Response to the review comment 2 on acp-2022-760

RC2: 'Comments on acp-2022-760', Anonymous Referee #2, 22 Mar 2023

There is a growing concern about future dust change induced by global climate change and human activity. The study be Zhao et al. has presented the future changes in global dust cycles based on the five CMIP6 models. Ten models are first used for model evaluation, and five of these models with better performance are selected for the projection. They also investigate the change in surface wind and precipitation/relative humidity, the factors associated with the dust changes in the future. The conclusions can provide a good reference to the relevant community. Most of the manuscript is well written and clearly presented. I have some comments for the authors to consider. In particular, if possible, please provide more information on the uncertainty in the model simulation of dust cycle and discuss whether the changes are significantly large in the future.

Response: Thank you very much for your valuable comments and constructive suggestions to further improve our manuscript. We have carefully considered all the comments and revised our manuscript accordingly. Our responses to each comment are summarized below.

Major comments:

Line 366 (solid): The change of future vegetation change due to both climate change and human activity is not considered in this study, which may induce large uncertainty in the projection of future dust change. I suggest the vegetation change should be considered as well. If the impacts of vegetation change are not included, the authors should add some discussions on this.

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). 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

Introduction and Conclusions and discussion: Some studies on dust cycle using CMIP6 models should be included for discussion:

Checa-Garcia et al. (2021, https://acp.copernicus.org/articles/21/10295/2021/),

Le and Bae (2022, https://acp.copernicus.org/articles/22/5253/2022/),

Li and Wang (2022, https://acp.copernicus.org/articles/22/7843/2022/),

Maki et al. (2022, https://www.jstage.jst.go.jp/article/sola/18/0/18_2022-035/_article/-char/ja/),

Woodward et al. (2022, https://acp.copernicus.org/articles/22/14503/2022/).

Response: Thank you for your suggestions. We have included the above references in different parts of our study:

"The recent phase 6 of CMIP (CMIP6) includes more complete dust variables (e.g., emissions, depositions, concentrations, and optical depth) from climate models. The ensemble of CMIP6 simulations has been used to depict historical changes in dust cycle and explore the possible climatic drivers (Le and Bae, 2022; Li and Wang, 2022)." (Lines 95-98)

"The predicted annual dust emissions of 2566±1996 Tg is close to the estimate of 2836 Tg yr^{-1} using an ensemble of five different dust models (Checa-Garcia et al., 2021)." (Lines 401-403)

"Previous studies have revealed that dynamic vegetation process could significantly alter future dust activity (Woodward et al., 2022). … 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." (Lines 387-392)

Selection of models for future projection: UKESM1-0-LL may produce too much dust emission compared to other models, according to Figure S7. I am wondering if it is reasonable to select UKESM1-0-LL.

Response: Yes, the UKESM1-0-LL produces too much dust emissions. However, this model shows reasonable performance in simulating both dust concentrations and AOD as revealed in Figure 1. As a result, we could not exclude it artificially. For this study, we use the ensemble median approach so that the extreme values from a single model will not affect the main conclusions. We have clarified in the manuscript as follows: "We applied the multi-model ensemble approach to minimize the projection biases from individual models. We used the median instead of mean values from the selected models so that our projections reflected the tendency of the majority models rather than that of the single model with maximum changes." (Lines 396-399)

Uncertainty: As Table 3, the values of the range should be also provided for understanding the uncertainty. In addition, please provide the values for each models in supplemental files to compare different models.

Response: We have added the inter-model range in the revised Tables 3 and 4. We also showed values for each model in Table S3.

Table 3. The summary of dust cycle at present day*

Region	Emission	Dry Deposition	Wet Deposition	Budget**
	Tg a^{-1}	Tg a^{-1}	Tg a^{-1}	Tg a^{-1}
Africa	1713±1288	1091±1235	236±155	386±87
Asia	736±458	432±419	226±161	77±32
Australia	165±237	110±211	20±25	35±13

South America	52±106	30±63	21±23	1±30
North America	15±27	13±31	9±20	-6±25
Europe	5±3	12±4	34±15	-41±19
Pacific Ocean	/	14±12	48±23	-62±33
Indian Ocean	/	46±23	71±36	-117±47
Atlantic Ocean	/	95±39	155±57	-250±62
Arctic Ocean	/	0±0.3	2±1	-3±1

[*] Values from individual climate models are shown in Table S3

[**] Budget = Emission - Dry Deposition - Wet Deposition

Table 4. Multi-model ensemble projection of the absolute (Tg a^{-1}) and relative changes (%) in dust emissions by the end of this century (2090-2099)

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	5.3±131.4	0.6	4.8±148.0	0.6	47.4±178.8	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±81.1	-1.8	6.8±87.2	2.7
AUS	1.1±17.0	2.8	2.1±20.7	5.1	-0.1±47.2	-0.4	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	0.02±32.3	0.3	0.4±42.1	6.7	-0.1±31.3	-2.0	-0.4±27.7	-6.1
SAF	0.2±4.1	2.1	0.5±4.2	5.5	0.9±11.4	9.9	0.9±5.0	10.3

* The domain of each region is shown in Figure 1a

Line 259: significant: How to determine the regions with significant changes?

Response: We revised the sentence to clarify: "We select four main source regions where dust emissions are projected to increase by at least 1 Tg a^{-1} under most of future climatic scenarios (Table 4). In these regions, we quantify the sensitivity of dust emissions to perturbations in meteorological factors (Fig. 7)." (Lines 293-296)

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Specific comments:

Line 22: meteorological conditions: meteorological conditions can affect the vegetation cover, which further affects the dust emission. But the impacts of vegetation change on dust emission are not mentioned in the study. Please clarify.

Response: Please check our responses to your major comment 1.

Line 33: relative humidity: I think soil moisture is the variable more closely related to dust emission.

Response: Yes. We have removed relative humidity in the revised manuscript.

Line 35 (central Asia and Taklimakan): The regions are not correctly named. According to Figure 3a, central Asia and Taklimakan should be East Asia (at least Gobi Deserts are not located in central Asia); Middle East should be Middle East and central Asia.

Response: Following your comment, we changed the original "central Asia and Taklimakan" to "Taklimakan and Gobi Desert" and the original "Middle East" to "Middle East and West Asia".

Line 39: due to: I think it is "partly due to".

Response: Corrected it as suggested.

Line 40: "As a result" should be "In total"?

Response: Corrected it as suggested.

Lines 65-67: First, according to Munktsetseg et al. (2016), it is more precise to say "soil moisture". Second, soil moisture alone does not control threshold friction velocity and dust emission intensity. Many factors including soil moisture determines them.

Response: We revised the sentence as follows: "Atmospheric humidity has a tight coupling effect with soil moisture, which in part controls the threshold of friction velocity and dust emission intensity (Munkhtsetseg et al., 2016)." (Lines 65-67)

We also found that relative humidity was less important than precipitation and wind speed for dust emissions. In the revised paper, we removed the relationships between dust emissions and relative humidity in Figure 7 and clarified as follows: "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)

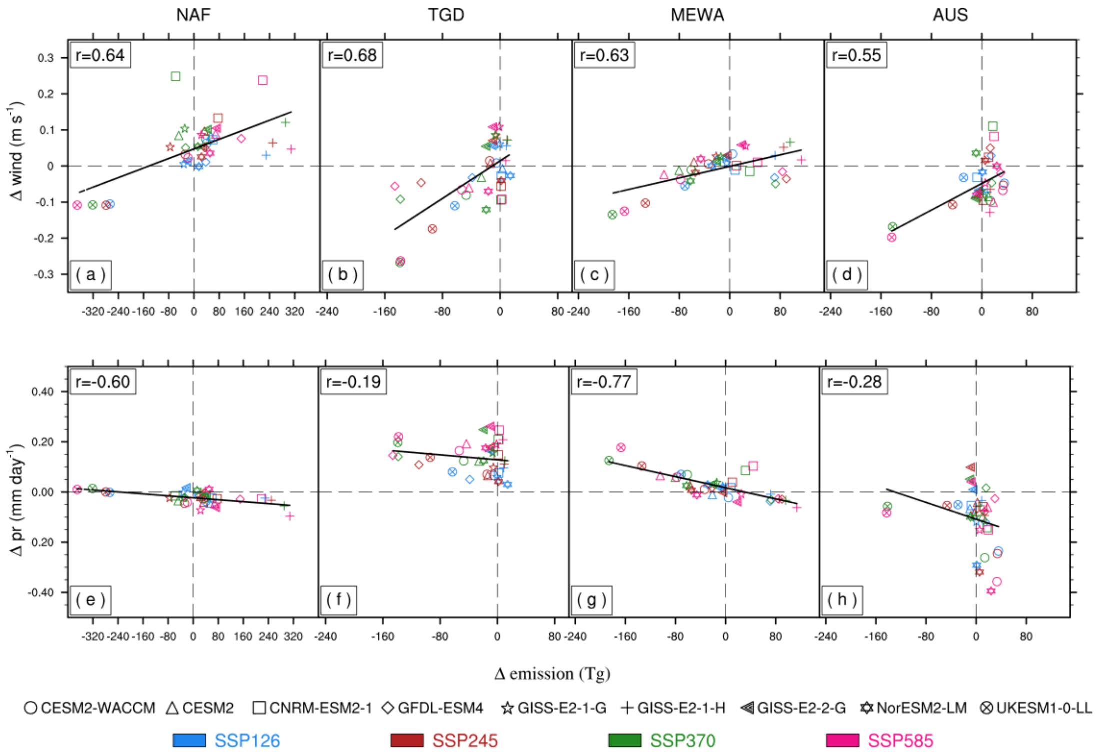

Figure 7. Relationships between the changes of dust emissions and the changes of meteorological factors. Each column represents a source region, including North Africa (NAF), Taklimakan and Gobi Deserts (TGD), Middle East and West Asia (MEWA), and Australia (AUS). Each row represents a meteorological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

Line 114: All: it may be better to mention the date when the data are accessed to, as more data may come out later.

Response: We added the date as suggested: "We select all available CMIP6 models (last access: April 20th, 2023) providing complete variables" (Lines 119-120)

Lines 161-163: It is not clear to me. Please check.

Response: We revised the sentence as follows: "In CNRM-ESM2-1, f_m and α are combined to calculate U_{*t} rather than acting as individual factors in the emission function" (Lines 175-177)

Lines 176-177: It is hard for me to check in Fig. 2b. Perhaps also provide a table with these values in supplemental file.

Response: We added Table S2 to list all the correlation coefficients and normalized standard deviations of individual models.

Table S2. The normalized standard deviations and correlation coefficients for individual models shown in Figure1

	Dust concentrations		AOD	
Model	Normalized standard deviations	Correlation coefficient	Normalized standard deviations	Correlation coefficient
CESM2-WACCM	0.78	0.86	0.87	0.64
CESM2	0.74	0.87	0.89	0.6
CNRM-ESM2-1	0.44	0.85	0.28	0.79
GFDL-ESM4	0.54	0.81	0.59	0.58
GISS-E2-1-G	0.76	0.83	0.55	0.67
GISS-E2-1-H	0.62	0.83	0.51	0.66
GISS-E2-2-G	1.34	0.84	0.95	0.61
INM-CM4-8	0.11	0.49	0.42	0.44
INM-CM5-0	0.09	0.30	0.38	0.26
MIROC-ES2L	0.24	0.82	0.64	0.3
MIROC6	0.07	0.86	0.44	0.64
MRI-ESM2-0	2.16	0.86	0.82	0.33
NorESM2-LM	0.33	0.82	0.68	0.63
UKESM1-0-LL	1.03	0.88	0.36	0.75

Line 194: Figure 3 captions: Please also mention the latitudes and longitudes for the three regions.

Response: We added the latitudes and longitudes of each box in Figure 4 caption: "The box regions on (a) are dust sources of North Africa (NAF) (15°N-33°N, 15°W-35°E), Middle East and West Asia (MEWA) (17°N-48°N, 40°E-70°E), Taklimakan and Gobi Deserts (TGD) (37°N-47°N, 77°E-112°E), Australia (AUS) (33°S-21°S, 113°E-144°E), North America (NAM) (28°N-37°N, 120°W-109°W), South America (SAM) (50°N-20°N, 74°S-60°S), and South Africa (SAF) (34°S-18°S, 14°E-26°E)."

Line 230: dominates: It is not clear to me. And it is hard for me to read this from Figure 4c.

Response: It has been revised as follows: "<u>Furthermore, dust emissions over Asia (including Taklimakan, Gobi Deserts, West Asia and Middle East) decrease in most scenarios especially for SSP3-7.0, in which the regional reduction causes the global decline of dust emissions (Fig. 5c).</u> " (Lines 259-261)

Lines 232-233: But dust emission may be sensitive to precipitation change. Please clarify.

Response: We revised the sentence to clarify: "<u>For North Africa, regional precipitation shows mild reductions under all four scenarios even though the baseline rainfall is very low.</u>" (Lines 265-266)

Lines 242-244: 18 regions: please check whether the numbers are correct.

Response: It's not 18 regions but 18 region labels. We clarified as follows: "<u>Among the total of 18 region labels (the red labels on Fig. 6) with increased dust emissions under the four scenarios, 14 labels show decreased relative humidity by at least 0.5%, 14 labels show decreased precipitation, and 10 labels show increased wind speed.</u>" (Lines 275-278)

Line 252: limited changes: It is not clear to me.

Response: We have removed the descriptions of relative humidity and clarified as follows: "For Middle East and West Asia, the slight increase of precipitation (Fig. 6) overweighs the moderate increase of surface wind speed, leading to a decline of regional dust emissions for SSP1-2.6 and SSP2-4.5 (Fig. 6)." (Lines 286-288)

Lines 323-325: The sentence does not read clearly. Please revise

Response: We revised the sentence to clarify: "The changes of dust loading in general follow that of emissions but with joint impacts of precipitation, which affects the loading through wet deposition. The decreased precipitation may further promote dust loading over regions with increased emissions (e.g. South Africa) through the reductions in wet deposition. In contrast, increased precipitation decreases dust loading by more wet deposition over regions with moderate or limited changes in dust emissions (e.g., East Asia). " (Lines 355-361)

Lines 579-580: Not exactly red/blue (but light red & blue). I think the colors are too light to distinguish easily.

Response: We have darkened the color of each bar shown on Figure 6.

Figures 6 and 8: Could you make the zero lines bolder? It is not easy to see.

Response: Corrected as suggested.

Table 2: u_*t and u_t are different. Please clarify.

Response: We have changed U_t to U_{*t} . U_{*t} is the threshold values.

Reference

Aryal, Y. N. and Evans, S.: Global Dust Variability Explained by Drought Sensitivity in CMIP6 Models, J. Geophys. Res.: Earth Surf., 126, e2021JF006073, doi: 10.1029/2021JF006073, 2021.

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