Reviewer #3

General Comments

Comment C1

This study implements an albedo-based drag partitioning scheme in the global GEOS-Chem model and simulates dust emissions at 0.5° × 0.625° resolution. Three model runs are performed using the source function without a drag partitioning algorithm (Exp1), the default simplified drag partitioning algorithm without the source function (Exp2), and the proposed albedo-based drag partitioning algorithm without the source function (Exp3). Comparisons among the three simulations and evaluations against observations reveal similar results for Exp3 and Exp1, leading to the conclusion that the dust model exhibits equifinality.

Investigation of the albedo-based drag partitioning scheme at a global scale is valuable. However, I have a fundamental concern about the study design. The source function is replaced with drag partitioning, although the two represent different physical processes. Additionally, the conclusion regarding equifinality is weakened by the coarse temporal resolution of the observational evaluation. I therefore recommend rejection at the current stage and encourage resubmission after the study design is revised, potentially with additional model simulations.

Response

We thank the reviewer for the overall evaluation of our study and for the constructive comments that helped improve the manuscript.

In response to the concerns raised, we have clarified the experimental design and its interpretation, particularly regarding the removal of the dust source function and the rationale for the sensitivity experiments (Exp1–Exp3). We emphasize that the study does not aim to establish a physical equivalence between drag partition and the source function, but rather to quantify the sensitivity of dust emission characteristics to empirical spatial constraints and alternative representations of surface processes.

In addition, we have addressed the concern regarding temporal resolution by including supplementary analyses based on daily model outputs and spatial diagnostics. These additional results further support our interpretation of equifinality by demonstrating that, although surface process modifications substantially alter the spatial structure and daily variability of dust emissions, the corresponding response in atmospheric dust is comparatively smoothed due to transport and mixing processes.

We believe that these revisions strengthen the interpretation of the results. We appreciate the reviewer's critical feedback, which has helped us refine both the experimental framing and the presentation of the results.

Major Comments

Comment C2

The study is designed with the intention of replacing the dust source function with the drag partition parameterization. Fundamentally, however, a dust source map represents the geographic availability or relative erodibility of soil particles, whereas drag partitioning represents how surface roughness divides wind stress between roughness elements and the exposed soil. These are distinct processes. For example, a flat concrete surface may have low aerodynamic roughness but cannot emit mineral dust. The two treatments are therefore not mutually exclusive, and both processes should be represented in dust models. I agree with the authors that static source functions have limitations, but they should be improved rather than eliminated.

On this basis, Exp1 and Exp3 are not physically equivalent configurations. Their similar performance provides useful information about model sensitivity to separate subprocesses, but it does not justify replacing the source function with drag partitioning. I believe simulations using both simplified and albedo-based roughness should also include the source function. Alternatively, the source function could be disabled to isolate the uncertainty associated with it. However, in such cases, the simulations should not be directly compared with observations without acknowledging the missing sediment-availability constraint.

Response

We refer to our response to Comment B2, where we clarify that the dust source function and drag partitioning represent distinct components in dust emission modeling. We fully agree that these processes are not physically equivalent, and our study does not assume or imply such equivalence.

Our objective is not to replace the dust source function with drag partitioning in a strict physical sense, but to investigate whether improving the representation of surface process controls can reduce the model's dependence on empirical geographical constraints.

In current global dust models, the source function is widely used as a prescribed spatial weighting field that modulates the magnitude and distribution of dust emissions, primarily by (1) restricting emissions to persistent arid and semi-arid regions and (2) enhancing emissions in areas identified as potential dust sources. In this sense, it acts as an empirical constraint that linearly tunes the spatial distribution of dust emissions.

Many models also rely on alternative formulations (e.g., vegetation-based bare soil fractions) to achieve similar spatial constraints, suggesting that the role of the source function can be represented through different parameterizations depending on model structure.

Therefore, this study is based on the hypothesis that the model's reliance on source functions come from the lack or simplification of key processes in dust emission modeling, and the intention of this study is to explore whether introducing a more process-based representation of surface roughness (i.e., albedo-based drag partitioning) can reduce reliance on such prescribed spatial constraints, allowing the spatial distribution of dust emissions to emerge more naturally from the underlying physics.

Within this framework, we emphasize that Exp1 and Exp3 are not physically equivalent configurations. However, this does not invalidate their comparison, because both experiments are conducted within an identical modeling framework and differ only by a targeted modification of the surface process parameterization.

This design follows a controlled sensitivity experiment approach, in which one specific component of the emission system is perturbed while all other model settings remain unchanged. Such a configuration allows the isolated assessment of how model behavior responds to changes in process representation, and in particular how this influences the model's dependence on empirical spatial constraints such as the dust source function.

The purpose of this experimental design is therefore not to establish physical equivalence between the two configurations, but to diagnose the role of the source function within the modeling system and to explore whether its function can be partially reproduced or replaced by more process-based representations of surface controls.

Regarding Exp2 in the original manuscript, we acknowledge that this configuration lacks both source function and improved drag partitioning representation, and its reduced performance is expected. We clarify in the revised manuscript that Exp2 is included as a diagnostic sensitivity case to illustrate the role of the source function, rather than as a configuration intended for performance evaluation.

Comment C3
The equifinality conclusion is based on monthly-to-annual averaged simulations (Figs. 5-8). However, Fig. 4 indicates that the occurrence of dust emission events differs between Exp1 and Exp3. Observations of DOD, concentration, and deposition flux are less sensitive to transient, episodic dust emissions, especially when evaluated at coarse temporal resolution. Comparisons at these coarser temporal scales therefore present only limited aspects of equifinality.

Response
Thanks for this comment. In our study, the discussion of equifinality is primarily based on the finding that, although the albedo-based experiment (Exp3) substantially

alters the structure and temporal characteristics of dust emissions relative to the standard simulation (Exp1), the corresponding response in DOD is comparatively reduced. To further clarify this point and to address the reviewer's concern regarding transient variability, we provide additional analyses here using daily model outputs and spatial diagnostics.

Specifically, Fig. SC1 compares the difference in coefficients of variation (CV) between Exp3 and Exp1 (ΔCV: CV_{Exp3} - CV_{Exp1}) for both dust emission flux and DOD (showing only grid cells identified as dust source regions in both simulations). The CV is calculated based on daily simulations. The results show that the variability of dust emissions increases markedly in Exp3 relative to Exp1. This is mainly due to a reduction in emission frequency in Exp3, which leads to fewer but relatively stronger individual emission events (after calibration of total emissions), and thus larger daily variability. In contrast, although DOD variability also increases, the magnitude of change is notably smaller than that of emissions, representing the fact that dust in the atmosphere persists over time and that DOD is less sensitive to the timing of individual emission events.

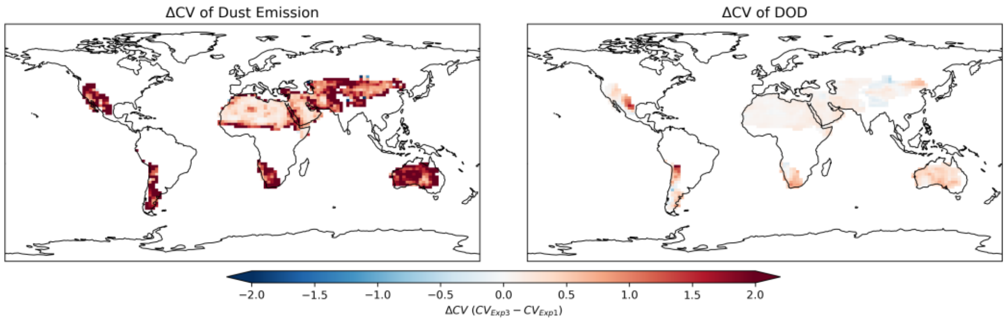

Figure SC1. Spatial distribution of differences in the coefficient of variation (ΔCV = CVExp3 − CVExp1) for daily dust emission flux and DOD between the albedo-based experiment (Exp3) and the control simulation (Exp1).

In addition, Fig. SC2 shows scatterplots between Exp1 and Exp3 for annual mean dust emission flux and DOD, along with Spearman correlation coefficients (considering only grid cells identified as dust source regions in both simulations). The results indicate that the spatial similarity between the two experiments is higher for DOD (rho = 0.984) than for emissions (rho = 0.854), because atmospheric transport and mixing reduces the sensitivity of atmospheric dust to localized differences in emission patterns.

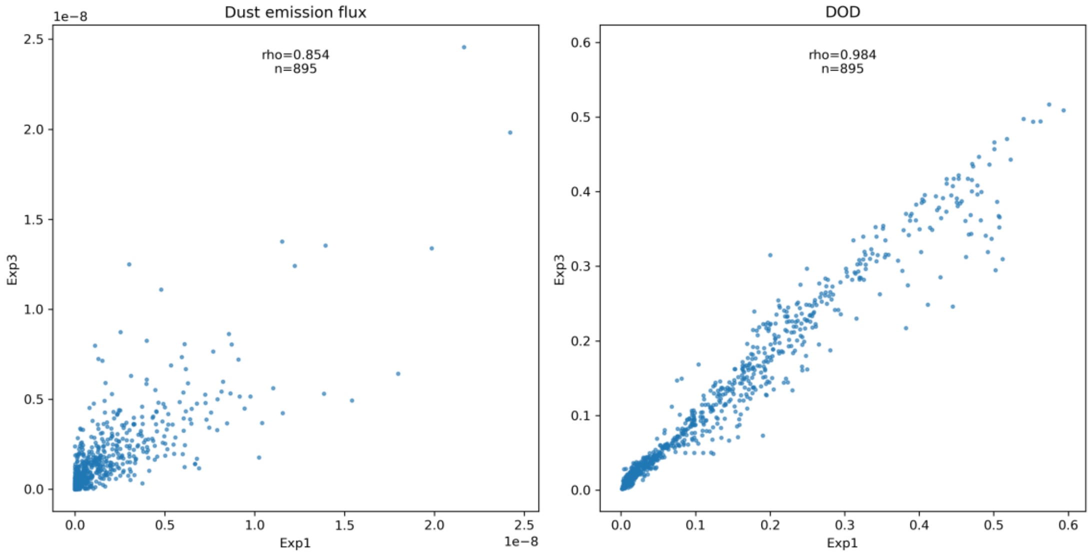

Figure SC2. Comparison of annual mean dust emission flux and DOD between Exp1 and Exp3, including spatial correlations and Spearman correlation coefficients.

Taken together, these additional results demonstrate that, relative to Exp1, Exp3 induces substantially larger changes in the temporal variability and spatial distribution of dust emissions. The corresponding changes in DOD are comparatively smoothed due to atmospheric transport processes. This further supports the equifinality interpretation discussed in the manuscript, indicating that atmospheric dust observations may not provide sufficient constraints on dust emission characteristics (when and where dust emission occurs) because they represent the comprehensive effects of dust emission, lifetime, transport, and deposition processes.

Minor Comments

Comment C4

Line 11: The first sentence of the Abstract may require grammatical editing.

Response

We thank the reviewer for this suggestion. The first sentence of the Abstract has been carefully revised for clarity and grammatical accuracy in the revised manuscript.

Comment C5

Line 96: Please cite several studies that use a similar “widely accepted approach.”

Response

We thank the reviewer for this suggestion. We have added several relevant references in the revised manuscript to support the statement.

Comment C6

Line 143: Because the paper focuses on implementing the albedo-based drag partitioning algorithm, it is relevant to include in the main text a description of the proposed roughness scheme, especially in the context of existing schemes. A discussion of its strengths (e.g., greater temporal variability than traditional fixed-value parameterizations and relatively easy implementation) and limitations (e.g., limited applicability to dense canopies) would be appreciated (Chappell and Webb, 2016). Key comments raised by Okin (2023) could also be discussed, including whether normalization of the MODIS BRDF using the f_{iso} parameter adequately removes interference from background darkness and other factors.

Response
We appreciate this constructive suggestion. In the revised manuscript, we have expanded the discussion of the albedo-based drag partitioning scheme about its advantages and limitations. We also provide a comparison with existing vegetation-based drag partitioning approaches to place the method in context.

Comment C7
Line 191: It would be helpful to provide a map of the static source function, perhaps in the Supporting Information.

Response
We thank the reviewer for this suggestion. In the revised manuscript, we have added a map of the static dust source function within GEOS-Chem in the Supporting Information.

Comment C8
Line 316: In Fig. 4, the annual peak mass emission from MECA (around July) increases substantially in both Exp2 and Exp3 relative to Exp1 and reaches approximately twice the annual peak emission from WNA or ENA. However, this increase is not reflected in the monthly DOD in Fig. 6. What are the possible explanations for this difference?

Response
We thank the reviewer for this insightful question. The increase in July dust emissions over the Middle East region (MECA) in Exp2 and Exp3 relative to Exp1 is indeed evident in Fig. 4, and a corresponding signal can also be observed in the DOD results in Fig. 6 (at the Mezaira station, which is located in the Middle East, simulated DOD in July for Exp2 and Exp3 is higher than that in Exp1).

However, the magnitude of the increase in DOD is smaller than that of the emissions. This discrepancy is primarily attributed to atmospheric transport and dilution processes. In particular, the enhanced emissions are largely contributed by Sistan (in eastern Iran), while the locations of the AERONET station are not necessarily collocated with the strongest emission sources. As dust is transported in the atmosphere, it undergoes dispersion and dilution, which reduces the sensitivity of DOD to localized increases in emission. As a result, the relative increase in simulated DOD is weaker than that of the emission flux.

Comment C9

Line 353: Please describe the "Reference" star and the surrounding semicircles in the figure caption.

Response

We thank the reviewer for this suggestion. A detailed description of the Taylor diagram has been added to the figure caption in the revised manuscript.