Reviewer #2

General Comments

Comment B1

This paper uses an albedo-based drag partition to simulate the global dust cycle using the DEAD dust emission scheme in the GEOS-Chem model. Three experiments are carried out, two of which use default settings (Exp 1 with source function, Exp 2 without source function), and the third one (Exp 3) excludes the source function but uses a detailed (albedo-based) drag partitioning. Year 2016 is simulated at horizontal resolution of 0.5° × 0.625° for emission and 2° × 2.5° for transport. Each simulation is scaled to produce the same total annual dust emission. The paper concludes that the albedo-based configuration (Exp 3) eliminates the need for dust source function because it produced similar results for atmospheric dust as in Exp 1 (equifinality). While the attempt to show equifinality is interesting, I find the overall methodology problematic and interpretations misleading for the reasons discussed below. Therefore, I recommend rejection with encouragement for resubmission after addressing the comments below.

Response

We thank the reviewer for the careful and constructive evaluation of our manuscript.

We do not share the reviewer's perspective of our experimental design and do not accept that those results are misleading. We respond to each comment in detail to clarify the purpose and interpretation of the experiments.

Major Comments

Comment B2

Incorrect Interpretation of Dust Source Function

A dust source function (Ginoux et al., 2001) is primarily used to represent sediment availability, not drag partitioning. In such models (e.g., Zender et al., 2003), the drag is typically simplified (as in Exp 2) and an additional control is applied to scale dust emissions from vegetated areas. Therefore, the comparison between Exp 1 and Exp 3 is problematic and misleading, as it incorrectly treats the source function as a representation of drag partitioning.

Response

We explained in the Introduction (third paragraph around line 50) that
"These difficulties in adequately representing drag partition are compounded by the long-standing unrealistic assumptions that the entrainment threshold is fixed over space, static over time and with endless sediment, contributing to biases in simulated dust and atmospheric loading and making these models unable to generate reasonable

spatial distribution of dust loading directly (without geographical adjustments) (Kok et al., 2014; Leung et al., 2023; Chappell et al., 2023a; Hennen et al., 2024; Shao et al., 2025)."

We made clear that drag partitioning is separate to geographical adjustments e.g., using the dust source function. It is also clear from the citations in that excerpt, that previous studies have suggested that the effectiveness of dust source functions may partly reflect the incomplete representation of physical controls on dust emission in existing models, and the need of source function could be reduced by physical parameterizations (Kok et al., 2014).

Whilst we agree that the source function is different from drag partitioning, we do not share the reviewer's perspective that the comparison between Exp1 and Exp3 is inappropriate. Consistent with previous work, our study examines whether a physically-based, observation-constrained drag partition parameterization can reproduce the effects that are conventionally achieved through the application of a source function. Specifically, whether two different approaches for constraining the spatial distribution of dust emissions can lead to similar large-scale model behavior, and if the use of the source function can be (partly) eliminated by the use of the albedo-based drag partition parameterization.

Comment B3
Models Should Be Viewed Holistically, Not by Breaking Parts Apart
Exp 2 removes the source function and is compared with Exp 3, leading to the conclusion that Exp 2 performs worse than Exp 3. This is expected, as Exp 2 uses a time-static drag partitioning without spatial variability (L125, Eq. 4), while Exp 3 applies a more comprehensive drag partitioning. This comparison would be meaningful if Exp 2 reflected a standard modeling configuration. However, dust models are generally set up to use a combination of a source function and a simple drag formulation, rather than applying the simple drag in isolation. As a result, it is unclear what additional insight Exp 2 provides.

Response
We agree that Exp2 does not represent a standard dust-model configuration. In most operational and research applications, dust emission schemes with simplified or no drag partitioning are typically used together with a source function, as implemented in Exp1. However, the purpose of Exp2 is not to evaluate model performance, but to diagnose model sensitivity to the empirical source function.

Firstly, removing the source function in Exp2 allows us to reveal structural limitations that are otherwise hidden by the empirical spatial constraint. Since the source function strongly controls the spatial distribution of emissions, it can compensate for limitations in other components of the emission scheme. Examining the model behavior without the source function therefore helps clarify which aspects of the simulated dust-source distribution depend on this empirical constraint rather than on the underlying physical parameterizations.

Secondly, the results from Exp2 provide a basis for evaluating the role of drag partitioning. By comparing Exp2 and Exp3, we assess whether the introduction of a spatially varying, observation-constrained drag partition can mitigate the issues that emerge when the source function is removed. This comparison isolates the contribution of drag partitioning and tests the hypothesis that part of the role conventionally played by the source function can be represented through a more physically based treatment of surface roughness effects.

Comment B4

Inadequate Evaluation/Comparison

As also noted in the comments from Referee #1, an analysis of individual dust events is needed to better test the fidelity of the albedo-based approach and its comparison with Exp 1. Moreover, (L220–229) the use of observational datasets from different years than the model simulation would not be very appropriate due to interannual variability in meteorology and land cover that affect the dust cycle.

Response

We thank the reviewer for this comment and agree that event-scale evaluation provides a more stringent test of the albedo-based drag partition approach than climatological statistics alone.

Following a similar suggestion from Referee #1, we have expanded the evaluation by including an event-based analysis using the MIDAS DOD dataset for the simulation year 2016. Dust events and extreme dust outbreaks were identified using observation-based thresholds, and performance statistics (CSI, POD, SR, and Bias) were calculated for all experiments. Details of this additional analysis can be found in our response to Referee #1 (Comment A8).

We also agree that temporal consistency between simulations and observations is important. Most of the dust deposition and PM_{10} datasets compiled by Albani et al., (2014) consist of long-term observations collected over different periods and are the only datasets available for many regions. Therefore, they were used in this study solely as climatological constraints. In contrast, the DOD datasets used for model evaluation (e.g., MIDAS and AERONET) are temporally consistent with the 2016 simulation period.

In the revised manuscript, we have clarified the temporal coverage and intended use of each observational dataset and added discussion of the potential influence of interannual variability.

Minor Comments

Comment B5

I believe the concerns about the albedo-based method raised in Okin, 2023 are not addressed. I think dividing by the isotropic reflectance parameter does not fully remove the spectral dependence due to mixing (inseparability) of spectral (compositional) and geometric effects. In this regard as well, simulating many individual dust cases would help test the utility of the method.

Response

In this study, we adopt the albedo-based formulation following Chappell and Webb, (2016) as a practical implementation of surface roughness effects within a global dust emission model. A full reassessment of its theoretical assumptions is beyond the scope of the present study, which focuses on evaluating its impact on simulated dust emissions within an existing modeling framework. For the following additional reasons we do not share the reviewer's perspective that the concerns raised in Okin (2023) need to be addressed here:

1. Fundamentally, take a look at Shuai et al. (2011; Eq. 5) and you will see the same normalised ratio approach (used for slightly different reasons to compute the Albedo-to-Nadir Reflectance ratios applied to Landsat surface reflectance) to remove / reduce the compositional effects.

2. A rebuttal of the claims made by Okin (2023) is provided in our response to the comment on our recent publication (Chappell et al., 2023) by Mahowald et al. (2024). In our letter (Chappell et al., 2025) we describe how Okin's model uses lateral cover which is not used in the albedo-based model and we explain that the model stated by Okin is not the original albedo-based model.

3. Field evaluations provide empirical support for the practical utility of the albedo-based approach. Ziegler et al. (2020) tested the method using radiometer and MODIS albedo data and showed that albedo-based estimates of wind friction velocity are robust across scales of roughness. Zhou et al. (2024) further evaluated the approach using field measurements across multiple land-cover types and found close agreement between ultrasonic-anemometer measurements and albedo-based estimates. These studies support the use of the method as a practical parameterization whose performance can be evaluated empirically.

Comment B6

Furthermore, the paper does not state how often the albedo parameters update. Using monthly or annual averages may limit the advantage of using the satellite data by smoothing important temporal variability in surface roughness.

Response
The albedo-based drag-partition parameters used in this study are updated daily rather than using monthly or annual averages. As described in Lines 167–170 of the original manuscript, daily ω_{ns} fields were generated for the year 2016 and used in the model simulations. In the revised manuscript, we have made the daily update frequency more explicit.

Comment B7
Sect 3.1 L280-285: The paper appears to show deficiencies in previous model configurations by isolating model components. Removing the controlling factor (S) will lead to dust emissions from forests, as expected.

Response
We agree that dust emissions from forested regions are an expected outcome when the source function (S) is removed, since S acts as an empirical spatial constraint that suppresses emissions in areas of low erodibility.

The purpose of Exp2 is not to interpret this behavior as a model error or deficiency, but to serve as a diagnostic experiment that isolates the role of the source function in controlling the spatial distribution of dust emissions. In this sense, the appearance of forest emissions represents the underlying emission formulation in the absence of this empirical constraint.

As also discussed in our response to Comment B3, this behavior helps illustrate the dependence of the simulated dust-source distribution on the source function, and how this dependence changes when a physically based drag-partitioning scheme is introduced in Exp3.

Comment B8
It is not clear how comparisons were made but when comparing with observations (e.g., AERONET), it is better to first collocate instantaneous values, rather than computing daily averages separately.

Response
The model output used in this study is generated at daily mean resolution, and therefore the comparisons with observations were performed using daily averaged values.

Comment B9
L144-147: Several previous studies also have explicitly stated that, to be strictly correct, the u* at the soil surface should be used (e.g., Kok et al., 2014). However, I do not see a particular need to highlight this point here because the drag factor in the referenced 'classical' model (Exp 2) remains spatially homogeneous.

Response
We agree that in the context of Exp2, the drag factor is spatially homogeneous and does not introduce spatial variability in surface roughness. Therefore, this distinction does not affect the spatial patterns of results in Exp2. However, we have retained a full description of the implementation of albedo-based drag partition in Sect. 2.1.2 for completeness.

Comment B10
Equifinality appears to hold only in seasonal or annual means, as atmospheric dust may differ more between Exp 1 and Exp 3 at shorter timescales. This characterization is important in stating equifinality.

Response
We agree that the equifinality demonstrated in this study is primarily supported by seasonal and annual-scale analyses, and that differences between experiments may be more pronounced at shorter temporal scales.

In the present study, our evaluation focuses on climatological (seasonal to annual) statistics of dust emissions and atmospheric dust distributions. Therefore, the equifinality conclusion presented in the manuscript should be interpreted within this temporal context.

Comment B11
L414-417: As a source of model uncertainty, the paper does not mention the issue of treating air density as a fixed quantity in many dust modeling studies, including in the cited Chappell et al., 2023 papers. Because air density varies spatially and temporally in a nonlinear way, using a globally uniform single value removes an important thermodynamic control on dust emission. This can introduce an error of ~20% in dust fluxes. For this and other issues in dust modeling (e.g., sandblasting efficiency), Joshi, 2024 (e.g., its Sect 3.6) should be used.

Response
We agree that air density is an important control on dust emission fluxes and that its spatial and temporal variability can introduce additional uncertainty in dust modeling studies.

In the GEOS-Chem model used here, air density is not prescribed as a constant value but is instead diagnosed from the meteorological fields provided by the MERRA-2 reanalysis, and therefore varies in both space and time, consistent with the recommendation discussed in Joshi, (2024).

We also agree that uncertainties in sandblasting efficiency and other factors are relevant sources of uncertainty in dust emission modeling. In this study, all experiments are scaled to the same global annual dust emission budget (2000 Tg yr^{-1}), which reduces the influence of such uncertainties on the absolute magnitude of emissions and allows a more direct focus on differences in spatial distribution among experiments.

References:

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