Reply to Eric Wolff's comment on

Krätschmer, S., van der Does, M., Lamy, F., Lohmann, G., Völker, C., and Werner, M.: *Simulating glacial dust changes in the Southern Hemisphere using ECHAM6.3-HAM2.3*, Clim. Past Discuss. [preprint], https://doi.org/10.5194/cp-2021-73, in review, 2021.

The paper by Krätschmer et al is a very welcome addition to the literature on dust modelling, particularly for the LGM. This adds to a number of studies such as those of Mahowald et al and it's excellent to have a new study using a more modern modelling set-up and with some novel diagnostics. It's an important topic because of its relevance to issues such as iron fertilisation, and its use in the interpretation of ice cores.

I do not intend to do a full review of the modelling aspects of the paper (best left to those with a modelling background), but rather to comment on particular issues related to what is seen in Antarctic ice cores. I enjoyed the description of what the model found and the comparison with previous modelling efforts. However I was rather astonished that the paper completely ignored recent discussions about the causes of increased dust in Antarctica during the LGM, and the extensive data papers that indicate a dominant South American source of dust across much of Antarctica in the LGM.

The latter issue (provenance) is the most glaring deficit in the paper. The authors conclude that Australia is the main source of dust to Antarctica in the LGM, with >70% contribution (Fig 4) over most of the continent. The authors then use this to discuss why other modelling studies might have got it wrong. In a very brief mention (line 401) it appears as if the authors are aware of the data (principally using Sr and Nd isotopes) showing a dominance of South American sources for the LGM (with a possibility of some Australian input in the Holocene, in contrast to their modelling results). This is not just a single result from one site, but is something documented at Vostok, Dome C, Talos Dome, and Taylor Glacier (e.g. Aarons et al 2017, Basile et al 1997, Delmonte et al 2008, Delmonte et al 2010). Given this obvious discrepancy between the modelling and the data it would surely be appropriate to either acknowledge that this is a discrepancy that implies an issue with the modelling, or offer reasons to suggest that the papers I mention have misinterpreted the geochemical data. It is certainly not OK to just ignore it, leaving the less informed reader with the misconception that it is likely that Australian sources dominate the Antarctic LGM dust budget.

We thank Eric Wolff for his very thoughtful and detailed comments on our manuscript.

It was never our intention to question the geochemical data regarding the provenance of dust found in Antarctic ice cores. Our model setup is certainly not suitable to question this data. The inconsistency highlights a problem on the modelling side and we will make this modelling deficit clearer in a revised manuscript.

The further discussion in the scope of our paper is intended to give insights on possible mechanisms causing Australia to be the predominant source of LGM dust deposited over Antarctica in our model simulations instead of southern South America, as indicated by the geochemical data. The model shows for both PI and LGM an overestimation of total dust deposition over Antarctica by a factor of 10 (*Fig. 3b, d*), of which 68% were contributed by Australia during the LGM (*Table 4*). Thus, this overestimation of total dust deposition in Antarctica could be caused by too much dust emitted from Australia in the model. However, the comparison of our model results to the marine data records of the Pacific SO region shows too little dust deposition in the simulations. These dust particles in the Pacific also stem from Australia (e.g. *Lamy et al., 2014*). These contradictory results for modeled dust depositions lead to the question whether the transport efficiency from Australia to Antarctica is overestimated. However, the absolute amounts of dust deposition over the Pacific SO and Antarctica differ by two orders of magnitude (*Fig. 3b, d*), i.e. even if less dust would get transported to Antarctica and deposit over the

Pacific SO instead, the discrepancy in this region would basically remain the same. The provenance studies for our model results allowed us to investigate changes in particle lifetime between PI and LGM for dust from each source individually. It turns out that the simulated wetter climate over southern South America and parts of the Atlantic SO (*Fig. 5b*) causes a decrease in particle lifetime (-1.69 days on average) of southern South American dust and an increase in particle lifetime (+1.12 days on average) of Australian dust (*Fig. 5a*) during the LGM. These changes in particle lifetime cause the deposition of a larger proportion of southern South American dust before transported to Antarctica, and longer transport ranges of Australian dust. Both effects combined lead to the Australian dust source dominance in our model.

Lamy, F., Gersonde, R., Winckler, G., Esper, O., Jaeschke, A., Kuhn, G., Ullermann, J., Martinez-Garcia, A., Lambert, F., and Kilian, R.: Increased Dust Deposition in the Pacific Southern Ocean During Glacial Periods, Science, 343, 403–407, https://doi.org/10.1126/science.1245424, 2014.

Less serious is that the paper ignores a quite strong debate in the ice core community about the relative importance of changes in source strength and lifetime in determining the LGM increase in dust concentration. Papers addressing this (sometimes discussing calcium as a dust proxy rather than dust per se) include (Wolff et al 2010, Fischer et al 2007, Petit et al 2009, Markle et al 2018). While the authors don't need to get into this debate in detail they could really offer some insight and it's a shame not to do so. The basic argument is that conceptual models suggest a big change in lifetime, while GCMs until now have not, having to rely on very big source changes to get the LGM dust increase. A question has been why the GCMs don't appear to document the change in dust lifetime one might expect due to the change in precipitation. The present paper is well-equipped to discuss this, mentioning that much of the transport is taking place above the level where precipitation occurs. However Fig 6 in the current paper suggests a new factor - that the transport level in the LGM is at lower altitude which does open the possibility of a second-order reason for a change in lifetime resulting from that (dust spending more time at altitudes where there is precipitation). Whether that change is really enough to explain the LGM increase (especially when in the current model the South American source sees a local precipitation increase) is not clear, but it would be valuable to see the discussion framed in this context.

Concerning changes in particle lifetime in our AGCM, we find the following results:

Generally, our model shows globally a particle lifetime increase (all modes) of +0.53 days during the LGM, and specifically +0.31 days in the Southern Hemisphere, which we attribute to the generally drier climate. However, *Fig. 5a* (*paper*) suggests opposing trends for the Pacific SO (increasing trend) and the Atlantic SO (decreasing trend) region. In the following, our discussion is based on values for burden and (wet) deposition (see *Table 1A*) for the two regions stated above for both PI and LGM. As shown in *Fig. 1A* and *Table 5* (*paper*), wet deposition is the predominant deposition mechanism (>90%) in the Southern Ocean region and consequently, we neglect contributions from dry deposition and sedimentation. *Table 1A* enables us to calculate the following particle lifetimes τ :

 $\begin{aligned} \tau_{LGM,AtlanticSO} &\approx 6.8 \ days \\ \tau_{PI,AtlanticSO} &\approx 7.4 \ days \\ \tau_{LGM,PacificSO} &\approx 9 \ days \\ \tau_{PI,PacificSO} &\approx 7.4 \ days \end{aligned}$

The trends in particle lifetime changes clearly correlate with the precipitation anomaly plot shown in *Fig. 5b (paper)*. However, we want to emphasize at this point that *we do not state* that dust spends more time at altitudes where there is precipitation. For technical reasons, it is very difficult to determine the exact level at which precipitation occurs and is not possible based on our current simulation data. A more detailed investigation of microphysical processes could yield more insights on factors contributing to the obtained trends. The condensation of sulphate on particles in the insoluble modes leads to their transfer into soluble modes, where they grow in size due to water uptake until their sedimentation



Figure 1A. Contribution of sedimentation and wet deposition to the total dust deposition for LGM (*a*, *b*) and PI (*c*, *d*) in percent.

		PI 1850-1879					LGM 21kyr BP				
		Insol. Accu. [%]	Sol. Accu. [%]	Insol. Coarse [%]	Sol. Coarse [%]	Σ	Insol. Accu. [%]	Sol. Accu. [%]	Insol. Coarse [%]	Sol. Coarse [%]	Σ
Atlantic	Burden	1	3	68	28	19 Gg	1	2	65	32	99 Gg
SO	Wet. Dep.	0	3	18	79	941 Gg yr ⁻¹	0	2	27	71	5.3 Tg yr ⁻¹
Pacific	Burden	1	3	65	31	67 Gg	2	1	78	19	914 Gg
SO	Wet. Dep	0	3	20	77	3.3 Tg yr ⁻¹	0	2	30	68	37 Tg yr-1

Table 1A. Key values for burden and wet deposition for the Atlantic SO and the Pacific SO region for PI and LGM.

velocity causes them to fall out (e.g. *Boucher, 2014*), i.e. a higher dust mass proportion in the soluble modes reduces the average particle lifetime. This is also supported by *Table 1A*, showing a decreasing trend of the dust proportion in the soluble mode for the Pacific SO region and an increasing trend in the Atlantic SO region during the LGM compared to PI. Though, the particle lifetime is also influenced by the water uptake rate. As described by *Stier et al. (2005)*, the partitioning of aerosols between the air and the cloud water in HAM2.3 is prescribed in the form of a size- and composition-dependent scavenging parameter, which in turn is lower for particles in the accumulation and coarse mode "[...] for mixed phase clouds than for liquid clouds due to the growth of ice crystals at the expense of water droplets as a result of the Bergeron-Findeisen process." Considering the substantially colder temperatures between 60°S and 90°S (see *Fig. 2b (paper)*) during the LGM compared to PI, this process can be assumed to play a crucial role. However, a thorough investigation of all processes influencing the particle lifetime in our model is clearly beyond the scope of our paper.



Figure 2A. Schematic representation of the atmospheric dust reservoir over the Pacific SO / Atlantic SO containing the dust burden B and all fluxes into and out of the reservoir (a). Figure (b) shows the net flux ratio depending on the particle lifetime ratio in order to get the simulated dust burden ratio of 13.6 for the Pacific SO region, respectively, 5.2 for the Atlantic SO region.

Finally, we want to take up on the debate about the relative importance of changes in source strength and lifetime in determining the LGM increase in dust concentration. Although an ultimate answer on this matter will not be possible, we try at least to give some new insights in the scope of our simulations. We use a highly simplified description (see *Fig. 2A a*), assuming the atmosphere above the Pacific SO, respectively, Atlantic SO to be a dust reservoir with capacity B (burden), which is filled by the dust influx F_{in} and loses mass due to wet deposition F_{wetdep} and dust transport to Antarctica F_{out} . Here, F_{in} is assumed to be proportional to the dust source strength F_{emi} . Consequently, the temporal change of B can be described by

$$\frac{dB(t)}{dt} = F_{in} - F_{wetdep} - F_{out} = -F_{wetdep} + (F_{in} - F_{out}) = -F_{wetdep} + F_{net}$$

The wet deposition flux F_{wetdep} can be assumed to be proportional to B with a decay constant λ (inverse particle lifetime) and we can finally write

$$\frac{dB(t)}{dt} = -\lambda B(t) + F_{net}$$

This differential equation has the solution

$$B(t) = Ae^{-\lambda t} + \frac{F_{net}}{\lambda}$$

Since we are interested in the long-term equilibrium between influxes and losses, we write

$$\lim_{t\to\infty}B(t)=\frac{F_{net}}{\lambda}$$

Consequently, the burden is determined by the net influx and the decay rate. For the LGM/PI ratio, we can write

$$\frac{B_{LGM}}{B_{PI}} = \frac{\lambda_{PI}}{\lambda_{LGM}} \frac{F_{net,LGM}}{F_{net,PI}} = \frac{\tau_{LGM}}{\tau_{PI}} \frac{F_{net,LGM}}{F_{net,PI}}$$

Since the high burden ratio is apparently required in our model for the increased dust concentration over Antarctica, we can now investigate the interplay between the particle lifetime ratio and the net influx ratio. *Figure 2A b* shows the results for the LGM/PI burden ratio for the Pacific SO region (13.6) and the Atlantic SO region (5.2). The plot suggests that the more the particle lifetime increases, the less of a source strength increase is necessary (and vice versa) to obtain the simulated dust burden ratio. The values for the lifetime and burden ratio are calculated based on *Table 1A*.

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