Referee#2

Interactive comment on

“Linkage between Dust Cycle and Loess of the Last Glacial Maximum in Europe”

by Erik Jan Schaffernicht et al.

Anonymous Referee #2

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R= Referee#2

A= Authors' reply

R:
This paper examines the contribution of mineral dust cycle to loess deposits in Europe during the Last Glacial Maximum (LGM) using the output from the Max-Plank-Institute Earth System Model (MPI-ESM) and simulations from the WRF-Chem model. The simulated dust deposition rates are largely consistent with site records of mass accumulation rates of the loess deposits. Using statistic dynamical downscaling, it is found that the east sector and cyclonic winds are the dominant circulation regimes during the LGM and thus result in a westward dust transport to the central and eastern Europe. The seasonal variations in dust emission and deposition are also analysed. Overall, the paper is well organized and written. However, in some places, the purpose of the analysis and methodology need further clarification.

A:
We thank the referee very much for the valuable comments and suggestions to improve the manuscript. Subsequently, the referee's comments are addressed point by point. It is our aim to fulfil the demands to publish this manuscript in ACP.

(Reference keys that are not fully written out in this document refer to the References section of the updated manuscript)

Major comments

R2.1 I’d suggest adding a discussion about the motivation to use the WRF-Chem and MPI-ESM to study dust cycles during the LGM.

A The MPI-ESM was used as its 1850−2005 experiment reproduces best the recent observed wind distribution over central Europe. This result was found by comparing the CWT distribution of four different global earth system/circulation models (MPI-ESM, CCSM, MRI and MIROC) to reanalyses data for central Europe (Schaffernicht, Erik Jan: *Linkage between Dust Cycle and European Loess in the Last Glacial Maximum Determined by Atmospheric Model Simulations.*
Inaugural Dissertation, PhD thesis, University of Cologne, Germany, 2018.
https://kups.ub.uni-koeln.de/9036/
http://kups.ub.uni-koeln.de/id/eprint/9036
).

In addition, access to boundary conditions that are updated frequently enough to carry out the intended WRF-Chem-LGM experiments was only offered by the MPI-LGM.

The WRF-Chem was chosen to be the core for the LGM dust simulation model because it has already been evaluated successfully in numerous recent studies comparing its dust simulations with observations (Bian et al. 2011, Zhao et al. 2011, Zhao et al. 2012, Rizza et al. 2016, Baumann el al. 2019).

R2.2 As mentioned in section 1, results from previous global simulations largely underestimate the mass accumulation rates (MARs) of dust depositions. Is this due to the coarse resolution of the global models...

A Yes and due to local small scale dust sources and deposition processes (Werner et al. 2002).

R2.3 ...or insufficiency of the dust emission schemes to capture certain processes of the dust emission and transport?….

A Yes (Werner et al. 2002) and also a missing process or a low sensitivity in the dust model is possible (Hopcroft et al. 2015 JGRA).

R2.4 ...Or is it related to unrealistic land surface settings for the LGM...

A Yes: Probably due to the missing glaciogenic dust sources (Mahowald et al. 2006, Hopcroft et al 2015JGRA) and parameterizations of source regions and source material availability are undersensitive to LGM conditions (Hopcroft et al. 2015 JGRA)

R2.5 ...or misrepresentation of the atmospheric circulation patterns in the models?

A Yes, e.g. Ludwig et al. (2016). Lacking interannual variability and dust storm events might be another factor (Hopcroft et al. 2015 JGRA).

Corresponding statements have been added to the manuscript.

R2.6 Similarly, please consider adding explanation/discussion about why current work better captures the magnitude of the MARs in the result section.

A Corresponding explanations/discussion has been added to the manuscript in the section: "Conforming Dust Deposition and Loess Accumulation Rates".

Current work captures better the magnitude of the MARs because:

- the regional simulations are run with a much higher resolution compared to previous studies
- its simulations include additional dust sources that likely existed due to the glacial topography.
- it takes into account Ginoux's dust function (Ginoux et al. 2001) and resolves Europe at higher spatiotemporal resolution
- it takes into account dynamic soil moisture, vegetation and snow cover
- its boundaries are driven by the LGM simulation of the MPI-ESM. For the end of the 20th century, this ESM reproduced the observed atmospheric circulation over Europe better than other ESM/GCMs (Ludwig et al. 2016).
- it uses a well-tested and observation-proofed dust emission scheme (Shao 2004)

R2.7 The purpose of using dynamic downscaling and statistic dynamic downscaling is not quite clear, and the method of dynamic downscaling is somewhat vague. For instance, 30 years of simulations are conducted using dynamic downscaling (line 82). What time period does the simulation cover? Are the 30 years consecutive?

A The dynamic and statistic dynamic downscaling serve to simulate the glacial dust cycle at high resolution using the WRF-Chem-LGM including seasonal and circulation weather type dependent aspects. More details are provided in the answer to R2.11.

The MPI-LGM (simulation in equilibrium setup) covers average LGM conditions. Its arbitrary timestamp is 1919-01-01 to 1948-12-31.

The 30 years are consecutive (see line 83 in the initial manuscript).

R2.8 What's the setting of sea surface temperature?

A The sea surface temperature and sea ice cover are updated daily based on the corresponding MPI-LGM variables.

R2.9 What's the setting of vegetation cover?

A The vegetation cover has been reconstructed from the CLIMAP LGM maximum vegetation cover and the vegetation dynamics extracted from the present-day WRF geo data. Details can be found in manuscript line 67 and Supplementary Table S2 and S3.

R2.10 More importantly, what's the benefit of using statistic dynamic downscaling?

A A high resolved (i.e. approximately 50 km grid spacing) reconstruction of the glacial dust cycle based on statistic dynamic downscaling requires much less computation time. It is the first proof-of-concept that statistic dynamic downscaling not only works for wind regime analyses but also for reconstructing the mineral dust cycle. Also, statistic dynamic downscaling enables analysing the dust cycle by wind regimes.

R2.11 Why not use the results from the dynamic downscaling directly, e.g., by selecting the circulation weather types (CWTs) from the 30-year run?

A Extracting CWT samples directly from the 30-year run would imply including a non-quantifiable amount of background dust; thus, the deposition rates extracted in this case might not solely be related to the specific CWT.
Also, the results based on the statistic dynamic downscaling of the 100-year MPI-LGM are intended for comparison to the dynamic downscaling results that base on only 30 years. Selecting CWTs only from the 30-year run would ignore 70 years of daily records for the LGM wind field over Europe.
In addition, when designing the concept for this study, there was a lack of studies showing that a dynamic climate-dust cycle downscaling over 30 years is possible within the numerical limitation of the available high performance computer (HPC). As the implementation of the statistical dynamic downscaling implied a reduction of the required simulation days by a factor of ten without missing any major wind direction feature, it is a promising approach. This finding can be important in particular for larger domains and/or models requiring much more computation time for dynamic downscaling.

R2.12 3. Please consider adding the dust emission scheme (Shao 2004) to section 2, so the readers would have a clearer idea about how dust emission is initiated and constrained in the model. Information such as dust size bins is also needed.

A The 0–20 µm particle size range is partitioned in five dust size bins: 0-2, 2-3.6, 3.6-6, 6-12, 12-20 µm. Added to the manuscript in the first paragraph of the section "Data and Methods".

The dust emission scheme (Shao 2004) is referred to in Section 2, first paragraph (e.g., in manuscript line 60): "This mode implies the application of the size-resolved University of Cologne dust emission scheme (Shao2004) […]". The structure and implementation of this dust emission scheme is extensive and cannot be summarized in a few sentences. It consists of many physical, mathematical and numerical/technical aspects, which are discussed in detail in 'Shao (2004)'. If there is a specific detail of the emission scheme that Referee2 requires here, we kindly ask Referee2 to let us know which particular formula or detail (s)he misses here. It would go beyond the scope of this study to (re-)discuss 'Shao (2004)'. It is kindly recommended to read 'Shao (2004)' for more information on the dust emission scheme.

Minor points

R2.13 1. By using the CWTs as criteria to conduct statistic dynamic downscaling, it assumes that atmospheric circulation pattern is the dominant factor influencing dust deposition, other factors, such as land surface features (e.g. vegetation coverage, soil moisture), and environmental factors (e.g. wind frequency and magnitude, precipitation) play minor roles. Is this a good assumption? You may want to add some discussion in section 2 about this.

A The deposition location(s) depend(s) on different factors, foremost the speed and direction (and thus implicitly also the emission locations) of the wind that caused emission and transport of the dust particles (Darmenova et al. 2009). This constrains the potential locations for deposition. In addition, land surface features can affect the deposition, yet, it is beyond the scope of this study to quantify their proportional effect in the WRF-Chem-LGM among other factors such as the CWTs.

The atmospheric circulation patterns are the most relevant factor for the complete dust cycle including emission, transport and deposition. They include environmental factors implicitly, e.g. the wind regime frequency and precipitation likelihood. The effects of soil moisture, snow and vegetation cover on the dust cycle emerge in particular on the seasonal scale (Fig. 9) and are taken into account by the applied dust emission scheme. The agreement between the statistic dynamic and the dynamic downscaling results demonstrates that the CWT-focused approach captures the dominant factors well. (Manuscript updated)

R2.14 2. Instead of showing schematic of the atmospheric circulation patterns (e.g., Fig. 2), I wonder if you may add figures in text or in the supplement to show the composite of wind patterns either from the MPI-ESM or WRF-Chem simulations to better demonstrate the transport pathways of the dust.

A The wind patterns are shown by the grey lines in Fig. 2. They were extracted directly from the WRF-Chem-LGM experiments. (The caption of Fig. 2 has been updated accordingly.)

The composite of wind patterns over Europe from the MPI-ESM can be found and has already been discussed in Ludwig et al. (2016).

R2.15 Lines 55-56, what’s the setting of sea surface temperature for the WRF-Chem? Is it also from the MPI-ESM simulation?

A Yes, it is from the MPI-LGM.

R2.16 4. Lines 68-69, are the vegetation coverage data monthly or annually?

A They are monthly:
"...using the corresponding **monthly** fractions of the present-day WRF maximum vegetation cover..." (near line 69).
Based on the CLIMAP maximum LGM vegetation cover reconstruction, a monthly vegetation cover was calculated as an analog to the present-day monthly WRF vegetation dynamics

R2.17 5. Lines 85-87, CWT on what level? Near-surface, 850 hPa, or a higher level?

A CWTs are based on the mean sea level pressure; references Jones et al 1993, Jones et al 2003 are in the manuscript and provide the details (near line 85).

R2.18 6. Lines 87-88, “to compare the prevailing wind directions over Europe during the Pre-Industrial (PI) and the LGM...”. Why not compare with present-day wind direction? In the abstract, “present-day prevailing westerlies” is mentioned, is it referred to the result from the PI simulation?

A The LGM CWT frequencies have also been compared with present-day CWT frequencies:

Table 2-extended:

	C	A	NE	E	SE	S	SW	W	NW	N
LGM	22.2	8.9	12.4	13.4	10.2	9.7	6.8	4.3	5.0	7.0
PI	10.6	24.1	7.9	5.2	4.9	7.6	11.6	11.1	9.4	8.3
present-day	10.6	23.9	7.3	5.1	4.7	7.5	12.4	11.4	9.2	8.0

The present-day frequencies are not shown in Table 2 for consistency. The LGM MPI-ESM experiment is an equilibrium experiment (without transient forcing). Thus, comparing it to equilibrium experiments such as for the PI is more robust because this does not induce uncertainty due to different kind of permanency of model forcing setups. Table 2-extended shows that the corresponding present-day CWT frequencies obtained from the transient MPI-ESM experiment are indeed almost identical with the PI CWT frequencies.

The manuscript is updated in section "East Sector Winds and Cyclones over Central Europe" by:

The CWT frequencies for the present (not shown) and PI are very similar, therefore it is possible to use the term present-day to refer to both the PI and the actual present-day frequencies.

R2.19 7. Line 89, what’s the difference between the MPI-LGM run and MPI-ESM-P run? How long are these simulations?

A The MPI-ESM-P is a typo. The sentence in line 89 (Data and Methods, paragraph 4) is now updated. The MPI-LGM is 100 years long.

R2.20 8. Line 90, why is this point selected? Is it the center of the Loess?

A Yes, approximately; taking into account that the present-day loess sites exist for example in northwestern France and also in Ukraine. Also, it (17.5°E, 47.5°N) is located near the Carpathian basin which is a prominent loess region.

R2.21 9. Line 94, what are the differences in 13 simulations? Initial conditions?

A Yes, the 13 simulations differ slightly in their initial and boundary conditions.

R2.22 10. Line 96, what is the definition of a “CWT set”? 8 consecutive days with the same CWT? Can you please list the number of CWT sets from the MPI-ESM simulation?

A A CWT set consists of 8 consecutive days. At least the CWT of the third, forth and fifth day of these 8 consecutive days (also called "the 3 main days", cf. Table 1) must be identical to the requested CWT. For most of the 13 simulations, all of their eight consecutive days belong to the same CWT.

130 CWT sets have been chosen from the MPI-LGM. (cf. near line 94)

R2.23 11. Fig. 1, can you please add the location of the Loess to the figure?

A Fig. 1 focuses on the numerical WRF-Chem-LGM setup (i.e. the model input data) and it contains already the dotted area that shows that all areas outside this area are excluded from being a potential dust source. It would overload this map with too many colours, shades, lines and symbols if we add more independent data sets that need to be clearly distinguishable without affecting the already shown layers. Adding these loess locations would also suggest that they were used as input data for the WRF-Chem-LGM experiments. This would be misleading because the loess sites samples are only used to compare the WRF-Chem-LGM results to. They are not part of any simulation.

R2.24 12. Can you please add some explanation about Table 1? e.g., what’s heterogeneous sequence? Why are spin-up records preferred?

A Table 1:
Each CWT sequence consists of 8 consecutive days, i.e. 2 spin-up, 3 main and 3 tracking days. In all CWT sequences, the CWT of the 3 main days is identical and defines the desired CWT for the whole 8-day episode.
For rare cases for which no 13 distinct 8-day samples for the same CWT were available in the MPI-LGM, the strict selection criteria has been weakened. That is, the 2 spin-up days are then allowed to be samples of a different CWT. If applying this weakened selection criteria was still insufficient to extract 13 different 8-day episodes from the MPI-LGM, then the selection criteria was weakened further, that is, also the 3 tracking days are allowed to deviate from the CWT of the main days.

This approach implies that the priority of the 3 tracking days to fit to the CWT of the main days is higher (++) than that of the 2 spin-up days (+).

An episode is called *heterogeneous* if at least 1 (out of 5 possible) record differs from the desired CWT of the episode's main days.

The caption of Table1 has been updated.

R2.25 13. Line 135, why do you mention Fig. 9a here?

A Fig. 9a is mentioned here since it shows the importance of east sector winds.

R2.26 14. Line 181, why do you select 12 and 20 µm?

Is 20 µm the largest dust size bin in the model?

The results from FD12 in Fig. 4 seem not discussed in section 3.4.

A 20 µm is selected because it is the upper limit of particle sizes included in the WRF-Chem-LGM with the applied dust emission scheme.

12 µm is selected because the WRF-Chem-LGM particle size bin distribution provides this limit as the nearest approximation of the deposition values for 10 µm particle size limit that are commonly published in studies based on mass accumulation rates (MAR10 = MAR 10 µm) from loess fieldwork samples.
Yes, 20 µm is the largest dust size bin in the model. (Manuscript updated)

R2.27 15. Line 214, add “(Fig. 7)” after “vegetation cover”.

A Thanks for this comment. In the new version, this is corrected. We assume Referee2 refers to line 213 as "veg. cover" does not occur in line 214.

R2.28 16. Can you please add the location of dust source (as displayed in Fig. 1) to Fig. 6?

A Parts of Fig. 1 and Fig. 6 are possibly misunderstood:
Fig. 1 does not show any dust source location. Instead, the dotted area limits the area for **potential** dust sources. That is, it rather excludes regions (i.e. the non-dotted) as potential dust sources since they have a very low or zero potential erodibility according to Ginoux's time-independent dust function (Ginoux et al. 2001). If the dotted regions eventually become dust sources depends on additional dynamic factors such as e.g. the atmospheric circulation (in particular the wind speed) and surface conditions (e.g. snow and vegetation cover, soil moisture). As Fig. 6 displays seasonal dust cycle aspects, it should be noted, that (in addition to the before mentioned) the dotted area results from spatiotemporal average (i.e. annual) LGM conditions. It does not take into account (nor adapt to) the seasonal changes that occurred during the LGM.

Fig. 6 focuses on the seasonal dust deposition rates. Adding Ginoux's time-independent potential erodibility mask (shown in Fig. 1) would suggest that this mask is adjusted to seasonal differences and particularly appropriate for seasons. Yet, this suggestion is misleading and would create a misleading understanding of the Fig.6 for the reader.

Nevertheless, the referee's request is already met in Fig. 5, which shows the location of the dust sources resolved by season. In addition, Fig. 5 shows the seasonal dust emission rates of the dust sources.

For clarity and readability, it is suggested to **not** add further colours, shapes, contours nor shades to Fig. 6. Otherwise, it would become overloaded.