Response to the review comment1 on acp-2022-760

RC1: 'Comment on acp-2022-760', Anonymous Referee #1, 03 Mar 2023

The manuscript by Zhao et al. aims at estimating future changes in global distributions and the budget of mineral dust aerosol by making use of results from the CMIP6 model experiments. Although this is an interesting topic and the use of CMIP results is a good starting point, the study has significant weaknesses and I cannot recommend publication in ACP.

Response: Thank you very much for your constructive suggestions. We have made our best to revise the manuscript following your comments. In this revision, we included all the available model output from CMIP6, validated the model performance with site-level AOD, added the uncertainty ranges for the projections, and compared the future changes of dust emissions over vegetation-free grids. We hope our revisions and responses could answer your concerns.

Major points:

The authors point out that taking into account the effects of changes in vegetation cover on dust emissions may play an important role but using vegetation model scenario results make the dust aerosol trends more uncertain. Indeed such changes would have a significant impact on dust emissions. The authors do not clarify to which extent vegetation cover changes were considered in the CMIP model experiments that were used for this study, especially for the future scenarios. If they want to avoid uncertainties related to potential vegetation changes by considering only the effects of wind and precipitation changes, then only in regions that are vegetation-free in both the historical and future scenarios should be considered. (see e.g Mahowald et al., 2003, Woodward et al., 2005).

Mahowald, N. M., and Luo, C. (2003), A less dusty future? Geophys. Res. Lett., 30, 1903, doi:10.1029/2003GL017880, 17.
Woodward, S., Roberts, D. L., and Betts, R. A. (2005), A simulation of the effect of climate change–induced desertification on mineral dust aerosol, Geophys. Res. Lett., 32, L18810, doi:10.1029/2005GL023482.

Response: Thank you for your suggestions. Inclusion of dynamic vegetation is expected to be an advance for the CMIP6 models. At the starting point, we hope to include vegetation cover changes as one of the drivers for future dust cycle. However, the changes of dust source areas are not provided by CMIP6 archives. In addition, the dynamic vegetation processes may instead introduce more uncertainties for the dust projections. As a result, we made great efforts to validate the simulated dust variables (concentrations and AOD, Figures 1-3) and selected the best models for future projections. In the introduction section, we have clarified as follows: "Compared to

CMIP5 models, more dust emission schemes are coupled with dynamic vegetation in the CMIP phase 6 (CMIP6) models to optimize land surface emission processes (Zhao et al., 2022). However, such improvement may instead amplify the uncertainties of dust simulations, because the predicted vegetation change may be inconsistent with the observed tendencies (Wu et al., 2020). As a result, it is important to validate the simulated present-day dust cycle before the application of different models in the future projection (Aryal and Evans, 2021).” (Lines 100-106)

We added Table S5 to compare the changes in dust emissions on the same vegetation-free grids as suggested: “Previous studies have revealed that dynamic vegetation process could significantly alter future dust activity (Woodward et al., 2022). However, we were not able to identify such effects because CMIP6 models do not output the information of dust sources and their strength. As a check, we compared the changes of dust emissions at vegetation-free grid points for both historical and future periods so as to exclude the impacts of vegetation changes. We found very limited differences for those grids (Table S5) relative to the changes for all grids (Table 4), suggesting that the changes of dust area are limited in most of the CMIP6 models.” (Lines 387-395)

Table S5. Multi-model ensemble projection of the absolute (Tg a^{-1}) and relative changes (%) in dust emissions by the end of this century (2090-2099) at vegetation-free grid points

Region	**SSP1-2.6**		**SSP2-4.5**		**SSP3-7.0**		**SSP5-8.5**	
	Absolute	Relative	Absolute	Relative	Absolute	Relative	Absolute	Relative
NAF	10.1±121.7	1.2	5.8±131.5	0.7	4.2±174.1	0.5	47.4±178.9	5.6
TGD	-0.4±23.5	-0.8	-2.5±41.3	-4.9	-6.2±53.6	-11.9	-4.6±55.7	-8.9
MEWA	-0.7±43.1	-0.3	-4.5±66.4	-1.8	-4.4±81.0	-1.8	6.8±87.2	2.7
AUS	1.2±16.9	2.9	2.0±20.5	5.1	-0.1±47.2	-0.3	4.3±51.6	10.7
NAM	0.03±4.7	2.2	0.02±6.1	1.3	0.01±5.4	0.8	0.02±5.7	1.4
SAM	0.01±32.3	0.2	0.4±42.1	6.7	-0.1±31.2	-2.1	-0.4±27.7	-6.2
SAF	0.2±4.1	2.3	0.5±4.1	6.1	0.7±10.6	9.0	0.9±5.0	11.4

* The domain of each region is shown in Fig. 4a

The selection criteria that the authors use to decide what are the ‘good’ models to be used in this study is vague. Only surface concentration data of mineral dust are compared with station data at several locations, which are likely covering different time periods (not given here). For several sites none of the models reproduces the observed concentrations at certain seasons, which hints toward a fundamental problem of dust modelling at global scales. Given that mineral dust concentrations are highly variable in time and space including altitude of dust transport, to show that that the dust cycle is reproduced well by the models other data such as optical thickness from satellites are *the AERONET network should be taken into account. It would also be interesting if the results on future trends would be different if all models would be considered.*

Response: Following this suggestion, we have added the validations of CMIP6 models with the aerosol optical depth (AOD) data from AERONET network in the revised Figure 1 and new Figure 3. We selected 'good' models with reasonable correlation coefficients and low biases against observations. We added the related descriptions as follows: "We also use the monthly AOD measurements from the Aerosol Robotic Network (AERONET) to validate CMIP6 models. Observed AOD is affected by many different components in addition to dust aerosols. We select a total of 19 sites with at least one-year records and the simulated DOD-to-AOD ratio larger than 0.6 as indicated by the ensemble of CMIP6 models. In this way, AOD at the selected AERONET sites is more likely dominated by dust aerosols." (Lines 150-156) "With the validations, we select 9 models for the future projections including CESM2-WACCM, CESM2, CNRM-ESM2-1, GFDL-ESM4, GISS-E2-1-G, GISS-E2-1-H, GISS-E2-2-G, NorESM2-LM and UKESM1-0-LL. All of these selected model yield NSD between 0.25 and 1.5 and correlation coefficients higher than 0.55 against observations of both dust concentrations and AOD." (Lines 188-193)

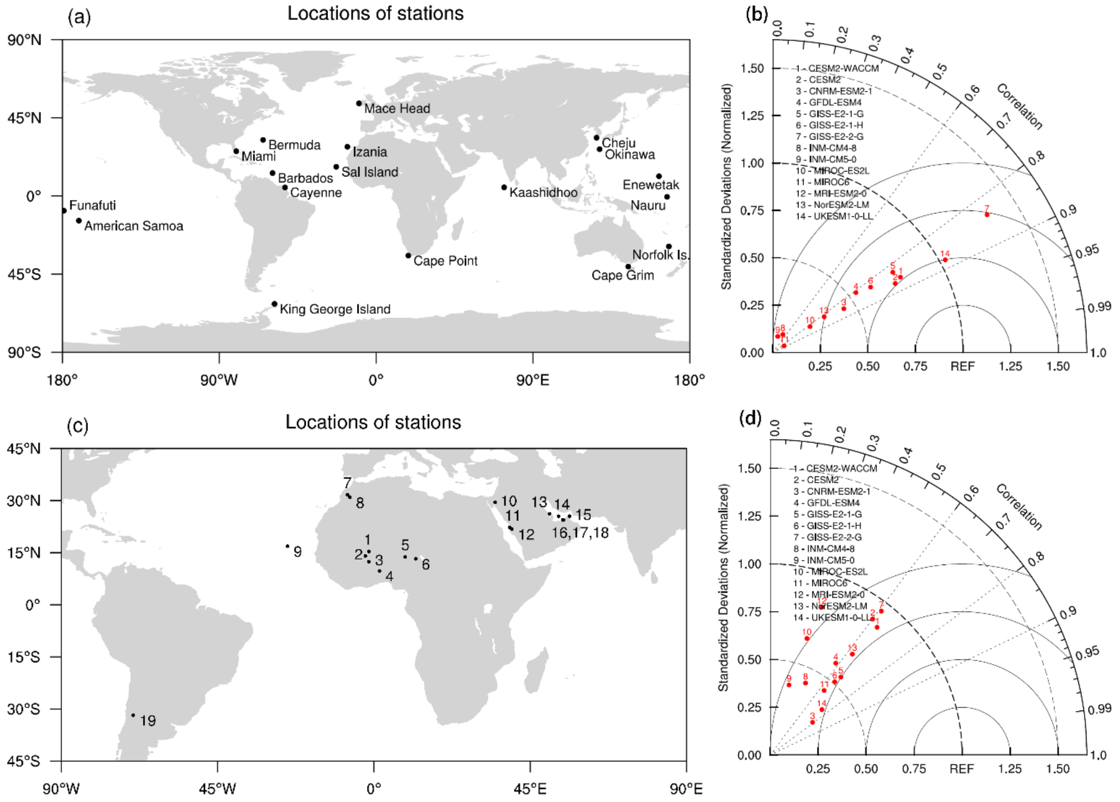

Figure 1. (a) Locations of 18 observational stations in the University of Miami Ocean Aerosol Network and the (b) evaluation of simulated dust concentrations from CMIP6 models at these stations. (c) Locations of 19 AERONET sites and the (d) evaluation of simulated AOD from CMIP6 models at these stations. The names of AERONET sites

in (c) are 1-Agoufou, 2-Bidi_Bahn, 3-Ouagadougou, 4-Djougou, 5-Zinder_Airport, 6-DMN_Maine_Soroa, 7-Ras_El_Ain, 8-Ouarzazate, 9-Calhau, 10-Eilat, 11-KAUST_Campus, 12-Hada_El-Sham, 13-Bahrain, 14-Abu_Al_Bukhoosh, 15-Dhadnah, 16-Mussafa, 17-Dhabi, 18-Masdar_Institute, 19-CASLEO. The longitudes and latitudes of these sites are indicated on Figures 2 and 3.

"The ensemble mean of AOD from 9 selected CMIP6 models is compared to observations at 19 AERONET stations (Fig. 3). For six sites (1-6) in the inner North Africa, the model prediction underestimates observed peaks in springtime, especially at Bidi Bahn and Djougou. As a result, the ensemble predictions at these sites are lower than observations by at least -20% except for DMN Maine Soroa. For three sites (7-9) along the coast of western Africa, the model ensemble captures the summertime maximum but tends to slightly overestimate AOD in other seasons. For 9 sites (10-18) in Middle East, the predicted AOD reproduces observed seasonality and magnitude with RMB between -27.7% and 20.7%. However, for the only site (CASLEO) in South America, the model prediction shows much higher AOD than measurements. The validations show that simulated AOD from the selected CMIP6 models agree well with the observed spatial pattern especially at regions near dust sources." (Lines 207-218)

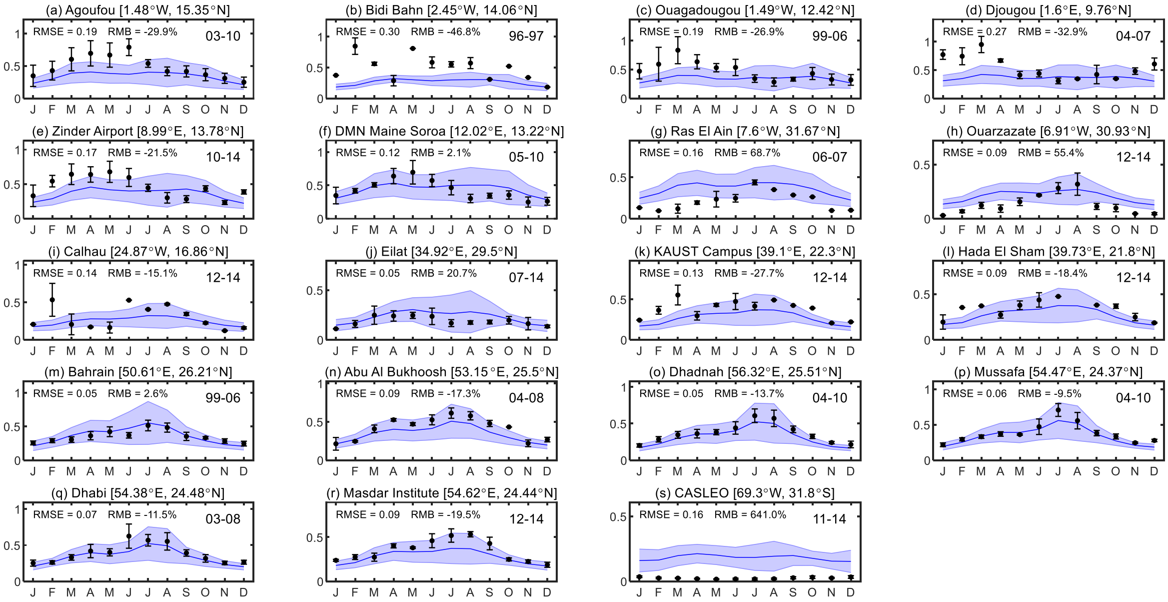

Figure 3. The same as Figure 2 but for the validation of the ensemble simulated aerosol optical depth at 19 AERONET sites.

We added a new Table S6 to compare the projection results using the selected and all models: "The ensemble projections with the 9 selected models (Table 4) are in general consistent with the projections using all 14 models (Table S6), especially for the enhancement of dust emissions in the North Africa under all scenarios. However, both projections revealed large inter-model variability that may dampen the significance of the predicted changes.” (Lines 409-413)

Table S6. Multi-model ensemble projection of the absolute (Tg a^{-1}) and relative changes (%) in dust emissions by the end of this century (2090-2099) using all 14 CMIP6 models

Region	**SSP1-2.6**		**SSP2-4.5**		**SSP3-7.0**		**SSP5-8.5**	
	Absolute median±SD	Relative	Absolute median±SD	Relative	Absolute median±SD	Relative	Absolute median±SD	Relative
NAF	10.3±131.5	1.4	15.8±159.9	2.2	19.5±181.6	2.7	48.0±215.2	6.6
TGD	0.6±32.3	1.1	-1.4±37.9	-2.9	-4.8±50.6	-9.6	-3.5±54.0	-6.9
MEWA	1.8±68.4	0.9	0.6±69.7	0.3	-1.7±68.1	-0.8	5.6±93.8	2.8
AUS	-0.6±15.5	-1.3	0.2±26.5	0.4	-0.3±49.4	-0.7	1.9±52.7	4.3
NAM	0.03±3.9	1.8	0.02±5.2	1.3	0.02±5.4	1.6	0.04±6.3	2.6
SAM	0.4±30.6	5.0	0.6±47.6	7.2	0.2±58.6	1.9	0.1±84.5	0.9
SAF	0.02±4.6	0.2	0.7±5.2	7.8	1.3±10.2	13.8	1.5±7.8	15.9

* The domain of each region is shown in Fig. 4a

Another point regarding the selection of models used in this study: Rather than comparing multi-year average concentrations, the decadal temporal trends in dust aerosols simulated by the models would give a better indication for their suitability of predicting future changes (eg., Kok et al 2023).

Kok, J.F., Storelvmo, T., Karydis, V.A. et al. Mineral dust aerosol impacts on global climate and climate change. Nat Rev Earth Environ ***4****, 71–86 (2023). https://doi.org/10.1038/s43017-022-00379-5*

Response: Thank you for the suggestion. We agree that it’s important to validate the long-term trend of dust aerosols in CMIP6 models. However, such validation is difficult due to the limitations in credible datasets. The recent loading dataset developed by Kok et al. (2023) is very unique but also needs further comparisons with other data sources. For example, the increasing trend revealed by Kok et al. (2023) was not consistent with the decreasing trend of dust storms in Asia (Figure R1) (Wang et al., 2005). We expect that the long-term trends of simulated dust aerosols could be further evaluated with more available observations in the future studies.

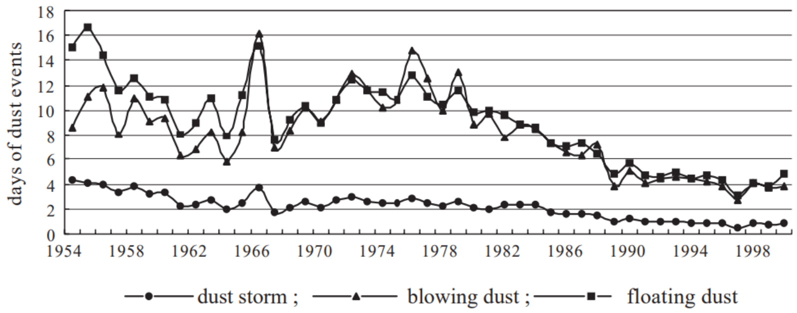

Fig. 4. Interannual variation of annual occurrence days of three kinds of dust storm events in China during 1954–2000.

Figure R1. Dust storm record from (Wang et al., 2005)

In the revised paper, we clarified as follows: "For this study, we did not validate the long-term trend of simulated dust variables due to the data limitations. A recent work by Kok et al. (2023) showed increasing global dust loading during historical periods with the glacier deposition records and found that all the CMIP6 models could not reproduce such tendency. While this newly derived dataset provides a unique aspect for global dust activity, more validations are required using the ground-based concentrations and/or satellite-retrieved AOD. For example, the long-term records in China showed a decreasing trend of dust storm in East Asia during 1954-2000 (Wang et al., 2005), inconsistent with the upward trend in the same region as revealed by Kok et al. (2023)." (Lines 378-386)

As shown in Figures S7-S11 in the supplemental material, the results for emission and deposition in selected individual models are differ greatly from each other (dust column loads should be added as additional figure). Ranges need to be given for all results. In those places where ranges are provided for scenario results (e.g. page 8 line 224 to 227) it is unclear what the range refers to – Standard deviations? Results from different Models?

Response: We added the standard deviations among different models as the inter-model variability for all results in Figures (Figs 4-5) and Tables (Table 3-4 and Table S4-S6). We also discussed the possible impacts of inter-model variability on the projections: "The inter-model variability is much higher than the projected median changes, suggesting the large uncertainties among climate models." (Lines 261-263) "However, both projections revealed large inter-model variability that may dampen the significance of the predicted changes." (Lines 412-413)

What is the reasoning behind focusing on relative humidity in addition to wind speed and precipitation as the main factors influencing dust trends? Relative humidity does not impact the dust cycle directly. Also in Figure 6 there appears to be a better *correlation for precipitation than relative humidity anyway. If the relative humidity is supposed to represent drought condition one could instead use.*

Response: We agree that relative humidity is less important than precipitation in modulating dust emissions. Our analyses of Figure 6 further confirm this point: "Specifically, almost all the 10 region labels with reduced dust emissions under the four scenarios show increased regional precipitation but decreased wind speed, though 8 labels show decreased relative humidity (Fig. 6). It suggests that changes in precipitation and wind speed play more dominant roles in the changes of dust emissions." (Lines 288-292)

In the revised paper, we have removed the relationships between relative humidity and dust emissions in Figure 7:

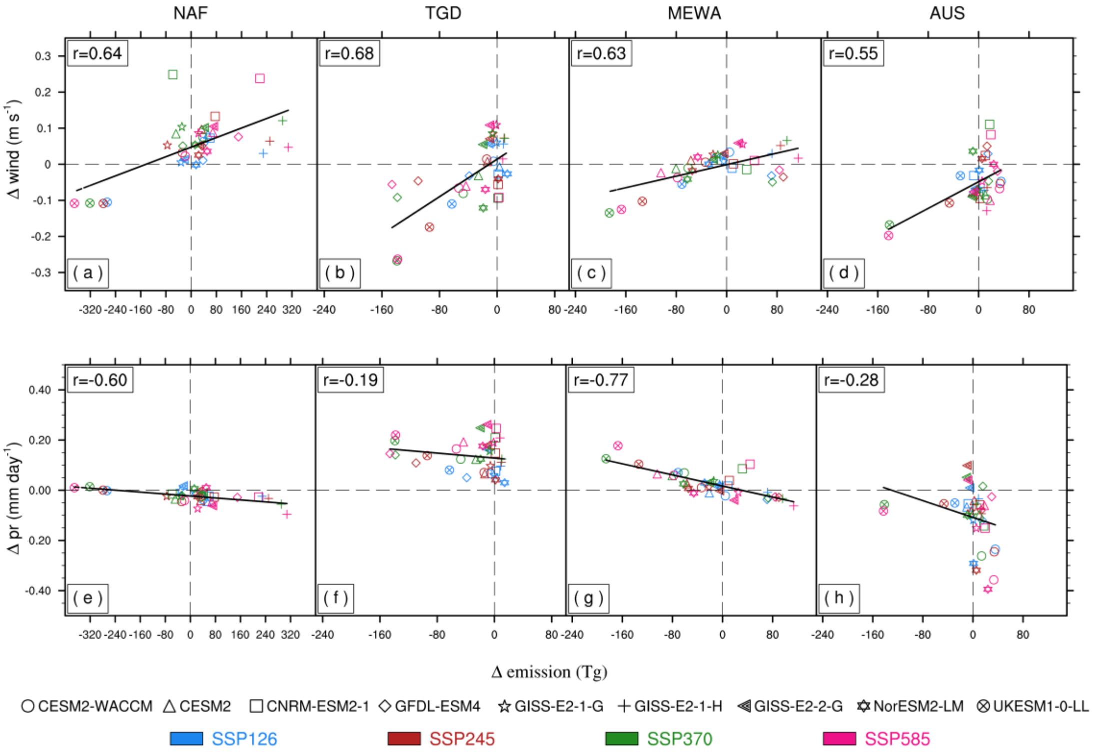

Figure 7. Relationships between the changes of dust emissions and the changes of meteorological factors. Each column represents a source region, including North Africa (NAF), Taklimakan and Gobi Deserts (TGD), Middle East and West Asia (MEWA), and Australia (AUS). Each row represents a meteorological factor, including surface wind (top) and precipitation (bottom).

In Figure 7 it hard to see the dotted areas which indicate significant changes in the figure. (I recommend to mask out areas with non-significant changes eg. by grey color). In any case, it appears that the focus regions downwind of East Asia do not contain significant changes and thus should not be highlighted in the paper.

Response: We bolded the points in the Figure 8 (original Figure 7). We mainly discussed the results with significant increases (South Africa) and reductions (East Asia) of dust loading: “the role of precipitation cannot be ignored as it can magnify the impact of emissions. For example, dust emissions in the source region of South Africa increase by 2.1%-10.3% under different scenarios (Table 4), while dust loading in this region increases by 2.2%-38.3% (Table S4). The higher enhancement of dust loading than emissions is mainly attributed to the decreased precipitation (Fig. S6), which reduces the proportion of wet deposition to the total deposition (Fig. S9).” (Lines 330-335) “For the non-source areas such as East Asia and South Asia, the moderate changes of dust emissions cannot explain the significant reductions in dust loading. Instead, the strong enhancement of regional precipitation (Fig. S6) helps promote wet deposition of dust in Asia, leading to the reduced amount of suspended particles (Fig. 8) and the increased percentage of wet-to-total deposition (Fig. S9).” (Lines 336-340)

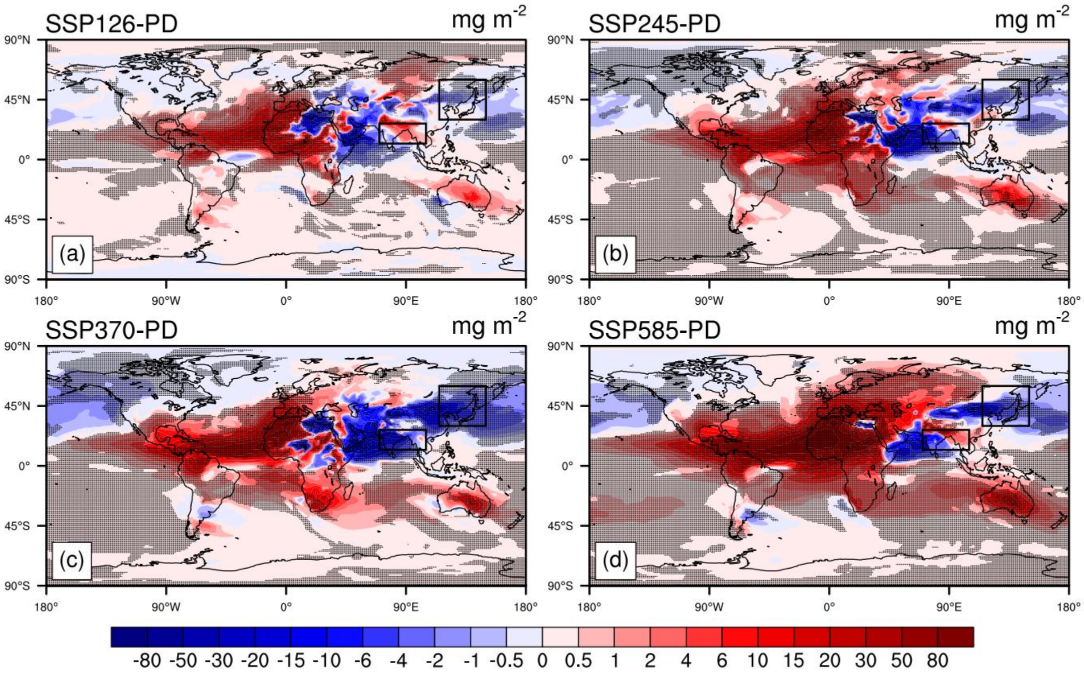

Figure 8. Multi-model ensemble projection of the changes in dust column concentrations by the end of 21st century (2090-2099) relative to present day (2005-2014). Dotted areas represent changes significant at 90% level. Two additional box areas are selected for South Asia (12°N-27°N, 70°E-105°E) and East Asia (30°N -60°N, 115°E -150°E).

High resolution convection-resolving results show that wet convection driven dust emissions (cold pools) cannot be represented correctly, and that strengthening convective activity in future scenarios may enhance dust emissions in the southern Sahara in NH summer, but may lead to overestimating of low-level jet emissions (Garcia Carreras, 2021). It is questionable to which extent the results of coarse-resolved global models such as used in CMIP are suitable future change estimates, at least in regions that are strongly affected by convective activity.

Garcia-Carreras, L., Marsham, J.H., Stratton, R.A. et al. Capturing convection essential for projections of climate change in African dust emission. npj Clim Atmos Sci 4, 44 (2021). https://doi.org/10.1038/s41612-021-00201-x

Response: It's a good question about the model capability in future projections. The coarse model resolution indeed hinders the prediction of convective activity, which may alter the dust emissions. However, there are no enough data to validate the model performance in capturing the convective activity and the consequent effects on dust emissions on the global scale. For this study, we have to use the up-to-date most advanced dust models coupled in climate models. We also applied the ensemble approach to minimize the impact of inter-model variability. Our site-level validations using concentrations and AOD demonstrate the capability of CMIP6 models. We believe our study provides the most reliable projections of future dust cycle based on our current understandings of dust schemes and the available observations.

Minor points:

The CMIP experiments should be explained in some more detail. Why is only one ensemble member selected for each model? Why is the analysis limited to 10 years?

Response: In the revised paper, we added all available models and ensemble runs for future projections. This largely increases our sample number from the original 50 (10 models with one run for each of 5 climatic scenarios) to 416 (14 models with varied runs under 5 climatic scenarios) for each dust variable. We limited our analysis to 10 years for each scenario just to estimate the decadal means. The choice of time period length will not change our main conclusions.

In the revised paper, we clarified as follows: "We use all available runs with different variants and labels from each of climate models, resulting in a total of 416 runs for every dust variable (120 for history and 296 for four future scenarios) and 770 runs for every meteorological variable (212 for history and 558 for four future scenarios). In addition, we collect both dust optical depth (DOD) and aerosol optical depth (AOD) at the historical periods from these models (Table S1). To facilitate the model validation and inter-comparison, we interpolate all model data with different spatial resolution to the same of 1°×1°. For each model, we average all the ensemble runs under one climatic scenario to minimize the uncertainties due to initial conditions. As a result, we derive 5 ensemble means (1 for history and 4 for future) for each variable of every model, leaving the same weight among CMIP6 models." (Lines 126-136)

Table 1. The information of CMIP6 models

Model [a]	Nation	Resolution	Number of runs for dust cycle				
			Hist	SSP126	SSP245	SSP370	SSP585
CESM2-WACCM	U.S.	1.25°×0.94°	3	1	5	3	5
CESM2	U.S.	1.25°×0.94°	11	3	3	3	3
CNRM-ESM2-1	France	1.4°×1.4°	3	5	10	5	5
GFDL-ESM4	U.S.	1.25°×1°	1	1	1	1	1
GISS-E2-1-G	U.S.	2.5°×2°	19	10	25	17	10
GISS-E2-1-H	U.S.	2.5°×2°	10	5	5	1	5
GISS-E2-2-G	U.S.	2.5°×2°	5	5	5	5	5
INM-CM4-8	Russia	2°×1.5°	1	1	1	1	1
INM-CM5-0	Russia	2°×1.5°	10	1	1	5	1
MIROC-ES2L	Japan	2.8°×2.8°	31	10	30	10	10
MIROC6	Japan	1.4°×1.4°	10	3	3	3	3
MRI-ESM2-0	Japan	1°×1°	12	5	10	5	6
NorESM2-LM	Norway	2°×2°	1	1	13	1	1
UKESM1-0-LL	U.K.	1.875°×1.25°	3	5	5	3	4
Total runs			120	56	117	63	60

[a] The models selected for future projections are bolded.

It is unclear what information content the regional budget column in Table 3 has. Again as everywhere, ranges should be shown for the results in this table.

Response: The budget is calculated as the difference between emissions and depositions. The positive budget indicates a dust source while the negative budget means a dust sink. We can see that Africa is a strong source region because the emissions are higher than deposition, and the remaining dust particles have to be transported elsewhere. In contrast, all the oceans are sinks with negative budgets because they have no emissions and have to receive dust transported from land. We have revised Table 3 to show the inter-model ranges for each budget.

Page 7, line 189: the sites offshore East Asia would certainly not be impacted from Middle Eastern dust sources

Response: In the revised paper, we removed this explanation.

Page 9 line 280 – "column concentration" should rather be named "column load"

Response: We have revised accordingly.

Some more discussion of the reasons of future precipitation and surface winds would be good.

Response: We have explained the possible cause of increased precipitation in East Asia: "Studies have projected that global warming tends to enhance East Asian summer monsoon and South Asian summer monsoon, leading to increased precipitation in the middle and low latitudes of Asia (Sabade et al., 2011; Wang et al., 2018; Wu et al., 2022)." (Lines 340-343) We also explained the possible cause of global changes in rainfall: "We found that the main features of increased drought and wind speed over North Africa and South Africa while enhanced rainfall over Asia was retained, following the 'drier in dry and wetter in wet' pattern due to the land-air interactions through water and energy exchange (Feng and Zhang, 2015)." (Lines 423-427)

Reference

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