Response to Anonymous Referee #1

Willeit et al. quantify the impact of snow albedo parametrisation (snow aging and dust deposition) for the simulation of the last glacial-interglacial cycle in a model of intermediate complexity. Snow albedo is a crucial parameter for the surface mass balance of the ice sheet and its temporal evolution (over this timescale) is poorly constrained. As such, the study is largely justified. However, in my opinion the manuscript suffers from some important omissions about: study justification/novelty, model description, model validation and methodology discussions (listed below). As it stands the authors mostly show the impact of a higher snow albedo in simulating the last glacial-interglacial cycle.

We would like to thank the reviewer for his constructive comments on our manuscript. We have responded to the issues raised by the reviewer below. The original reviewer comments are in black, our responses in blue.

General comments

- The novelty in this work is not presented in a clear way. The snow albedo is known to be one of a major control on ice sheet surface mass balance and several authors have already explicitly tested this in coupled ice sheet – climate simulations (e.g. Calov et al. 2005; Bonelli et al. 2009; Helsen et al. 2017; Fyke et al. 2011). Also, it seems difficult to see clearly the difference between this study and the one of Ganopolski et al. (2010), except for the use of an interactive scheme for dust deposition (which is not validated here). Ganopolski et al. (2010) have already shown the importance of dust in their results (Sec. 5.3, quoting): "Hence, at least in our model, accounting for the additional source of dust related to the glacial erosion is crucial for simulating of a complete termination of the glacial cycle [...]". Given that: i) the conclusions in Willeit et al. (2017) are almost identical to the one of Ganopolski et al. (2010) and; ii) there is no real improvement in the model; I feel like the study needs a stronger justification.

The reviewer is absolutely right – the importance of snow and ice albedo parameterizations for ice sheets modeling has been known for long time. To the contrary, the role of snow albedo parameterization on modeling of glacial cycles is much less understood and so far was only shortly discussed in several of our papers. Most of other simulations of glacial cycle(s), like the above cited Bonelli et al. (2009) as well as Tarasov and Richard Peltier (2002), Zweck and Huybrechts (2005), Charbit et al. (2007), Abe-Ouchi et al. (2007), Lunt et al. (2008), Gregoire et al. (2012), Liakka et al. (2016) and many others employed the so-called Positive Degree Day scheme which does not even account explicitly for snow and ice albedos. Indeed, in Ganopolski et al. (2010) we concluded that the dust (of glaciogenic origin) plays an important role in termination of glacial cycle. But this paper contains only one figure (Fig. 11c) demonstrating the effect of dust deposition on simulated glacial cycle, and only for the dust originated from glacial erosion. In Ganopolski et al (2010) we did not perform a systematic analysis of the effect of different parameterizations of the dust darkening effect on snow albedo, how important snow aging is and how sensitive the model is to the total amount of dust which is deposited on the ice sheets. Why such analysis became so important now? Because of the major development in paleoclimate modeling, namely because it became possible to use complex Earth system Models based on GCMs to test Milankovich theory and simulate the last glacial cycle. One of such ambitious projects is the German National Modeling Initiative PalMod (Latif et al., 2016) from which this work is partly funded. In the framework of this and similar projects over-simplistic obsolete scheme like PDD will be substituted by a physically based energy balance approach similar to that used in CLIMBER-2. However, unlike CLIMBER-2, complex ESMs are extremely computationally expensive and cannot afford to use the try and error method. In fact, they can only perform a single simulation of one glacial cycle. This implies that the crucial model parameters and parameterizations have to be properly calibrated before launching long-term simulations. Our study clearly shows that the proper parameterizations of snow albedo which includes snow aging effect, effect of impurities and the synergy between both, is absolutely crucial for successful simulation of glacial cycle. Even the choice of different parameterizations for the effect of dust on snow albedo can lead to very different outcomes of glacial cycle simulations. We believe, these findings are important and will significantly facilitate simulations of glacial cycles with complex ESMs. Part of this discussion have been included in the introduction of the revised paper.

Concerning “real improvement in the model”. The aim of introducing the fully interactive dust cycle in CLIMBER-2 is not to improve model results if under “improvement” the reviewer understands better agreement between model and data. This agreement is already good in Ganopolski et al. (2010). Development of a comprehensive Earth system model where all important processes are included and all components (climate, ice sheet, carbon and dust cycles) are fully interactive is necessary for the decisive test of Milankovitch theory by simulating realistic glacial cycles by using orbital forcing as the only prescribed forcing.

- Methodology. The model has been tuned to reproduce the glacial-interglacial cycles for a specific snow parametrisation. I am thus not surprised that the omission of one process affecting the snow albedo lead to an erroneous ice sheet evolution. Are the authors testing the actual processes (dust/aging) or simply the value of the albedo? Switching between off and on the two processes with the same value for the fresh snow albedo is an unjustified oversimplification. They could have tried to retune the model without the aging and/or dust (considering a perpetual “dirty fresh snow” for example): if they were able to show that it is impossible to get a realistic ice sheet volume evolution in doing so, then they might have claimed that aging/dust are clearly important. In addition, if the real novelty of this work is to use the interactive dust, they should have shown the difference of their model compared to the prescribed dust version of Ganopolski et al. (2010).

The fact that CLIMBER-2 is capable of reproducing glacial-interglacial cycles is the result of many years of work, which included model improvements, inclusion of new processes based on new process understanding and obviously also tuning of unconstrained model parameters. Even with a relatively fast model like CLIMBER-2 it is practically impossible to explore the whole parameter space and it could well be that other parameter combinations could lead to a successful simulation of glacial cycles. This is beyond the scope of the present study. The goal of this study is to clearly show that surface albedo plays a crucial role for ice sheet evolution and not only do fundamental processes affecting snow albedo, such as snow aging and dust deposition, play an important role, but even using slightly different parameterisations of the same process (e.g. the effect of mineral dust impurities on snow albedo) can lead to qualitatively very different results. This is a clear message to readers who are interested in simulating glacial cycles and more in general the long-term evolution of ice sheets.

Concerning differences between new results and Ganopolski et al. (2010). They exist of course, but they are not significant. As has been explained above, the aim for substitution of prescribed spatial patterns of dust deposition based on GCM time slice simulations used in our earlier studies, by the dust deposition fields simulated by our own dust cycle component is not to “improve” model performance but to design a fully interactive and internally consistent Earth System model suitable for testing Milankovitch theory.

- Validation of the scheme: the study could be more convincing if the aging and dust parametrisations were validated against observations or state-of-the-art model simulations. In particular, it could be useful to see if the scheme reproduces the seasonal variations of albedo of the Greenland ice sheet and high latitudes regions. Again, as it stands, the reader is left with the impression that the parametrisations have been chosen (tuned) to reproduce the last glacial-interglacial cycle. As a result it is obvious that the model will not work if the processes are not included. I would also like to see how well the dust deposition changes over Greenland along the cycle simulated by the model compares to actual dust in Greenland ice cores.

The model parameterization has been developed based on existing schemes (BATS (Dickinson et al., 1986)) which in turn were calibrated against observational data. Direct comparison of CLIMBER-2 results with observational data is not very useful because of coarse resolution and schematic geography. However, the newest land scheme for the next CLIMBER model (Willeit and Ganopolski, 2016), which employs a similar albedo parameterization but has a much higher spatial resolution shows a good agreement of simulated albedo with empirical data (Fig. 5 in Willeit and Ganopolski (2016)). Concerning the comparison of seasonal variations of Greenland albedo with observations, such a comparison does not make much sense because the elevation, temperature, precipitation, surface radiation, etc. in model simulations differ from reality and all these factors (not just the parameterization of albedo) affect surface albedo. Comparison can be made in specially designed off-line simulation where elevation and climatology are prescribed from observation and only albedo is computed. We did such an experiment for the present day Greenland using a daily climatology of the regional model MAR (Fettweis et al., 2013) available from ftp://ftp.climato.be/fettweis/MARv3.7/Greenland/NCEPv1_1948-2017_20km-daily-raw/ as forcing. We prescribed daily snow thickness, surface temperature and snowfall rate and computed the surface albedo with the CLIMBER-2 scheme described in the paper, for all days over a climatological year. Dust is ignored in this experiment because of the negligibly low deposition rates over present day Greenland. The albedo can then be compared to the albedo modelled by MAR itself and to available observations based on satellite measurements. The results are shown in Fig. A below. From Fig. A it is clear that there are substantial differences in albedo between different regional climate model simulations and between different observational products. In general the CLIMBER-2 results are in the range covered by the different datasets, except for South-West Greenland, where summer albedo seems to be slightly underestimated in our model.

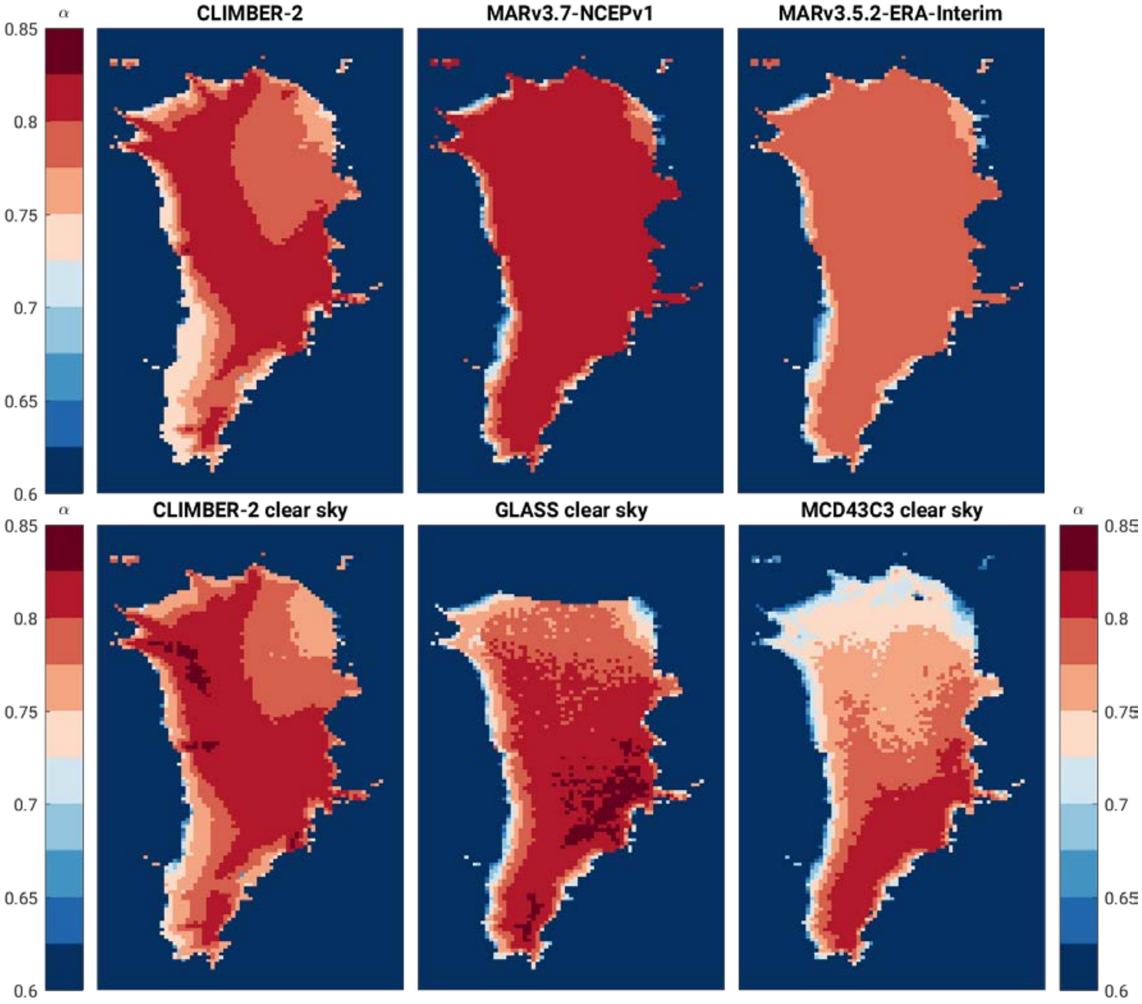

Figure A Comparison of modelled surface summer (JJA) albedo over Greenland in an offline experiment driven by daily MARv3.7-NCEPv1 climatology compared with (top) MAR regional climate model results for the period 1980-2010 and (bottom) MODIS satellite based clear sky albedo products for the period 2000-2010 (Liang and Liu (2012) and Schaaf and Wang (2015)).

I would also like to see how well the dust deposition changes over Greenland along the cycle simulated by the model compares to actual dust in Greenland ice cores.

We discussed the dust model performance against data and other models in Bauer and Ganopolski (2010, 2014). This comparison shows that the model is doing reasonably well when data uncertainty and big discrepancies between different state of the art models are taken into consideration. We did not show model performance for Greenland for several reasons. Firstly, even during glacial time the observed dust deposition over Greenland was very low (order of 0.1 g/m2/a) and had no impact on the Greenland ice sheet mass balance. Second, the main dust sources for Greenland are located in Central Asia, which implies an extremely long atmospheric dust transport along very complex orography. Obviously, the coarse-resolution CLIMBER-2 is not good for modeling such process. Third, the model grid cell which incorporates the real Greenland is only by 50% covered by ice sheet and by 50% by ocean. Therefore the averaged elevation of this model grid cell is very different from the elevation of Greenland summit. Similarly, the average precipitation rate over the entire “Greenland grid cell” is an order of magnitude higher than precipitation at the locations of the ice cores. All this makes comparison between modeled and ice core data not very useful.

- Model presentation: the albedo computation in the model should be presented in this paper, in particular on how age and dust relate to albedo. The reader has to check the appendix of Calov et al. 2005 to get more information on this. Also, the same is true for the dust from glaciogenic sediments, for which the authors only state that the model accounts for. I also think that more information on the SEMI model could be added (which variables are bilinearly interpolated? Which variables depend on subgrid topography? Etc.).

Although all aspects of albedo parameterization, dust and surface mass balance simulations have been given in our previous papers (Bauer and Ganopolski, 2010; Calov et al., 2005; Ganopolski et al., 2010, etc…), following reviewer's suggestion we added a more complete description of the snow albedo parameterization, dust cycle and SEMI model.

Specific comments

P2L1 In fact, algae could be more important than non-algal impurities for bare ice albedo (Musilova et al. 2016; Stibal et al. 2017).

We have included references to these two papers in the revised manuscript.

P2L23-24 SEMI does not perform a physically based downscaling of climatological fields. Most of the variables are bilinearly interpolated. The SMB is physically based though.

This is not correct. Importantly, precipitation is downscaled accounting for the slope effect and the desert-elevation effect. Radiation and atmospheric temperature and humidity are first interpolated bilinearly and then corrected for the surface elevation of the ice sheet.

P2L27-28 Does this include the Antarctic ice sheet?

No, Sicopolis is applied only to the Northern Hemisphere.

P3L5 How this is computed? Can you really differentiate between the two types of dust? Please expand on this.

To clarify this point we added the following paragraph in the revised paper:
"This dust source is not included in the global dust cycle model due to its very local origin, which can not be represented on the coarse atmospheric grid. Dust deposition produced from glaciogenic sources is parameterized based on the assumption that the emission of glaciogenic dust is proportional to the delivery of glacial sediments to the edge of an ice sheet (see Ganopolski et al. 2010 Appendix A for details). Most of the glaciogenic dust originates from the southern flanks of the ice sheets and this source is significant only for mature ice sheets, which reach well into areas covered by thick terrestrial sediments."

P3L7 On which grid are you looking that? The SICOPOLIS grid or the native atmospheric grid?

The snow albedo parameterisations are applied both to the surface scheme on the atmospheric grid and to SEMI on the ice sheet grid.

P3 Eq.X? Is this calculated on each atmospheric timestep? What is the value of the atmospheric timestep?

The snow age factor is computed on each atmospheric timestep and the timestep is one day.

P4 Fig 1 The CLIMBER2 albedo presented here is the one tuned to reproduce the glacial interglacial cycles and they are systematically below the values of Dang et al. and Gardner and Sharp (0.1 difference, except for pure snow where it is very close). This is not surprising that using one of Dang et al. or Gardner and Sharp results in an overestimation of the ice volume.

We agree that it is not surprising that using one of Dang et al. or Gardner and Sharp results in a larger simulated ice volume. However, it is not obvious a priori that using these alternative albedo schemes results in a total failure to simulate the last glacial cycle. The snow albedo for the different schemes shown in Fig.1 is substantially different only when dust is involved. Hence, as dust deposition varies strongly in space and time, the albedo difference between the different schemes will also be a complex function of space and time.

P4L12 Antarctic kept constant to present-day observations?

Sicopolis is applied only to the NH and Antarctica is kept constant to present day observations. This is explicitly stated in the revised version of the manuscript.

P5 Figure 2 Why the surface mass balance is increasing over the Holocene whilst the ice volume remains constant?

The increasing SMB is related to the decrease of Greenland melt during the Holocene and is almost completely balanced by increased ice calving to the ocean and therefore not seen in global ice volume.

P6L19-20 You state in line 8 that the simulated dust deposition is roughly 3000 Tg/yr but later you mention the scaling factor to get 3000 Tg/yr. This is confusing: what is the actual simulated dust deposition before the application of the scaling factor? Using an other scaling factor you could end up with significant study conclusions (maybe for more dust, you might no need the snow aging to reproduce the cycles...).

In the revised paper we make clear that the 3000 Tg/yr deposition is a result of adjusting the dimensionless global calibration constant cq in Eq. (8) of Bauer and Ganopolski (2010). The cq factor is part of the original dust model (cq = 0.0212) and has been slightly increased in the present study (cq = 0.03) to get present global dust emissions of 3000 Tg/yr. The effect of scaling dust emissions up or down from the reference value on simulated glacial cycles is illustrated in Fig. 10.

P6 Fig 3 This is only aeolian dust? Do Mahowald and Lambert include the glaciogenic dust as well?

The modelled dust deposition includes both aeolian and glaciogenic dust. The same is true for the Lambert dataset, while Mahowald 1999 does not include glaciogenic dust (Mahowald 2006 does, but is not shown here). This is now specified in the caption of Fig. 3 in the revised manuscript.

P6 Fig 3 It could be nice to have the extent of the (observed) ice sheets for the two time periods on this plot.

We added the modeled (observed) ice sheet extent to the figure.

P7L8 The dust effect is larger at the LGM because you have the contribution from the glaciogenic sediments?

No, the glaciogenic dust starts to become important after LGM, during deglaciation (see e.g. Fig. 9). The larger effect of dust on albedo at LGM is a result of larger aeolian dust emissions at LGM compared to other times (Fig. 2g) combined with ice sheet extent reaching further south where dust deposition is larger.

P7L13 I do not understand this statement: your ice albedo is 0.4 and your old/dirty snow has an albedo which can be lower than 0.4.

This is correct, but most of the time the dust concentration in the snow is fairly low (below ~300 ppmw) and therefore the albedo of snow is usually larger than the albedo of ice. This has been added to the paper.

P8 Fig 5 Why there is a corridor of low albedo values between the coastal grid points of the gulf of Alaska and the rest of the Laurentide ice sheet?

Because of lower ice elevation along the corridor.

P8 Fig 5 Is the depicted albedo only for grid points covered by an ice sheet? If not, please add the extent of the simulated ice sheet in this.

As mentioned in the figure caption the albedo is only shown for ice covered grid points.

P9 Fig 6 Does the surface mass balance scheme includes any kind of refreezing?

Yes, refreezing is accounted for and represents a constant fraction of 30% of melt. This has been added to the paper.

P9 L17-20 [...] “From the experiments presented and for this model formulation” should be added. Again, I am not convinced that you actually test the actual processes. Extrapolating: the use of Dang et al. and Gardner and Sharp does not allow for a realistic cycle neither, does this mean that there is still a missing process like algae?

The sentence has been modified as suggested.
There is no obvious reason to assume that the albedo parameterisations of Dang et al. and Gardner and Sharp are better or more realistic than the original CLIMBER-2 scheme based on Warren and Wiscombe (1980). They basically differ in the strength of the dust effect on snow albedo, which mainly depends on the assumed dust radiation absorption properties. A number of different papers have recently shown that algae could play an important role and in the future we will consider the possibility to represent this effect in the model.

P10 L1 How this is computed? Can we really distinguish this from the rest of the dust? It could be useful to have a map of this.

This is just the glaciogenic dust that is described in the paper, with some more details in the revised version as explained in the response to a reviewers question above. Figure 9 gives already an idea of the temporal evolution of glaciogenic versus aeolian dust and we think that a map would not add much more information here. A spatially explicit representation of the glaciogenic dust production can be found in Ganopolski et al. (2010), Fig. 9c.

P10 L3-4 Is it fair to say that this is a tunable additional source of dust in order to produce a realistic cycle?

No, it is not. This (glaciogenic) source of dust is not “tunable”- it is real. The DIRTMAP data (Kohfeld and Harrison, 2001) show that dust deposition near to the southern margins of the Laurentide and Fenoscandian ice sheets during LGM are typically within the range 50-200 g/m2/a, which is one or even two orders of magnitude large than the model can simulate without taking into consideration glaciogenic dust sources (i.e. Mahowald et al. (2006)). Note that the dust deposition rates at the LGM in the same areas in CLIMBER simulations (Fig. 10 in Ganopolski et al. (2010)) are about 50 g/m2/s. Therefore there is no reason to believe that the effect of glaciogenic dust is overestimated in our simulations.

P10 L3-4 Your maximum dust over the whole cycle is at about 15k thanks to this glaciogenic dust. It seems important to clearly state where does this come from and why this process only appears at the end of the cycle. A few maps at selected snapshots could be nice for albedo, dust and SMB.

More details on the origin of the glaciogenic dust have been included in the revised version of the paper. This, together with Fig. 7 and Fig. 9 should be sufficient to allow the reader to better understand where it comes from and where and when it is important.

P11 L10-12 “ice is covered by snow most of the year, even in net ablation areas” To melt the ice sheet you need to melt the ice in summer, using the ice albedo. Can you give more explanation on why the ice albedo is not playing in your deglaciation scenario?

Yes, but the length of the (snow-free) ice melt season is controlled by snow albedo and in the model the length of the melt season is more important than the actual value of ice albedo.

P11 L12-16 These experiments are interesting, to my opinion. It would have been nice to see these experiments combined with the omission of snow aging. Increased dust but no aging might produce a realistic cycle? Or combining dust deposition scaling factor with Dang et al. or Gardner and Sharp parametrisation.

Indeed, the right results can be obtained for the wrong reason. We cannot rule out a possibility that combination of a model version without snow aging effect with excessive dust deposition can lead to reasonably realistic results. But what one can learn from that if we know that the snow aging effect on albedo is real and important? As we explained above, the purpose of this study is to contribute to the successful simulation of glacial cycles with complex Earth system models. These models do account for aging effect on albedo but do not yet account for the effect of dust and the synergy between the two. Our study shows that all three (aging, dust and synergy) are important.

General

- What about the sea ice albedo? Do you have a similar scheme that includes dust and aging? If not, why.

Modeling the albedo of sea ice is even more complex than the albedo of snow and it can be done properly only with a high spatial resolution model. Note that the resolution of climate component of the CLIMBER-2 model (unlike the resolution of ice sheet model and SEMI) is very coarse – 10°x51°. This is why we use a simple parameterization for sea ice albedo, where the latter depends only on surface temperature. The reason why we ignore the effect of dust deposition on sea ice albedo is obvious: the dust deposition over areas covered by sea ice even during the LGM was very low, typically 1g/cm2/a or less, which is two orders of magnitude smaller that the dust deposition rate over the southern flanks of Laurentide and Eurasian ice sheets.

- The computed SMB is a function of albedo, but also it depends on the other energy balance terms. In particular, how transparent your clouds are is probably very important for the surface mass balance. Snow albedo is always crucial for the SMB, but you might not need dust to reproduce the cycle for different parametrisation of clouds.

According to our simulations, dust deposition is important. We would not be surprised if future studies would show that the dust deposition is less (or more) important for glacial cycles than we report here. After all, even the equilibrium climate sensitivity is known only with the accuracy of 50%. However, it is very unlikely that clouds alone will make the job. In spite of relatively simple parameterizations, CLIMBER-2 simulates planetary albedo and atmospheric energy balance in a good agreement with observational data (Petoukhov et al., 2000). This implies that the errors in simulated downward short-wave radiations flux are of the order of 10%. At the same time, the difference between co-albedo (i.e. amount of absorbed shortwave radiation) between clean fresh snow and old dirty snow is 500% (0.1 vs. 0.5).

Technical corrections

P9 Fig 6 The location of the two sites are not indicated by black boxes.

The location of the sites were indicated by black boxes, perhaps a bit too small. We made them larger and changed the color to red.

P9 L15 Replace Nord by Northern

Done.

P9 L16 && L18 Separately instead of “in isolation”

Done.

P11 Fig 9 there is no blue boxes in Fig 5.

Corrected, the blue boxes are shown in Fig. 8a.

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Response to Referee #2

Willeit and Ganopolski show the importance of considering the effects of snow aging and dust on the snow albedo and consequently on satisfactorily simulating glacial cycles. The article is well written and its relevance is properly justified. In my opininon, the novely of the paper does not lie directly on the results but on the presentation of the parameterizations for accounting on the mentioned effects on snow albedo. Accordingly, the main weakness of the study is reproducibility. The authors should expand on the snow albedo parameterization in order to other groups being able to reproduce (and benefit from) the current study.

We would like to thank the reviewer for his comments on our manuscript. We have responded to the issues raised by the reviewer below. The original reviewer comments are in black, our responses in blue.

General comments

About reproducibility:

Ice sheet – climate coupling represents a considerable ongoing effort for modeling groups. The authors of this article have already convincingly shown in previous studies the necessity of accounting for the snow albedo reduction from ice aging and dust in order to successfully simulate a deglaciation. This article furtherly contributes to this idea and presents the needed albedo parameterizations to do so. This later aspect can be of great importance to groups currently starting to couple GCMs to thermodynamical ice sheet models. Thus, these parameterizations need to be accordingly described.

In the revised version of the paper we included a more detailed description of the albedo parameterization in the model.

1. In page 3, line 14, the snow age factor parameterization is described:

1.1 It might be obvious, but the reader could wonder whether the aging of the snow can simply be computed as a function of temperature and snowfall. Please, elaborate on this and add references.

In reality, the aging of snow is a very complicated process and physically based modeling of snow aging effect on albedo requires high resolution multilayer snowpack models forced by realistic synoptic variability of all climate and hydrological components (e.g. Brun et al., 1992; Flanner et al., 2007). And, as intercomparison projects show, even such complex models simulate very different snow albedo. Needless to say that such approach cannot be used in the CLIMBER model. This is why we have no other choice as to use the only two available characteristics – temperature and precipitation – to parameterize the effect of snow aging on surface albedo. These two characteristics exert primary control on snow aging effect because the growth rate of ice crystals depends strongly on surface temperature while frequent precipitations reduces average size of snow crystals at the surface of snow cover. Our parameterization is simple but still captures the first order effect. This is definitely much better than doing nothing because, as our manuscript shows, this effect is vitally important for simulating realistic glacial cycles.

1.2 The definition of T_0 is missing.

Has been included.

1.3 The age factor is used to represent the grain size. And Fig.1 shows grain radius. How is CLIMBER-2 translating each other? It is linear? Please provide the related expression.

The relation between snow grain radius and snow age factor is now included in the paper.

1.4 Fig.1: Besides the pure snow case, CLIMBER-2 seems to be underestimating the albedo compared to the two other parameterizations. Why? A potential explanation is given by the sentence: "... explained by the choice of the imaginary refractive index of dust". Please, be more specific. On the other hand, the effect of the alternative parameterizations on simulating the glacial cycle is described in the Results section, but it s not explained. I imagine this can simply be a matter of "tunning". Re-calibrating the age factor (or other components of the model) for the two alternative approaches will produce a successful ice-volume evolution. If this is the case, please acknowledge in the paper. Otherwise, the reader remains wondering about the realism of the different approaches.

Yes the difference can be mainly explained by the choice of the imaginary refractive index of dust, which, as shown in different studies and as also mentioned in this paper, varies largely as a function of mineral dust composition. One value might be more appropriate for one source of dust and another for a different source. It is therefore problematic to use one constant global value. On the other hand, tracking poorly known properties of dust based on its origin seems challenging.
In the revised version of the manuscript we now mention that a retuning of the model could possibly allow to successfully reproduce glacial cycles even with alternative albedo parameterisations. The message of the paper should not be that a successful simulation of glacial cycles is possible only with the CLIMBER-2 representation of albedo, but that slightly different schemes could result in very different outcomes.

2. In page 10, the effects of considering aeolian and glaciogenic dust individually are discussed. The interactive aeolian dust representation is conveniently described in previous studies. I could not, however, find the equivalent for glaciogenic dust. How is glaciogenic dust generated in CLIMBER-2? Please provide the necessary information. Furthermore, when Fig.7 shows glaciogenic dust as a necessary condition for a full deglaciation.

More details on the processes generating glaciogenic dust in the model are included in the revised version of the paper. Additional details can be found in Ganopolski et al. (2010), Appendix A.

About discussing the necessity of including a dust cycle:

In the Conclusions section it can be read: "In this study we used an Earth system model of intermediate complexity to show that a proper parameterisation of snow albedo over ice sheets is a crucial ingredient for a successful simulation of the last glacial cycle." This and previous studies from these authors support this conclusion. Nevertheless, other models/groups have shown succesfull glacial cycle simulations without the necessity to invoke "a proper parameterisation of snow albedo". For example, in Abe-Ouchi et al 2007 CP and 2013 Nature, the ablation-isostatic adjustment feedback together with elevation and other feedbacks appear to represent enough processes to simulate the deglaciation.

First, the deglaciation simulated by Abe-Ouchi et al. is not so good. Fig 1d in Abe-Ouchi et al (2013) (and this is obviously their best simulation) shows that Northern Hemisphere ice sheets with the volume corresponding to 20 meters in sea level survived the last deglaciation. This is a lot and by our standard such experiment cannot be considered as successful simulation of deglaciation. Second, Abe-Ouchi et al (2007, 2013) used the PDD scheme. This scheme does not account for albedo at all but it can melt a lot of ice when necessary, partly for the wrong reason (see Bauer and Ganopolski (2017)). In that paper we demonstrated that with properly selected PDD parameters, we also are able to simulate a reasonably realistic glacial cycle (see Fig 10 in Bauer and Ganopolski, 2017). This fact, however, tells us nothing about the importance of surface albedo. The later can only be studies with the models which are based on the physically sounded energy balance approach.

The current main conclusion (see above) of this paper give rise to interesting related questions: Could CLIMBER-2 simulate a deglaciation without considering the effects of dust on snow albedo? If affirmative, which are then the key processes? Are those other processes equally realistic? Is all the relevant physics necessary for understanding deglaciations already contained in EMICs? ... I understand that the authors could see these questions as out of the scope for the current article, but I also believe the readers will appreciate further the current paper if a discussion on this aspect is included.

We here repeat what we have already written in response to one of the comments of reviewer #1. The fact that CLIMBER-2 is capable of reproducing glacial-interglacial cycles is the result of many years of work, which included model improvements, inclusion of new processes based on new process understanding and obviously also tuning of unconstrained model parameters. Even with a relatively fast model like CLIMBER-2 it is practically impossible to explore the whole parameter space and it could well be that other parameter combinations could lead to a successful simulation of glacial cycles. This is beyond the scope of the present study. The goal of this study is to clearly show that surface albedo plays a crucial role for ice sheet evolution and not only do fundamental processes affecting snow albedo, such as snow aging and dust deposition, play an important role, but even using slightly different parameterisations of the same process (e.g. the effect of mineral dust impurities on snow albedo) can lead to qualitatively very different results. This is a clear message to readers who are interested in simulating glacial cycles and more in general the long-term evolution of ice sheets.
We will include a bit more discussion on this aspect in the revised version of the paper.

Specif comments:

Page 1, line 10 and 14: Please use “light-absorbing ...” as later in the paper.

Changed.

Page 3, line 8: add “in” afer “snow albedo used...”

Done.

Caption figure 9: erratum: glaciogenic

Fixed.

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The importance of snow albedo for ice sheet evolution over the last glacial cycle

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Abstract. The surface energy and mass balance of ice sheets strongly depends on the amount of solar radiation absorbed at the surface, which is mainly controlled by the albedo of snow and ice. Here, using an Earth system model of intermediate complexity, we explore the role played by surface albedo for the simulation of glacial cycles. We show that the evolution of the Northern Hemisphere ice sheets over the last glacial cycle is very sensitive to the representation of snow albedo in the model. It is well known that the albedo of snow depends strongly on ~~the~~ snow grain size and the content of light-~~-~~absorbing impurities. Excluding either the snow aging effect or the dust darkening effect on snow albedo leads to an excessive ice build-up during glacial times and consequently to a failure in simulating deglaciation. While the effect of snow grain growth on snow albedo is well constrained, the albedo reduction due to the presence of dust in snow is much more uncertain, because the light-~~-~~absorbing properties of dust vary widely as a function of dust mineral composition. We also show that assuming slightly different optical properties of dust leads to very different ice sheet and climate evolutions in the model. Conversely, ice sheet evolution is less sensitive to the choice of ice albedo in the model. We conclude that a proper representation of snow albedo is a fundamental prerequisite for a successful simulation of glacial cycles.

1. Introduction

The net surface mass balance of ice sheets is equal to the difference between accumulation, which is controlled by the hydrological cycle, and of ablation, which is determined by the surface energy balance. The surface energy balance strongly depends on the amount of solar radiation absorbed at the surface. While the amount of radiation reaching the surface is mainly determined by the insolation at the top of the atmosphere and cloud cover, the fraction of radiation absorbed at the surface is controlled by its albedo. Since ice sheets are mostly covered by snow, the albedo of snow plays a crucial role for the surface energy and mass balance of ice sheets.

The importance of snow and ice albedo parameterizations for ice sheet modeling has been known for long time. To the contrary, the role of snow albedo parameterization on modeling of glacial cycles is much less understood. Most of previous simulations of glacial cycle(s), e.g. Bonelli et al. (2009), Tarasov and Richard Peltier (2002), Zweck and Huybrechts (2005), Charbit et al. (2007), Abe-Ouchi et al. (2007), Lunt et al. (2008), Gregoire et al. (2012), Liakka et al. (2016) and many others employed the so-called positive degree day (PDD) scheme, which does not account explicitly for snow and ice albedoes.

The albedo of snow is a complex function of snow grain size and concentration of light-absorbing impurities (Warren, 1982; Warren and Wiscombe, 1980). After snowfall, snow crystals undergo rapid transformations in size and shape, with a tendency for snow grains to grow larger with time (Colbeck, 1982). The rate of change is controlled by snow temperature and the temperature gradient inside the snow, with melt-freeze cycles beeing additionally very efficient in accelerating grain growth during snowmelt (Brun et al., 1992; Flanner and Zender, 2006). The change in snow grain size affects the interaction of the snow surface with the incoming solar radiation, with larger grains increasing the path that photons are traveling in the snow and therefore decreasing its albedo. The decrease in albedo due to a growth of the optically equivalent snow grain size from 100 µm, typical for fresh snow, to 1000 µm, typical for melting snow, is ~10 % (Fig. 1).

Both radiative transfer models (Aoki et al., 2011; Hadley and Kirchstetter, 2012; Warren and Wiscombe, 1980) and direct measurements (Bryant et al., 2013; Doherty et al., 2013; Gautam et al., 2013; Painter et al., 2010, 2012; Skiles et al., 2012; Skiles and Painter, 2017) demonstrate that even small amounts of light absorbing impurities (LAI) affect the surface albedo of snow significantly. Black carbon and desert dust are the main sources of LAI in snow, but algal blooms and organic carbon could also play a role. Black carbon concentrations of less than 1 ppmw (parts per million in weight) in fresh snow can already cause decreases in albedo by several percent (Warren and Wiscombe, 1980). The effect of mineral dust on snow albedo is much lower, with 1 ppmw of black carbon being equivalent to roughly 100-200 ppmw of mineral dust (Dang et al., 2015; Warren and Wiscombe, 1980). Algal blooms over Greenland have been shown to ~~reduce~~substantially reduce surface albedo ~~locally by up to 20 % ~~(Lutz et al., 2016; Musilova et al., 2016; Stibal et al., 2017). Simulations show that changes in albedo due to LAI might significantly affect the surface mass balance of ice sheets during glacial times (Ganopolski et al., 2010; Krinner et al., 2006), at present (Dumont et al., 2014; Tedesco et al., 2016) and in future climate change scenarios (Goelles et al., 2015).

In this study we explore the sensitivity of ice sheet and climate evolution over the last glacial cycle to the representation of snow albedo in the CLIMBER-2 Earth system model of intermediate complexity. We limit the scope of our study to the effect of snow aging and mineral dust concentration in snow. Several lines of evidence suggest that dust deposition was substantially larger during glacial times (Kohfeld and Harrison, 2001; Lambert et al., 2015; Mahowald et al., 2006), particularly also at the southern margins of the NH ice sheets, the areas most affected by ablation. Dust is therefore likely to be an important player for the ice sheet ablation through its effect on snow albedo. The effect of black carbon is neglected in this study. Although it has been suggested that the effect of black carbon on surface albedo might play an important role in the present day climate (Flanner et al., 2007; Hansen and Nazarenko, 2004; Yasunari et al., 2015), most of the black carbon which is deposited over the boreal region comes from sources related to industrial activities (Bauer et al., 2013; Lamarque et al., 2010). We therefore assume that black carbon deposition over regions potentially covered by ice sheets was negligible in pre-industrial times. The effect of other LAI, like algae, are still far from being properly understood and are therefore not considered in the present study.

It is now becoming possible to use complex Earth system models based on general circulation models to simulate the last glacial cycle (e.g. ~~(~~Latif et al., (2016)). In these models, over-simplistic obsolete schemes like PDD will be substituted by a physically based energy balance approach similar to that used in CLIMBER-2. An exploration of the impact of albedo parameterization on glacial cycles simulations with a computationally efficient model like CLIMBER-2 can provide useful insights into which processes are important and should therefore be accounted for.

2. Methods

2.1. The CLIMBER-2 model

CLIMBER-2 (Ganopolski et al., 2001; Petoukhov et al., 2000) includes a coarse resolution statistical-dynamical atmosphere model, a 3 basin zonally averaged ocean model, a land surface and vegetation model (Brovkin et al., 1997) and the 3-d polythermal ice sheet model SICOPOLIS (Greve, 1997). SICOPOLIS is applied only to the Northern Hemisphere, with a resolution of 1.5° x 0.75°. Antarctica is prescribed from present day observations. The climate component and SICOPOLIS are coupled once per 10 years through a surface energy and mass balance interface module (SEMI) (Calov et al., 2005). SEMI performes a physically based 3-dimensional downscaling of climatological fields from the coarse atmospheric grid to the ice sheet model grid and computes the surface mass balance and the surface temperature using a physically based surface energy balance approach. Importantly, precipitation is downscaled accounting for the slope effect and the desert-elevation effect. Radiation and atmospheric temperature and humidity are first interpolated bilinearly and then corrected for the surface elevation of the ice sheet. Refreezing is accounted for as a constant fraction, 0.3, of surface melt. Computed annual fields of surface ice sheet mass balance and of surface temperature are used in SICOPOLIS as surface boundary conditions. In turn, SICOPOLIS feeds back the average ice sheet elevation, the fraction of land area covered by ice sheets, the sea level and the freshwater flux into the ocean from the ablation of ice sheets and from ice calving to the climate component.

The model has been used to explore the hysteresis in the climate-cryosphere system (Calov and Ganopolski, 2005) and has successfully simulated the last eight glacial cycles (Ganopolski et al., 2010; Ganopolski and Calov, 2011). It has been used to explore the effect of dust radiative forcing on glacial-interglacial cycles (Bauer and Ganopolski, 2014), the impact of permafrost on simulation of glacial cycles (Willeit and Ganopolski, 2015) and the initiation of Northern Hemisphere glaciation (Willeit et al., 2015).

The model version used in this study includes a fully interactive dust cycle as described in (Bauer and Ganopolski, 2010, 2014). The direct radiative forcing of dust loading in the atmosphere is explicitly accounted for and dust deposition at the surface affects snow albedo both in the land surface module and in SEMI. Compared to (Bauer and Ganopolski, 2010) we replaced the precipitation dependence of dust emissions with a relative soil moisture (θ) dependence, so that their equation (12) for the threshold value for the climatological wind speed for dust emissions becomes:

$$u_t = u_0\big(1 + \tanh\big(c_\theta(\theta - \theta_t)\big)\big),$$

where $u_0 = 3\ \mathrm{m/s}$ is the reference threshold wind speed, $\theta_t = 0.3$ is the soil moisture of transition from semi-arid to humid conditions, and $c_\theta = 10$ is a normalization constant.

We use the parameters corresponding to the solution L1 in ~~(~~Bauer and Ganopolski~~,~~ (2014), which assumes that the fraction of precipitation-driven wet dust deposition is 70 % of the total, and an imaginary refractive index of airborne dust of 0.003.

The dust deposition on ice sheets further includes dust from simulated sediments produced by glacial erosion. This dust source is not included in the global dust cycle model due to its very local origin, which can not be represented on the coarse atmospheric grid. ~~(Ganopolski et al., 2010)~~. Dust deposition produced from glaciogenic sources is parameterized based on the assumption that the emission of glaciogenic dust is proportional to the delivery of glacial sediments to the edge of an ice sheet (see Ganopolski et al. 2010 Appendix A for details). Most of the glaciogenic dust originates from the southern flanks of the ice sheets and this source is significant only for mature ice sheets, which reach well into areas covered by thick terrestrial sediments.

2.2. Snow albedo parameterization

Three components in the parameterization of snow albedo used in CLIMBER-2 are critically important, namely, the aging of pure snow, the concentration of light-absorbing impurities in snow from dust deposition and the synergy between aging of snow and impurities (Warren, 1982; Warren and Wiscombe, 1980). Under “synergy” we understand here the fact that the effect of impurities on snow albedo is much higher for ~~the~~ “old” snow than for ~~the~~ fresh snow. The parameterisations described below are applied both to the surface scheme on the atmospheric grid and to SEMI on the ice sheet grid. The surface albedo over ice sheets is computed as:

$$\alpha = f_{snow}\alpha_{snow} + (1 - f_{snow})\alpha_{ice},$$

w~~W~~here f_{snow} is the grid cell fraction which is considered to be snow covered, α_{snow} is the albedo of snow and α_{ice} is the albedo of bare ice. α_{ice} is set to 0.4. f_{snow} is ~~computed as…~~1 if the snow water equivalent in the grid cell is larger than 30 $\mathrm{kg/m^2}$ and linearly related to the ratio between snowfall and ablation if the snow water equivalent is below 30 $\mathrm{kg/m^2}$. Snow albedo is computed for two spectral bands (visible and near infrared radiation) and separately for direct beam and diffuse radiation. ~~It~~The diffuse albedo values are a function of~~depends on~~ snow grain size and dust concentration at the surface following ~~(~~Warren and Wiscombe~~,~~ (1980) (their Fig. 5 for dust radius of 1 µm and imaginary refractive index of 0.01). It is shown in Fig. 1.

~~$\alpha_{snow}^{vis,dif} = 0.99 - f_{age}$~~

~~alb_vis_dif_snow = 0.99 - f_age*c_age_vis - c_dust_new_vis~~

~~alb_nir_dif_snow = 0.65 - f_age*c_age_nir - c_dust_new_nir~~

A snow aging factor is used to represent the grain size evolution and its effect on albedo, similarly to Dickinson et al. (1986). The snow age factor, f_{age}, is parameterized as a function of snow temperature T_s and snowfall rate S on each atmospheric time step (one day) as:

$$\mathrm{f_{age}} = 1 - \frac{\ln\left(1 + \mathrm{f_{age}^{T}} \frac{\mathrm{S_c}}{\mathrm{S}}\right)}{\mathrm{f_{age}^{T}} \frac{\mathrm{S_c}}{\mathrm{S}}},$$

with $\mathrm{S_c} = 2 \cdot 10^{-5}\ \mathrm{kg\ m^{-2} s^{-1}}$ and

$$\mathrm{f_{age}^{T}} = \mathrm{e}^{0.05(\mathrm{T_S} - \mathrm{T_0})} + \mathrm{e}^{\mathrm{T_S} - \mathrm{T_0}}.$$

$$T_0 = 273.15\ K.$$

The snow grain size, r_e in µm, and snow age factor are related by:

$$r_e = 50 + 200 \cdot \left(10^{f_{age} \cdot \log_{10}\left(1 + \frac{1000-50}{200}\right)} - 1\right).$$

The dust mass concentration in snow is simply computed as the ratio of dust deposition rate and precipitation rate. During snowmelt dust is assumed to concentrate near the snow surface and dust concentration is allowed to increase by up to a factor of five, consistent with observations for the top 4 cm presented in Doherty et al. (2013).

The direct beam snow albedo values depend on the solar zenith angle and the standard deviation of orography, σ_z, as:

$$\alpha_{snow}^{vis,dir} = \alpha_{snow}^{vis,dif} + f_{oro} f_{cosz} \left(1 - \alpha_{snow}^{vis,dif}\right),$$

where

$$f_{oro} = 0.4 \cdot \left(1 - \tanh \frac{\sigma_z}{1000}\right),$$

$$f_{\mu} = 0.5 \cdot \left(\frac{3}{1 + 2\mu} - 1\right),$$

and µ is the cosine of the solar zenith angle.

~~The dependence of albedo on snow grain size and dust concentration follows Warren and Wiscombe (1980) with an effective dust particles radius of 1 µm and imaginary index of dust of 0.01. It is shown in Fig. 1.~~

To test the sensitivity of our results to the representation of snow albedo, we have additionally introduced two alternative parameterisations of snow albedo. The first one is from Dang et al. (2015) and the second from Gardner and Sharp (2010). Both include the effect of snow grain size and black carbon content. The effect of dust is computed through a black carbon equivalent following Dang et al. (2015). The two alternative parameterisations are compared to the standard one in Fig. 1. The different models agree on a ~10 % albedo reduction caused by the aging of snow, for a snow grain growth from ~100 to ~1000 µm (Fig. 1a). The impact of dust concentration on fresh snow albedo is generally larger but much more uncertain, ranging between 15-25 % albedo reduction for a dust concentration of 1000 ppmw relative to pure snow (Fig. 1c). The differences can be largely explained by the choice of the imaginary refractive index of dust. The imaginary refractive index of dust varies over an order of magnitude as a function of ~~the~~ dust composition (e.g. Fig. 7 in Dang et al. (2015)) and this range of possible values is reflected in the differences in albedo seen in Fig. 1. The combination of aged snow with high dust concentrations reduces snow albedo to values below 0.4 (Fig. 1b,d).

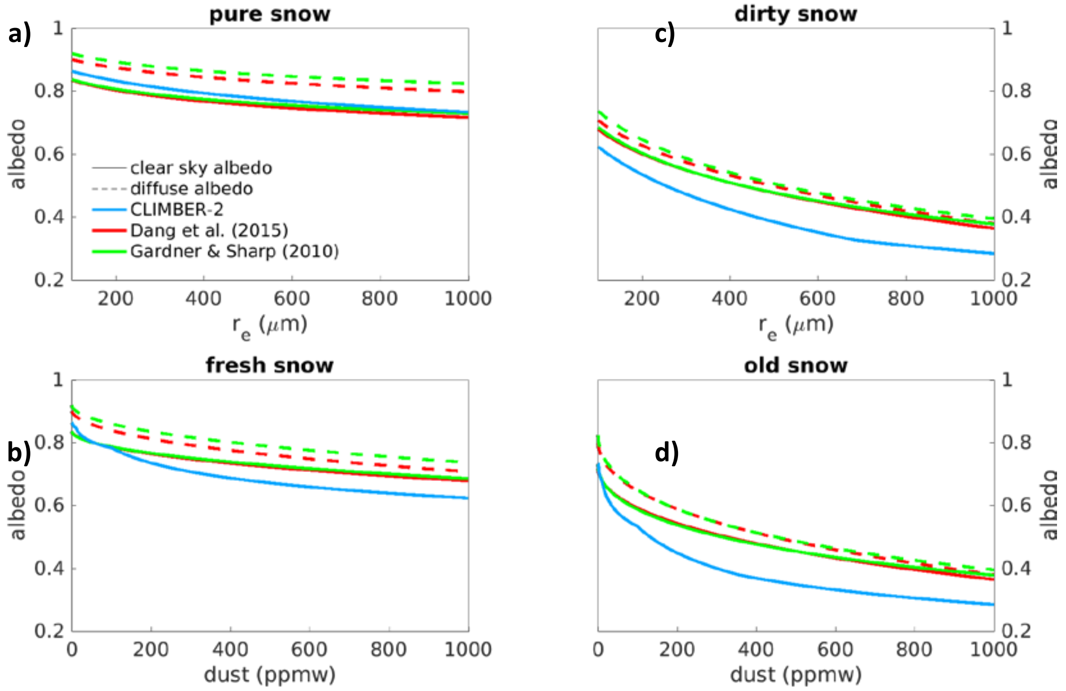

Figure 1: Clear sky and diffuse snow albedo dependence for a number of different parameterisations (Dang et al., 2015; Gardner and Sharp, 2010; Warren and Wiscombe, 1980) as indicated in the legend. a) Pure snow albedo dependence on effective snow grain radius. b) Fresh snow albedo (re = 100 µm) as a function of dust concentration. c) Dirty snow albedo (dust concentration of 1000 ppmw) as a function of snow grain size. d) Old snow albedo (re = 1000 µm) as a function of dust concentration. The clear sky albedo is for a solar zenith angle of 50°. In CLIMBER-2 the snow albedo for diffuse and direct radiation is identical for solar zenith angles below 60°.

2.3. Experiments

We used CLIMBER-2 to simulate the last glacial cycle, from 130 ka (1000 years ago) to the present day. The transient model simulations are driven by orbital forcing (Laskar et al., 2004) and the time-varying concentration of greenhouse gases expressed as equivalent CO2 concentration (Ganopolski et al., 2010). The initial condition is the equilibrium climate state computed with greenhouse gas concentration and orbital forcing of the preindustrial period.

First we performed a reference model simulation using the standard CLIMBER-2 surface albedo parameterisation. Then we run a set of offline simulations in which, similarly to Bauer and Ganopolski (2017), the climate and ice sheets are prescribed from the reference simulation and the surface mass balance is diagnosed for experiments with different surface albedo setups. To separate the importance of snow aging and dust on snow albedo, we run offline experiments with and without snow aging and with and without the effect of aeolian and glaciogenic dust sources on snow albedo.

Finally we performed a set of online simulations using the different surface albedo setups but this time allowing bidirectional coupling between the climate and ice sheet models. Additional experiments with the alternative albedo parameterisations described in Section 2.2 are used to explore the sensitivity to different snow albedo schemes. We also tested the model sensitivity to different values of ice albedo, ranging from 0.3 to 0.5, and to different global dust emissions scaling factors (from 1/4x to 4x). All online experiments are listed in Table 1.

Table 1: List of online model simulations.

	Snow aging	Dust deposition	Snow albedo	Ice albedo
REF	On	On	Std	0.4
A1D0	On	Off	std	0.4
A0D1	Off	On	std	0.4
A0D0	Off	Off	std	0.4
A1D1g	On	Glaciogenic only	std	0.4

A1D1p1	On	On	Gardner & Sharp	0.4
A1D1p2	On	On	Dang et al	0.4
A1D1i03	On	On	Std	0.3
A1D1i05	On	On	Std	0.5
A1D1d1/4	On	On, ¼ x	Std	0.4
A1D1d1/2	On	On, ½ x	Std	0.4
A1D1d2	On	On, 2 x	Std	0.4
A1D1d4	On	On, 4 x	Std	0.4

3. Results and discussion

Figure 2 shows the evolution of several modelled variables over the last glacial cycle in the reference simulation. The global temperature decreases by ~ 6°C from the Eemian interglacial (126 ka) to the last glacial maximum (LGM, 21 ka) (Fig. 2a). The modelled sea level variations agree reasonably well with available reconstructions (Spratt and Lisiecki, 2016), with a minimum sea level ~120 m below the present day during the LGM (Fig. 2b). The largest contribution to sea level comes from the Laurentide ice sheet (Fig 2c). The surface mass balance of the NH ice sheets is positive through most of the last glacial cycle, except for the deglaciation period between 20 and 10 ka (Fig. 2d), when the ablation rate exceeds the accumulation rate (Fig. 2e,f).

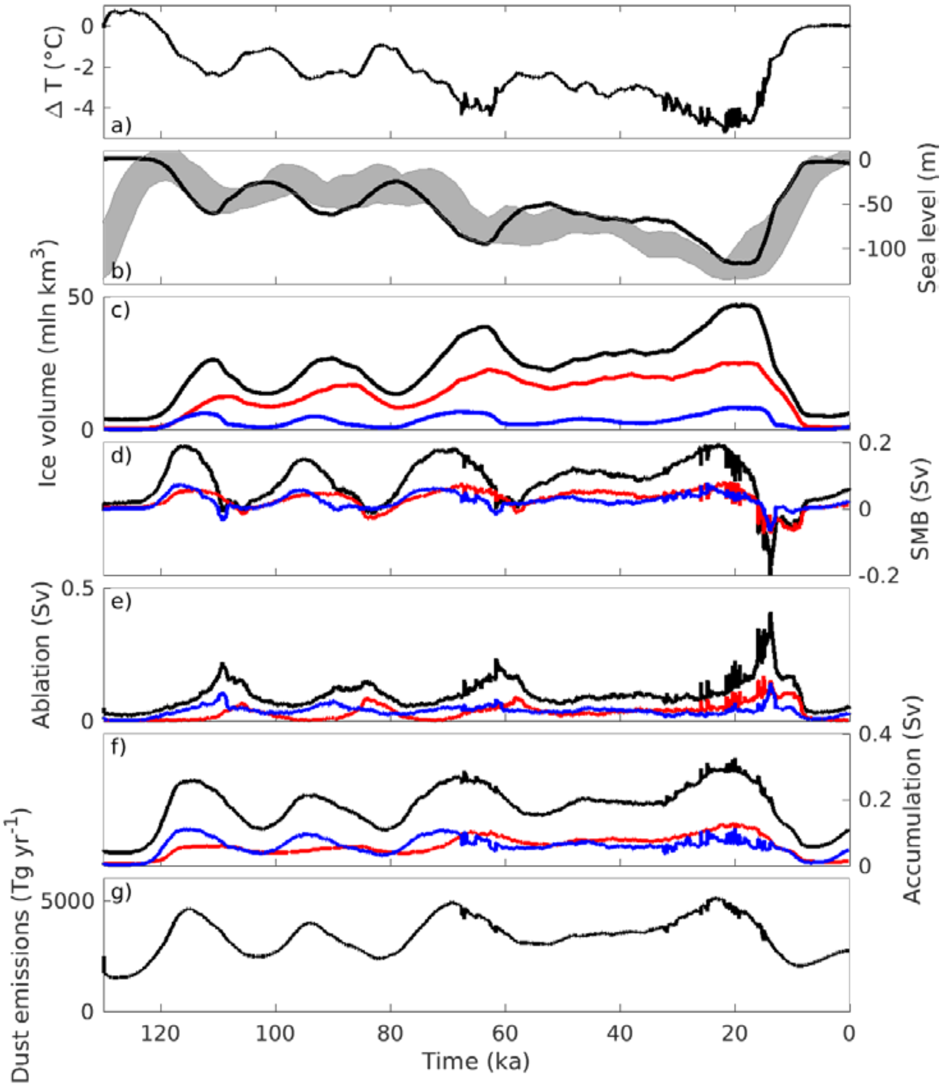

Figure 2: Simulated a) global temperature anomaly, b) sea level, c) ice volume, d) surface mass balance, e) ablation, f) accumulation and g) global dust emissions for the reference experiment. The red and blue lines in c-f represent the Laurentide and Fennoscandian ice sheet, respectively. The shading in b) is the sea level range from Spratt and Lisiecki (2016).

The reference simulation in this study differs from previous CLIMBER-2 last glacial cycle simulations presented in Bauer and Ganopolski (2014) and Ganopolski et al. (2010) in that it includes a fully interactive dust cycle, as described in Section 2.1. The modelled dust deposition for the present day and the LGM is compared to available observation-based estimates in Fig. 3. A detailed model evaluation based on these data is challenging, because of the large variability among different observation-based reconstructions (Fig. 3b,c and Fig. 3e,f) (Lambert et al., 2015; Mahowald et al., 1999, 2006). Even at present the estimated global value of dust deposition and atmospheric load varies largely between different studies (e.g. Table 1 in Bauer and Ganopolski (2014)). ~~It should be mentioned that~~ Ganopolski et al. (2010) used the Mahowald et al. (1999) data for present day and LGM, with their relative contributions scaled with sea level, as prescribed forcing in the surface energy and mass balance interface module. The climate-ice sheet model has therefore been tuned for dust amounts similar to Mahowald et al. (1999). Hence, to avoid the need to retune the model, we scaled the model dust emissions by adjusting the dimensionless global calibration constant c_q in Eq. (8) of Bauer and Ganopolski (2010) to get a present-day global dust deposition of ~3000 Tg/yr (Fig. 2g), comparable to Mahowald et al. (1999).

~~The simulated present day dust deposition is ~3000 Tg/yr (Fig. 2g), well in the range of different estimates~~. At LGM the global dust deposition is roughly doubled in our simulations (Fig. 2g). What is more important for the impact on surface albedo is the spatial distribution of dust deposition. In general, at present, the dust deposition pattern seen in observations is reasonably well captured by the model, although it tends to slightly overestimate the annual dust deposition at high northern latitudes (Fig. 3a-c). At the LGM, the modelled geographic distribution of dust deposition resembles in many aspects the reconstructions from Mahowald et al. (1999), with increased dust deposition over Siberia and at the southern boundary of the Laurentide ice sheet over North America (Fig. 3d,f). Although the LGM dust deposition pattern is similar also in the reconstructions of Lambert et al. (2015), the absolute values are substantially larger in the latter compared to the model or Mahowald et al. (1999). ~~It should be mentioned that Ganopolski et al. (2010) used the Mahowald et al. (1999) data for present day and LGM, with their relative contributions scaled with sea level, as prescribed forcing in the surface energy and mass balance interface module. The climate-ice sheet model has therefore been tuned for dust amounts similar to Mahowald et al. (1999). Hence, to avoid the need to retune the model, we scaled the model dust emissions by adjusting the dimensionless global calibration constant cq in Eq. (8) of Bauer and Ganopolski (2010) to get a present-day global dust deposition of ~3000 Tg/yr, comparable to Mahowald et al. (1999).~~

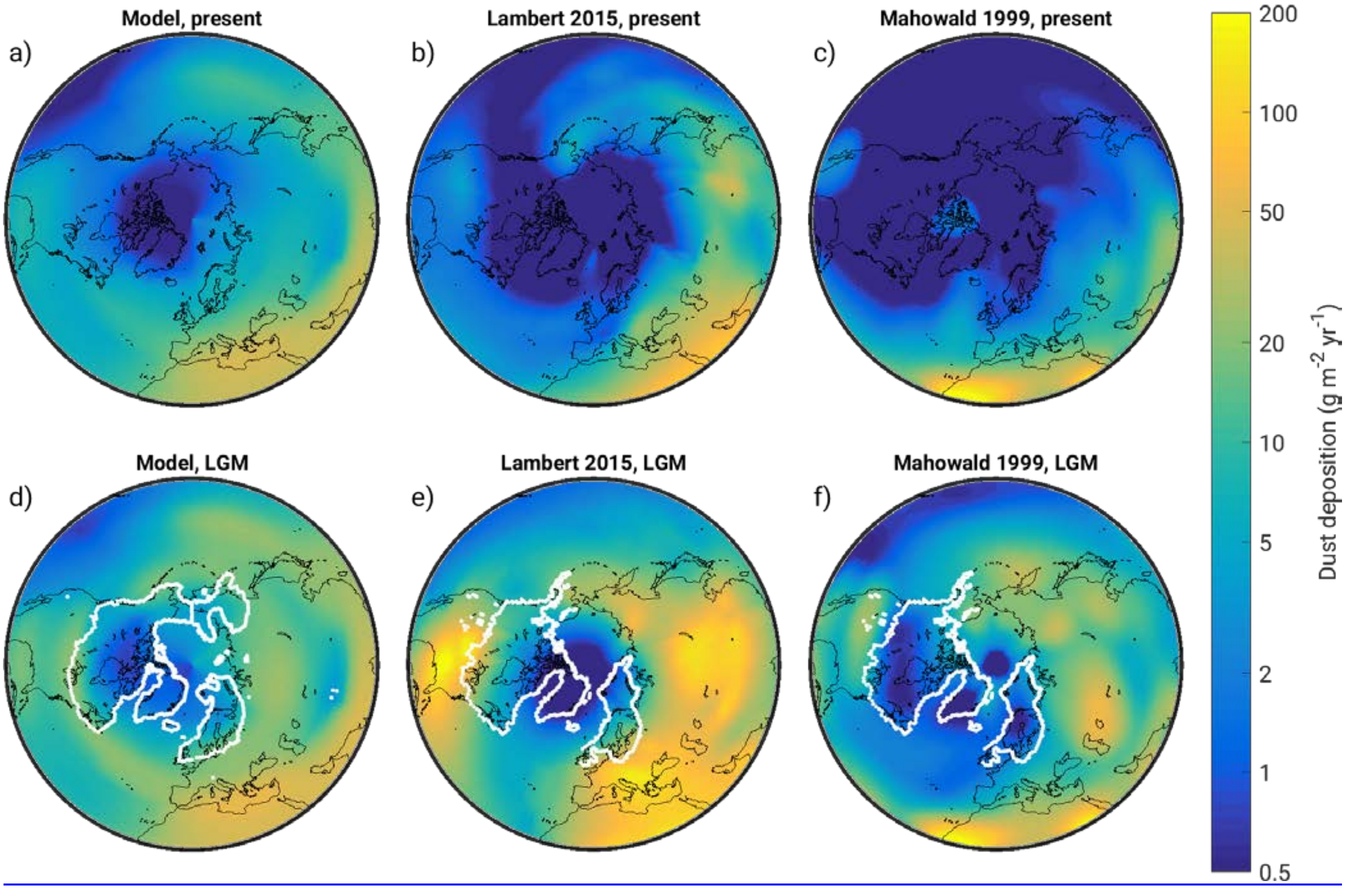

Figure 3: Modelled annual dust deposition compared to observations for the present day (top) and reconstructions for the last glacial maximum (bottom). The model results (left) are compared to data from Lambert et al., 2015 (middle) and Mahowald et al., 1999 (right). The dataset of Mahowald et al. 1999 does not include glaciogenic dust. For the LGM, the white lines indicate the modelled (d) and reconstructed (e,f, (Tarasov et al., 2012)**) extent of the ice sheets.**

Due to the highly non-linear nature of the climate-cryosphere system, relatively small changes in the model can have a very large impact on the simulated coupled system response to orbital forcing. The offline simulations with prescribed climate and ice sheets from the reference simulation provide a mean to understand the impact of the different factors affecting snow albedo, avoiding the model drift into unrealistic states.

In the reference simulation, the mean snow albedo over ice-covered areas varies between 0.65 and 0.8 (Fig. 4a). This represents a substantial reduction compared to simulations assuming fresh and pure snow. In this case the mean albedo is ~0.85, with only tiny variations due to the dependence of snow albedo on the solar zenith angle (Fig. 4a). Most of the time, the reduction of surface albedo by the snow aging effect is larger than the reduction due to dust. Only around the LGM, the dust-induced effect is larger than the pure snow aging effect (Fig. 4a). Geographically explicit surface albedo differences between the different offline experiments are shown in Fig. 5 for a time slice at 15 ka, when ablation reaches its maximum during deglaciation. The reference simulation shows summer albedos as low as 0.4 at the ice sheet margins, where ablation occurs and the snow is old and dust accumulates at the surface while snow is melting (Fig. 5a). Additionally, in localized regions along the margin all snow is melted during summer and bare ice is exposed, which additionally reduces surface albedo, as snow albedo is larger than bare ice albedo over most of the ice sheet because of dust concentrations below ~300 ppmw. Ignoring the effect of snow aging or dust, or both, results in increased surface albedo, mostly along the ice sheet margins (Fig. 5b-d).

The differences in albedo are reflected in the ablation and consequently in the surface mass balance (Fig. 4b,c). When either the snow aging or the dust effect are ignored, the ablation integrated over the NH ice sheets is only ~25 % of the value in the reference simulation (Fig. 4c). This strong reduction in ablation results in a net surface mass balance that is positive throughout the whole last glacial cycle (Fig. 4b).

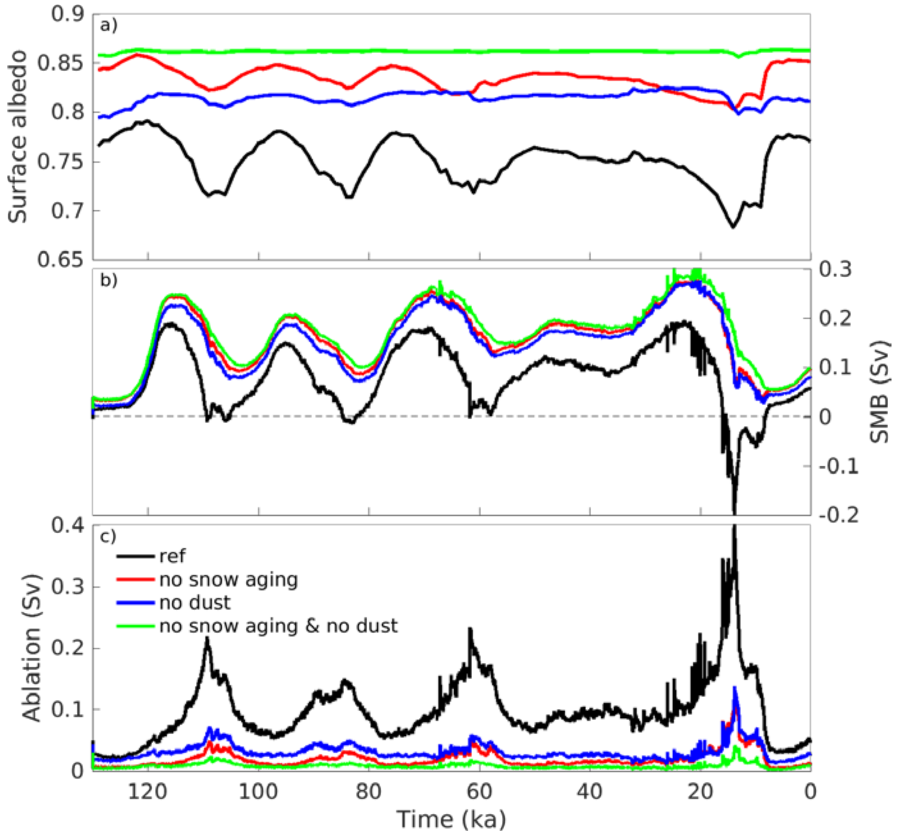

Figure 4: Results from the offline simulations. a) Mean surface albedo over the area covered by NH ice sheets, b) total surface mass balance and c) total ablation for the experiments indicated in the legend.

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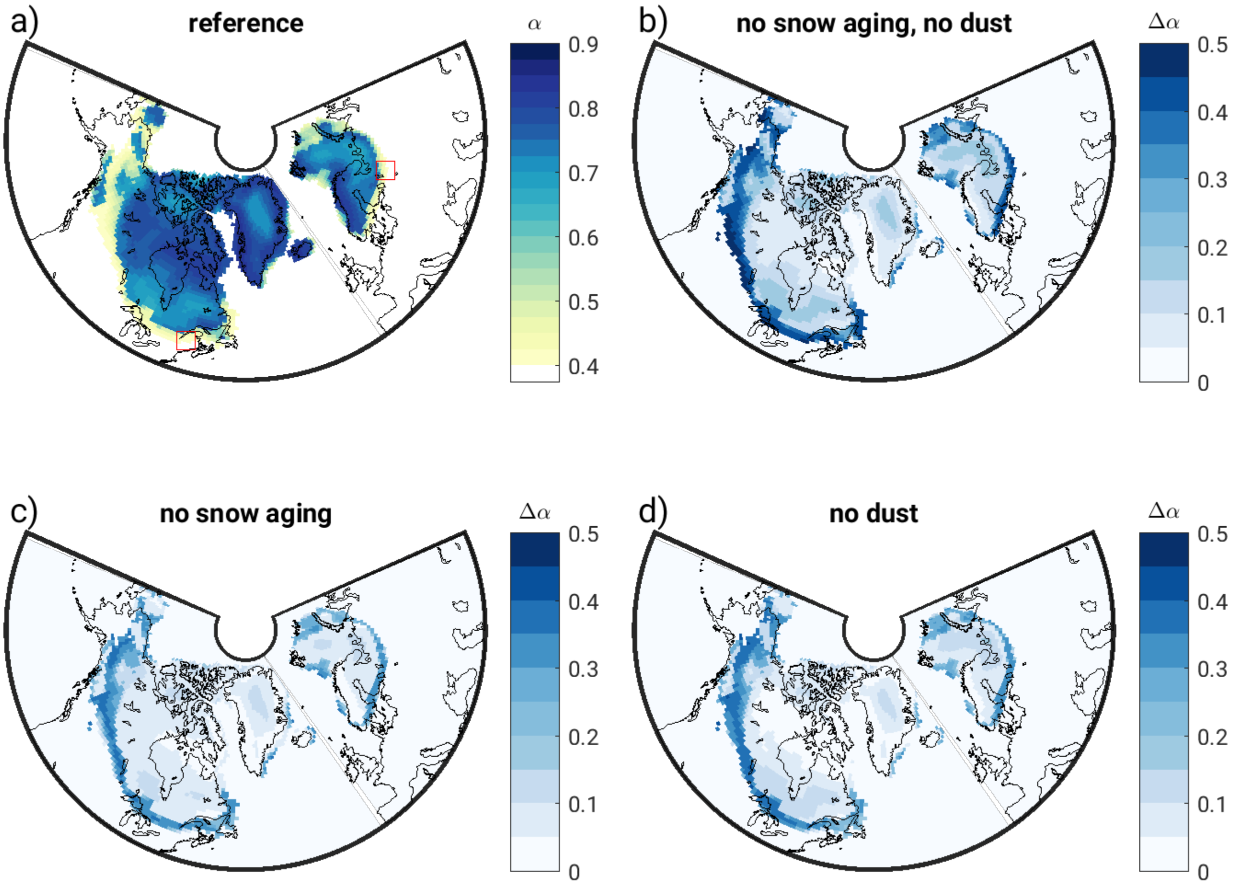

Figure 5: a) Summer (June-July-August) ice sheets surface albedo at 15 ka for the reference simulation. b-d) Surface albedo anomalies relative to the reference for the three different offline simulations specified in the subplots.

5 The albedo of snow is so important for the ice sheet surface energy and mass balance because it strongly controls the length of the snow season and consequently ice melt (Fig. 6). Variations in the albedo of snow during the melt season induced by snow aging and dust content can lead to variations in the length of the snow season of several months (Fig. 6a,b) and consequently to substantial variations in ablation and ice melt (Fig. 6e,f).

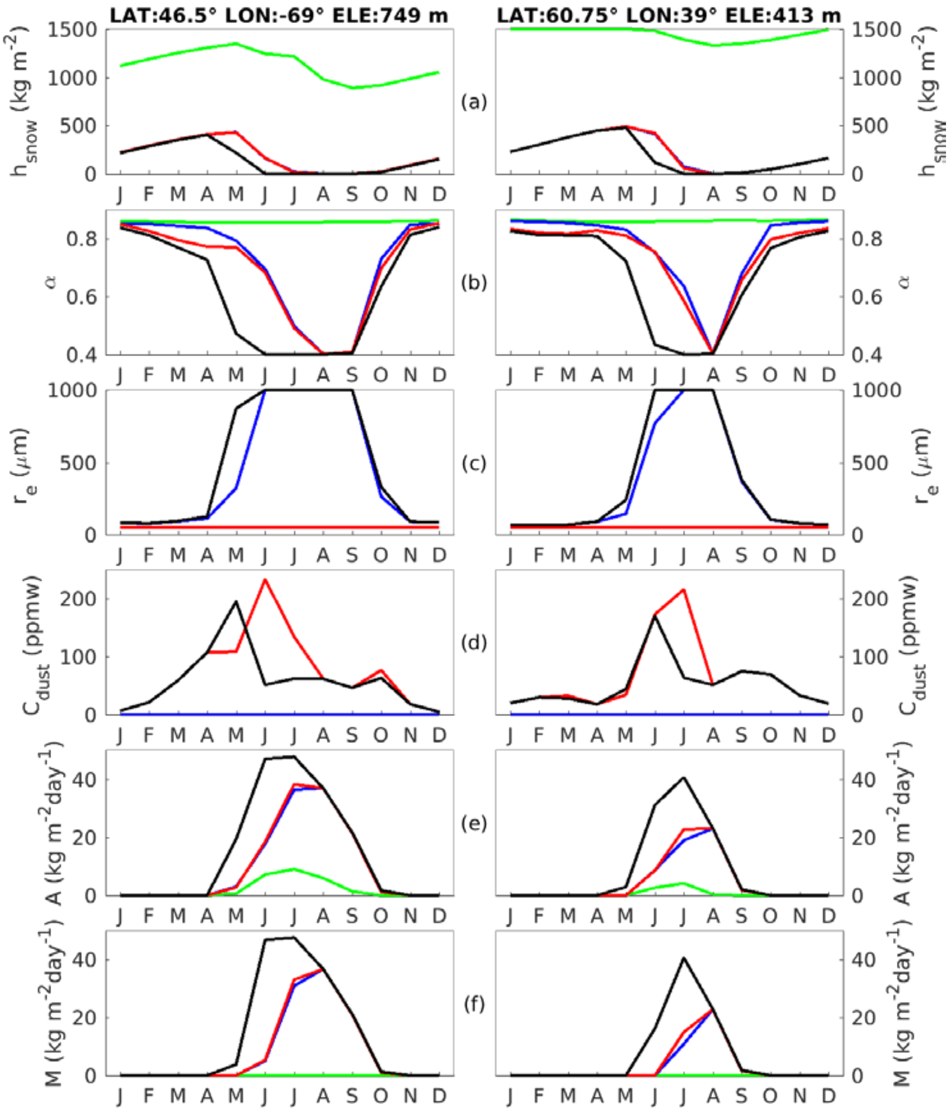

Figure 6: Seasonal evolution of several modelled variables at 15 ka at two locations at the southern margin of the Laurentide (left) and Fennoscandian (right) ice sheets for the reference simulation (black lines) and from offline simulations with no dust deposition (blue), no snow aging (red) and no dust deposition and no snow aging (green). The variables shown are a) snow water equivalent, b) surface albedo, c) snow grain size, d) dust concentration in snow, e) ablation and f) ice melt. The location of the two sites is indicated by the ~~black~~ red boxes in Fig. 5a.

When the same experiments with and without the effect of snow aging and dust deposition on snow albedo are repeated in the online setup, with the different parameterisations affecting the actual surface energy and mass balance of the ice sheets, the modelled sea level is very different from the reference simulation. In the most extreme case, both the snow aging and the dust darkening effect on snow albedo are ignored. This is equivalent to assuming that snow is always fresh and pure. In this case rapid ice build-up occurs in the model, with sea level dropping below 400 m relative to the present day and with the model subsequently responding only weakly to changes in orbital forcing and greenhouse gases radiative forcing (Fig. 7). Under these conditions, at the LGM ice sheets cover most of Northern~~d~~ America and Eurasia (Fig. 8b). In the experiments where the snow aging or the dust impact on snow albedo are considered ~~in isolation~~separately, excessive ice is grown over North America and a large ice sheet develops over Eurasia (Fig. 8c,d). Also in these experiments, sea level drops well below the estimated LGM value of ~120 m (Fig. 7). Therefore, from the experiments presented and for this model formulation, the effects of dust deposition or snow grain growth acting ~~in isolation~~separately do not allow to simulate a last glacial cycle that is in agreement with climate and sea level reconstructions, because each factor alone is insufficient to prevent glacial inception over Siberia.

If the snow albedo reduction by deposition of dust produced by glacial sediment transport is ignored, the simulated sea level is very similar to the reference experiment until the LGM. Afterwards, this additional source of dust becomes important to reproduce a full deglaciation in the model (Fig. 7). Dust deposition from glaciogenic origin is negligible compared to aeolian dust over most of the glacial cycle, except during deglaciation, when it becomes comparable or even the dominant source of dust (Fig. 9).

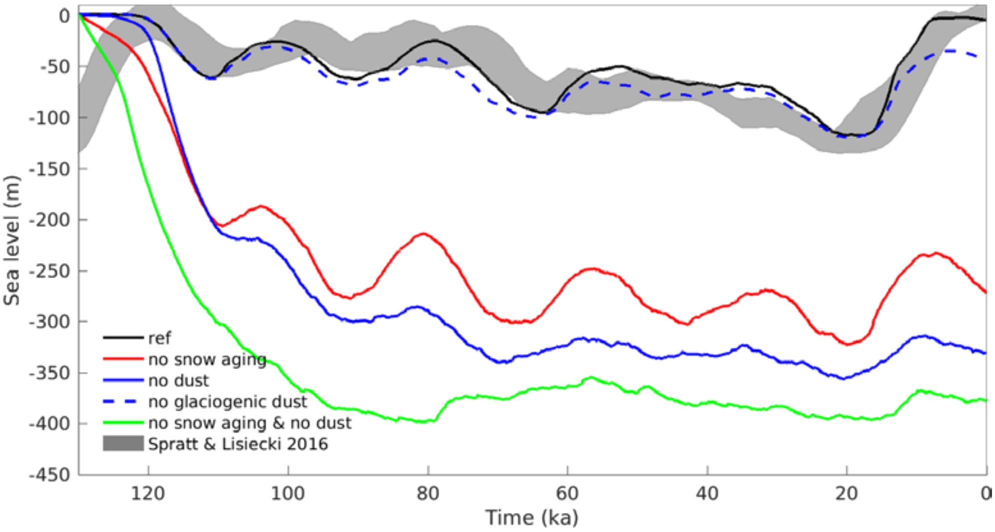

Figure 7: Effect of snow aging and dust deposition on modelled sea level over the last glacial cycle for different online experiments as indicated in the legend.

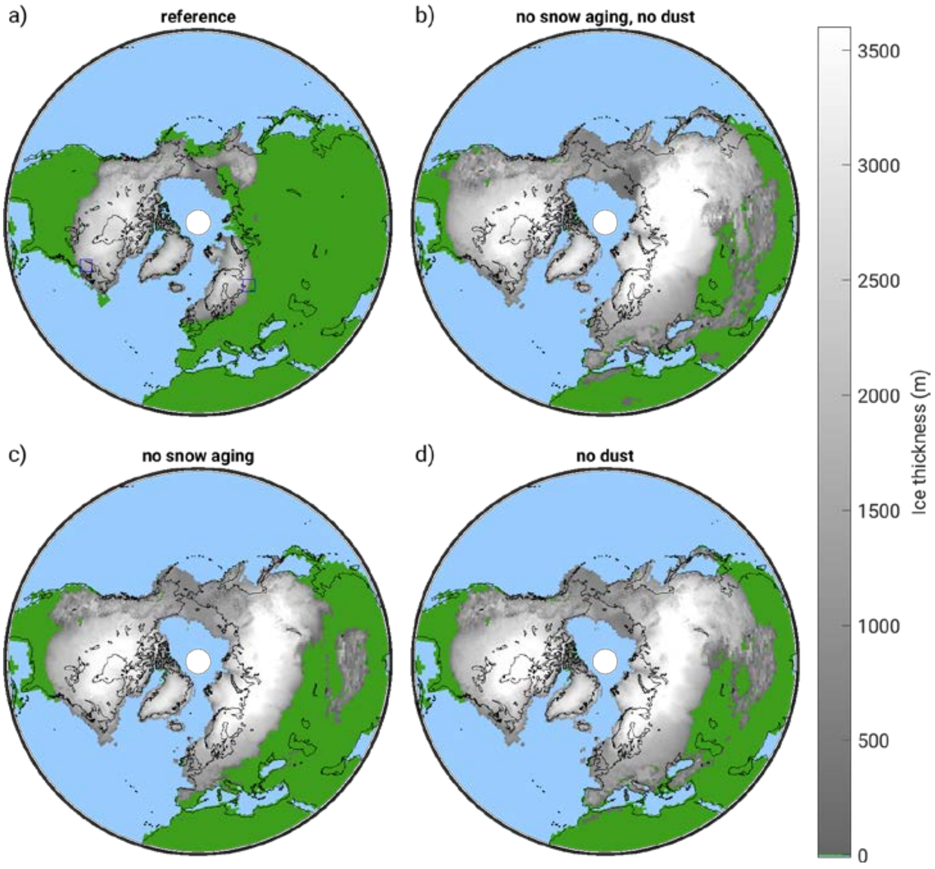

Figure 8: Ice sheet extent at the last glacial maximum (21 ka) for a) the reference simulation, b) the simulation without snow aging and dust effect on snow albedo, c) the simulation without snow aging and d) the simulation without dust on snow.

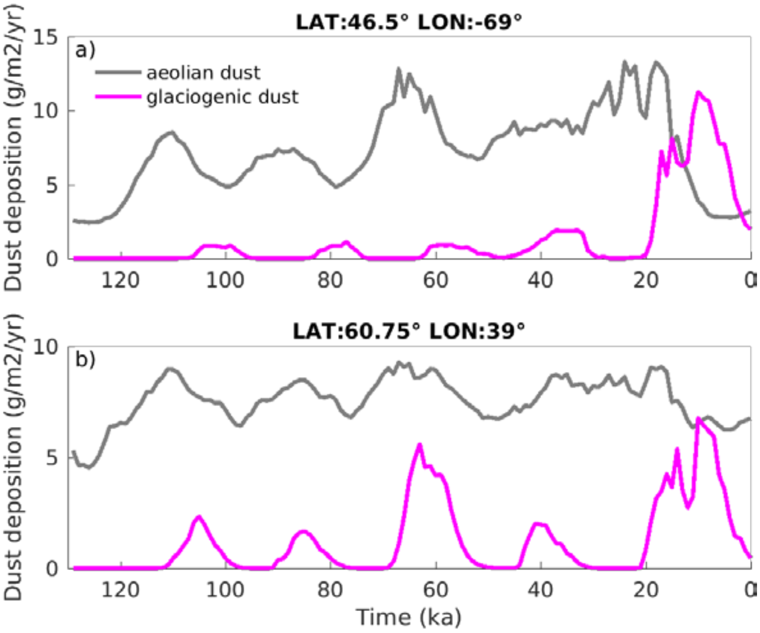

Figure 9: Evolution of modelled Aeolian (grey) and glaciog~~e~~enic (magenta) dust deposition at two locations at the southern margin of the LGM Laurentide (top) and Fennoscandian (bottom) ice sheets. The location of the two sites is indicated by the blue boxes in Fig. 8~~5~~a.

The choice of the snow albedo scheme also has a considerable impact on the simulated ice volume evolution over the last glacial cycle (Fig. 10a). Using the alternative albedo schemes of Dang et al. (2015) and Gardner and Sharp (2010), which in general show a weaker darkening effect of dust on snow albedo than the standard scheme used in CLIMBER-2 (Fig. 1), results again in excessive ice growth with LGM ice volume too large by a factor of two (Fig. 10a). However, it is possible that retuning of the model could allow to successfully simulate the last glacial cycle also with these alternative albedo schemes. Conversely, the value used for the albedo of bare ice has a rather limited impact on the simulated glacial cycle (Fig. 10b), because ~~ice is covered by snow throughout most of the year, even in net ablation areas (Fig. 6a).~~ in the model ice ablation is controlled to a large extent by the length of the snow-free season, which is mainly controlled by snow albedo (Fig. 6a). The magnitude of global aeolian dust emissions has a strong control on the modelled glacial cycle evolution. Scaling the dust emissions in the model up or down by a factor of up to 4 leads to a large spread in modelled sea level (Fig. 10c), with simulations with enhanced dust emissions failing to build up enough ice at LGM and simulations with reduced dust emissions leading to excessive ice build up and consequent incomplete deglaciation.

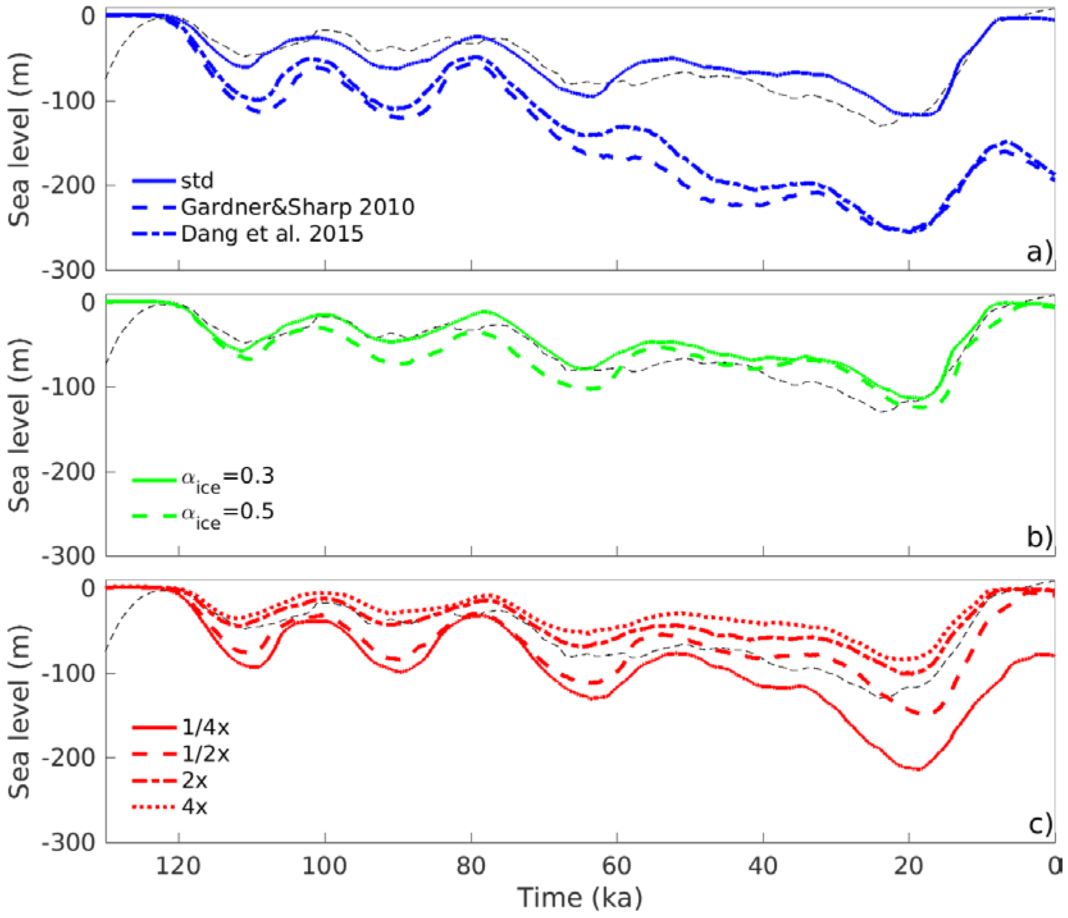

Figure 10: Uncertainties in modelled sea level evolution over the last glacial cycles resulting from different parameterisations of (a) snow albedo, (b) different values of bare ice albedo and (c) scaling of dust emissions by factors ¼, ½, 2 and 4. The dashed black line represents the sea level reconstruction from Spratt and Lisiecki (2016).

4. Conclusions

In this study we used an Earth system model of intermediate complexity to show that a proper parameterisation of snow albedo over ice sheets is a crucial ingredient for a successful simulation of the last glacial cycle. Both the snow aging effect and the effect of dust deposition on snow albedo play a fundamental role in reducing surface albedo, particularly in the ablation areas. While the snow aging effect on snow albedo is well constrained by observations and theoretical modelling studies, the effect of dust strongly depends on the assumptions about the optical properties of dust. A realistic estimate of the effect of dust on snow albedo does therefore probably have to account for the origin and composition of the dust deposited over ice sheets. Additionally, substantial uncertainties in global and regional dust fluxes during glacial times hinder a quantification of the role of dust darkening of snow for simulating glacial cycles.

Acknowledgements

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