Author's response to Anonymous Referee #1 report (shown in italic font)

The manuscript by Bauer and Ganopolski investigates the dust shortwave direct radiative forcing over the last four glacial-interglacial cycles using the intermediate complexity Earth system model CLIMBER-2. This is a follow up from a paper by the same authors (Bauer and Ganopolski, 2010), that described an offline version of the dust model coupled to CLIMBER-2 (including simulation of emission, transport and deposition) validated against observational data.
The new work incorporates the use of a radiative transfer model and simulates dust radiative effects and climate feedbacks under six different scenarios resulting from the combination of different assumptions in terms of mass balance of the dust cycle and optical properties of dust, allowing to evaluate the sensitivity of the climate to dust. The rationale of the study is grounded in the necessity of improving the understanding of aerosol climate interactions, as also stated by IPCC AR5. The incorporation of the dust cycle in intermediate complexity Earth system models is an important addition to the set of tools relevant for dust-climate research and paleoclimate research.
The manuscript is well written and the figures and tables are clear and provide adequate support to the main text. The work is clearly described and presented results are discussed in a consistent way. It is indeed an interesting work, but I have one major point of concern that I think the authors should properly address before the manuscript can be accepted for publication.

The assumption that dust aerosols transported over long distances have sizes falling mainly within the accumulation mode lacks an acceptable justification and is in contrast with observations. Most important, it is likely to significantly affect the results discussed in the manuscript. The details of my analysis are provided below.

We fully agree with the Reviewer that our assumption of aggregating the airborne dust mass into a single mode of particles, which we called accumulation mode, is a strong simplification. We are aware about the enormous complexity of the real dust cycle and also “state of the art models” use approximations for treating that complexity. Our task of simulating the long-term climate evolution is rather as follows. We use an intermediate complexity approach. The model has a coarse spatial resolution and our atmospheric model uses a parametric description of the vertical structure. In line with the model structure we use a strongly simplified dust cycle model. Our study represents the first step toward understanding possible effects from radiative forcing of aeolian dust on the glacial cycles and it is naturally to run tests with a simplified approach instead of waiting till such a study will be possible with complex Earth system models. At the same time, we fully understand the Reviewer’s concern and will discuss model limitations and caveats in the paper. Please find below further reasoning of our approach.

Major remark
The assumption that dust aerosols transported over long distances have sizes falling mainly within the accumulation mode described in the introduction is justified based on Sow et al. (2009). The mass vs diameter distributions in that study does not support this claim: Figure 11 in Sow et al. (2009) shows that only a significant but relatively small fraction of the dust mass falls in the sub-micron range typical of the accumulation mode, compared to the super-micron fraction. In addition a variety of observations far from the source areas (hence relevant for long-range transport) from the surface (e.g.Maring et al., 2003; Ruth et al., 2003) confirm this fact. Even vertical profiles (Reid et al., 2003b) and column-integrated estimates of size distributions (Reid et al., 2003a),

which may be the more relevant parameters for the specific purpose of this study, do not support the authors' claim. The possible relevance of the assumption that the airborne dust mass can be approximated to the accumulation mode is related to a couple of aspects, which relate to the mechanism described by the authors (162.24-29).

First, the modeled dust mass balance was tuned (Bauer and Ganopolski, 2010) by a global scale factor in order to match the DIRTMAP2 dataset, which is reasonable for a bulk dust model that does not simulate the dust size. In the new manuscript though, considering that all that dust has sub-micron size is equivalent to artificially shifting all the mass from the coarse to the accumulation mode. Second, the consequence is that the dust (which is already largely overestimated for the accumulation mode) is biased towards small particles that are going to be more effective scatterers in the model because of the Mie theory (e.g. Tegen and Lacis, 1996).

In view of those considerations, it is likely that the assumption has significant impacts on the results. In the conclusion of the manuscript the authors indicate that inclusion of a coarse dust mode in their model will be the object of future work. I would be eager to consider the assumption acceptable for the work in these terms, provided it did not involve unrealistic justifications, but instead if its implications and limitations for the model and interpretations were thoroughly discussed, ideally with an additional sensitivity test or at least by a strong discussion and some reasonable estimates compared to the other sensitivity tests on the refractive index and dust load.

In response to the Major Remark we will properly revise our description of calculating the dust direct radiative forcing (DRF). Actually our model does not resolve the size distribution of aerosol particles. We wish to clarify that, first, our approach is without artificially shifting any dust mass into a certain size bin, and second, that no bias is introduced toward small particles which could lead to an overestimation of DRF. In order to avoid misunderstandings we will not refer to accumulation mode in the revised manuscript. This term was only meant to say that we ignore the radiative forcing effects induced by very coarse particles and by very fine particles, usually attributed to Aitken mode.

The shortwave (SW) DRF of aeolian dust is computed with the shortwave scheme of our climate model (Petoukhov et al.,2000). This scheme computes the SW DRF as a function of aerosol optical thickness (AOT) and the imaginary part of the complex refractive index (RI) specified for the UV and the visible wavelength bands. We assume that the simulated atmospheric dust mass consists of particles which are important for scattering and absorption effects at the mid-visible wavelengths. The equivalent dust AOT is computed for each atmospheric model column from the atmospheric dust mass load. This is done by converting the column-integrated dust mass per area with the mass extinction efficiency (ME) into dust AOT for wavelength of 0.55 micrometer using a median value of ME=0.95 m^2/g given by Kinne et al. (2007). Of course, this is a strong simplification. We are aware, that the extinction of shortwave radiation fluxes by aerosols varies, in particular, with particle size and particle composition, and that insufficient information on particle properties can cause large uncertainties in numerical modelling.

We will refer to studies in a more detailed manner which can give some support for our choice of a constant ME value. The used ME value is fully consistent with the results on dust mass emission, dust mass load and dust AOT at 0.55 micrometer provided by the AEROCOM study. An estimate of the uncertainty range of the global mean ME value is available from the diversity measure obtained from models participating in the AEROCOM exercise. The central diversity (without the two largest and smallest values for ME) lies in the range 0.60 – 1.38 m^2/g. The dust

ME diversity with a ratio of about 2, obtained from the maximum and minimum values without the two largest and smallest values, is seen to vary little with geographic region. This gives some support for the dust ME not to vary largely for different sources regions.

The uncertainty in ME is further connected with uncertainties in the particle size distribution. A systematic change in the size distribution will lead to a change in ME. The measurement study of Sow et al. (2009) from the African Monsoon Multidisciplinary Analysis (AMMA) gives some support that the size distribution of atmospheric dust particles is relatively insensitive to surface wind variations. If this analysis from the African region can be seen representative also for other regions and wind conditions then this analysis gives some support that the number distribution of dust particles as a function of particle size is rather invariant. The Reviewer’s point that only a relatively small fraction of the dust mass falls in the sub-micron range is correct but as we explained above this fact is of secondary importance for our calculation of dust AOT.

We are aware that details of the dust aerosol size distribution are aggregated which cause uncertainties in the calculation of the dust radiative effects. In the present study we focus on uncertainties connected with uncertainties in dust AOT distributions and with uncertainties in RI which are found to have a major impact on climate cycle simulations. We consider uncertainties in dust AOT from dust lifetime uncertainties and uncertainties in RI within reasonable bounds. The use of a high and a low dust AOT combined with with a low, medium and high RI value gives six possible configurations for the sensitivity simulations used in our off-line and online simulation experiments.

Minor observations
Title and text: since the model just includes SW-dust interactions, I think this should be made explicit, e.g. by changing throughout the manuscript “DRF” with “SW DRF”,including in the title.

We agree and will change the title accordingly.

152.20: Wind gustiness has also been indicated as a possible driver for dust emission changes on orbital time scales (e.g. McGee et al., 2010).

The effect of wind gustiness is important for dust emission and we will refer to McGee et al. (2010). Although our atmosphere model does not resolve gustiness explicitly, wind gustiness is implicitly accounted for since the surface wind speed responsible for dust emission is simulated by including the second moment of the synoptic-scale velocity. The synoptic-scale velocity is affected by changes in baroclinicity (Petoukhov et al., 2000) and, in general, is higher under glacial conditions.

154.12: “presumably”? Please check

We will replace the sentence containing “presumably” by a more detailed discussion.
Differences in the radiative forcing could be induced by differing optical parameters and the use of different shortwave schemes which impede a direct comparison. Claquin et al. (2003) accounted for different single scattering albedos which were obtained from measurements with desert soils of variable mineralogical composition. Takemura et al. (2009) accounted for size-dependent

extinction coefficients (Takemura et al., 2002) and used an imaginary refractive index of soil dust of 0.002 based on recent studies (Takemura et al., 2005).

155.21: When mentioning dust size, please indicate explicitly if you refer to radius or diameter.

We will revise the text with respect to particle size (see response to Major Remark).

157.20: "The dust deposition of snow is prescribed" seems in contradiction with the description of the simulation of dust removal by dry and wet deposition. Please clarify this aspect.

As it was shown in Ganopolski et al. (2010) and several other studies dust deposition affects significantly snow surface albedo and has a profound effect on the simulated glacial cycle. To separate this effect from the effect of airborne dust on the planetary albedo, we kept the ice sheet surface albedo scheme unchanged. This scheme (as described in Calov et al 2005) is based on properly weighted dust deposition from high resolution simulations of Mahowald et al. (1999). Such an approach is only justified to perform factor analysis and is indeed inconsistent. In future we are going to use simulated rather than prescribed dust deposition but this would require a proper downscaling technique because the spatial resolution of the ice sheet (ca. 75 km) is much higher than the resolution of our atmospheric model.

161.7-10: Motivate "implies a long-range transport mainly from South America"

Dust deposition in Eastern Antarctica originates mainly from land surfaces located in South America. This is based both on simulation experiments and empirical data (analysis of dust mineralogy).

163.27: Define the "critical surface albedo"

The "critical surface albedo" is introduced on page 162, line 29 as the surface albedo at which DRF at TOA changes its sign. As seen from Fig. 3, the critical surface albedo varies with the imaginary part of the refractive index, dust load and cloudiness.

165.24: "varies IN TIME"

We will modify the text.

166.13-14: What is the relation between AOT and the choice of the refractive index? How is the AOT calculated in the model?

The dust AOT is calculated from the atmospheric dust load per area by use of the dust mass extinction efficiency. The choice of the refractive index is based on literature values (see response to Major Remark).

168.13-14: This is an interesting point, I think it deserves more discussion. What are the possible causes? Just the bias induced by the size assumptions? A too slow response because of the attribution of glacial times sources in this model mostly *to low/mid latitude desert sources rather than glaciogenic sources?*

In course of the transient climate simulation the induced cooling by the negative dust radiative forcing is connected with a rather strong response of the ice sheet model and the dust cycle model. This is seen from the enhanced ice sheet growth and the dust emission flux. Simulating the termination of the ice age in agreement with data then requires a corresponding stronger positive forcing. These simulation results of the present study give some new understanding of the sensitivity of the model components to the shortwave dust radiative forcing only.

170.17-20: This statement should be reconsidered once the possible bias induced by the size assumptions made for this work has been addressed.

Please see our discussion on this issue above.

Figures 4 and 9: Several labels are missing.

Probably the Reviewer meant fig. 4 and 7. These figures will be modified to show proper labeling of vertical axes.

Table 4: Please add either the reference value or the anomaly to that for each case. Naming conventions: it may be helpful to add a coding also for the three refractive indices options, similar to the L1/L2 convention so that each of the six cases has a unique synthetic identifier to be used in the text e.g. as all the L1 cases or all the *R0015 cases, or something equivalent.*

The table shows absolute values of the dust emission flux and of dust AOT rather than anomalies. We will improve the table caption. Please see the response to the Major Remark with respect to the configuration of the sensitivity experiments.

Additional References

McGee, D., Broecker, W. S., and Winckler, G.: Gustiness: The driver of glacial dustiness?, Quaternary Science Reviews, 2010.

Takemura, T., Nakajima, T., Dubovik, O., Holben, B. N., and Kinne, S.: Single-scattering albedo and radiative forcing of various aerosol species with a global three-dimensional model, J. Climate, 15, 333–352, 2002.

Takemura, T., Nozawa, T., Emori, S., Nakajima, T. Y., and Nakajima, T.: Simulation of climate response to aerosol direct and indirect effects with aerosol transport-radiation model, J. Geophys. Res., 110, D02202, doi:10.1029/2004JD005029, 2005.