

We would like to thank the referees for their careful reading of our manuscript. We are most grateful for the comments, constructive criticism and very useful suggestions received on how to improve the paper. Please find attached our detailed answers to the questions and a new version of the paper, which we hope satisfactorily to address the points raised during the discussion. The referee's comments are presented in black, and our responses in blue.

Response to Reviewer 2:RC 2

General comments:

This study evaluates the performance of the WRF-Chem model in simulating dust aerosols over the Northern Hemisphere dust belt with different combinations of three dust emission schemes (GOCART, GOCART-AFWA, UoC) and two land surface models (LSMs; Noah-MP and CLM4). By comparing with observational datasets such as AERONET and EMEP and reanalysis, the study evaluates modeled aerosol optical depth (AOD), dust AOD (DOD), surface concentrations of coarse particulate matter (PM₁₀-PM_{2.5}), and surface emission drivers (soil moisture and surface winds) across the six ensemble members. It is found that overall the GOCART and AFWA emission schemes show better agreement with AERONET AOD and MIDAS DOD, while the UoC scheme better captures the observed features of coarse particulate matter measurements. Empirical scaling factors for each combination of dust emission scheme and LSM are also provided for future similar studies. Overall, the paper is well written with well-prepared figures. Including an analysis of the representation of dust seasonality, providing statistics at regional levels, and expanding the discussion of uncertainties associated with the simulation settings would further strengthen the paper.

Reply: We thank the reviewer for the positive assessment and constructive suggestions. We have revised the manuscript extensively following these recommendations. Regarding evaluations against AERONET, we have now expanded the analysis to include the seasonal variability of dust AOD together with region-level statistics. We have also added regional analysis to the evaluation against ERA5-Land. Additionally, we have extended the discussion to now include the uncertainties in the MIDAS dataset affecting the scale factors obtained from the WRF-CHEM model output dataset. Responses to all specific comments are provided below.

Specific comments:

1. The dust belt is quite a large and geographically diverse area. While the paper aims to provide an overall evaluation over the entire region, it would also be valuable to identify which regions are better represented by the model than others. As discussed in the text and shown in figures (e.g., Figs. 2, 5), model

performance shows large spatial variability. It would therefore be helpful to extend the statistical analysis (e.g., Table 1) into several sub-regions, such as North Africa, the Arabian Peninsula, and Central Asia. This would provide a more quantitative assessment of regional differences in model performance in addition to the domain-wide evaluation.

We thank the referee for this recommendation. The statistical analysis has been extended to sub-regions following the classification of ((Kok et al., 2021)). We have extended Table 1 to include regional analysis as suggested by the reviewer – and moved to Supplement Table S1 due size considerations. We have now also added regional analysis in Fig. 3 ,Sect. 4.1.2:

“The lower panel of Fig. 3 demonstrates the model statistical skill in simulating dust at regional level. The stations are distributed into the emission regions of North Africa, Arabian peninsula and the Middle east, and transport regions that include Southern Europe and the Mediterranean. As can be expected, in the source egions there is a lower spread of the metrics, while larger spread is evident in remote regions, due to the effects of transport and deposition. For all six configurations, the median values for MBE are relatively lower near the source regions, and increase by at least 50% in receptor regions. Regarding specific DES-LSM configurations, at the sources GOCART and AFWA exhibit better agreement with observations, (the former paired with CLM4 and the later with Noah-MP) with low MBE-medians ranging from -0.09 to -0.11, whereas UoC shows higher values going up to -0.27. UoC-Noah-MP is characterised by lowest spread at the sources, indicating consistent behaviour across stations. The average error magnitudes, MAE = 0.22 and NME = 46% values indicate that GOCART achieves the smallest absolute and fractional deviations across stations, whereas AFWA exhibits higher error magnitudes despite its comparable mean bias. Further away from emission zones, all the combinations show similar results with relatively large errors (NME > 58%, MAE $\approx$ 0.3), with the exception of UoC paired with CLM4 which consistently shows poor performance (MAE $\sim$ 0.4), also signifying pronounced LSM dependency as reported in past studies ((Yoon et al., 2025); (LeGrand et al., 2019)).”

2. Section 4.2 examines the model representation of key surface drivers of dust emissions, e.g., soil moisture and surface winds. It would also be helpful to provide some regional-level statistics when compared to the ERA5-Land reanalysis. Also, relating the model representation of these surface variables to model performance in simulating AOD would help understand model capability.

We have extended Sect. 4.2 to include regional statistics for soil moisture and wind speed against ERA-5 Land using MBE and RMSE, across the major dust source regions considered in the study and added Fig. 6 with comparison of

annual average modelled soil moisture and 10m wind speed against ERA5-Land over the main dust source regions. Added text in Sect. 4.2:

“We assess the regional variability of surface emission drivers across the major dust-source regions in our domain (Western North Africa, Eastern North Africa, Sahel and Middle East and central Asia) as defined in ((Kok et al., 2021))). Figure 6 presents statistical evaluation of the surface parameters against ERA5-Land. There are relatively small biases over North Africa, while larger errors and variability occur over the Middle East, Central Asia and the Sahel. In the Eastern and Western North Africa, the model generally overestimates soil moisture, which can subsequently effect dust emission and mobilisation resulting in lower dust concentration and AOD. The Sahel region exhibits a systematic negative MBE, signifying that WRF-Chem tends to simulate drier soil in this region. Surface wind speed is better represented over North Africa, notably for CLM4, while Noah-MP shows subtle overestimation. Strong positive biases are evident over the Sahel, Middle East and Central Asia.”

3. Since the simulations were conducted over the entire year, it would be useful to provide some evaluation of how well the seasonality of dust aerosols is represented. It would be interesting to know whether the seasonal features are well captured by each combination of dust emission scheme-LSM, and if not, whether the biases in surface emission drivers contribute to the discrepancies.

We thank the reviewer for the suggestion. We have included seasonal statistics to analyse how well each configuration captures the seasonal variability, as well as annual and seasonal distributions of mean bias error (MBE) between modelled dust AOD and AERONET AOD observations (Fig. 4). The complete set of individual station statistics is included in the Appendix Table A1 and the seasonal plots are presented in the Supplement Fig. S1. Added in Section 4.1.2:

“Correspondingly we also analysed model behaviour (Fig. 4) for AOD across seasons, and report that overall the model configurations show a tendency over negative bias for AOD. The magnitude of these biases varies seasonally, with AFWA and GOCART generally exhibiting smaller values during summer months, and stronger negative biases during winter autumn. The seasonal variation in the model bias broadly reflects the seasonality of dust over Eastern Mediterranean and Middle east, where dust activity and AOD are generally enhanced from spring to summer and reduced during winter (Basart et al., 2009; Xu et al., 2020). UoC shows a different behaviour, with pronounced sensitivity to the choice of LSM, which is more prominent in the winter with CLM4 performing considerably worse. The complete set of individual station statistics is included in the

Appendix Table A1 and the seasonal plots are presented in the Supplement Fig. S1.”

4. It is mentioned that model wind components, temperature, and humidity were nudged toward reanalysis (line 87). Was the nudge applied to the whole atmosphere at every pressure level, or only above the boundary layer, or at the surface level?

The wind components, temperature, and humidity were nudged towards reanalysis at every vertical level, including the planetary boundary layer. This is now stated in the manuscript text in Sect. 2.

“The model horizontal wind components, temperature and humidity are nudged at every time-step and at every vertical level including the planetary boundary layer (PBL).”

5. Different empirical scaling factors for dust emissions were used for each combination of dust emission scheme and LSM to achieve better agreement with the MIDAS dataset. While the information is quite helpful for future similar studies, it should be noted that, because different scaling factors were applied for each ensemble member, the discrepancies among the ensemble members may reflect three factors: dust emission scheme, LSM, and empirical scale factors. The uncertainties associated with this should be discussed in Section 5.

Thank you for the comment. Section 5 is extended to include the uncertainties mentioned: “Finally, we provide reference empirical dust emission scale factors (Table 1) for all combinations of emission mechanisms and LSMs, that are applicable to be used in WRF-Chem model simulations. The scale factors presented in Table 1 are in principle applicable to all WRF-Chem simulations, with equivalent dust-emission-LSM parameterisation configurations, encompassing aeolian dust emissions from sources in the dust belt. Additional uncertainties arise from use of different scaling factors for each model configuration. Therefore, differences among the simulations reflect the combined effects of the selected dust emission, land surface properties and corresponding emission scaling.”

6. In Section 2.1, it would be helpful to clarify whether the threshold wind velocity (U_t) in the GOCART model and the threshold friction velocity (U_{*t}) in the AFWA scheme were prescribed or calculated.

These parameters are prescribed and now it has been made clear in the text.

: “The wind components are prescribed.” in (Sect.2.1).

7. Line 230, please consider including more information regarding the soil moisture from the ERA5-Land reanalysis. Are there any observations assimilated into the dataset?

Thank you for the suggestion. Details regarding ERA5-Land have been now added to Sect. 3.4: *“ERA5-Land is an enhanced global reanalysis dataset focused on land surface variables, produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) as part of the Copernicus Climate Change Service of the European Commission. The dataset spans the period from 1950 to the present, with a horizontal resolution of 9 km. ERA5-Land is driven by ERA5 atmospheric forcing, which incorporates conventional meteorological and satellite observations through data assimilation ((Muñoz-Sabater et al., 2021)). In ERA-5 soil moisture is analysed for four volumetric soil water layers: (0-7, 7-28, 28-100, 100-289) cm.”*

8. Line 252, “derived from MIDAS dust AOD observations”, MIDAS dust AOD is not a purely observational dataset, as the ratio of DOD to total AOD is derived from the MERRA-2 reanalysis. Uncertainties regarding the dataset should be discussed.

We thank the reviewer for this comment. We note that this is also highlighted by reviewer 1 and in the community comments. We agree and acknowledge the uncertainties associated with the MIDAS dataset, since it is not purely observational, and we have revised the manuscript (Sec. 5) to discuss this: “The evaluation of our WRF-Chem configurations with MIDAS is subject to several uncertainties as it is based on MODIS-Aqua AOD and MERRA-2 dust-to-total AOD ratio, whose individual biases can propagate into the derived DOD ((Gkikas et al., 2021)). Although MERRA-2 assimilates observed total AOD, its aerosol speciation is not directly constrained and may depend on underlying aerosol model and associated parameterisations ((Buchard et al., 2017)). Nevertheless, the MIDAS DOD product has been evaluated against AERONET observations under dust-dominated conditions ((Gkikas et al., 2021)), and supporting its suitability as a reference dataset for DOD evaluation. A further consideration is that the MERRA-2 aerosols fields used to derive MIDAS are generated using the GOCART aerosol module ((Randles et al., 2017)) and this overlap with the GOCART as well as the AFWA (which is based on GOCART) modules of the WRF-Chem model can contribute to the closer agreement between the modelled and MIDAS data. The scaling factors derived from MIDAS therefore inherit uncertainties associated with the dataset.”

9. Line 256, since this is the first table mentioned in the text, it should be numbered as Table 1.

Corrected. Table 1 is now represented in the Appendix, as Table A1

10. Fig. 1, it would be helpful to add latitude and longitude labels.

The labels are now added to the Figure.

11. Fig. 3, please consider adding the same statistics as shown in Fig. 2 (e.g., SF, R^2 , RMSE).

Added.

Technical corrections:

Line 179, "... and surface fiels", do you mean "surface fields"?

Corrected: Changed to -> "*surface fields*"

Fig. 2, top panel, the figure title shows "MIDAS (AOD)" while the figure caption indicates dust AOD, please clarify which variable was plotted.

The MIDAS AOD was plotted in the Figure. We have changed the caption to clarify the variable that was presented.

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