistical conventions.

(2) Non-statistical usage: In contexts where the term was used to describe the magnitude or importance of changes rather than statistical meaning, we have replaced “significant” with more precise and neutral terms such as “substantial,” “considerable,” or “notable,” to avoid ambiguity.

Through these revisions, the term “significant” is now used exclusively in the statistical sense in the revised manuscript. We once again thank the reviewer for their careful examination and valuable suggestion, which has greatly improved the scientific rigor and linguistic precision of the paper.

(3)It appears that the authors presented absolute dust emissions and deposition under the SSP scenarios rather than changes relative to the historical period, even

though the figure captions describe them as showing changes (Figures 3,5, and Supplementary Figures 7-8). To better highlight the increasing or decreasing trends, I recommend revising these figures to show relative changes compared to the historical baseline.

We sincerely thank the reviewer for this valuable suggestion. The point raised is highly pertinent, as presenting results in terms of relative changes offers a clearer depiction of future trends and improves the interpretability of the figures.

In accordance with your recommendation, we have thoroughly revised the relevant figures **(Figures 3 [p. 13, line 303], 5 [p. 15, line 353], and Supplementary Figures 7 – 8 [Supp. Info, pp. 4 – 6])**, with the following specific modifications:

(1) Core revision: The absolute values of dust emissions and deposition originally displayed in the figures have been replaced with relative changes relative to the historical baseline period (2000–2014). These are calculated as: Relative change = Future value – Historical value.

(2) Quantitative presentation: To more intuitively convey the magnitude of regional changes, we have added a circular inset chart in the upper-right corner of each spatial subplot, displaying the regional mean relative change rate. This is computed using the formula:

$$\text{Relative change rate (\%)} = \frac{\text{Future value} - \text{Historical value}}{\text{Historical value}} \times 100\%$$

Through these modifications, the revised figures now convey not only the spatial distribution of relative changes but also quantitative indicators of regional trends. This facilitates a more intuitive interpretation of enhancements or reductions in dust emissions and deposition across Central Asia under different SSP scenarios. We believe these revisions substantially enhance the clarity, scientific rigor, and expressiveness of the projected future trends. We once again sincerely appreciate the reviewer's insightful feedback, which has greatly aided us in presenting our results more effectively.

Revised excerpt:

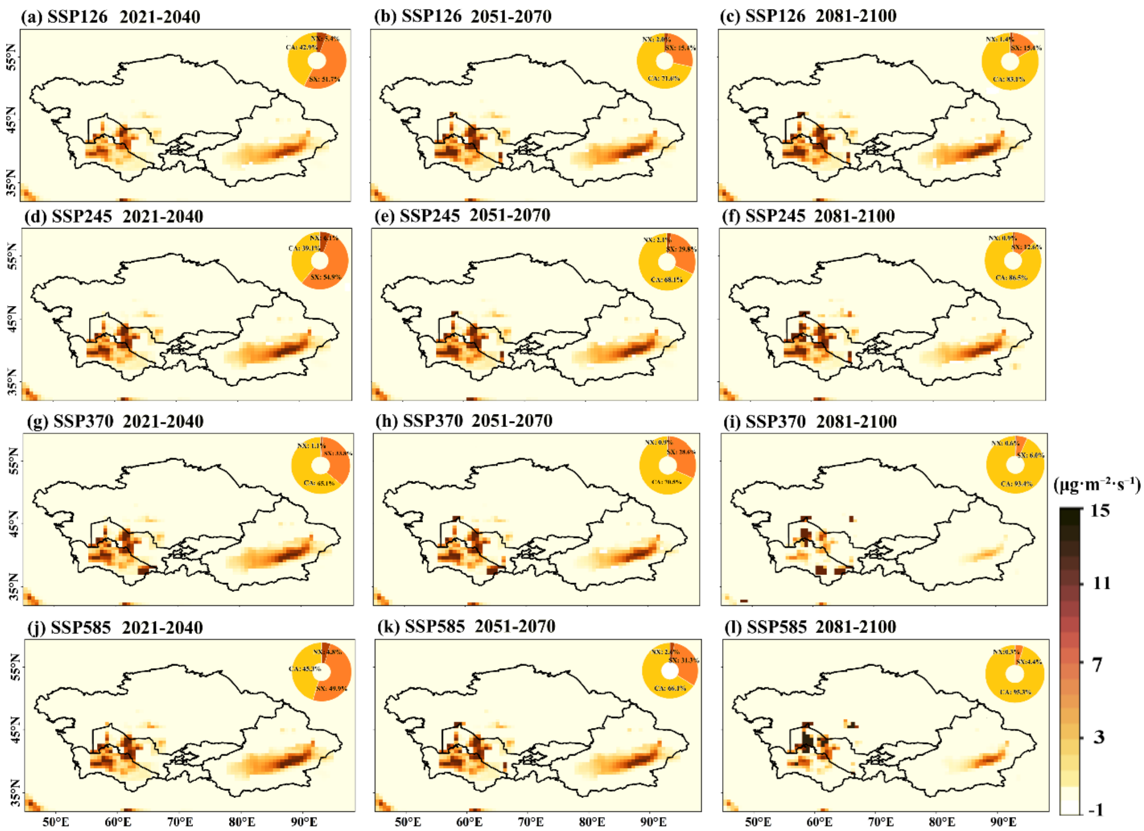


Figure. 3 Future changes in dust emissions across different periods. Spatial distribution of the relative changes in dust emissions over Central Asia under four CMIP6 multi-model ensemble (MME) SSP scenarios: panels (a – d) near term (2021 – 2040), (e – h) midterm (2051 – 2070), and (i – l) long term (2081 – 2100), relative to the historical period (2000 – 2014). The circular inset in the upper-right corner of each panel indicates the mean relative change rate (%) for the corresponding region.

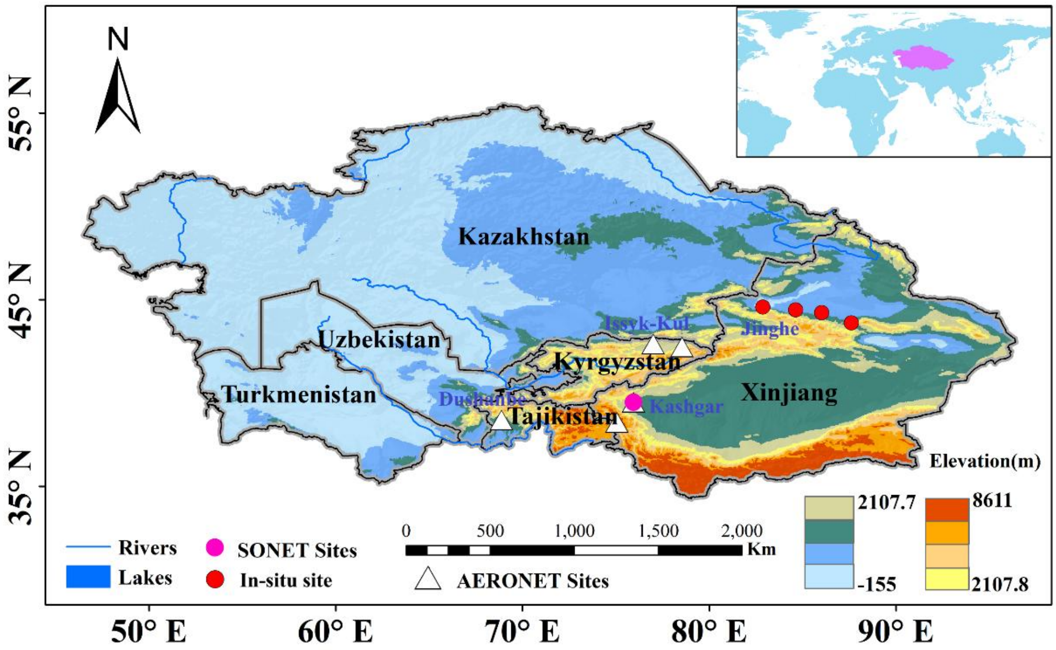
(4) Figure 1: Abbreviations such as Kaz, Uzb, etc. should be written in full or explained in the figure caption. In addition, since you refer to multiple sites later in the manuscript, I also suggest specifying their names here (e.g., Dushanbe, Issyk-Kul, Jinghe). This will help readers clearly understand where the stations are located.

We sincerely thank the reviewer for this careful and helpful comment. In response to your suggestion, we have revised Figure 1 as follows:

Country abbreviations (e.g., Kaz, Uzb) have been replaced with their full English names (e.g., Kazakhstan, Uzbekistan).

All observational sites referenced in subsequent analyses have been clearly labeled, including Dushanbe, Issyk-Kul, Jinghe, and Kashgar, along with their precise geographic locations.

Revised Figure1:



（5）Line 233: “The reanalysis data agrees with the MME simulations, with the Taylor skill score (SS) close to 1.” I recommend clarifying the exact value of the Taylor skill score rather than the qualitative description. Providing the precise number will improve the rigor and transparency of the results.

We thank the reviewer for pointing out this issue. Providing precise numerical values indeed enhances the rigor and transparency of the results.

Accordingly, we have revised **p. 11, lines 252－254** in the manuscript by replacing the qualitative description of the Taylor skill score as “close to 1” with the exact calculated value of 0.87.

(6) Line 268: “In contrast, the Tarim Basin experienced a long-term decrease in emissions…”. The decreasing trend is not clearly visible.

(7) Line 274: “a gradual decreasing trend” — same comment as above.

We thank the reviewer for highlighting the need to clarify the description of trends in the Tarim Basin and southern Xinjiang. In response, we have revised the relevant sentences to employ more precise and quantitative language**(pp. 12–13, lines293–301)**.

Specifically, “experienced a long-term decrease” has been updated to “exhibits an overall decreasing trend in dust emissions,” and “gradual decreasing trend” is now described as “a slight declining tendency.” These revisions are accompanied by explicit quantitative values (e.g., 18.7% decrease under SSP2-4.5, 29.3% under SSP3-7.0, and ~26.1% under SSP5-8.5) and contextual explanations emphasizing the roles of ecological restoration, enhanced precipitation, and human interventions in shaping regional dust emission patterns. We believe these changes substantially enhance the clarity and accuracy of the trend reporting.

（8）Line 286: I don’t think they are “in good agreement”. The maps appear different both spatially and in magnitude. Could you provide a quantitative measure of similarity (e.g., Taylor skill score) to support this?

We sincerely thank the reviewer for this rigorous and insightful comment. In accordance with your suggestion, we have revised line 286 and the associated text as follows**(p. 14, lines314–317)**:

The previous subjective phrase “in good agreement” has been removed.

An objective quantitative assessment has been incorporated to bolster the conclusion's credibility: the consistency between the multi-model ensemble (MME) and observations was evaluated using the Taylor Skill Score (TSS = 0.82), providing statistical substantiation for their overall alignment.

The revised description now explicitly notes that, while the MME and observations demonstrate general consistency in simulating total dust deposition over Central Asia, notable discrepancies persist in absolute values, with MERRA-2 exhibiting a substantially stronger trend in deposition intensity than the model ensemble.

（9）Line 312-317: In my view, the Supplementary Figures 7-8 do not clearly support your argument. Regardless of the future scenario and time ranges, they appear very similar. Since they present absolute values rather than changes relative to the historical period, I recommend revising them to show relative differences so that the trends are more clearly visible.

We sincerely thank the reviewer for these detailed and constructive comments on Supplementary **Figures 7–8 (Supp. Info, pp. 4–6)**. In accordance with your suggestion, we have revised these figures to present relative changes relative to the historical baseline period, thereby providing a clearer depiction of future variation trends.

To more effectively highlight the magnitude differences that are not readily discernible in the spatial maps and to strengthen the overall argument, we implemented the following improvements:

(1) We have explicitly stated in both the figure captions and the main text that the

maps illustrate the spatial distribution of relative trend strength. Additionally, a circular inset in the upper-right corner of each subpanel now displays the regional mean relative change rate.

(2) These quantitative values clearly demonstrate that, with increasing radiative forcing across the SSP scenarios (from SSP1-2.6 to SSP5-8.5) and over time, the magnitudes of dust emission and deposition changes progressively intensify.

(3) To further clarify the trends and enhance interpretability, we particularly recommend referring to Figure 6 (temporal evolution of the dust budget). This figure, through direct time-series representations, unambiguously illustrates the substantial differences in dust emission and deposition among various regions and scenarios, consistent with the spatial patterns in Supplementary Figures 7–8.

Revised Figure S9:

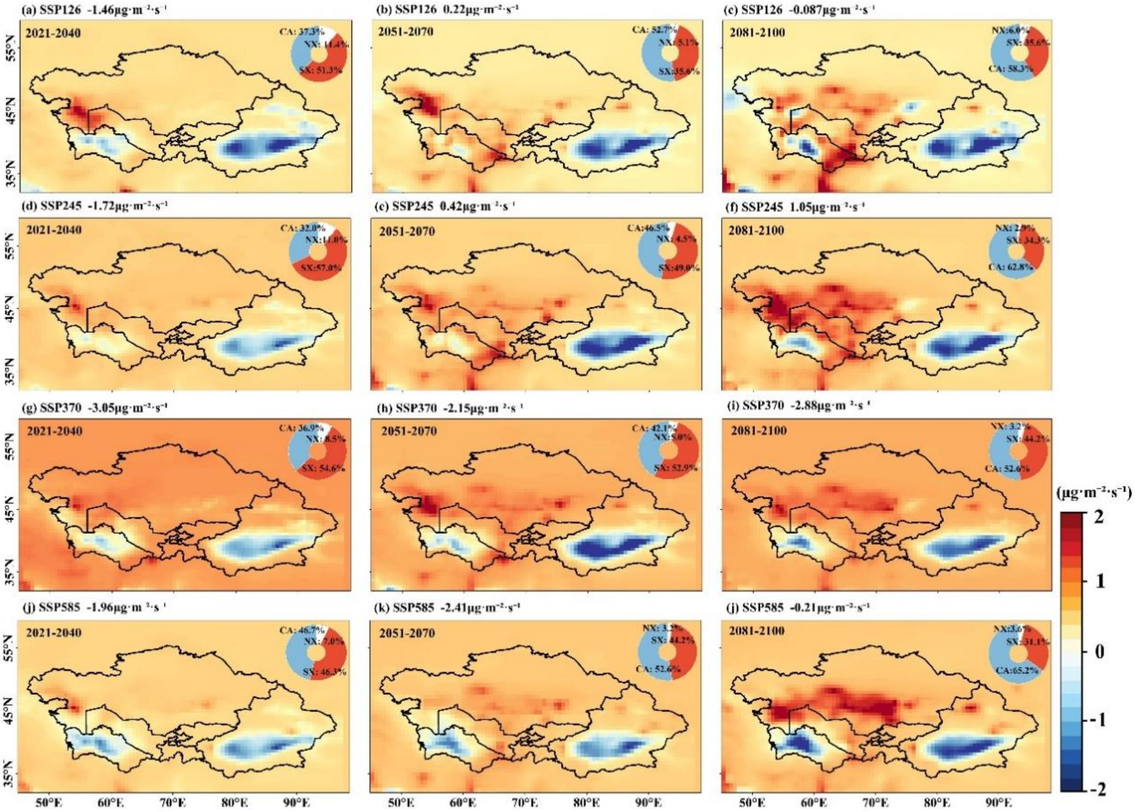


Fig. S9. Future changes in dry deposition of dust at different times. Spatial variations of dust-dry deposition in Central Asia under the four CMIP 6 MME SSP scenarios for (a–d) the recent period (2021–2040), (e–h) the medium term (2051–2070), and (i–l) the long term (2081–2100) relative to the historical period (2000–2014).

（10）Line357-360: A more detailed explanation of the seasonal characteristics of dust would be helpful.

We sincerely thank the reviewer for this valuable suggestion regarding the seasonal characteristics of dust activity. To enhance the depth of our analysis, we have revised and expanded the discussion on **pages 17–18, lines 393–416 of the manuscript.** The main improvements are summarized as follows:

Seasonal mechanisms of radiative forcing:

The strongest radiative forcing occurs in spring, directly linked to intensified surface wind erosion, elevated dust emissions, and increased atmospheric dust loading and optical depth. In summer, the forcing is slightly weaker, owing to reduced near-surface wind erosion and the resulting decrease in dust loading.

Physical causes of radiative forcing at different levels:

The strong negative forcing at the surface arises from the combined scattering and absorption of incoming shortwave radiation by dust particles. In contrast, the atmosphere exhibits positive forcing, reflecting dust's capacity to redistribute energy by absorbing shortwave radiation and retaining it within the atmospheric system.

Potential impacts on regional climate:

Surface cooling suppresses sensible heat flux and evaporation, thereby exacerbating moisture deficits in Central Asia's arid regions and potentially constraining vegetation growth and agricultural productivity. Meanwhile, atmospheric heating strengthens the temperature gradient from the boundary layer to the troposphere, which may heighten the likelihood of deep convection. This, in turn, could amplify the frequency and intensity of spring and summer dust storms while altering regional precipitation patterns.

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

"Seasonal analysis reveals that the negative TOA forcing intensity decreases in the order spring (–3.32 W/m²) > summer (–3.21 W/m²) > autumn (–3.07 W/m²) > winter (–1.94 W/m²), which aligns closely with the seasonal characteristics of dust activity. In spring, strong surface wind erosion across Central Asia drives intense dust emissions, resulting in high atmospheric dust loading and optical depth and, consequently, the strongest radiative forcing. Although summer convective activity can transport dust to higher altitudes, weakened near-surface wind erosion reduces the overall dust burden relative to spring (Ginoux et al., 2012). 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... The atmospheric radiative forcing (ADRF) exhibits... positive values (10.02 W/m² in spring and 9.89 W/m² in summer), indicating the energy redistribution role of dust aerosols... 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... exacerbating moisture deficits in Central Asia’s arid regions and limiting vegetation growth... On the other hand, atmospheric heating strengthens the temperature gradient... enhancing the potential for deep convection, which could intensify the frequency and severity of spring–summer dust storms and modify regional precipitation patterns..."

（11）Line 381: The radiative forcing you used is ATM. Please specify this clearly so readers understand that it is not TOA or SFC. In addition, it would be helpful to briefly explain why ATM was chosen here, so readers can better understand the rationale behind this choice.

We sincerely thank the reviewer for this important and insightful comment. In accordance with your suggestion, we have implemented two key revisions to clarify and justify the use of atmospheric radiative forcing (ATM) throughout the manuscript **(p. 19, lines 431–434):**

(1) Clarification of the variable: In the Results section (e.g., line 381 and associated site descriptions), we have explicitly specified that the analyzed radiative forcing refers to atmospheric radiative forcing (ATM), thereby avoiding confusion with forcing at the top of the atmosphere (TOA) or the surface (SFC).

(2) Rationale for selection: The manuscript now includes a clear explanation of why ATM was chosen. This study aims to elucidate the thermal effects of dust aerosols on the atmospheric column and the associated atmospheric heating rate. ATM directly quantifies the energy retained in the atmosphere by dust aerosols, making it the most relevant and representative physical parameter for characterizing this thermodynamic process. Accordingly, our analysis of site-level aerosol direct radiative forcing (ADRF) focuses on ATM and its associated atmospheric heating rate.

Technical corrections

(1) Line 86: “long-term trend of the shortwave radiation forcing (ADRF)”. The

meaning of ADRF is not clearly conveyed here. I suggest writing out the full name of ADRF explicitly.

We thank the reviewer for the careful reminder. In accordance with your suggestion, **on page 4, line 94**, the abbreviation **"ADRF"** has been replaced with its full form, **"dust aerosol direct radiative forcing"**, to ensure that readers can clearly understand its meaning.

(2) Line 151: "The selection criteria include key variables of the dust cycle: monthly mean dust emission fields and dry/wet deposition fluxes". Since you have used variable names in your figures (e.g., Figures. 2, 4, 6···), I recommend also specifying the variable names here for consistency and clarity.

We thank the reviewer for highlighting the importance of consistent terminology. Following your suggestion, **on page 7, lines 163–166**, we have revised the original description "monthly mean dust emission fields and dry/wet deposition fluxes" to match the variable names used in the figures and tables. The revised phrasing now reads: **"dust emission flux, as well as dust dry and wet deposition fluxes (their sum representing total deposition flux)."**

(3) Line 305: Do you mean Supplementary Figures 7-8? Supplementary Figure 5-6 only shows the historical period, not the future.

We sincerely thank the reviewer for this careful correction. You are absolutely correct—the reference to "Supplementary Figures 5–6" in line 305 was a typographical error. It has now been corrected to "**Supplementary Figures 9–10**" (**p. 15, lines 338–339 of the revised manuscript**), which present the data for the future periods and are fully consistent with the discussion in the text. We appreciate your attention to detail, which has helped improve the accuracy of the manuscript.

(4) Line345: Do you mean northern (a-c) and southern (d-f) Xinjiang? Please clarify.

We sincerely thank the reviewer for this helpful clarification. The statement indeed refers to northern (a–c) and southern (d–f) Xinjiang. Accordingly, the text has been revised to clearly specify this distinction and avoid ambiguity **(p. 17, Figure 6)**.

(5) Figure 9: Panels (a) through (j) should be clearly explained in the caption.

We sincerely thank the reviewer for this valuable suggestion. To improve clarity and facilitate reader understanding, the caption of **Figure 9** has been revised and expanded

(p. 22). The updated caption now explicitly specifies:

The corresponding sites for each subpanel—e.g., (a, d) Dushanbe, (b, e) Issyk-Kul, and so on.

The physical quantities displayed: the upper panels (a, b, c, g, h) represent shortwave dust direct radiative forcing (ADRF), while the lower panels (d, e, f, i, j) depict the corresponding atmospheric heating rates.

These revisions enhance the figure’s interpretability and ensure consistent presentation throughout the manuscript.

(6) Line 439: The wording is contradictory. “increased”, a negative rate (-0.3), and “declining trend” conflict with one another. If the flux is decreasing, it should be described as a decrease at that rate.

We thank the reviewer for pointing out this important issue. As noted, trend descriptions must be consistent with the data sign conventions. Accordingly, we have revised the text at **lines 499–500 (page 23)** to ensure consistency. The updated sentence now reads: “Emission fluxes in the Tarim Basin exhibit a declining trend at a rate of ≈–0.3 $\mu g \cdot m^{-2} \cdot s^{-1} \cdot yr^{-1}$.”

We appreciate the reviewer’s careful attention, which has helped improve the accuracy and clarity of the manuscript.

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.