Response to the Comments of Referees

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Title: Exploring the Mechanisms of Dust Emission and Transport based on Observations and GEOS-Chem Simulations

Author(s): Peili Zou, Xiaoyan Ma, Rong Tian, Jianqi Zhao, Tong Yang and Yingying Ku

We thank the reviewers and editor for providing helpful comments to improve the manuscript. We have revised the manuscript according to the comments and suggestions of the referees.

The referee's comments are reproduced (black) along with our replies (blue). All the authors have read the revised manuscript and agreed with the submission in its revised form.

Anonymous Referee #2

Review comments of "Exploring the Mechanisms of Dust Emission and Transport based on Observations and GEOS-Chem Simulations" by Zou et al., 2025

General comments

The paper studied a severe dust storm originating in the Western Inner Mongolia (WIM) that was transported southward to southern China during April 11-14, 2025. Using ground observations, reanalysis (ERA5), satellite retrievals (MODIS/Aqua), and an improved GEOS-Chem model, the authors demonstrate that the emission and long-range transport of Inner Mongolian dust were mainly driven by anomalously strong northerly winds associated with the Siberian high and the Mongolian cyclone, along with reduced local precipitation, soil moisture, and high surface temperatures. The event is then compared with two other extreme dust events in northern China that occurred in March 2021 and April 2023. By comparing the meteorological conditions and PM10 evolution patterns, it is found that the absence of strong northerly winds is the primary reason why dust plumes during the other two events were not transported to Hainan Province in southern coastal China. The paper is generally well written and easy to follow. However, the study would be strengthened by better clarifying the motivation and novelty, justifying the use of the modeling approach, and providing a more detailed analysis in the multi-event comparison.

We thank the reviewer for their positive evaluation and careful review of our study. The suggestions to "further clarify the motivation and novelty, justify the use of the modeling approach, and provide a more detailed analysis in the multi-event comparison" are highly pertinent and crucial for enhancing the scientific depth and clarity of this paper. In response to these specific comments, we have systematically revised and expanded the manuscript as follows:

1. Strengthening the Motivation and Novelty: In both the Introduction and the summary section, we have expanded the discussion on the unique scientific value of the 2025 dust event. We explicitly highlight that this event represents a rare case documented to have reached Hainan Island and is distinctive for its effective southward transport

despite the presence of heavy precipitation. By contrasting it with other severe East Asian dust events recorded in the literature, we emphasize its scarcity and research significance, thereby clarifying the motivation and novelty of this study.

2. Justifying the Use of the Modeling Approach: In Section 4.2 (Model Simulations), we have added a brief discussion explaining why the GEOS-Chem model was employed in addition to the available observational data. We explicitly state that model simulations can quantitatively resolve physical processes, such as the detailed emission fluxes, contributions of vertical and meridional transport, and the separation of dry and wet deposition processes, which is difficult to differentiate through observations alone—This clarifies the indispensable value of the model in diagnosing the underlying mechanisms of this study.

3. Deepening the Multi-Event Comparative Analysis: In Section 4.3.2 (Event Comparison) and the related figures, we have made the following important additions:

(1) Unified Analytical Framework: Wind speed data for comparison have been adjusted to anomalies relative to the 30-year climatological mean (Figure 10 has been updated), allowing a fair comparison of dynamical conditions across events from different years on a common baseline.

(2) Improved Evolution Representation: Additional timesteps closer to the dissipation stage for the 2021 and 2023 events have been added to Figure 11, providing a more complete life-cycle comparison.

(3) Enhanced Circulation Mechanism Analysis: Supplementary Figure S5 now includes sea-level pressure and wind fields during the peak phases of the two historical events. In the main text, we comparatively analyze key differences in the intensity, location, and configuration of the "Mongolian Cyclone–Siberian High" system across the three events, explaining the variations in transport pathways and intensity from the perspective of large-scale dynamical drivers.

We hope these targeted revisions have significantly strengthened the study in terms of focusing the scientific questions, justifying the methodology, and deepening the mechanistic analysis. We sincerely thank the reviewer again for their insightful comments, which have been instrumental in improving the quality of this paper.

Specific comments

1. Adding more information on the motivation of this study would further strengthen the manuscript. For example, beyond its unusual transport pathway, it would be helpful to clarify what unique features or mechanisms of this dust storm are revealed here that have not been addressed in previous studies.

   We thank the reviewer for the constructive suggestion. We have expanded the motivation of this study in the Introduction, emphasizing not only the unusual transport pathway of the April 2025 dust storm, but also its unique features and the scientific issues that have received limited attention in previous studies.

   Specifically, unlike typical dust events that are mostly confined to northern or northeastern China, this storm moved southward across the Yangtze River Basin and ultimately affected southwestern China and the South China Sea, indicating an exceptionally broad transport range. During the dust transport toward South China and Hainan Island, widespread precipitation occurred in the Yangtze River Basin. Such precipitation would normally lead to a marked reduction in aerosol concentration through wet scavenging, yet in this case, the dust maintained relatively high concentrations and successfully underwent ultra-long-range transport to Hainan Island (lines 75-83).

These characteristics provide a valuable case for studying the processes of dust emission, transport, and deposition under extreme meteorological conditions, and help improve our understanding of the relative roles of dynamic forcing and wet scavenging in long-range transport, while addressing the lack of high-impact, strongly transported dust event cases in existing research.

2. In Section 4.2, including a brief discussion explaining why model simulations are used and what specific questions can be addressed through modeling (or cannot be addressed through observations alone) would highlight the added value of the modeling component.

In response, we have added a brief discussion in Section 4.2 to clarify why model simulations were employed and what specific questions they help address.

Observational data provide essential information on the spatiotemporal distribution of dust concentrations. However, due to limited observational coverage—especially the cessation of the CALIPSO satellite mission on 1 August 2023—it is difficult to fully resolve key aspects of the event, such as the detailed dust emission fluxes, vertical transport processes, and the relative contributions of different source regions.

By using the GEOS-Chem model, we were able to simulate dust emission and vertical transport under realistic meteorological conditions, perform sensitivity tests on factors such as soil moisture, surface wind, and vegetation cover, and examine processes that are challenging to observe directly, including the partitioning between saltation and suspension and the impact of wet scavenging along the transport pathway.

This combined approach of observations and model simulations not only enables a more complete depiction of the dust event's characteristics but also helps to elucidate the mechanisms responsible for its unusual intensity and long-range transport, thereby highlighting the added value of the modeling component.

The relevant additions are included in the revised Section 4.2.

3. Regarding modeling, are atmospheric circulation nudged to the GEOS-FP reanalysis? If not, it would be informative to show a comparison of modeled winds versus station observations or reanalysis, since winds are a key factor of dust emissions and transport.

We thank the reviewer for the important comment. In this study, the GEOS-Chem simulation did not apply nudging (assimilation-constraint) to align the atmospheric circulation with the GEOS-FP reanalysis data. The simulation was conducted in a free-running framework, with GEOS-FP data serving as initial and boundary conditions.

We fully agree that the wind field is a key factor influencing dust emission and transport. To evaluate the model's performance in simulating wind fields, Figure S1 in the supplementary material presents a comparison of the diurnal variations between observed and simulated wind fields. Additionally, we have supplemented Figure S2, which specifically presents a comparison of the simulated daily maximum wind speed in the WIM region with ERA5 reanalysis data and station observations. To further compare the reanalysis data with the model wind field, Figure 2 here provides an hourly variation comparison between the two. The results show that the model reasonably reproduces the characteristics of the wind field during the dust event.

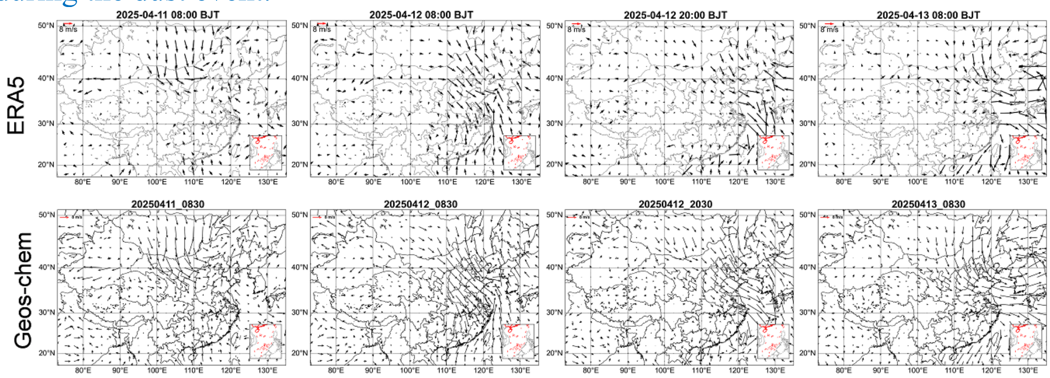

Figure 2. Comparison of simulated wind fields with ERA5 reanalysis data during 11–13 April 2025 (BJT).

4. Daily wind speeds are examined for the 2025 event (Fig. 8) and the other two springtime severe dust events in 2021 and 2023 (Fig. 10). Since dust emissions are more sensitive to high wind speeds at sub-daily time scales, it may be informative to display hourly wind speeds from the ERA5 reanalysis, station data, and model, or alternatively to show daily maximum wind speeds.

We thank you for the valuable suggestion. We fully agree that sub-daily time scales, especially peak wind speeds, are key factors for evaluating dust emission conditions. To better highlight the high-wind periods associated with dust activity, we have made corresponding revisions to the wind speed analyses in Figures 8 and 10.

The specific revisions are as follows:

Figure 8: The original daily mean wind speed time series has been replaced with daily anomaly time series of both daily mean and daily maximum wind speeds.

Figure 10: The wind speed analysis plot has similarly been updated to display the daily anomaly time series of daily maximum wind speed.

Furthermore, a detailed comparison of the simulated daily maximum wind speed in the WIM region with ERA5 reanalysis data and station observations has been provided in Figure S2 of the Supplementary Material. The corresponding figure captions and descriptions in the main text have been updated accordingly in the revised manuscript.

5. Section 4.3.2, additional clarification on how the two historical dust events were selected would be helpful. It is briefly mentioned that the two events were selected among "historical dust events in northern China since 2000" (Line 268). However, it is unclear which dataset was used to identify dust events and how a dust event is defined. The two events were referred to as "two most severe dust events" (line 268), but it was not clear whether severity refers to their magnitude (if so, the 2025 event is more severe), their impacts, or their duration. What's confusing is that later in the discussion, these events are referred to as "typical historical dust storms" (lines 323, 342). Clarifying the selection criteria and the purpose of using these events for comparison would help guide the reader.

With reference to Yu et al., Atmospheric Research, 2023, and Yang et al., Atmospheric Pollution Research, 2025, these two historical events were selected as benchmarks primarily for the following two reasons:

(1) To highlight the "extreme anomaly" of the 2025 event:

The 2021 event serves as a reference for "intensity and spatial extent": it demonstrates the theoretical maximum instantaneous intensity and broad horizontal impact (affecting about 17 provinces) that dust can achieve under the strongest Mongolian cyclone. However, it halted in central-eastern China. By comparing with it, we can ask: Why did the 2025 event, which also exhibited strong outbreak and wide impact, achieve southward transport, whereas the 2021 event resulted in broader lateral influence?

The 2023 event serves as a reference for "process and southward potential": it shows that dust can persistently affect North China and exhibit a southward trend (reaching Shandong), with a complex process (including secondary pollution). Yet it ultimately failed to penetrate deeply southward. By comparing with it, we can ask: Why, despite sharing a similar southward tendency, could the 2025 event overcome the precipitation barrier in the Yangtze River Basin and achieve stable ultra-long-range southward transport, while the 2023 event could not?

(2) To control variables and focus on key differential mechanisms:

Given that both historical events and the 2025 event involved the influence of Mongolian cyclones, the factors leading to their distinct final transport pathways and outcomes must lie in the details of circulation configuration, such as the intensity, location, and persistence of synoptic systems.

We have revised Section 4.3.2 in accordance with your suggestions to further clarify the selection criteria for the two historical dust events and to unify the related terminology throughout the text, thereby improving the clarity and consistency of the manuscript.

Besides, we have uniformly used the term "severe" to describe the two historical events throughout the text to maintain consistency in context.

6. The comparison between the 2025 event and the other two events could be strengthened by discussing uncertainties, using similar evolution time frames, and adding analysis on circulation patterns. As mentioned in the text, these two events generally originated in northern China, so their emission areas are not exactly centered over the WIM (Fig. S3). Acknowledging these discrepancies helps explain their different magnitudes over the VIM and their paths. In addition, showing more time steps for the 2021 and 2023 events may provide a more complete picture of their evolution. For example, in Fig. 11 (bottom left), by 1200 BJT on March 16, 2021, the PM10 concentrations were still very high, with some areas above 1100 μg/m3, suggesting that the event had not yet fully dissipated (in contrast to the 2025 event, for which PM10 cementations decreased to around 200-400 μg/m3 by 0600 BJT on April 13, 2025). Similarly, by 0300 BJT on April 12, 2023 (Fig. 11, bottom middle), dust concentrations also remained very high, around 700-900 μg/m3. Including additional snapshots closer to the dissipation stage of these events would enhance the comparison. Lastly, including an analysis on circulation patterns would help understand wind directions and transport pathways (Fig. 11). For example, it is mentioned that both the March 2021 and April 2023 events were associated with Mongolian cyclones (line 270). Were they also associated with the Siberian High? What about other differences?

We thank the reviewer for the detailed and constructive comments. We fully agree that enhancing the temporal evolution framework, supplementing key dissipation stages, and strengthening the analysis of circulation patterns can significantly improve the depth and clarity of the event comparison. Based on each of your specific suggestions, we have systematically revised the manuscript as follows:

(1) Expanded Figure 11 to comprehensively depict the entire dust event process.
(2) Added the circulation patterns of the historical events (Figure S5).
(3) In the manuscript, we conducted a comparative analysis of the circulation fields of the three events, clearly highlighting the similarities and differences in circulation configurations — particularly the intensity, location, and synergistic relationships of the high-pressure and cyclone systems—and their decisive impacts on the transport pathways.

7. It is recommended to discuss the results in the context of previous studies. For instance, it is found that dust emissions in the WIM exceeded 400 μg/m² and the altitude of the dust plume reached 3.6 km. Are these values comparable to previous events, or are they substantially larger? Regarding the southward transport to Hainan province, was this the first occurrence of such a southward transport, or has it documented previously? It was noted that about 50% of springtime dust events in Mongolia and northern China are associated with "the combined influence of Mongolian cyclones and cold high-pressure systems" (line 162). Was the combination of a Mongolian cyclone and the Siberian high found in the April 2025 event unique?

We have added the following content in the Discussion section (Section 5) of the manuscript:

(1) The dust emission flux in the WIM region and the height of the dust plume during this event are comparable to those reported for typical severe dust events in recent literature.
(2) The transport of dust from northern China to Hainan Island is extremely rare and may even represent the first systematically documented case of such an occurrence.
(3) The "Mongolian Cyclone–Siberian High" coupling that drove this event exhibited unique characteristics in terms of its intensity configuration (an exceptionally strong high-pressure system) and spatial configuration (a southerly displaced cyclone position). Together, these factors contributed to the rare dynamical conditions and extraordinary transport outcomes observed.

8. In Section 2.2, consider including a brief introduction to the dust emission scheme in the model.

A brief introduction to the dust emission scheme has been added in Section 2.2.

9. Figs. 2, 4-5, 8d, 10a, and 11, are the wind fields surface winds? Please clarify in the figure captions.

Yes, they are surface wind fields (10-m near-surface winds). This has been clarified in the figure captions.

10. Fig. 7, it would be helpful to also include modeled vertical and meridional winds in the figure.

Simulated vertical and meridional winds have been added to Figure 7.

11. Fig. 8, is the time series of daily wind speed from the ERA5 or station observations?

All data in Figure 8 are from ERA5, and a note specifying this has been added to the figure caption.

12. Fig. 10, it is preferred to show anomalies with reference to the long-term mean.
    We fully agree that using anomalies relative to the long-term mean can more clearly reveal abnormal signals and facilitate comparisons of relative changes across different periods and events. We have revised Figure 10 to display time series of anomalies relative to the 30-year climatological mean (1995–2024). The corresponding descriptions in the main text have also been updated accordingly.

Technique correction:

Fig. S2, although the figure caption refers to “AOD spatial distributions”, MODIS data do not appear to be displayed in the top row.
We have corrected this technical issue.