3 Response to Reviewer #3's comments

The paper presents an analysis on the influence of the El Niño–Southern Oscillation (ENSO) on the global dust activities (emission, concentration and transportation and dry and wet deposition) based on CMIP6 historical simulations. The manuscript is structured and concise and the topic is of scientific interest, therefore I would encourage publication provided that the following point are addressed:

Response: We thank the reviewer for your comments. We modified the manuscript based on your suggestions as below.

General comments:

3.1 Among the key results that are emphasized by the manuscript (abstract included) there is the suggestion of the role of human activity in the intensity of dust emission as a consequence of a lack of clear causal impact of ENSO on dust availability. This point does not seem to be clearly explained, nor properly supported in the discussion. Also, it is not clear why is the human activity the only other possible factor considered when finding a weak role of ENSO in regional dust emissions over major dust sources.

Response: We thank the reviewer for raising this point. We agree that the role of human activity on global dust activities is not supported by the results of this manuscript. This discussion is only the inference of the main results as shown in Figures 3 and 6. We removed this conclusion in the abstract to avoid confusing the readers. We also rewrote this discussion in Section 4.

3.2 Lines 35-38 list a series of references mentioning studies who observed the ENSO influences on dust activities but only one of them is then compared with the results of the manuscript itself (Marx et al 2009) regarding the emission over Australia. The reader is left questioning if there is any other agreement/disagreement with the previous studies.

Response: We thank the reviewer for raising this point. We added the following sentences to Section 4 Discussion to further discuss our results in relation with previous works as below:

"The causal impacts of ENSO on dust deposition over South America (Figure 1) are consistent with previous studies (Boy and Wilcke, 2008; Shao et al., 2013). Figures 1 and 2 show an agreement with recent works for the potential influences of ENSO on dust activities over regions from Arabian Peninsula to Central Asia (Huang et al., 2021) and East Asia (Jeong et al., 2018).”

3.3 The methodology section is way too brief and not explicative, totally referring to the text S1 of the supplementary. I would encourage to better explain the methods and/or move part of the supplementary in this section.

Response: We thank the reviewer for this suggestion. We moved part of the supplementary to Section 2.2 as below:

“We use the following multivariate predictive model (Mosedale et al., 2006; Stern and Kaufmann, 2013) to estimate the causal links between the ENSO and dust deposition:

$$\boldsymbol{X_t = \sum_{i=1}^{p} \alpha_i X_{t-i} + \sum_{i=1}^{p} \beta_i Y_{t-i} + \sum_{j=1}^{m} \sum_{i=1}^{p} \delta_{j,i} Z_{j,t-i} + \varepsilon_t} \qquad (1)$$

where X_t is the annual mean (or seasonal mean) dust deposition for year t, Y_t is the ENSO index, and $Z_{j,t}$ is the confounding factor j for year t. In the predictive model presented in equation 1, while assessing the effect of Y on X (i.e., the contribution of the term $\sum_{i=1}^{p} \beta_i Y_{t-i}$ in predicting X), the possible influence of past X events are considered by adding the term $\sum_{i=1}^{p} \alpha_i X_{t-i}$. Thus, the causal influence of Y on X, if detected, is robust and the impact of past X events are accounted in the analyses. Here, m is the number of confounding factors and $p \geq 1$ is the order of the multivariate predictive model. The optimal order p is computed by minimizing the Schwarz criterion or the Bayesian information criterion (Schwarz, 1978). The optimal orders may be different for each model.

Here we take into account the impacts of confounding factors and therefore provide further information of the real-world teleconnections. In the analyses, we use three different confounding factors; hence, m is equal to 3. The noise residuals ε_t and the regression coefficients α_i, β_i and $\delta_{j,i}$ are computed by using the multiple linear regression analysis of the least squares method. We detrend and normalize all the climate indices.”

3.4 I was wondering also if there is any way to mention how significant is the ENSO variation on dust activities with respect to the total global dust activity, for example the AOD variation due to ENSO with respect to the global AOD average.

Response: We thank the reviewer for raising this point. We agree that we could compute the significance of ENSO impacts on global mean AOD. While this single indicator is useful, it is however too general and might confusing the readers as ENSO impacts are dependent on specific region. In our opinion, the maps of ENSO impacts shown in Figure 2a might provide better illustration and details. For this reason, we have not tried to estimate the impacts of ENSO on global mean AOD.

Specific comments:

3.5 Lines 68-70: The authors mention the “confounding influence” of SAM, IOD and NAO but should explain at least briefly why and how those modes can be relevant on their study.

Response: We thank the reviewer for raising this point. We added the following sentences to Section 2.2 to explain the selection of the three factors Indian Ocean Dipole, Southern Annular Mode, and the North Atlantic Oscillation:

“The climate modes SAM, the IOD and the NAO are the important sources of global climate variability (Hurrell et al., 2003; Luo et al., 2012; Roxy et al., 2015). For instance, the NAO is the prominent mode of atmospheric circulation variability over the North Atlantic and surrounding regions (Delworth et al., 2016; Hurrell et al., 2003) and variations in NAO are crucial for the environment and society (Hurrell et al., 2003). The IOD affects climate extremes over the Indian Ocean and surrounding areas (Abram et al., 2008; Kripalani et al., 2009; Kripalani and Kulkarni, 1997) and might cause severe economic consequences (Ummenhofer et al., 2009). The SAM is the major mode of atmospheric circulation variability in the southern Hemisphere (Cai et al., 2011; Raphael and Holland, 2006). In addition, changes in these modes may affect the variations of ENSO (Abram et al., 2020; Cai et al., 2011, 2019; Le et al., 2020; Le and Bae, 2019). Nevertheless, it is likely that these factors may alter the influences of ENSO on dust activities.”

3.6 Lines 80-91: I do not understand the choice of using the “total earth surface” percentage quantity as a parameter. Especially, this does not make much sense to me when dividing the study on land areas and ocean areas. It would already give more information by dividing in % of total ocean surface when considering ocean areas, and % of total land surface when considering land.

Response: We thank the reviewer for raising this point. We think choosing only one parameter “total earth surface” may reduce the confusion. In addition, we may convert the areas between “total earth surface”, “total land areas” and “total oceans areas” (i.e., “total land areas” is approximately 29.2% of “total earth surface” and “total ocean areas” is approximately 70.8% of “total earth surface”).

We modified these sentences to clarify this point as your suggestion:

“Over oceans, the areas affected by ENSO are estimated at approximately 17.6%, 32.3%, and 20.7% of total earth surface (i.e., 24.9%, 45.6% and 29.2% of total ocean areas) for deposition of dry dust, dust aerosol optical depth, and deposition of wet dust, respectively (Figure 2b). The land areas affected by ENSO are estimated at approximately 5.1%, 7.5%, and 6.8% of the total earth surface (i.e., 17.5%, 25.7% and 23.3% of total land areas) for deposition of dry dust, dust aerosol optical depth, and deposition of wet dust, respectively (Figure 2b).

The causal effects of ENSO on seasonal mean dry dust deposition are shown in Figure S1. The largest impacts of winter (DJF) ENSO are observed in the following spring (MAM), with approximately 3.4% of total earth surface over land (i.e., 11.6% of total land areas) and approximately 16% of total earth surface over the ocean (i.e., 22.6% of total ocean areas) are affected (Figure S2). The impacts of ENSO on dry dust deposition gradually decrease in the following summer, fall, and winter (Figures S1 and S2). In particular, the influences of ENSO on winter dry dust deposition are mainly limited in Antarctica (approximately 0.5% of total earth surface or 1.7% of total land areas) and the tropical Pacific (approximately 0.7% of total earth surface or 1% of total ocean areas).”

3.7 Section 3.2: The authors should explain why there are a different number of models compared for the different cases (12 models for the ENSO effect on dry deposition, 9 for the aerosol optical depth, 11 for the dust emission)

Response: We thank the reviewer for raising this point. We selected all the models with accessible dust deposition-related data. Considering the total models is somewhat low (i.e., 12 models), we kept all these models. Dry and wet deposition of dust are key variables which directly affect local environment, thus we selected all models having these data.

We add the following sentences to Section 2.1 to clarify this point:

“We limited our study to all the models having both dry dust and wet dust data (i.e., there is total of 12 models with accessible dry dust and wet dust data as described in Table S2). Dust deposition on land and ocean surface are important metrics to assess the impacts of dust activities on ecosystems and environment (Bao et al., 2017; Fan et al., 2006; Jickells et al., 2005; Jiménez et al., 2018; Kanakidou et al., 2018; Schulz et al., 2012). Additional data of od550dust and emidust supplied by these 12 models provide further understanding of ENSO impacts on dust activities."

3.8 Line 122: It would be worth to mention briefly what is meant by "marine productivity"

Response: We thank the reviewer for this suggestion. We clarify this sentence as below:

"Significant impacts of ENSO on atmospheric aerosol loading (Figures 2a and 5) may lead to a strong response of marine productivity (i.e., the production of organic matter in the ocean from carbon dioxide by phytoplankton) to ENSO. For example, there is strong correlation between aerosol optical depth and iron deposition and satellite chlorophyll (Carslaw et al., 2010; Jickells et al., 2005)."

3.9 Line 134-136: The paper mention before that there is little consensus of the models on the impact of ENSO on dust emissions. Would it be still possible to draw any relevant conclusion on the effect of ENSO on dust emissions, including the suggestion of the possible anthropogenic impact on dust emissions?

Response: We thank the reviewer for raising this point. We agree that there is still large uncertainty regarding the effect of ENSO on dust emissions and robust conclusion is not feasible. We added the following sentence to Section 4 to clarify this point:

"As the consistency between models is low (Figure 3), large uncertainties remain for the causal impacts of ENSO on dust emissions."

We agree that the role of human activity on global dust activities is not supported by the results of this manuscript. This discussion is the inference of the main results as shown in Figures 3 and 6. Here, we tried to discuss this point rather than drawing a conclusion. We rewrote this discussion to avoid confusing the readers.

We also added the following sentence to Section 4 to motivate further works:

"Hence, the impacts of human activities and changes in land use on regional dust emissions might be a topic of future works."

References

Abram, N. J., Gagan, M. K., Cole, J. E., Hantoro, W. S. and Mudelsee, M.: Recent intensification of tropical climate variability in the Indian Ocean, Nat. Geosci., 1(12), 849–853, doi:10.1038/ngeo357, 2008.

Abram, N. J., Wright, N. M., Ellis, B., Dixon, B. C., Wurtzel, J. B., England, M. H., Ummenhofer, C. C., Philibosian, B., Cahyarini, S. Y., Yu, T.-L., Shen, C.-C., Cheng, H., Edwards, R. L. and Heslop, D.: Coupling of Indo-Pacific climate variability over the last millennium, Nature, 579(7799), 385–392, doi:10.1038/s41586-020-2084-4, 2020.

Bao, H., Niggemann, J., Luo, L., Dittmar, T. and Kao, S. J.: Aerosols as a source of dissolved black carbon to the ocean, Nat. Commun., 8(1), doi:10.1038/s41467-017-00437-3, 2017.

Boy, J. and Wilcke, W.: Tropical Andean forest derives calcium and magnesium from Saharan dust, Global Biogeochem. Cycles, 22(1), 1–11, doi:10.1029/2007GB002960, 2008.

Cai, W., Sullivan, A. and Cowan, T.: Interactions of ENSO, the IOD, and the SAM in CMIP3 Models, J. Clim., 24(6), 1688–1704, doi:10.1175/2010JCLI3744.1, 2011.

Cai, W., Wu, L., Lengaigne, M., Li, T., McGregor, S., Kug, J.-S., Yu, J.-Y., Stuecker, M. F., Santoso, A., Li, X., Ham, Y.-G., Chikamoto, Y., Ng, B., McPhaden, M. J., Du, Y., Dommenget, D., Jia, F., Kajtar, J. B., Keenlyside, N., Lin, X., Luo, J.-J., Martín-Rey, M., Ruprich-Robert, Y., Wang, G., Xie, S.-P., Yang, Y., Kang, S. M., Choi, J.-Y., Gan, B., Kim, G.-I., Kim, C.-E., Kim, S., Kim, J.-H. and Chang, P.: Pantropical climate interactions, Science (80-.)., 363(6430), eaav4236, doi:10.1126/science.aav4236, 2019.

Carslaw, K. S., Boucher, O., Spracklen, D. V., Mann, G. W., Rae, J. G. L., Woodward, S. and Kulmala, M.: A review of natural aerosol interactions and feedbacks within the Earth system, Atmos. Chem. Phys., 10(4), 1701–1737, doi:10.5194/acp-10-1701-2010, 2010.

Delworth, T. L., Zeng, F., Vecchi, G. A., Yang, X., Zhang, L. and Zhang, R.: The North Atlantic Oscillation as a driver of rapid climate change in the Northern Hemisphere, Nat. Geosci., 9(7), 509–512, doi:10.1038/ngeo2738, 2016.

Fan, S. M., Moxim, W. J. and Levy, H.: Aeolian input of bioavailable iron to the ocean, Geophys. Res. Lett., 33(7), 2–5, doi:10.1029/2005GL024852, 2006.

Huang, Y., Liu, X., Yin, Z. Y. and An, Z.: Global Impact of ENSO on Dust Activities with Emphasis on the Key Region from the Arabian Peninsula to Central Asia, J. Geophys. Res. Atmos., 126(9), 1–24, doi:10.1029/2020JD034068, 2021.

Hurrell, J. W., Kushnir, Y., Ottersen, G. and Visbeck, M.: An overview of the North Atlantic Oscillation, in Geophysical Monograph American Geophysical Union, pp. 1–35, American Geophysical Union., 2003.

Jeong, J. I., Park, R. J. and Yeh, S. W.: Dissimilar effects of two El Niño types on PM2.5

concentrations in East Asia, Environ. Pollut., 242, 1395–1403, doi:10.1016/j.envpol.2018.08.031, 2018.

Jickells, T. D., An, Z. S., Andersen, K. K., Baker, A. R., Bergametti, C., Brooks, N., Cao, J. J., Boyd, P. W., Duce, R. A., Hunter, K. A., Kawahata, H., Kubilay, N., LaRoche, J., Liss, P. S., Mahowald, N., Prospero, J. M., Ridgwell, A. J., Tegen, I. and Torres, R.: Global iron connections between desert dust, ocean biogeochemistry, and climate, Science (80-.)., 308(5718), 67–71, doi:10.1126/science.1105959, 2005.

Jiménez, L., Rühland, K. M., Jeziorski, A., Smol, J. P. and Pérez-Martínez, C.: Climate change and Saharan dust drive recent cladoceran and primary production changes in remote alpine lakes of Sierra Nevada, Spain, Glob. Chang. Biol., 24(1), e139–e158, doi:10.1111/gcb.13878, 2018.

Kanakidou, M., Myriokefalitakis, S. and Tsigaridis, K.: Aerosols in atmospheric chemistry and biogeochemical cycles of nutrients, Environ. Res. Lett., 13(6), doi:10.1088/1748-9326/aabcdb, 2018.

Kripalani, R. H. and Kulkarni, A.: Rainfall variability over South-East Asia - Connections with Indian monsoon and Enso extremes: New perspectives, Int. J. Climatol., 17(11), 1155–1168, doi:10.1002/(SICI)1097-0088(199709)17:11<1155::AID-JOC188>3.0.CO;2-B, 1997.

Kripalani, R. H., Oh, J. H. and Chaudhari, H. S.: Delayed influence of the Indian Ocean Dipole mode on the East Asia-West Pacific monsoon: possible mechanism, Int. J. Climatol., 30(2), 197–209, doi:10.1002/joc.1890, 2009.

Le, T. and Bae, D.-H. H.: Causal links on interannual timescale between ENSO and the IOD in CMIP5 future simulations, Geophys. Res. Lett., 46(5), 1–9, doi:10.1029/2018GL081633, 2019.

Le, T., Ha, K.-J. J., Bae, D.-H. H. and Kim, S.-H. H.: Causal effects of Indian Ocean Dipole on El Niño-Southern Oscillation during 1950-2014 based on high-resolution models and reanalysis data, Environ. Res. Lett., 15(10), 1040b6, doi:10.1088/1748-9326/abb96d, 2020.

Luo, J.-J., Sasaki, W. and Masumoto, Y.: Indian Ocean warming modulates Pacific climate change, Proc. Natl. Acad. Sci., 109(46), 18701–18706, doi:10.1073/pnas.1210239109, 2012.

Mosedale, T. J., Stephenson, D. B., Collins, M. and Mills, T. C.: Granger Causality of Coupled Climate Processes: Ocean Feedback on the North Atlantic Oscillation, J. Clim., 19(7), 1182–1194, doi:10.1175/JCLI3653.1, 2006.

Raphael, M. N. and Holland, M. M.: Twentieth century simulation of the southern hemisphere climate in coupled models. Part 1: Large scale circulation variability, Clim. Dyn., 26(2–3), 217–

228, doi:10.1007/s00382-005-0082-8, 2006.

Roxy, M. K., Ritika, K., Terray, P., Murtugudde, R., Ashok, K. and Goswami, B. N.: Drying of Indian subcontinent by rapid Indian ocean warming and a weakening land-sea thermal gradient, Nat. Commun., 6(May), 7423, doi:10.1038/ncomms8423, 2015.

Schulz, M., Prospero, J. M., Baker, A. R., Dentener, F., Ickes, L., Liss, P. S., Mahowald, N. M., Nickovic, S., García-Pando, C. P., Rodríguez, S., Sarin, M., Tegen, I. and Duce, R. A.: Atmospheric transport and deposition of mineral dust to the ocean: Implications for research needs, Environ. Sci. Technol., 46(19), 10390–10404, doi:10.1021/es300073u, 2012.

Schwarz, G.: Estimating the dimension of a model, Ann. Stat. [online] Available from: http://projecteuclid.org/euclid.aos/1176344136 (Accessed 30 May 2014), 1978.

Shao, Y., Klose, M. and Wyrwoll, K.-H.: Recent global dust trend and connections to climate forcing, J. Geophys. Res. Atmos., 118(19), 11,107-11,118, doi:10.1002/jgrd.50836, 2013.

Stern, D. I. and Kaufmann, R. K.: Anthropogenic and natural causes of climate change, Clim. Change, 122(1–2), 257–269, doi:10.1007/s10584-013-1007-x, 2013.

Ummenhofer, C. C., England, M. H., McIntosh, P. C., Meyers, G. A., Pook, M. J., Risbey, J. S., Sen Gupta, A. and Taschetto, A. S.: What causes southeast Australia's worst droughts?, Geophys. Res. Lett., 36(4), L04706, doi:10.1029/2008GL036801, 2009.