We would like to thank both reviewers for their very helpful comments and suggestions. We significantly revised the manuscript following reviewers' comments and suggestions. In particular we

- replaced Figure 4 by the new one
- discussed ITM method, its strengths and weaknesses
- explained difference between offline and online simulations
- add entire new section (5) describing new experiments which shed light on importance of snow albedo parameterization for modeling of ice sheets evolution during glacial cycles

In the following, we provide specific responses to each of the points raised in reviewers comments.

Reviewer 1

GENERAL COMMENTS

1. The ablation simulated through the positive-degree-day (PDD) method is compared to the ablation as simulated by the surface energy balance approach (SEB) in the coupled climate and ice sheet model set-up. Another ablation scheme that is currently quite popular is the insolation-- temperature--melt (ITM) approach (see for example, Robinson et al., 2011; Robinson and Goelzer, 2014). I understand that additionally assessing this melt scheme would be a lot of extra work, but this alternative approach should at least be mentioned and referred to in the discussion. One of the likely reasons why the PDD method cannot perfectly capture the SEB simulated ablation evolution over long time scales (such as a glacial cycle) could be because it does not account for insolation changes. The ITM method does include the effect of varying insolation on melt (although it might have other drawbacks). Please discuss.

Indeed, several years ago we developed the regional model REMBO which is based on ITM approach and we used REMBO in a number of our publications. However, it is important to note that REMBO was specially designed for Greenland and for climate conditions which are not very different from present. The ITM scheme contains apart from two empirical parameters, which are likely spatially and temporally dependent, one parameter – transparency of the atmosphere - which is known to vary strongly spatially and in time. We have no idea how ITM can be parameterized for the purpose of simulations of large scale glaciations during entire glacial cycles. Therefore we never used ITM for this purpose. And, although, ITM does have some advantages over the PDD approach, we do not believe that ITM can be considered as the real alternative to the physically based SEB approach.

2) I also miss a section in the introduction explaining the time period you focus on. Explain why the last glacial cycle, and give some background information. Introduce terms like inception, termination, LGM, and Holocene. And give dates for your "target windows", and call it "target periods" or similar.

3) Also lacking is a discussion of your reference simulation with respect to geological reconstructions of the ice sheets over the last glacial cycle, and other modelling approaches.

The choice of the last glacial cycle is rather obvious – it is period of time best covered by paleoclimate records, especially since the LGM. This is why most of previous modeling study of glacial cycles has been performed for the last glacial cycle. As far as our model performance for the glacial cycle is concerned (reference run), it has been described in detail and compared with available climatological data in Ganopolski et al. (2010). Our reference run is practically identical to that model which is analyzed in Ganopolski et al. (2010). We just refer to that paper which was published in open access journal and is readily available for any reader.

4) The set-up of the "offline" and "online" PDD ablation methods need to be explained in more detail (e.g. page 4, line 25).

We agree that its was not clear described. Now we devoted entire paragraph (last paragraph, section 2.3) describing the difference between "offline" and "online" simulations.

5) *Discussion resolutions: what is the effect of the rather large grid boxes used in CLIMBER and SICOPOLIS?*

We do not believe that the manuscript under consideration is the right one for discussing the resolution issue. In a number of our papers we presented an extensive comparison of CLIMBER-2 results with observed present, reconstructed past and simulated future climates by GCMs. These studies revealed that on its very coarse grid CLIMBER-2 does a reasonably good job. The coupling between the coarse resolution climate component of CLIMBER-2 and the relatively high resolution (70km) ice sheet component is, indeed, a nontrivial task to which we devoted significant efforts. The coupling is based on spatial and vertical interpolation and, additionally, parameterization of sub-grid processes, such as orographic precipitation. How it is done is described in detail in Calov et al. (2005) and Ganopolski et al. (2010). Obviously, using a higher spatial resolution is always desirable but for simulations of glacial cycles a high spatial resolution is costly. At present, the CLIMBER-2 model is the only comprehensive Earth system model which is able to simulate numerous glacial cycles. Therefore we cannot compare performance of our model with higher resolution climate-ice sheets models on the orbital time scales . However, coarse spatial resolution of atmospheric component of CLMBER-2 is obvious limitation of our study and we admit this fact in the conclusions.

6) Also, the PDD method is originally developed for daily temperature input, as are the literature values for PDD factors and the standard deviation for temperature. You use 3 - day mean temperatures. Please discuss.

In fact, PDD methods are developed for using climatological monthly temperatures which are then interpolated to produce daily temperatures. Therefore calculation of PDD by using of a 1-day or 3-day time step produces essentially the same result. Since in CLIMBER-2, the time step in the physically-based SEB surface mass balance scheme is three days, we used the same time step for calculation of PDD. Of course, the factor 3 was taken into account when we computed sum of positive degree days.

7) What are the initial conditions for the (reference) simulation(s)? Same as pre-industrial? Does that mean only ice on Greenland (how much?), or where else? A map of the inital ice distribution for the reference simulation would be helpful.

In all our experiments, equilibrium state of the climate-cryosphere system obtained for present-day conditions was used as initial condition and the model was run from 130 ka until present. We now clarify this in the text. Since initial distribution of ice sheets is very much alike the observed present-day state with the Greenland ice sheet being the only ice sheet in NH, we do not believe that such a figure would be very useful.

8) *Basing the selection of the PDD factors for the online simulations on the best PDD factors for the offline simulations is not very convincing. I though the whole point was to show that interactions/feedbacks between the climate and ice sheets are important. Why not test a range of factors, and select the best through some statistical evaluation, such as the rms-- error approach used for the offline simulations?*

First, computational cost of offline simulations is small compare to the online simulations and we cannot perform online simulations with all possible combinations of melt parameters as we've done in offline simulations. Therefore we believe that using of the "best" PDD factors found in offline simulations is a rather natural choice for online simulations. Second, we believe that out study (in particular Figure 10) nicely illustrates importance of feedbacks between climate and ice sheet. For example, for σ=5^{o}C, change of snow melt parameter from 3 to 6 mm C^{-1} d^{-1} leads to almost ten-fold decrease in LGM ice volume. However, the main result of our study is that it is not possible to find a set of three PDD factors which are suitable for simulation of the entire glacial cycle. We did not try to find the best PDD factors which we would recommend to other modelers to use. To the contrary, the conclusion of our paper is very clear – we do not recommend to use PDD approach for simulations glacial cycles. And this is related to the last general comment:

Some scientists do not have access to a climate model or not the computational resources to run it over long time scales, and therefore do not have access to SEB - derived ablation. Could you give a recommendation on how to best apply the PDD method. I.e. emphasize testing different PDD values, use a short time period, select one ice sheet, …?

Our study shows that a realistic simulation of the entire glacial cycle with the same PDD parameters is not possible. Sure, one can pursue a kind of inverse modeling approach to infer PDD parameters for different time intervals and ice sheets (even different latitudes or elevations) to obtain results comparable with paleoclimate reconstructions. However, the scientific value of such modeling is questionable. In the case of modeling of individual aspects of a glacial cycle, such as glacial inception or glacial termination, the conclusions of our study is quite clear. Namely, to simulate glacial inception one has to use smaller PDD parameters values than for simulation of glacial termination.

SPECIFIC AND TECHNICAL COMMENTS

Abstract, lines 10---18: not clear, please rewrite. Make clear that you tested a range of literature values, and that it was not possible to find one set of PDD values that result in a good fit of both the American and the European ice sheets to your reference simulation. Neither can fixed values satisfactorily explain the ablation evolution over the entire glacial cycle for the individual ice sheets.

The abstract has been almost completely rewritten. We now stated clearly what reviewer suggested. We only omitted mentioning of "standard literature values" because these values exist mostly only for Greenland and there is no reason why they should be suitable for very different ice sheets during glacial cycle. Therefore in offline simulations we explore a much broader range, but still came to the same conclusion – there is no single set of PDD parameters which is suitable for both major ice sheets during the entire glacial cycle.

Abstract, line 18---19: change to: According to our simulations, the SEB approach is superior to the PDD methods when simulation Northern Hemisphere glacial cycles. This is partly due to the SEB approach including effects of change snow albedo, which is particularly important for the American ice sheet margins.

We now reformulate the last sentence of the abstract as following: "According to our simulations, the SEB approach, including effects of changing snow albedo from dust deposition and aging, proves superior for simulation of glacial cycles"

Page 1, line 20: change "gains and losses" to "fluctuations"

Done

Page 2, line 1: Is it correct to say that the surface mass balance is the main factor affecting the evolution of ice sheets? What about calving, and basal processes? Needs a reference.

This sentence was removed.

Page 2, line 6: rewrite "very close to each other".

This sentence was modified.

Page 2, line 23: change to "demonstrated that feedbacks between climate …"

Done

Page 2, lines 24---31: Here add some more information on the ITM method

Now we added (p. 3) discussion of the ITM scheme

Page 2, line 32: change "problem" to "disadvantage"

Done

Page 3, line 10: change to "Charbit et al. (2013) who discuss the effect of different PDD parameterizations on Northern Hemisphere ice evolution, we"

Done

Page 3, line 29: please explain what you mean with "balance year"

The term "balance years" has been removed from the manuscript

Page 5, line 18: delete "supposedly"

Done

Page 6, line 12: change to "on North America and in Eurasia extending up to 120E. Note that the Greenland ice sheet is not included in the selections, but is part of the NH total.", or similar.

Done

Page 6, lines 19---28: Please rewrite, could be shortened as well.

Done. This paragraph has been shortened significantly.

Page 7, line 3: The surface mass balance is also positive during periods of ice volume reductions (e.g. ~110ka, 90ka), indicating that a positive surface mass balance does not automatically lead to the build-up of ice. Please explain.

Now we reformulated this sentence as following: "The resulting surface mass balance (Fig. 2f) is positive and exceeds calving rate (not shown) during most of the glacial cycle leading to the buildup of large ice sheets at the LGM." We agree that positive mass balance is not sufficient condition for ice sheet growth. For that mass balance should exceed calving rate. During several periods when ice volume is decreasing (prior to glacial termination), mass balance is positive but smaller than calving.

Page 7, line 6: change to "the Atlantic meridional overturning"

This sentence was removed but on the next page we now use the correct term - "Atlantic meridional overturning circulation"

Page 7, line 11: change “control” to “tunable”

Done

Page 7, lines 28---30. Confusing to read, please rephrase.

This sentence was reformulated. We hope that it is more clear now.

Page 8, section 3.2: Why is the entire ensemble discussed for the rms---error, and only a selection for the anomaly/offset m? Figure 4 could be replaced by a figure similar to Figure 5, but than for the anomaly m. The information of the original Figure 4 can also be seen in Figure 6, especially if you add a (blue) line for the PDD---derived ablation evolution of the simulation that fit best to the reference simulation, over the entire 130ka.

New Fig. 4 (which replaces the old Fig. 4) shows the bivariate distributions of the mean anomaly and the rms-error calculated for the total NH ice sheet. It shows that the minimum of absolute value of anomaly m (m=0) does not determine to a unique pair of melt factors. At the same time, as seen from comparison of m-plots and rms-plots, for both sigma values minimum in rms is located close to zero value of m. This justifies our choice of minimum in rms as the criteria for selection of the “optimal” values of melt factors.

Page 8, lines 18---19: Change to “Figure 6 shows the PDD---derived ablation evolution for the American and European ice sheets for the entire ensemble.”

Done

Page 8, lines 22---23: describe the “shorter” time intervals using “inception” and “deglaciation”

The word “shorter” was removed. Indeed, interval 130-30 ka is not “short” but it also cannot be named “glacial inception”. Similarly, 30-0 ka is not glacial termination.

Page 8, lines 27---32: bit redundant, it was already clear from Figure 6 an Table 2 that different PDD factors are needed for different ice sheets. Maybe shorten?

Done. The paragraph has been shortened considerably.

Page 9, lines 1---9: make more clear that here the spatial patterns are investigated, not anymore the time evolution.

Done. We added inserted “spatial patterns” in this sentence

Page 9, lines 14---15: change to “.. the ice sheets are coupled through the PDD methods. In doing so, processes ignored by the PDD method, such as the impact from changing snow…”

The sentence “In this way … is ignored” was removed

Page 10: change "The simulation X" to "Simulation X"

Done

Page 11, lines 8---16: Make clear that this discusses the offline simulations. Is it possible that the American ice sheet is less well simulated in the offline PDD method because the PDD scheme does not account for dust deposition?

Discussion was completely rewritten. The role of eolian dust is discussed in the new section 5.

Page 11, lines 17---19. Unclear, please rewrite. (blurred?)

This sentence was removed

Page 11, discussion of Figure 12 is also not clear, please rewrite.

Old Figure 12 was replaced by a new Figure 12 showing time series of insolation and ablation for June and July, as in June insolation is largest and in July ablation is largest. New Figure 13 shows results from online simulations which illustrate high sensitivity of simulated ice sheet to parameterization of snow albedo.

Conclusions, lines 10---13: too technical. This means that different sets of PDD constants should be used depending on (1) the ice sheet, (2) the time period interested in. Right?

This section was completely rewritten. Actually, we do not recommend to use different PDD parameter values for different ice sheets and for different periods of time, because scientific values of simulations with explicitly time-dependent model parameters is rather questionable. Instead we recommend to use solely SEB approach.

Figure 9: change "topography" to "coastlines"

Done

Figure 11: change "15ka" to "21ka" and "topography" to "coastlines"

Done

Reviewer 2

***Page 1, Line 10 to 18**: This paragraph of the abstract is somewhat confusing. It would be good if the authors could revise this section; I would suggest either by explaining the simulation setups in more detail or by putting more emphasize on the results and less on the simulations setup, given that they will introduce the setups in detail later.*

Abstract was completely rewritten.

Page 3, Line 17 to 20*: Please introduce here the "offline" and "online" PDD approaches. This will help to understand what is meant by those two approaches (as they are not explicitly mentioned in the Section "Model description"). To understand the difference is crucial for interpreting the results.*

We now describe the difference between "offline" and "online" simulations in section 2.3 .

Page 4, Section 2.2*: The PDD approach is described in detail but the SEB approach is only briefly mentioned. Although the reference Calov et al. (2005) is given additional information regarding the setup would be useful. How is the downscaling from the 7x18 atmospheric grid to the higher resolution SICOPOLIS grid done? How are certain processes regarded when downscaling (e.g. height desertification effect)? Further, it would be good to mention that a one-layer snow model is used. Please also introduce the parameterization of the albedo, given that changes in the albedo of the ice sheet seem to be crucial for the simulation of the last glacial cycle.*

A detailed description of the surface energy and mass balance scheme (SEMI) is given in Calov et al. (2015) and it is not possible to repeat all details here. However, for readers' convenience we added a paragraph where we briefly describe the coupling procedure.

Page 6, Line 29-31*: While discussing the differences between the American and European ice sheet I am wondering how well CLIMBER represents the interactions between the two ice sheets. Previous studies (e.g. Liakka et al., 2016) have shown that the European ice sheet is significantly influenced by the American Ice Sheet. While discussing reasons for the different responses of the European and American ice sheets these processes should be shortly discussed in regards to the presented results.*

It is difficult to compare our modeling results with Liakka et al. (2016) because they performed equilibrium time slice experiments while we performed transient experiments. In the model running over the orbital time scales, ice sheets are never in equilibrium with climate. In our simulations, the Laurentide ice sheet does exert a strong cooling over the North Atlantic and significantly influences the European climate. However, it is important to note that due to coarse spatial resolution of CLIMBER-2, we only account for thermally driven atmospheric stationary waves but not for topographically forced waves. The omission of the latter affects long-distance climate teleconnections.

Page 12, Discussion*: While the results clearly indicate that the SEB approach is superior to the PDD approach for simulating the last glacial cycle it would be good to point towards the weaknesses of both approaches. This might be covered by a more detailed description of the SEB in the method section (see above) or one or two sentences in the discussion section. Further, how realistic are the SEB results? Most of the results are integrated over the Northern Hemisphere but how* *is the spatial distribution? It could be good to see e.g. a comparison between the ice sheets derived with the SEB approach during LGM in comparison to LGM reconstructions on a spatial map.*

We believe that weaknesses of the PDD approach are obvious from our study. The SEB approach is entirely physically based and therefore the only right but of course, its implementation in the model, which does not simulate synoptic and intra-annual climate variability, requires a number of assumptions and additional parameterizations. We discuss this is the Discussion section. As far as the performance of our standard run is concerned (including spatial distribution of ice sheets) it is discussed in detail in Ganopolski et al. (2010).

***Page 11, Line 14-16 and Conclusions**: The authors state that the American melt depends largely on the snow melt factor, which can be attributed to the effect of dust deposition. I think the authors need to clarify how dust deposition and snow age interplay in the model. Is the albedo change a linear function of the snow age/dust or do other factors play in? What is the relationship between snow age (simply changes of snow properties) and dust deposition? Could it be other factors that cause these differences?*

The albedo scheme is described in Calov et al (2005). Indeed, albedo depends on snow age, concentration of impurities, and the effect of latter depends on snow age – the older snow is – the large effect of impurities. We now devoted entire new section 5 and two figures (12 and 13) discussing the role of parameterization of snow albedo on simulation of glacial cycle.

***Page 11, Line 25 to 31**: Fig. 12 needs to be explained better. Please clarify this paragraph. Currently it is hard to follow the reasoning.*

The former Figure 12 was replaced by the new one. Please see our response to the comment above and also to Reviewer#1.

MINOR ISSUES

Page 1, Line 2: precessional

This sentence was removed

Page 2, Line 20: . . . meteorological conditions on high frequency time scales – the difference of the input data between SEB and PDD is not clear.

It is written in the previous paragraph that PDD "requires information only about surface air temperature" while SEB "requires a complete set of meteorological conditions".

Page 7 and 8: There is a mismatch between the figure order as mentioned in the text

and the actual figure order. Fig. 6 before Fig 4 and 5.

Now Fig. 6 is not mentioned before Fig. 4 and 5

Page 7, Line 18 to 19: Remove second 'lie in the range'. Repetition.

Done

Page 7, Line 23: Remove "range". Repetition.

Done

Page 7, Line 30: "." Before "Thereby".

Corrected

Page 9, Line 25: "we use the latter alphaI value and vary alphaS"

Several times throughout the text: "vice versa" and not "vice verse"

Corrected

Fig. 9 and 11: The authors could consider a more realistic map projection.

We agree that these figures look a bit odd but for producing figures we used MATLAB which does not contain map projections

Throughout the text: Please revise for language mistakes.

We made an extensive revision of the entire manuscript

Comparison of surface mass balance of ice sheets simulated by positive-degree-day method and energy balance approach

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Abstract. Glacial cycles of the late Quaternary are ~~shaped~~ controlled by the asymmetrically varying mass balance of continental ice sheets in the Northern Hemisphere. ~~The surface mass balance is mostly positive during about four precessional periods and turns strongly negative at glacial terminations. The surface~~ Surface mass balance is governed by processes of ablation and accumulation. Here two ablation schemes, namely the positive-degree-day (PDD) method and the surface energy balance (SEB) approach, are compared in transient simulations of the last glacial cycle with ~~an~~ the Earth system model of intermediate complexity ~~. The standard version of the~~ CLIMBER-2~~model simulates ice volume variations reasonably close to reconstructions~~. It uses the SEB approach which comprises fluxes of short-wave and long-wave radiation~~and~~ , of sensible and latent heat and accounts explicitly for snow albedo changes from eolian dust deposition and snow aging. The ~~PDD-driven ablation is computed offline in ensemble simulations to study the sensitivity with respect to short-term temperature variability and to melt factors for snow and ice . With standard literature values,~~ standard version of the CLIMBER-2 model simulates ice volume variations in a reasonable agreement with paleoclimate reconstructions during the entire last glacial cycle. Using results of the standard CLIMBER-2 model for the last glacial cycle, we simulate ablation with the PDD method in off-line mode by applying different combinations of three empirical parameters of the PDD scheme. We found that none of the parameters combination allows us to simulate surface mass balance of American and European ice sheets similar to that obtained with the standard SEB method. The use of constant values of empirical PDD parameters lead either to too large ablation during the first phase of the last glacial cycle or to too little ablation during the final phase. We then substituted the standard SEB scheme in CLIMBER-2 by the PDD scheme and performed a suit of simulations of the last glacial cycle with different combinations of PDD parameters. Results of these simulations confirmed results of the off-line simulations: we failed to find a combination of PDD parameters which allow us to simulate realistically ice sheets evolution during the entire glacial cycle. The use of constant parameter values leads either to a buildup of too much ice volume at the end of glacial cycle or too little ice volume at the beginning. Even when the model correctly simulates global ice volume at the ~~anomaly between the 130-long ablation series from the two schemes is minimized but, more suitable are smaller values for inception than for termination and larger values for ice sheets in America than in Europe. Accordingly, PDD-online simulations require smaller values for inception than for termination to reproduce global ice volume variations. However, a reproduction at inception involves afterward excessive ice volume growth up to twice as large as reconstructed at LGM while a reproduction at termination implies ice volume growth about half as reconstructed at LGM. The PDD-online simulation with standard values generates at LGM a huge sea level drop of 250and a global cooling of 8. The PDD-online simulation reproducing the LGM ice volume produces insufficient ablation at the turning point from~~

~~glacial to interglacial climate, hence termination is delayed~~Last Glacial Maximum (21 ka), it is unable to simulate complete deglaciation during Holocene. According to our simulations, the SEB approach, including effects of changing snow albedo ~~, in particular at the American ice sheet margins~~from dust deposition and aging, proves superior for ~~simulating~~ simulation of glacial cycles.

1 Introduction

Glacial-interglacial cycles of the Quaternary are characterized by massive ~~gains and losses~~ fluctuations of continental ice mass ~~. The difference between gains from~~ in the Northern Hemisphere (NH). These fluctuations result from gains and losses of ice mass through the interplay of the processes of snow accumulation and ~~losses from processes of~~ surface ice ablation ~~defines the surface mass balanceof ice sheets.~~ and the dynamic processes of calving and basal melt. The sum of gains and losses of ice mass constitutes the net mass balance. During a glacial cycle, ice sheets typically build up relatively slowly over roughly four precessional periods until glacial maximum and thereafter they retreat rapidly over about ten millennia. In the initial phase of a glacial cycle the accumulation predominates and ice sheets grow while at glacial termination the ablation predominates and ice sheets melt.

The net surface mass balance is the volumetric change across ~~the~~ an entire ice sheet and across a full accumulation and melt season~~constituting a balance year. The~~ . On existing ice sheets or glaciers, the surface mass balance can be obtained from local measurements of the amounts of snow accumulated in winter and of snow and ice melted in summer~~is given in which is usually shortened by . The total~~ . On long orbital time scales, the changing surface mass balance of ~~ice sheets includes further dynamic mass losses through calving and basal melt but the surface mass balance is~~ the NH ice sheets is considered the main factor ~~affecting the evolution~~ for the ice sheet evolution during a glacial cycle.

The net surface mass balance of ice sheets ~~on long (e.g. orbital) time scales.~~

~~Surface accumulation is connected to climate change through~~ is equal to the difference between accumulation, which is controlled by the hydrological cycle~~and results mostly from snowfall. Surface ablation is controlled~~ , and of ablation which is determined by the surface energy balance (SEB)~~which~~ . SEB primarily depends on ~~air temperature and insolation. During inception of a glacial cycle, accumulation predominates and ice sheets build up while at glacial termination the ablation predominates and ice sheets retreat~~absorption of insolation reaching the ice sheet surface and on temperature. Numerical modeling ~~shows that accumulation and~~ suggests that both the accumulation and the ablation of the major ice sheets in America and Europe ~~are very close to each other~~ vary in the range of 0.05 to 0.2 Sv ($1\,\mathrm{Sv} = 10^6\,\mathrm{m^3\,s^{-1}}$) for most of glacial time period (Ganopolski et al., 2010). ~~Hence, to simulate successfully the relatively slow buildup and the relatively rapid retreat of ice sheets during~~ This means that the surface mass balance is highly sensitive to small changes in accumulation and ablation and a successful simulation of a glacial cycle ~~depends crucially on an adequate description of~~ evolution depends decisively on adequate descriptions of the accumulation and ablation processes. Difficulties to describe the processes arise from the nonlinear nature of the climate system and from insufficient data which are needed to constrain model parameters.

Two ~~alternative methods are in use to simulate ablation~~methods are widely used to simulate surface mass balance of ice sheets. One method is the so-called positive-degree-day (PDD) method. This ~~is a~~ semi-empirical parameterization ~~which~~ requires information only about surface air temperature (usually, monthly mean values are used). This method is computationally fast and therefore widely used to simulate the surface mass balance of ice sheets both in past (Tarasov and Peltier, 1999, 2002; Zweck and Huybrechts, 2003, 2005; Charbit et al., 2007; Abe-Ouchi et al., 2007; Lunt et al., 2008; Gregoire et al., 2012; Beghin et al., 2014; Liakka et al., 2016) and in future climate simulations (van de Wal and Oerlemans, 1997; Huybrechts and de Wolde, 1999; Greve, 2000; Huybrechts et al., 2004; Ridley et al., 2005; Charbit et al., 2008; Winkelmann et al., 2015). The PDD method can be calibrated by use of measurements from glacier's surfaces but different glaciers give different values for the PDD scaling parameters.

The other method is the ~~physically-based~~ physical-based SEB method which computes ~~the energy available for~~ from a surplus in the surface energy balance the melting of snow ~~or~~ and ice in case the ice sheet surface temperature is above melting point~~(T>273.15)~~. This method requires calculations of all components of the energy balance (short-wave and long-wave radiation, sensible and latent heat fluxes) which, in turn, requires a complete set of meteorological conditions. This method is computationally much more demanding than the PDD method and therefore was used till recently mostly in the framework of regional climate models for short-term climate predictions (Bougamont et al., 2006; Box et al., 2006, 2012; Fettweis, 2007, 2013; Ettema et al., 2009). However, simulations with a comprehensive Earth system model demonstrated that ~~feedback effects~~ feedbacks between climate and ice sheets~~play an important role~~, which are not resolved by the PDD method, are important for simulating the ice mass balance ~~in~~ of future climate change scenarios (Vizcaino et al., 2010).

In spite of the obvious advantages of the PDD method for modeling the long-term climate-ice sheet interaction, ~~such as Quaternary glacial cycles, there is~~ there is also a growing body of evidence that the PDD method is inadequate ~~to simulate~~ for modeling of Quaternary glacial cycles. One obvious problem ~~with~~ is that the PDD method ~~is that it~~ does not explicitly account for ~~the~~ absorption of short-wave radiation which represents the ~~main~~ fundamental energy component of the SEB. This can lead to significant underestimation of the effect from the varying insolation on orbital time scales which is seen the primary driver of the glacial cycles ~~. Also for the reason of ignoring the short-wave absorption, the PDD approachcannot account explicitly for impacts of impurities (dust and soot) on the~~ (Robinson et al., 2010; van de Berg et al., 2011; Ullman et al., 2015). Another semi-empirical approach, namely ITM (Insolation-Temperature-Melt)scheme does explicitly account for absorption of insolation and reveals reasonable agreement with the SEB method in simulation of Greenland ice sheet surface mass balance ~~of the ice sheet~~for the Eemian interglacial (Robinson et al., 2011; Robinson and Goelzer, 2014). However, ITM requires prescription of 'atmospheric transmissivity' which is strongly spatially and temporally dependent and in general not known. In addition, ITM also does not account explicitly to the effect of dust deposition on surface albedo. This could be a serious ~~problem~~ disadvantage since paleoclimate data indicate significant increases of eolian dust deposition during glacial times, especially along the southern margins of the ~~Northern Hemisphere (NH)~~ NH ice sheets (Kohfeld and Harrison, 2001; Mahowald et al., 2006). Both theoretical analysis (Warren and Wiscombe, 1980; Aoki et al., 2011) and direct measurements (Painter et al., 2010, 2012; Skiles et al., 2012; Bryant et al., 2013; Doherty et al., 2013, 2014; Gautam et al., 2013) demonstrate that even a small amount of impurities affects the surface albedo significantly. In turn, results from SEB simulations show that these changes in albedo might significantly affect the surface mass balance of ice sheets during glacial times (Krinner et al., 2006; Ganopolski et al., 2010) and in future climate change scenarios (Dumont et al., 2014; Goelles et al., 2015). At last, numerical parameters for the PDD method can only be derived from observations over the existing ice sheets, primarily Greenland, and it is unclear a priory how different such parameters should be when the PDD method is applied to completely different climate conditions and different geographical distributions of ice sheets during glacial times.

~~So far,~~ Charbit et al. (2013) discuss the effect of different PDD parameterizations on the NH ice sheet evolution, but a direct comparison between PDD ~~modeling and SEB modeling in a coupled~~ and SEB approaches in a transient simulation over the glacial cycle with a climate-ice ~~sheet model over a glacial cycle~~ sheet model is missing. Here ~~we discuss~~ using results from ensemble ~~simulations of more than hundred transient simulations for~~ transient simulations of the last glacial cycle ~~. In contrast to the study of on different parameterizations inserted in a PDD model , we investigate space-time differences in the~~ performed with an Earth system model of intermediate complexity we undertake a systematic comparison of ice sheet surface mass balance ~~from using either the PDD method or the SEB approach. We use an Earth system model of intermediate complexity (EMIC) which simulates~~ simulated using SEB and PDD approaches for different ice sheets and during different periods of the last glacial cycle~~in a computationally efficient manner, though with the side effect that the description of details of the physical processes is limited. The EMIC consists of the climate model CLIMBER-2 interactively coupled with the ice sheet model SICOPOLIS. The standard version of the model uses the SEB approach and the simulated ice volume changes, expressed by sea level variation, agrees reasonable with the sea level reconstructions of . We take the space-time evolution simulated by the model as reference and compute in parallel the ablation by the PDD method. Thus, horizontally resolved ablation rates from two different methods can be compared under identical environmental conditions during the entire glacial cycle . In a second set of simulations, we exchange the SEB-derived ablation for the PDD-derived ablation and evaluate the glacial cycle simulations using the PDD method in online mode against sea level reconstructions~~.

2 Model description

2.1 Model setup

~~The setup of the climate model~~

The setup of the climate model CLIMBER-2 ~~coupled with the ice sheet model SICOPOLIS is used as in~~ (Petoukhov et al., 2000; Ganopolski et al., 2001) for simulations of glacial cycles and its performance are described in Calov et al. (2005) and Ganopolski et al. (2010). This model is designed to investigate processes and their interactions in the Earth climate system over the long time scales, such as Quaternary glacial cycles, which is achieved at expense of complexity and spatial resolution. The model has been used already in glacial cycle simulations to study the 100 ka climatic cyclicity of the Quaternary (Ganopolski and Calov, 2011), the mineral dust cycle (Bauer and Ganopolski, 2010), the climate response to the dust radiative forcing (Bauer and Ganopolski, 2014) and the impact of permafrost on simulation of glacial cycles (Willeit and Ganopolski, 2015).

CLIMBER-2 consists of interactively coupled models for the atmosphere, the ocean~~and the vegetation .~~, the land surface, the vegetation and the ice sheets. The atmospheric fields are computed on a longitude $\times$ latitude grid containing 7×18 grid cells. The 3-d polythermal ice sheet model SICOPOLIS operates on the NH between 21 and 85.5 °N on a longitude, latitude grid (x_s, y_s) with a resolution of (1.5°, 0.75°). Thus one ~~CLIMBER-2~~ atmospheric grid cell can overlap with more than 450 grid cells of ~~SICOPOLIS~~the ice sheet model. CLIMBER-2 computes the atmospheric fields with a daily time step, the oceanic fields every five days and the vegetation distribution every year. SICOPOLIS computes the ice sheet evolution ~~over a balance year. The CLIMBER-2 and SICOPOLIS models~~ from losses and gains of ice mass over a one-year period. The climate component and SICOPOLIS are coupled once per 10 years through the interface module SEMI (Surface Energy and Mass balance Interface)~~which works on the fine SICOPOLIS grid. SEMI~~. SEMI performes physically based 3-dimensional downscaling of climatological fields from coarse atmospheric grid to ice sheet model grid and computes the surface mass balance and the surface temperature ~~with a~~ using SEB approach with 3-day time step~~and transfers the~~. Computed annual fields of surface ice sheet mass balance and of surface temperature ~~to the SICOPOLISmodel~~are used in SICOPOLIS. In turn, SICOPOLIS feeds back to ~~CLIMBER-2~~ climate component 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. ~~Further processes as avalanches and windblown snow are not considered and ice streams, meltwater channels or ice-dammed lakes are not resolved. This model configuration has been used before in glacial cycle simulations to study the 100climatic cyclicity of the Quaternary , the mineral dust cycle , the climate response to the dust radiative forcing and the impact of permafrost .~~

2.2 Surface energy and mass balance interface (SEMI)

The interface module SEMI ~~solves the prognostic equations for ice surface temperature and snow thickness based on SEB and~~ computes the surface mass balance on the ~~fine grid of the SICOPOLIS model~~ SICOPOLIS grid (Calov et al., 2005). The ~~SEB comprises short-wave and long-wave radiative fluxes and turbulent energy fluxes and utilizes information from the CLIMBER-2 model on insolation, temperature at the surface and in the near-surface air, wind and ice sheet elevation. The surface ablation is computed from a surplus in SEB values and is hereafter called SEB-derived ablation. The ablation depends on snow layer thickness and snow albedo which is a function of dust deposition from aeolian and glaciogenic sources and snow aging. Then, SEMI computes the~~ surface mass balance $F_{SEB}(x_s, y_s)$ is defined by

$$F_{SEB}(x_s, y_s) = P(x_s, y_s) - A_{SEB}(x_s, y_s) \tag{1}$$

where $P(x_s, y_s)$ is the snow accumulation and $A_{SEB}(x_s, y_s)$ is the ~~SEB-derived~~ surface ablation (positively defined) which is hereafter called SEB-derived ablation. In SEMI, prognostic equations for ice surface temperature and snow layer thickness are solved based on the surface energy balance. The SEB comprises short-wave and ~~$P(x_s, y_s)$ is the snow accumulation. The determination~~ long-wave radiative fluxes and turbulent energy fluxes. These fluxes are calculated through horizontal and vertical interpolation of the fields of the coarse-resolution atmospheric component, as of insolation, solar incidence angle, longwave radiation, cloud fraction, air temperature, precipitation, and wind velocity.

A_{SEB} is computed from a surplus in SEB values which contains an explicit dependence on snow albedo. Here, snow albedo refers to broadband albedo composed of contributions from visible and near-infrared bands. Snow albedo is a function of snow aging and deposition of dust mass (Warren and Wiscombe, 1980). Effective snow age in CLIMBER-2 is a function of temperature and snow fall. Dust deposition is composed of aeolian dust transported from remote desert regions and of glaciogenic dust from glacial erosion Ganopolski et al. (2010). The computation of P includes the elevation-desert effect which causes decreasing P with increasing ice sheet elevation, and the elevation-slope effect which causes increasing P with increasing slope of the ice sheet surface~~in up-wind conditions~~. The slope effects also depends on the direction of average wind(Calov et al., 2005). Sublimation is ~~here~~ neglected.

2.3 Positive-degree-day (PDD) method

The PDD-derived ablation ~~is calculated for a balance year~~ A_{PDD} is calculated on the SICOPOLIS grid ~~inside~~ within the SEMI module. The PDD method is based on the reasoning that ablation is driven by the annual sum of positive ~~daily~~ temperature values which is seen as a proxy for melt energy (Braithwaite, 1984; Braithwaite and Olsen, 1989; Reeh, 1991). The semi-empirical PDD method ~~represents a linear relation between the~~ is represented by a linear relationship using PDD ~~value and uses~~ values and proportionality factors for snow and ice melt. ~~Values of the melt factors which would be suitable for buildup and retreat of ice sheets over the entire glacial cycle are not known . In the following, potential values of the melt factors are explored by ensemble simulations first in offline mode and second in online mode.~~

The PDD value (in $^\circ\mathrm{C\,d}$) is defined as excess of daily surface air temperature above the melting point accumulated over a ~~balance year. Because most~~ year. Most implementations of the PDD method take daily temperature values from interpolated monthly mean climatological data~~and to~~. To account for the missing diurnal cycle and synoptic variability, a temperature variability term is ~~added. The~~ included because the short-term temperature variability may implicate melt occurrences, ~~in particular at ice sheet margins,~~ even if the mean temperature is negative. ~~Usually, the standard deviation for temperature (σ) is prescribed in the range 4.5-5.5. analyzed observations and showed that σ for the Greenland ice sheet may increase from 1.6 to 5.2for altitude increasing from 0 up to 3000.~~

The PDD value is computed from the integral over time t

$$PDD = \int\limits_{\Delta t} dt\, [\frac{\sigma}{\sqrt{2\pi}}\, exp(-\frac{T^2}{2\sigma^2}) + \frac{T}{2}\, erfc(-\frac{T}{\sqrt{2}\,\sigma})] \tag{2}$$

where $\Delta t = 1\,\mathrm{year}$, T (in $^\circ$C) is the ~~3-day mean of~~ climatological mean surface air temperature, $erfc(x)$ is the complementary error function and σ is the standard deviation ~~for temperature~~ of daily temperature from climatological mean value (Calov and Greve, 2005). Usually, σ is prescribed in the range 4.5-5.5 $^\circ$C (Reeh, 1991; Ritz et al., 1997; Tarasov and Peltier, 1999, 2002; Greve, 2005). Fausto et al. (2009) analyzed observations and showed that σ for the Greenland ice sheet may increase from 1.6 to 5.2 $^\circ$C for altitude increasing from 0 up to 3000 m.

The PDD-derived ablation is defined analogous to Eq. (1)

$$A_{PDD}(x_s,y_s) = P(x_s,y_s) - F_{PDD}(x_s,y_s) \tag{3}$$

where ~~$P(x_s,y_s)$ in Eq. and Eq. are computed in the same way in SEMI. In the offline simulations,~~ the description for $P(x_s,y_s)$ in Eq. (1) and Eq. (3) ~~are identical because they result from the environmental conditions of the reference simulation~~is unchanged. The surface mass balance F_{PDD} (in $\mathrm{mm\,y^{-1}}$) is calculated by

$$F_{PDD} = \begin{cases} \alpha_I\, Q & : \quad Q < 0 \\ 0 & : \quad Q = 0 \\ \alpha_S\,(1 - r_S)\, Q & : \quad Q > 0 \end{cases} \tag{4}$$

where α_S and α_I (in $\mathrm{mm\,^\circ C^{-1}\,d^{-1}}$) are the melt factors of snow and ice, respectively, and $r_S = 0.3$ is a constant refreezing factor. This factor is introduced for the nocturnal refreezing of ~~snows~~ snow and causes a slow down of the snow melt. The factor Q (in $\mathrm{^\circ C\,d\ y^{-1}}$) is the actual remain of PDD per year Δt

$$Q = \frac{PDD_S - PDD}{\Delta t} \tag{5}$$

where PDD is given in Eq. (2) and PDD_S is

$$PDD_S = \frac{P\,\Delta t}{\alpha_S\,(1 - r_S)} \tag{6}$$

which represents that PDD value which is ~~supposedly~~ required to melt the annual accumulated snow P. The sign of Q determines the sign of the surface mass balance F_{PDD}. When the PDD value (Eq. 2) is too small to melt the available snow then the remaining snow at the end of the ~~balance~~ year builds ice mass and F_{PDD} is positive. Reversely, when the PDD value is large enough to melt all snow in the grid cell then the remain Q (Eq. 5) melts surface ice and F_{PDD} is negative.

2.4 ~~Reference simulation of last glacial cycle~~

Values of the melt factors in the PDD scheme which are suitable for realistic simulation of ice sheets over the entire glacial cycle are not known (Hock, 2003). In the following, we attempted to find a unique set of three empirical parameters of the PDD scheme which are optimal for this task. To this end we used PDD scheme to simulate ablation in the ‘offline’ mode and then in the ‘online’ mode. In the first case, the PDD scheme is used to calculate annual ablation rate in parallel with the standard SEB scheme employed in SEMI. Ablation simulated with the PDD scheme does not affect ice sheet evolution and is only used for comparison with the standard SEB scheme. Note than this approach is fully equivalent to the standard ‘offline’ technique, when temperature and precipitation fields are stored in the process of simulations with the standard CLIMBER-2 model and only then used to simulate surface mass balance with the PDD scheme. In the online mode, the SEB scheme of the SEMI module is disabled and ablation is computed with the PDD scheme. Note that in both cases (online and offline) accumulation is computed the same way but precipitation fields are not the same for these two methods because precipitation also depends on ice sheets distribution and elevation, which are not the same in online and offline simulations. Offline and online modes are both useful to compare different ablation schemes because in offline mode both schemes are forced by identical climate forcing but it does not tell how much differences in simulated ablation would affect ice sheet evolution. In the case of online simulation, comparison of two ablation schemes is complicated by strong nonlinearity of climate-cryosphere system where even small differences in the forcings can lead to dramatic differences in the system response on long time scales.

2.4 Reference simulation of the last glacial cycle

~~The reference simulation of the last glacial cycle utilizes the SEB-derived ablation from SEMI. All glacial cycle simulationsare~~ The reference simulation of the last glacial cycle is driven by the insolation calculated from the varying orbital parameters (Berger, 1978) and the ~~varying~~ time-varying concentration of greenhouse gases (Fig. 1a) expressed as equivalent CO_2 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 with the Greenland ice sheet as the only NH ice sheet. The shortwave radiative forcing by aeolian dust and the ~~aeolian dust deposition on snow affecting the snow albedo~~ deposition of desert dust on snow of ice sheets are computed by ~~using~~ use of time slice simulations from general circulation models. ~~Temporally varying fields are obtained~~ The horizontal fields of the time slices are transformed to temporally varying fields by scaling the time slices with the simulated ice volume ~~. The snow albedo of the ice sheets depends further on dust deposition~~ (Calov et al., 2005) . The dust deposition on ice sheets includes further dust from internally simulated ~~glaciogenic dust sources and snow aging~~sediments produced by glacial erosion (Ganopolski et al., 2010). Note that in online simulations, both the dust radiative forcing and the snow albedo differ from that in offline experiment.

Figure 1b shows the reference time series of global mean surface air temperature and global mean precipitation over 130 ka. The global temperature T decreases ~~irregularly~~ by more than 6 °C from the ~~last interglacial , the EEM,~~ Eemian interglacial until 21 ka, the last glacial maximum (LGM). Subsequently, T rises rapidly by 5.5 °C within about 10 ka until the early Holocene. The global precipitation is thermodynamically controlled and varies in close relationship to T (Fig. 1b). Figure 1c shows the mean sea level variation computed from the NH ice volume (assuming constant ocean surface area and an additional 10% contribution from the Antarctic ice sheet) in comparison to the global mean sea level from reconstructions (Waelbroeck et al., 2002).

Figure 2 shows the characteristics of the NH ice sheets by comparing NH total values with values from ~~two main partitions. Hereafter, we name the two partitions~~ the American and the European ice sheets which represent, respectively, ~~the ice sheets on the northern American continent and in northwestern Eurasia extending as far as~~ all ice sheets in North America and in Eurasia up to 120 °E. Note that the Greenland ice sheet is not included in the selections, but contributes to globally average values. . Up to 70 % of the total ice-covered area occurs ~~on the American continent~~ in America and mostly less than 20 % occurs in Europe (Fig. 2a). The total ice volume, given in meter sea level equivalent (msle), varies about proportional to the total ice sheet area (Fig. 2b). The ~~volume of the ice sheets is given in () which is determined under the assumption that changes in the ocean surface area are negligibly small over the glacial cycle. The~~ area and the volume vary ~~inversely proportional to the precession-driven variation~~ in parallel with the precession and obliquity-driven variations of the northern summer insolation. ~~The local maxima due to the precessional varying insolation grow gradually until LGM where the growth of ice volume is more steep than the growth of ice area.~~

Figure 2c shows areal averages of ~~ice sheet thickness. These have to be interpreted with care because the area-weighted average thickness is related to the variable ice sheet area. In the glacial period, the American~~ the time-varying ice sheet thickness~~is larger than the total average thickness whereas the American ice area is a fraction (although major) of the total~~

~~ice-covered area~~. During the interglacial periods, the relatively high average ~~thickness of the total ice sheet~~ ice thickness over NH is related to the persisting Greenland ice sheet. In the initial millennia of glacial inception, the drop in the average ice thickness results from the fast spreading of the ice sheet area during inception (Calov et al., 2005). Thereafter the average thickness of the American ice sheet grows, stays high beyond the LGM and drops rapidly toward to beginning of the Holocene. The European ice sheet thickness starts to grow at glacial inception a few millennia before the American ice thickness. ~~The European average ice thickness shows relatively little variations in the glacial four precessional periods while the area and volume vary with precessional periods.~~ Around the LGM, the European ice thickness increases by about 30 % which is accompanied with an extra cooling over the northern Atlantic. The lead of the thinning of the European ice sheet compared to American ice sheet at glacial termination is attributed to the lower elevation of the European ice sheet which facilitates the ice melt. Yet, during glacial termination the thinning of the American ice sheet occurs more rapidly than of the European ice sheet.

The ~~components of the surface mass balance are shown in (1=) for the total ice sheet together with the partitions from America and Europe. The~~ time series of snow accumulation (Fig. 2d) and surface ablation (Fig. 2e) vary in comparable ranges. P is well correlated with the ice sheet area and varies with the precessional period in a rather ~~harmonic manner. The ablation (Fig. 2e) varies irregularly~~ linear manner. A_{SEB} varies in response to different driving factors, as insolation, surface ice area exposed to temperature above melting point and albedo of the snow surface. The maximum ablation after the LGM occurs in America some millennia earlier than in Europe. The lead of the maximum ablation in America is related to the larger perimeter exposed to melt conditions and the more southerly extent of the American ice sheet. The resulting surface mass balance (Fig. 2f) is positive ~~during the glacial period~~ and exceeds calving rate (not shown) during most of the last glacial cycle leading to the buildup of ~~ice mass. After the LGM the mass balance turns negative and the ice sheets retreat. In the time interval around 65(MIS 4) the simulated negative surface mass balance results from a climatic excursion involving interactions between atmospheric cooling amplified by dust short-wave radiative forcing and changes in the North Atlantic meridional overturning circulation (AMOC)~~ large NH ice sheets at the LGM.

3 Mass balance computed by ~~offline~~ PDD method ~~during glacial cycle~~ in offline simulation

~~Any simulation~~ Since over the last glacial cycle ~~with the PDD method suffers from missing empirical data which are necessary~~ empirical data needed to calibrate the PDD ~~method. Therefore, we use the reference simulation for the last glacial cycle and compute ensembles of PDD-derived ablation in offline mode by varying the parameter values. The~~ scheme are absent, we considered results of the standard, SEB-based mass balance simulations as the target for the PDD scheme. We compare ablation simulated by the PDD method with different empirical parameters with the results of the standard model version. We performed a large set of offline simulations with the PDD scheme where the standard deviation for temperature σ (Eq. 2) and melt factors α_S and α_I (Eq. 4) are considered as ~~control~~ tunable parameters. Each simulation is run with constant parameter values over the entire glacial cycle.

3.1 Selection of PDD parameter values

The PDD value computed with the (Eq. 2) ~~is calculated with~~ depends on prescribed standard deviation for temperature. ~~We insert~~ In this study we used two different values , i.e., σ=3 °C and σ=5 °C. Figure 3 shows time series of T and the corresponding PDD values as areal averages over the ice sheets. ~~The~~ After the Eemian at about 120 ka, the temperature averaged over the NH ice sheet area decreases by 13 °C (from -16 to -29 °C) ~~after the last interglacial~~ in a time interval of ~~about~~ nearly 100 ka and then T ~~returns~~ recovers rapidly within about 10 ka ~~, thus shaping the asymmetry of the glacial cycle~~ (Fig. 3a). The PDD values are closely correlated with T showing a progressive decrease after glacial inception and a rapid increase during glacial termination. The ~~areal~~ averages of the PDD value for the total ice sheet lie in the ~~range~~ ranges 10–70 ~~with σ=3and lie in the range~~ and 20–120 °C d with σ=3 and 5 °C, respectively (Fig. 3a). The ~~asymmetric evolution is substantiated mostly by the temperature evolution over the massive ice sheet on the American continent~~ glacial cycle asymmetry is substantiated by the massive and widespread ice sheet in America which shows a temperature evolution from -16 to -27 °C (Fig. 3b)~~ranging from -16 to -27~~. The temperature of the smaller European ice sheet fluctuates ~~strongly between~~ more strongly, i.e. from -10 ~~and~~ to -29 °C. These fluctuations are connected with changes in the sea-ice albedo effect in the northern Atlantic and changes ~~in the heat advection by the AMOC. The European~~ of the Atlantic meridional overturning circulation. The PDD values for Europe range over 10–260 °C d with σ=3 °C and ~~range~~ over 30–370 °C d with σ=5 °C (Fig. 3c).

Previous climate model studies often used σ ~~about~~ =5 °C and so-called standard melt factors ~~, i.e.,~~ for snow and ice which are (α_S, α_I) = (3, 8) mm °C^{-1} d^{-1} ~~which were~~ as derived from measurements on the Greenland ice sheet (Huybrechts and de Wolde, 1999; Tarasov and Peltier, 1999, 2000). However, other observations show that melt factors may vary with latitude and height of the glacier. ~~Worldwide~~ Hock (2003) summarized worldwide measurements during the melt season of glaciers and snow-covered basins ~~yield melt factors for α_S and α_I (in)~~ and showed that (α_S, α_I) may vary in the ranges ([2.5–11.6]~~and 5.4–20, respectively . We study the PDD-derived ablation by varying~~ , [5.4–20]) mm °C^{-1} d^{-1}. The ranges of the melt factors are relatively wide because they are obtained from different environments and incorporate variations in space and time, insolation, ice sheet elevation, sensible heat flux and surface albedo. Here, we consider two σ values to test the possible effect on A_{PDD} from unresolved space-time variations in the modeled temperature. For each σ value, the values for α_S and α_I ~~(in) in~~ are varied in wide ranges. In case σ=3 °C, (α_S, α_I) are varied in the ranges ([3-10]~~and 8-24,respectively~~, [8-24]) mm °C^{-1} d^{-1}, and in case σ=5 °C in the ranges ([2-6]~~and 4-18, respectively,Thereby~~ , [4-18]) mm °C^{-1} d^{-1}. Thus the offline PDD-derived ablation can capture the entire variability of the ~~SEB-derived ablation simulated for the ice sheets is enclosed by the ensembles of the offline PDD-derived ablation which is shown in Fig. 6 for the American and the European ice sheets~~simulated SEB-derived ablation during the glacial cycle.

3.2 Ablation time series for ~~American and European~~ ice sheets over glacial cycle

~~We use~~ In an attempt to find PDD parameter values which produce the best fit to A_{SEB}, we calculate as measures of agreement ~~between the reference and the PDD method~~ the mean anomaly m and the rms–error r ~~averaged over the NH ice sheet (or~~

~~over the American and European ice sheets) and the entire glacial cycle (or shorter time intervals)~~from time series of ablation averaged over ice sheets. Figure 4 ~~compares ablation series from the PDD method with the reference series over the last~~ shows contour plots of m and r as function of α_S and α_I calculated from 130 ka~~averaged for the American and European~~ -long series of A_{PDD} and A_{SEB} for the all NH ice sheets. ~~The five ensemble members for each~~ For both σ ~~-set which are selected for Fig. 4 show relatively small mean anomalies (see Tab. ?? for corresponding~~ values, no unique pair of (α_S, α_I) values exists at the minimum in m ~~and r) . The ensemble members with σ=3~~(Fig 4a, ~~b) are produced with~~ c) while the minimum in r can be associated with a specific pair of (α_S~~=5and~~ , α_I~~in the range 8–24, and the ensemble members with σ=5(Fig 4c~~) values (Fig. 4b, d)~~are produced with smaller melt factors, i.e. , α_S=3and α_I in the range 4–12. For the American ice sheet, m is between -0.023 and -0.007and for the European ice sheet, m is between -0.011 and 0.006~~. However, the minimum rms-error of about 0.025 Sv ~~in case σ=3. In case σ=5, the minimum anomaly m for both ice sheets is found by use of the standard melt factors, i.e. (α_S, α_I) = (3, 8)~~is large and amounts to more than 50% of the peak value in A_{SEB} simulated at 15 ~~. Apparently, the agreement between the series is much lower~~ ka. In another attempt, we try to find optimal PDD parameter values separately for the American ~~than for~~ and the European ice sheets~~irrespective of the σ value. An outstanding feature is the enhanced ablation from the American ice sheet during MIS 4 which is difficult to reproduce with the PDD method.~~

~~Another selection of ensemble simulations looks for minima in rms–error. Minima in m and minima in r do not necessarily have common melt factors (Tab. ??)~~. The contour plots of the rms–error ~~shown~~ as a function of α_S and α_I ~~illustrate that no unique pair~~ (Fig. 5) show that very different values of (α_S, α_I) ~~is suitable for both~~ are optimal for American and European ice sheets (~~Fig. 5~~Tab. 1). Overall, r for the American ice sheet (Fig. 5a, c) is about a factor three larger than for the European ice sheet (Fig. 5b, d) in both σ-sets.

~~The~~ Figure 6 shows the PDD-derived ablation ~~series produced with the smallest and largest α_S and α_I values envelop the reference ablationseries~~ evolution for the American and the European ice sheets for the entire ensemble together with the SEB-derived ablation. The agreement between the series is much lower for the American ~~and~~ than for the European ice sheets ~~(Fig. 6). As seen already in Fig. 4, a particular PDD-derived ablation series which overestimates the SEB-derived ablation~~ irrespective of the σ value. Typically A_{PDD} and A_{SEB} agree better during glacial inception ~~underestimates the peaks of the reference ablation~~ then A_{PDD} underestimates the peak in A_{SEB} at glacial termination and, reversely, if A_{PDD} reproduces the peak in A_{SEB} at glacial termination then A_{PDD} overestimates A_{SEB} at glacial inception. Hence, ~~optimal melt factors~~ smaller melt factors would be needed for glacial inception ~~are most likely smaller~~ than for glacial termination. ~~Table 1 gives an example for PDD parameter values which produce minimum rms–errors for shorter time intervals, first for~~ So, we divide the time series into the intervals 130–30 ka and ~~second for the last 30~~30–0 ka and determine for each sub-interval the PDD parameter values which minimize the rms–error (Tab. 1). Nonetheless, ablation series fitted ~~separately~~ for the American ice sheet ~~deviate~~ and for sub-intervals diverge repeatedly from the ~~irregularly fluctuating~~ reference series (Fig. 6a, c). ~~The~~ In particular, the enhanced ablation from the American ice sheet during MIS 4 (ca. 75-60 ka) is difficult to reproduce with the PDD method. Otherwise, the PDD-derived ablation series fitted for the European ice sheet for ~~these time intervals, however,~~ sub-intervals agree quite well with the reference and the discontinuity at 30 ka is small (Fig. 6b, d).

3.3 ~~Ablation~~ Geographical resolved ablation rates ~~on fine resolution~~ at ~~glacial termination~~15 ka

At 15 ka, the total SEB-derived ablation ~~has a~~ reaches its maximum of 0.41 Sv (Tab. 2). This is why we choose this time slice to analyze geographical distribution of ablation simulated with the PDD scheme versus the standard SEB approach. The ensemble member which produces ~~about the same~~ similar total ablation as ~~the reference~~ in the reference simulation at 15 ka is obtained with ~~σ=3and~~ (α_S, α_I)=(9, 16) mm °C^{-1} d^{-1} ~~(Fig. 7). But that ensemble member produces at 15~~and σ=3 ~~a smaller American ice melt and a larger European ice melt than the respective references~~ °C (Fig. 7). ~~However, that ensemble member produces for the European ice sheet a maximum in ablation at 14which is also seen in the reference (Tab. 2). No single ensemble simulation is found that can produce for both ice sheets in America and in Europe ablation maxima at the same time instances as the reference simulation.~~

~~The comparison of the ablation rates of~~ Figure 8 compares the spatial patterns of ablation rates simulated with both methods on the ~~fine SICOPOLIS grid shows, in case of equal~~ SICOPOLIS grid using the ensemble which produces the same NH total ablation ~~,~~ as the reference simulation at 15 ka (Fig. 7). The scatter diagram shows that the PDD method tends to overestimate large ablation rates and to underestimate low ablation rates. ~~This is demonstrated in a scatter diagram (Fig. 8) comparing the ablation rates at 15from the above ensemble simulation (Fig. 7) with the reference.~~ The PDD-derived American melt rates overestimate the reference ~~ablation~~ melt rates larger than $\sim$10 mm d^{-1} but underestimate the American ice melt rates less than $\sim$8 mm d^{-1} (Fig. 8a). The PDD-derived European melt rates are overestimated mainly for ablation rates larger than $\sim$6 mm d^{-1} (Fig. 8b). The largest ablation rates occur naturally at the ice sheet margins and here the largest differences ~~are located. This can be seen in Fig. 9~~ occur. This is evident from the geographic distribution of the differences between the PDD-derived ablation relative to the SEB-derived ablation at 15 ka (Fig. 9). The differences are positive mostly at the outer margins of the ice sheets. Negative differences occur predominately around the Rocky Mountains.

4 Glacial cycle simulations with online PDD method

~~The~~ Above we evaluated PDD-derived ablation from ~~the above offline simulations are evaluated~~ offline simulations against the SEB-derived ablation~~by assuming that the reference simulation provides acceptable climate characteristics since~~. In doing so we explicitly assumed that the latter gives realistic spatial and temporal distribution of ablation since in the reference simulation ~~reproduces the reconstructed sea level reasonably well. In the following~~ ice sheets evolution during the last glacial cycle is in reasonably good agreement with paleoclimate reconstructions. We found that ablation simulated with the PDD scheme in general deviates appreciably from that simulated with the standard SEB approach. To asses how these differences will influence ice sheet evolution during the last glacial cycle, we performed a set of PDD-online simulations, ~~the PDD-derived~~ where the PDD scheme for ablation replaces the ~~SEB-derived ablation. In this way, the simulated climate and the ice sheets are internally consistent with the PDD method but thereby the impact from changing snow albedo on the absorption of short-wave energy at ice sheet surfaces is ignored~~standard SEB scheme. Note, that the scheme for simulations of accumulation remains the same in these simulations. We evaluate the PDD-online simulation by ~~comparisons~~ comparing their results with the reconstructed global sea level and climate characteristics ~~of~~ from the reference simulation.

4.1 Selection of PDD parameters values

~~The globally and temporally constant PDD parameter valuesare selected with the aim to reproduce the reconstructed sea level at three target windows which are glacial inception, glacial termination and LGM. Table 3 lists the PDD parameter values which are suitable for simulating the climate at the three target windows and which produce representative results. These representative results are obtained by applying the PDD method online in a set~~ A few dozens of glacial cycle simulations with online application of the PDD method were performed. In these experiments we tested how well evolution of ice sheets and climate can be simulated with constant PDD parameters values. It appears that the values of three PDD parameters can be tuned adequately for certain time periods but not for the entire glacial cycle. The PDD online simulations can be split into two clusters. In the first one, the temperature and the sea level are reasonably simulated during glacial inception (from 120 ka until about 110 ka) but diverge dramatically from paleoclimate reconstructions for the rest of glacial cycle~~simulations.~~

~~The targets at inception and termination could be fulfilled with a range of PDD melt factors and we select parameter values on the basis of the results from the offline simulations. The offline simulations of A_{PDD} using σ=3which produced minimum rms–errors for American and European ice sheets indicate that A_{PDD} is mainly sensitive to the snow melt factor while the ice melt factor is invariant, namely α_I=16(Tab. 1). So we use that α_I value and varied α_S to fulfill the first two targets by PDD-online simulations. The offline simulations of A_{PDD} with σ=5yield differing melt factors at minimum rms–errors. We recall that with the standard PDD parameter values the mean anomaly in~~ . In particular, all these simulations fail to simulate deglaciation toward the end of Holocene. Simulations of the ~~PDD-offline simulations is minimized (~~second cluster are able to simulate complete deglaciation before the end of the experiment and reproduce the climate of the Holocene realistically but significantly underestimate ice sheets volume during most of glacial cycle. In the following, we show representative simulations from the two clusters with parameter values given in Tab. ~~??). By use of the standard~~ 3. The target periods inception and termination are seen to impose a rather weak constraint for selecting the PDD parameter values~~in the PDD-online simulation the first target is fulfilled and the second target can be fulfilled by doubling the α_S value. The reproduction of the sea level at LGM~~ . In contrast, the target period LGM (21 ka) emerged as a rather strong ~~constraint and only~~ empirical constraint. Only one specific pair of melt factors values for each σ value (Tab. 3) is found suitable to simulate the LGM climate with the online PDD method.

4.2 Target ~~window~~periods: glacial inception and termination

~~The~~ During glacial inception (from about 120 ka until 110 ka, PDD-online simulations I3 and I5 (Tab. 3) reproduce closely the global temperature (Fig. 10a, c) and the sea level (Fig. 10b, d)~~during inception over the first precessional period~~. In this time interval, the ice sheet area grows sufficiently fast in company with accumulation. The reproduction of T implies reproductions of both the ice sheet thickness and the ablation and consequently the surface mass balance agrees with the reference (not shown). Thereafter the ice volume grows too fast in concert with amplified snow accumulation and the simulation drifts into excessive cold climate. At 21 ka, in these experiments the ice volume is about twice as large as reconstructed (Tab. 3) and ~~then the~~ simulations I3 and I5 fail to terminate the glacial climate state. ~~Note, the simulation I5 which uses the standard~~

~~PDD parameter values (Table 3) simulates the climate characteristics in the first multi-millennia in close agreement with the reference but then drifts into excessive cold climate without recurrence (Fig. 10c, d).~~

~~The~~ Contrary to the experiments described above, the temperature and the sea level in simulations T3 and T5 ~~recover~~ simulate realistically the Holocene climate characteristics after a weak glacial phase (Tab. 3). The global cooling after inception is about in phase with the reference temperature though the cooling in the PDD-online simulations is substantially underestimated (Fig. 10a, c). The sea level drop in simulation T3 is about half as large as reconstructed over the glacial phase (Fig. 10b) and in simulation T5, the maximum sea level drop ~~is~~ of 40 m ~~occuring~~ occurs after the LGM (Fig. 10d). From 38 to 20 ka the cooling rate in both simulations T3 and T5 intensifies and thereby the ice volume grows continuously beyond 21 ka until around 18 ka. The recurrence to Holocene climate begins from a less cool climate and a smaller ice-covered area than in the reference ~~.~~ ~~So~~experiment. Therefore, both simulations T3 and T5 undershoot the buildup of the ice volume substantially.

4.3 Target ~~window~~period: LGM

~~The~~ PDD-online simulations L3 and L5 reproduce reasonably well the reconstructed sea level at 21 ka (Tab. 3). In the initial phase of the glacial cycle, ~~the~~ simulation L3 produces a weaker cooling and less ice volume than the reference but in the time interval 40–21 ka the agreement is close (Fig. 10a, b). ~~The simulation~~ Simulation L5 ~~with the high temperature variability~~ generates a growing ice volume over the entire glacial phase which agrees well within uncertainties inferred from the reference and the reconstructed sea level (Fig. 10c, d). ~~After the LGM, the ice volume in~~ However, in simulations L3 and L5~~grows further~~, the ice volume grows beyond 21 ka by several msle. The continued growth of the ice volume is ~~associated with~~ caused by a continued positive mass balance from less ablation than in the reference simulation, mainly in America. Consequently, glacial termination is delayed and the recurrence to Holocene climate characteristics is not achieved.

The geographic distribution of the ice sheet thickness at 21 ka from ~~the~~ PDD-online simulation L3 agrees closely with the reference simulation (Fig. 11). ~~The simulation~~ Simulation L3 reproduces the maximum thickness of 3500 m in America as simulated by the reference ~~. The~~ but in simulation L3 ~~produces a slightly more southerly spreading ice sheet~~ the ice sheet spreads slightly more southward beyond the American Great Lakes and ~~a thinner~~ the ice sheet in the European Arctic and in northeastern Asia is slightly thinner. Also, simulation L5 produces an ice sheet distribution similar to the reference although the maximum thickness in America is only 3300 m at LGM. Both PDD-online simulations L3 and L5 simulate at LGM a sea level of -120 m, but thereafter their mass balances remain more positive than in the reference which results in lagged climate warming and in case of simulation L5 the deglaciation is incomplete (ca. 50 msle remain at present).

5 ~~Discussion~~Impact of snow albedo parameterizations on simulated surface mass balance and ice sheet evolution

~~Simulations of the long-term climate changes during glacial cycles are here discussed with focus on the coupling mechanisms between the climate system and the ice sheet distribution. The coupling module SEMI between the CLIMBER-2 model and the relatively high-resolution SICOPOLIS model provides the ice sheet modelwith the surface ice mass balance and in turn provides the climate model with the spatial distribution of the ice sheet. Differences in~~ In nature, ablation is largest when insolation reaches a maximum and when the surface temperature is above freezing. Hence, ablation zones are highly localized in time and space and ablation occurs only in summer at ice sheet margins. In the reference simulation, ablation is computed by SEMI module based on the physically-based SEB approach. Snow albedo parameterization is one of the key elements of the SEMI module. To demonstrate the importance of proper parameterization of snow albedo we performed additionally a set of experiments where we split the function describing snow albedo into its components to test their individual effect on ablation. In doing so, we run again offline and online simulations of the last glacial cycle with the CLIMBER-2 model. Three components in the parameterization of snow albedo used in the SEMI module are critically important, namely, the aging of pure snow depending on temperature, the concentration in snow of light-absorbing impurities 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. We select four test cases where snow albedo is defined in C1 as pure snow without aging (snow remains fresh), in C2 as snow with dust deposition but without snow aging (impure snow remains fresh), in C3 as pure snow with snow aging, and in C4 as with effect of dust deposition and snow aging but without the synergy between aging and dust deposition. (Tab. 4).

We first performed a set of offline simulations in which surface mass balance ~~computed by the PDD method and the SEB approach are studied in transient simulations~~ was computed for different snow albedo parameterizations using results of the reference experiments. In these experiments, the perturbed mass balance does not affect climate and ice sheet simulations and is used only for comparison with mass balance simulated in the reference experiemnt. Fig. 12 shows characteristic time series over the last glacial cycle ~~for the American and the European ice sheets and at a fixed output time for climate variables on the relatively fine geographic resolution.~~

~~The comparison of PDD-derived ablation and SEB-derived ablation accumulated for the ice sheets suggests that PDD melt factors should be larger for glacial termination than for glacial inception and larger for the American ice sheet than for the European ice sheet.~~obtained from the offline simulations in comparison to the reference simulation. These time series are shown as monthly means for June and July averaged over the NH ice sheets. The ~~rms-error between A_{PDD} and A_{SEB} for the American ice sheet is found threefold larger than for the European ice sheet (Tab. **??** and~~ modified descriptions of snow albedo according to the four cases lead to substantial changes in co-albedo. Although the insolation in June is larger than in July (Fig. 12a, e), the ablation in July is more than 60 % larger than in June (Fig. 12d, h). The larger June insolation is accompanied by a lower co-albedo (Fig. ~~5). Hence, the European ice sheet appears to be closer correlated with the positive temperature sum than the American ice sheet. The bivariate rms-error distributions show that low rms-errors in the ablation from the American ice sheet are more sensitive to the snow melt factor than to the ice melt factor, while the rms-error in ablation from the European ice sheet showsa similar sensitivity to both α_I and α_S (~~12b, f) such that the absorbed shortwave radiation in June and July are similar (not shown). The test case C1 imposes the maximum effect and causes a reduction in the co-albedo by about 30 % relative to the reference experiment. Case C2 shows that the dust-induced darkening effect is roughly proportional to ice volume. Case C3 however shows, that the aging effect from growing snow grain sizes has a larger effect than the dust-darkening in case C2. Only around LGM, the dust-induced effect is larger than the pure snow aging effect. Case

C4 shows, that neglecting the synergy between aging and impurities effect on albedo leads to a reduction in co-albedo by about 10 % relative to the reference experiment.

Fig. ~~5). Thus the simulated American ice melt is seen to depend more closely on the snow melt factor which can be attributed to the effect of dust deposition on the American ice sheet .~~

~~Comparisons of the local ablation rates from the PDD and the SEB methods with climate variables on the fine SICOPOLIS grid are blurred because of the large variability, for instance, with location, ice sheet thickness and absorbed short-wave insolation changing with snow albedo through dust deposition. Another reason for differing ablation rates is that the SEB method includes influences from the nonlinear interplay of~~ 13 compares the reference simulation with the online simulations from the four cases (Tab. 4). In these experiments changes in parameterization of surface albedo directly affected ice sheet evolution. Note that in these experiments we did not change parameterization of snow albedo in climate component of CLIMBER-2. Common to all four online simulations is that the climate cools extremely in accompany with excessive buildup of ice volume such that eventually no recovery to interglacial climate is achieved. Simulation C4 without the synergy between aging and impurities effect on snow albedo is the ~~short-term varying climate variables which are calculated with a 3-day time step. In order to reduce the deficiencies of the PDD method, already pointed out that melt factors should explicitly account for temperature, albedo and turbulence or in other words, better to employ the SEB approach. Therefore we analyze the PDD-derived ablation (offline) and the SEB-derived ablation for their relation to the concurrently simulated SEB values. The largest differences between the ablation from the PDD and the SEB methods are visible at glacial termination and we take the ablation rates simulated at 15~~closest to the reference experiment but still about 150 msle of ice remains at 0 ka~~as used above (Fig. 7,~~. Simulation C3 without dust deposition but accounting for snow aging produces a reasonable climate until only 120 ~~8,~~ka. This is due to the interglacial climate condition in which ice sheets are not yet existing and dust deposition plays no role. In simulation C2 with dust deposition but without snow aging the climate begins to cool immediately after the start of the simulation. After about 100 ~~9). Figure 12a clearly shows that A_{SEB} grows steadily with SEB. The offline computed A_{PDD} grows proportional with PDD values and additionally A_{PDD} grows slightly with P (Fig. 12b). When A_{PDD} is interpolated with respect to SEB and P then only the largest values of A_{PDD} coincide with the largest SEB values. The largest A_{PDD} values are located at the outer margin of the American ice sheet and are seen to overshoot the corresponding A_{SEB} values (Fig. 8). Clearly, most of the A_{PDD} values (i.e., between 5 and 15~~ka, the effect of dust deposition is substantial and the cooling attenuates in comparison to simulation C3. Simulation C1 in which the snow albedo is computed for fresh and pure snow an excessive ice sheet builds up in Asia such that the model crashed already at 86 ~~) vary randomly with SEB (Fig. 12c). This poor correlation between A_{PDD} and SEB is an illustration of the shortcoming of the PDD method~~ka.

These first-order estimates of factors influencing the snow albedo discussed for the total NH ice sheets are depending on our model setup and further investigations with more advanced parameterizations (Dang et al., 2015) are desirable. In particular, recent observations of the Greenland ice sheet indicate a strong effect on surface albedo decline from the combination of climate warming, growth of snow grains and the accumulation of light-absorbing impurities (Tedesco et al., 2016).

6 Conclusions

The ~~overall target is to simulate the asymmetric evolution of the NH ice sheets of the last glacial cycle which build up over about 100and retreat within about 10. The changing surface ice~~ changing in space and time surface ice sheets mass balance plays a crucial role in shaping the glacial cycles of the Quaternary. ~~The surface ice mass balance is the annual difference of accumulation minus ablation which have similar values during most of the glacial period. Under the assumption that accumulation simulated by~~ Here, using the Earth system model of intermediate complexity CLIMBER-2 with a rather coarse resolution climate component we studied whether a simple and computationally efficient PDD scheme can satisfactorily emulate the much more complex and computationally demanding SEB-based scheme implemented in CLIMBER-2. To this end we performed a large set of experiments in offline and online modes. Ablation in offline mode is computed with the same climate forcing as in the reference simulation that allows a direct comparison of ablation series simulated by PDD and SEB schemes. By doing this comparison we assumed that reference simulation of the CLIMBER-2 model ~~is plausible since the asymmetric climate evolution is simulated satisfactorily, we compare the ablation from the offline PDD method and the SEB approach. The PDD-derived ablation is computed in a set of more than hundred transient glacial cycle simulations using in each simulation constant values for the temperature variability term and the PDD melt factors. The comparison between ablation series from the offline PDD method and~~ with the SEB approach is sufficiently realistic since the model simulates evolution of climate and ice sheets rather realistically. At the same time, climate component of the ~~SEB method shows:~~ model has a rather coarse spatial resolution and sophisticated downscaling to ice sheet model grid includes a number of tunable parameters not all of them well constrained by empirical data. Therefore our comparison between SEB and PDD approached should be considered as tentative and using of higher resolution climate models would be desirable to make a final conclusion.

~~i) if the rms–error is small for the European ice sheet then A_{PDD} is too low for the American ice sheet, and vice verse if the rms–error is small~~ In summary, the offline simulated ablation by the PDD method with constant parameter values and the ablation simulated with the SEB approach are not compatible over the last glacial cycle. Hence, a use of the PDD method in case of large climate changes and geographically varying continental ice sheets, as observed in NH during a glacial cycle, is found problematic. Our study suggests that for realistic simulation of glacial termination, larger PDD melt factors are required than for glacial inception, and also larger melt factors for the American ice sheet ~~then A_{PDD} is too large for the European ice sheet,~~

~~ii) if the rms–error is small at glacial inception then A_{PDD} is too small at glacial termination, and vice verse if the rms–error is small at glacial termination then A_{PDD} is too large at glacial inception.~~

~~This indicates that the PDD-derived ablation with constant parameter values is not compatible with the SEB-derived ablation in long-term simulations with varying climate conditions and with geographically varying continental ice sheets as is observed in NH during glacial cycles~~compare to the European one. In general, it appears that mass balance of European ice sheet is better correlated with the positive temperature sum than the American ice sheet. This suggests that the evolution of the American ice sheet is more strongly influenced by changes in absorbed shortwave radiation and surface albedo.

~~The glacial cycle simulations using~~ Online simulations with the PDD method ~~in online mode can reproduce~~ show that no universal PDD parameter values are found by which the entire glacial cycle is simulated satisfactorily. Different, although not unique, PDD parameter values are required for reproducing the reconstructed sea level ~~quite well either for glacial inception or for glacial terminationbut only by use of different PDD parameter values for the different phases. Hence, those~~ at glacial inception and at glacial termination. However, PDD-online simulations which generate a plausible sea level drop at ~~inception overshoot strongly~~ glacial inception strongly overshoot thereafter the sea level drop at LGM and fail to recover to the interglacial sea level. ~~This is, for instance, true for the simulation using standard PDD parameter values.~~ PDD-online simulations ~~which recover the sea level of the Holocene produce prior, in the glacial phase, a rather flat sea level decrease and underestimate the sea level drop at LGM substantially. One triple~~ where the Holocene sea level is correctly reproduce, too little ice is simulated during glacial inception. One set of PDD parameters is found by which the sea level is simulated ~~remarkable~~ quite well during the glacial phase and at LGM. After the LGM, however, the ice volume grows further during several millennia ~~by a few~~ and subsequently the sea level ~~rise~~ at present is about 50 msle ~~too low. No universal PDD parameter values are found by which the entire glacial cycle is simulated satisfactorily with the online PDD method. The simulations~~ below observed one.

The reference simulation with the SEB approach ~~suggest~~ suggests that the relatively fast spreading of the ice sheet area at glacial inception and the snow albedo changes from dust deposition at termination are important elements for the glacial cycle evolution. ~~This study motivates further investigations on the role of dust in the climate system. Influences~~ Further simulations with the SEB approach to analyze the factors influencing snow albedo show that dust deposition has a twofold impact on snow melt. Dust deposition itself causes a reduction in snow albedo which is additionally affected by the synergy between aging of snow and impact of impurities on snow albedo. Admittedly, the influences of dust radiative forcing and dust deposition on snow ~~of ice sheet surfaces~~ over ice sheet are included in a rather simplified manner in the current CLIMBER-2 ~~simulations. Improvements are expected by using a dynamically and bio-geochemical consistent dust cycle model . The effects of interactions between the climate system and the dust cycle are seen to be variable during the Quaternary and are likely involved also in future climate change studies.~~

model version. We hope that this study will motivates further investigations on the effect of eolian dust on snow albedo for climate-ice sheet interaction.

Acknowledgements. E.B. acknowledges support by the German Climate Modeling Initiative grant PalMod. Comments by two anonymous reviewer are greatly acknowledged.

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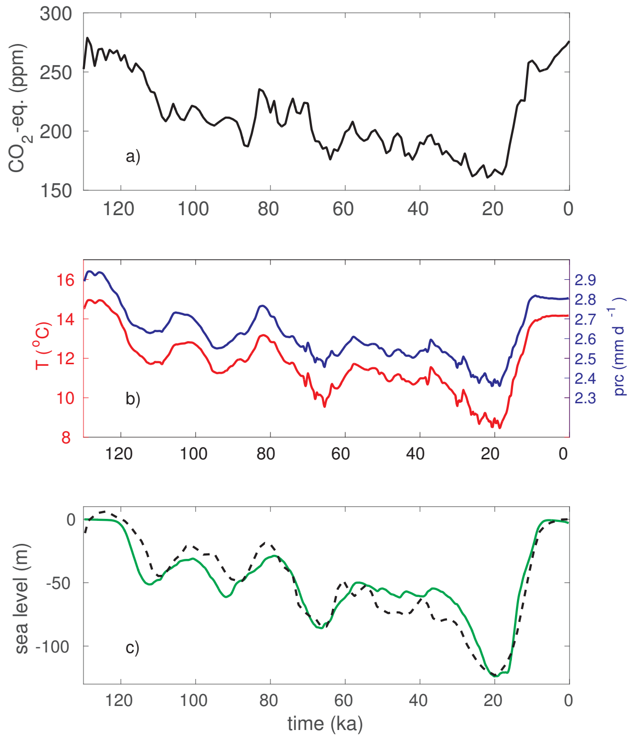


Figure 1. Reference simulation of last glacial cycle with CLIMBER-2 model coupled with SICOPOLIS model via SEB approach. **(a)** Driving equivalent CO_2 concentration, **(b, red)** global mean surface air temperature, **(b, blue)** global mean precipitation and **(c)** sea level shown by **green line** from simulated ice volume variation and by **black dashed line** from reconstructions by Waelbroeck et al. (2002).

~~Mean anomaly (m) and rms–error (r) from 130-long series for American and European ice sheets calculated from offline A_{PDD} with temperature variability (σ) and melt factors (α_S,α_I) relative to A_{SEB} as shown in Fig. 4. Note, m is smallest for both ice sheets with standard PDD parameter values (bold) and r is about factor three larger for American ice sheet than for European ice sheet. σ (α_S,α_I) m r m r 3(5, 24) -0.007 0.023 0.006 0.007 3(5, 20) -0.011 0.023 0.002 0.005 3(5, 16) -0.015 0.024 -0.003 0.005 3(5, 12) -0.019 0.025 -0.007 0.007 3(5,8) -0.023 0.027 -0.011 0.009 5(3, 12) 0.008 0.021 0.008 0.010 5(3, 10) 0.003 0.021 0.004 0.008 0.022 0.0085(3,6) -0.006 0.024 -0.003 0.008 5(3,4) -0.010 0.026 -0.007 0.010~~

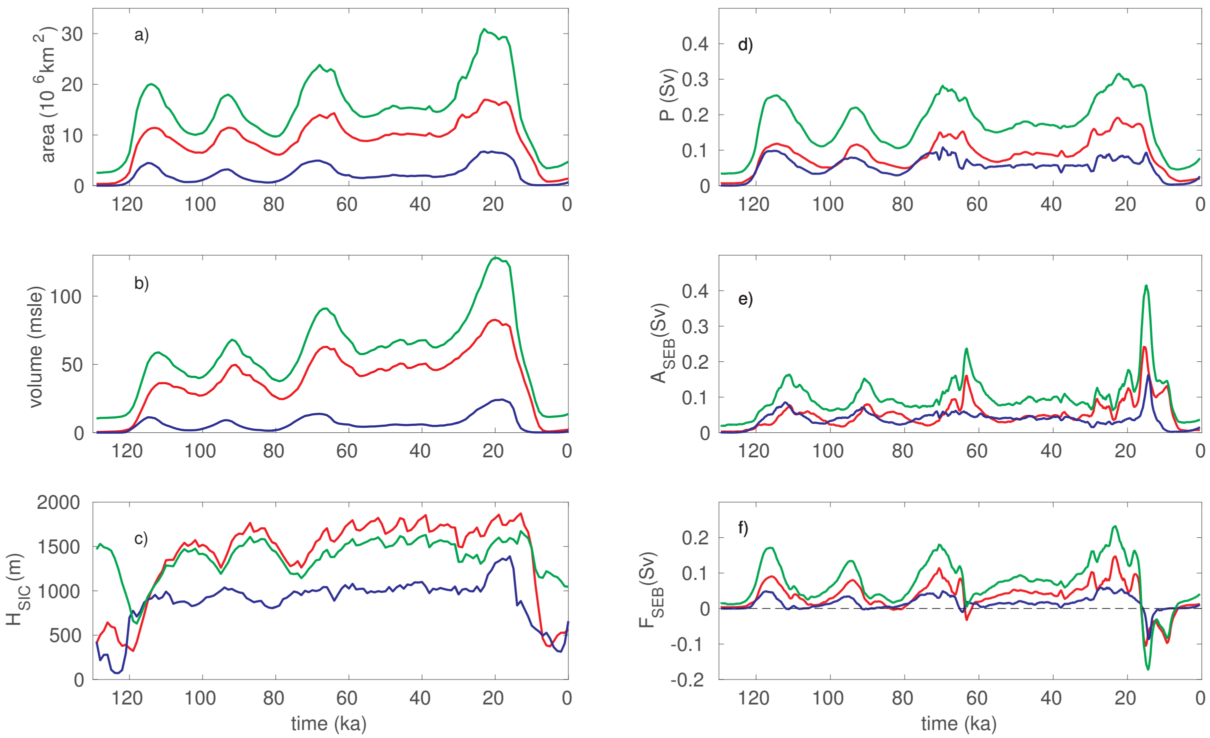


Figure 2. Glacial cycle series from reference simulation for NH total **(green lines)**, American **(red lines)** and European **(blue lines)** ice sheets showing **(a)** ice-covered area, **(b)** ice sheet volume, **(c)** average ice sheet thickness, **(d)** accumulation, **(e)** SEB-derived ablation and **(f)** surface ice mass balance.

Table 1. Summary of PDD parameters inducing minimum rms–errors between series of offline A_{PDD} and A_{SEB} for American and European ice sheets covering entire glacial cycle (see Fig. 5), glacial phase and glacial termination (see Fig. 6).

interval ka	σ °C	America $(\alpha_S,\ \alpha_I)$ $\mathrm{mm\,^\circ C^{-1} d^{-1}}$	Europe $(\alpha_S,\ \alpha_I)$ $\mathrm{mm\,^\circ C^{-1} d^{-1}}$
130 – 0	3	(10, 16)	(5, 16)
130 –30	3	(8, 16)	(5, 16)
30 – 0	3	(10, 16)	(6, 16)
130 – 0	5	(5, 12)	(3, 14)
130 –30	5	(4, 10)	(4, 6)
30 – 0	5	(6, 12)	(3, 16)

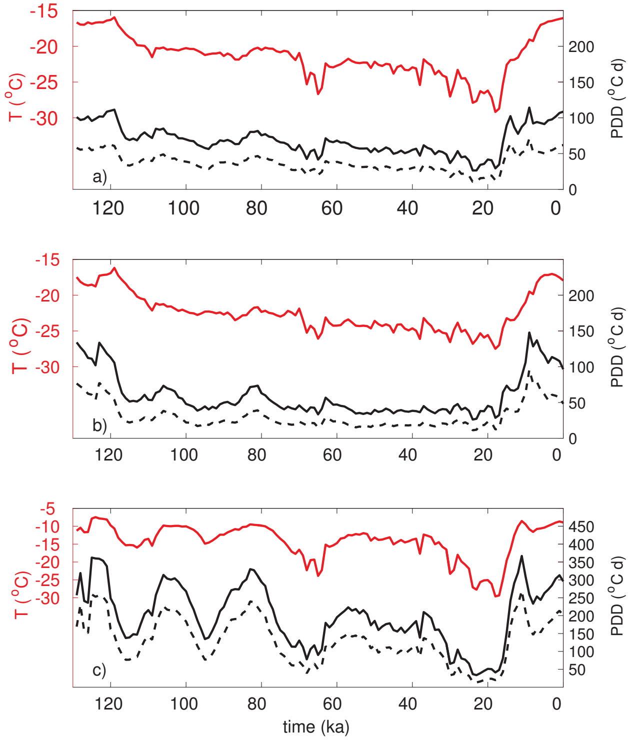


Figure 3. Glacial cycle series averaged over **(a)** NH total, **(b)** American and **(c)** European ice sheets showing on **left axes (red)** surface air temperature and on **right axes (black)** PDD values (Eq. 2) computed with σ=3 °C **(dashed lines)** and with σ=5 °C **(continuous lines)**.

Table 2. Ablation (in Sv) from NH total, American and European ice sheets at glacial termination (16–14 ka) where maximum in A_{SEB} at 15 ka for NH is closely reproduced with offline PDD method using σ=3 °C and (α_S, α_I)=(6, 19) in mm °C^{-1}d^{-1} (see Fig. 7). But maxima in ablation (**bold**) occur a millennium earlier in A_{SEB} than in A_{PDD} for NH total and American ice sheets. Note, while the total ablation at 15 ka from both method are close, A_{SEB} in America is underestimated and A_{SEB} in Europe is overestimated by the PDD method.

time	NH		America		Europe	
ka	A_{SEB}	A_{PDD}	A_{SEB}	A_{PDD}	A_{SEB}	A_{PDD}
16	0.37	0.32	**0.25**	0.18	0.07	0.08
15	**0.41**	0.42	0.24	**0.19**	0.12	0.16
14	0.38	**0.45**	0.16	0.14	**0.18**	**0.24**

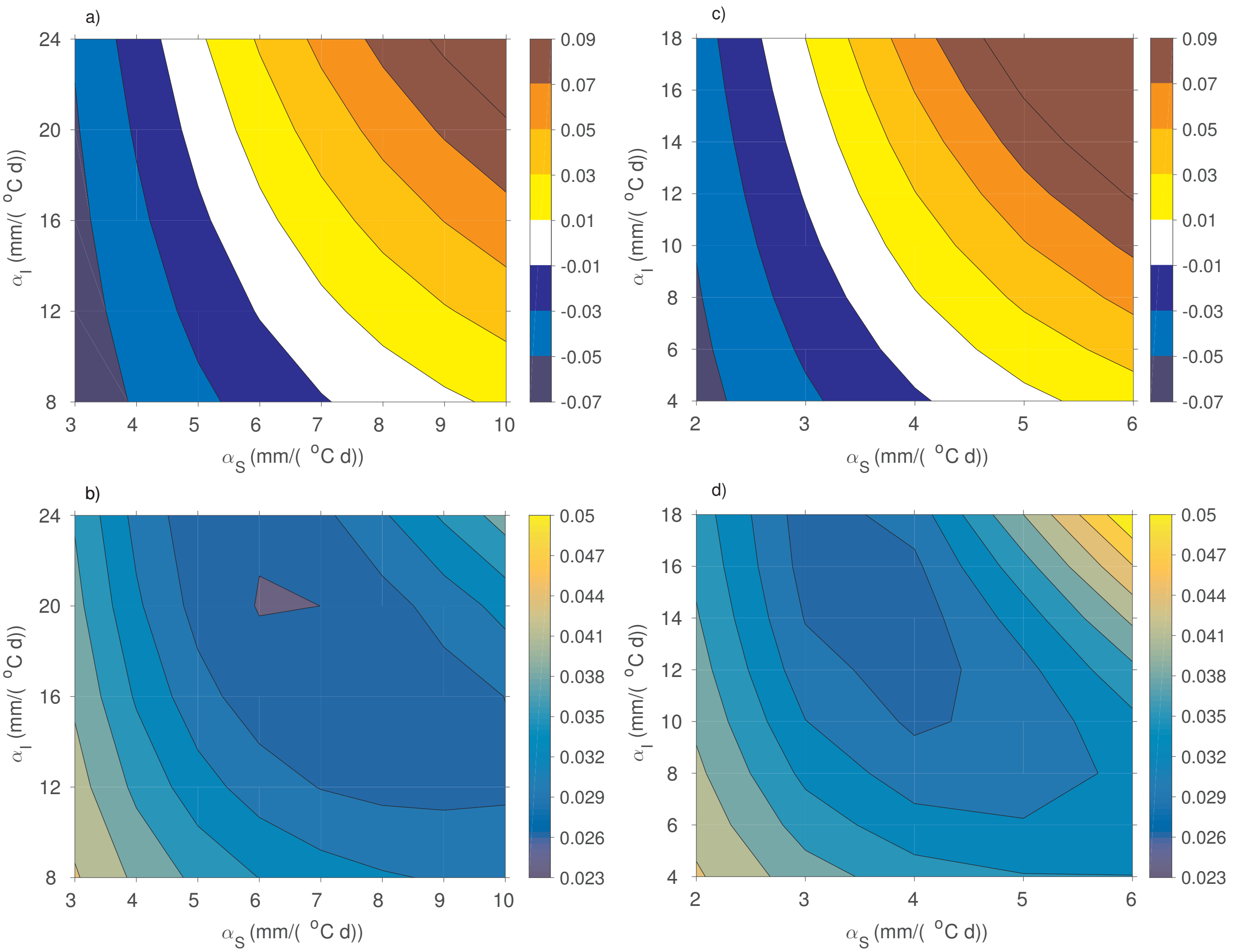


Figure 4. ~~Glacial cycle series of ablation for~~ Bivariate distributions in **(a, c)** ~~American~~ of mean anomaly m and in **(b, d)** ~~European ice sheets comparing ensembles~~ of ~~offline PDD-derived ablation~~ rms–error r (~~colored lines~~in Sv) ~~with SEB-derived~~ from 130 ka-long NH ablation series as function of ~~reference simulation~~ α_S and α_I using ensemble simulations of A_{PDD} (~~black dashed line~~offline) relative to A_{SEB}. ~~PDD-derived ablation use~~ A_{PDD} simulations in **(a, b)** use σ=3 °C ~~, α_S=5and five different α_I values~~ and in **(c, d)** σ=5 °C ~~, α_S=3and five different α_I~~ which involves larger values ~~. The different for~~ (α_S, α_I ~~values are shown by different colors~~) in ~~each panel. Note, **red lines**~~ **(a, b)** than in ~~(~~**(c, d)** ~~**are obtained with standard PDD parameter values**~~. See Tab. ~~??~~ 1 for ~~mean anomalies and rms–errors~~ PDD parameter values at minimum of rms–error in **(b, d)**.

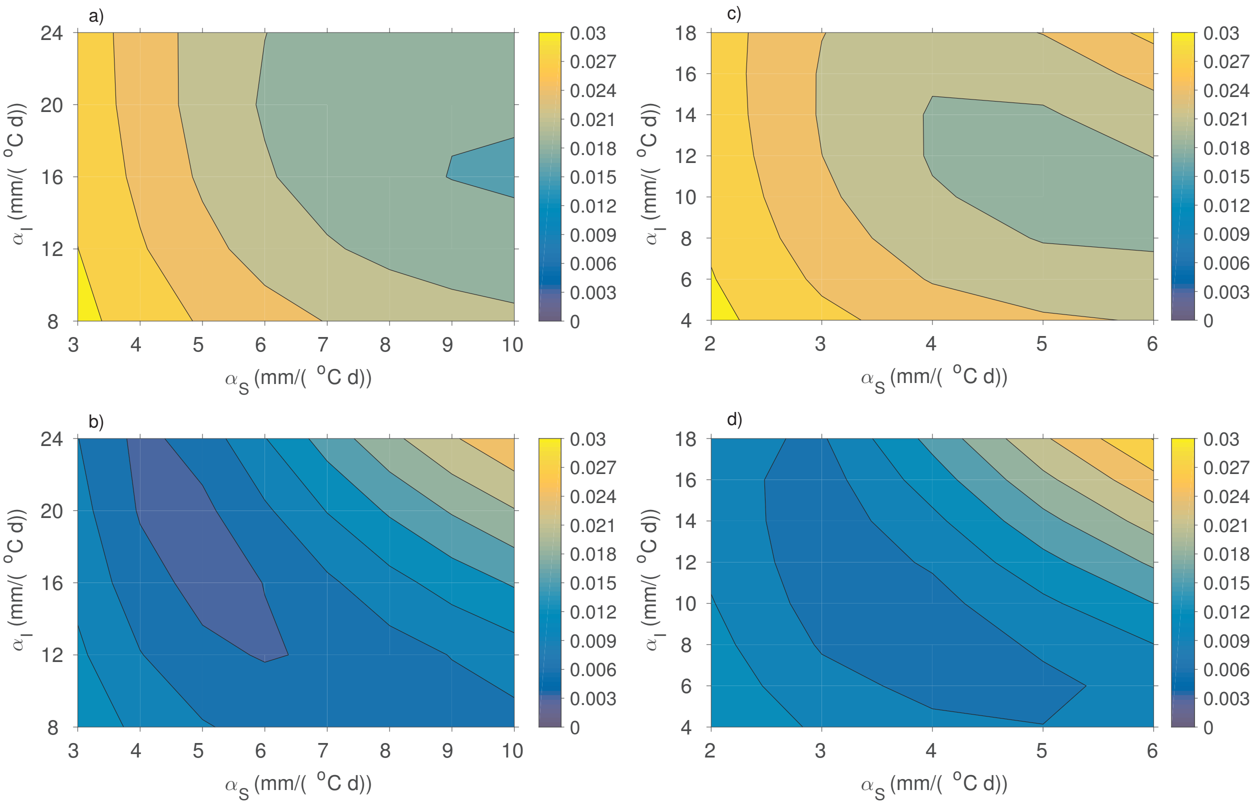


Figure 5. Bivariate distributions of rms–error r (in Sv) ~~as function of α_S and α_I where r is~~ from ~~ensemble simulations of A_{PDD} (offline) relative to A_{SEB} using entire~~ 130 ka-long ablation series ~~. Calculations of r~~ as in Fig. 4 but separately for **(a, c)** for American ice sheet ~~and~~ in (~~b~~**a**, ~~d~~**c**) and for European ice sheet in **(b, d)**. ~~Ensemble simulations of~~ A_{PDD} ~~use~~ simulation in **(a, b)** with σ=3 °C and in **(c, d)** with σ=5 °C~~which involves larger values for (α_S, α_I) in (a, b)than in (c, d)~~. See Tab. 1 for PDD parameter values at minimum of rms–error in each panel.

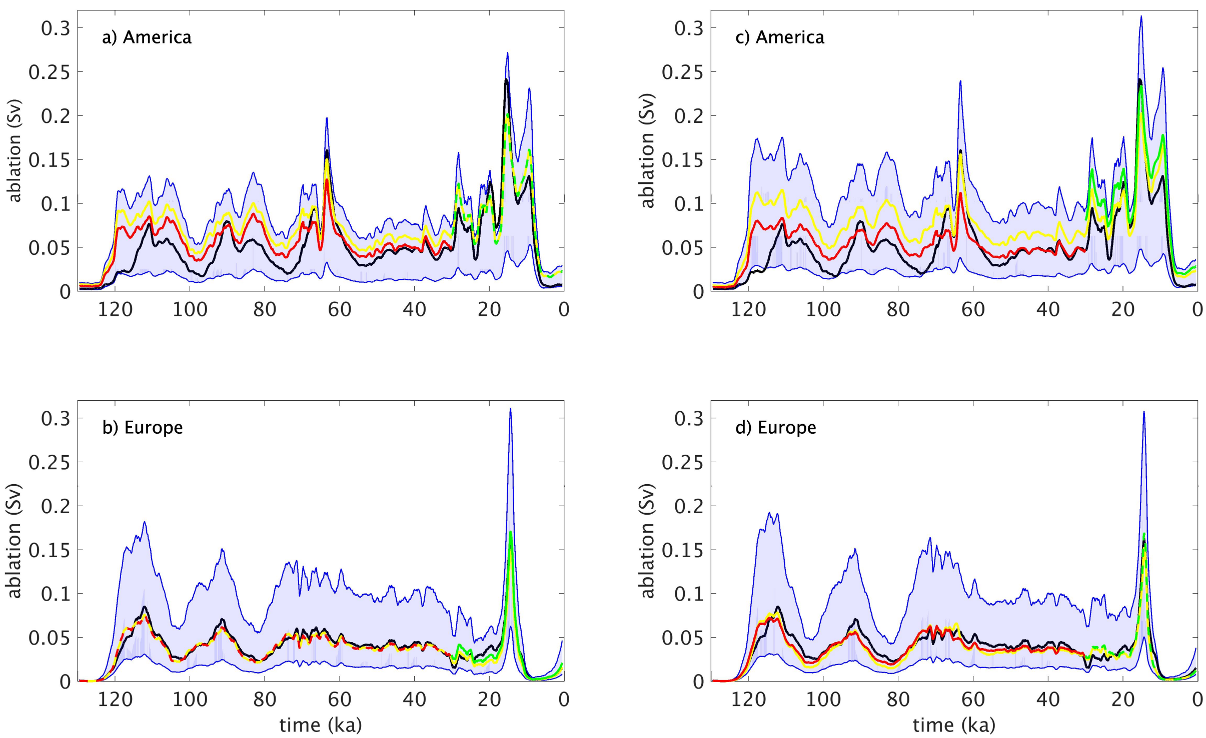


Figure 6. Glacial cycle series of ablation in **(a~~- d~~, c)** ~~as~~ for American and in ~~Fig. 4. **Black lines**~~**(b, d)** ~~are A_{SEB}~~ for European ice sheets comparing offline A_{PDD} from ~~reference simulation and~~ full range of ensemble simulations **(blue shaded areas)** ~~show full ranges~~ with A_{SEB} of ~~offline~~ reference simulation **(black lines)**. **(a, b)** shows A_{PDD} ~~from ensemble simulations~~with σ=3 °C and **(c, d)** with σ=5 °C. PDD parameter values (σ, (α_S, α_I)) in (°C, (mm °C^{-1} d^{-1})) used for lower and upper boundary are in **(a, b)** (3, (3,8)) and (3, (10,24)), respectively, and in **(c, d)** (5, (2,4)) and (5, (6,18)), respectively. Further ~~PDD-derived ablation~~ A_{PDD} series are shown ~~by~~ which minimize rms–errors for American and European ice sheets ~~minimize~~ over 130–0 ka **(yellow lines)**, 130–30 ka (**red lines**) and ~~over~~ 30–0 ka (**green lines**). PDD parameter values used in (**a**) ~~in~~ **yellow**: (3, (10,16)), **red**: (3, (8,16)) and ~~in~~ **green**: (3, (10,16)), in (**b**) ~~in~~ **yellow**: (3, (5,16)), **red**: (3, (5,16)) and ~~in~~ **green**: (3, (6,16)), in (**c**) ~~in~~ **yellow**: (5, (5,12)), **red**: (5, (4,10)) and ~~in~~ **green**: (5, (6,12)) and in (**d**) ~~in~~ **yellow**: (5, (3,14)), **red**: (5, (4,6)) and ~~in~~ **green**: (5, (3,16)). See Tab. 1 for summary of PDD parameter values at minima of r.

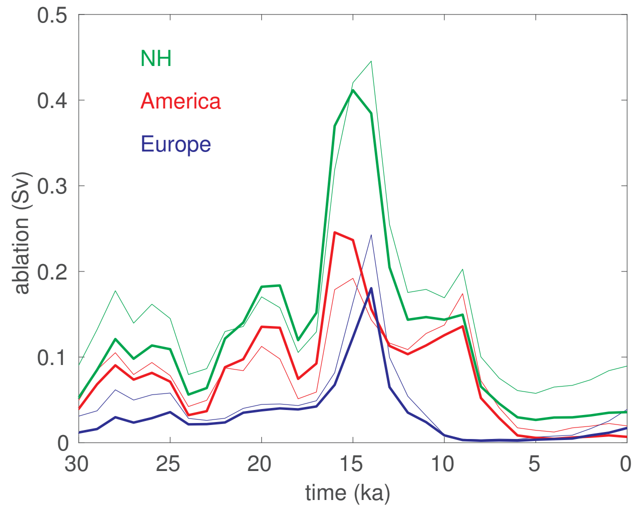


Figure 7. Ablation series from interval 30–0 ka for NH total (**green lines**), for American (**red lines**) and for European (**blue lines**) ice sheets showing A_{SEB} of reference simulation by **thick lines** and offline A_{PDD} by **thin lines**. A_{PDD} with ~~parameter values~~ σ=3 °C and $(\alpha_S\ \alpha_I)$=(9, 16) mm °C^{-1} d^{-1} is compatible with A_{SEB} at 15 ka. See Tab. 2 for peak ablation values.

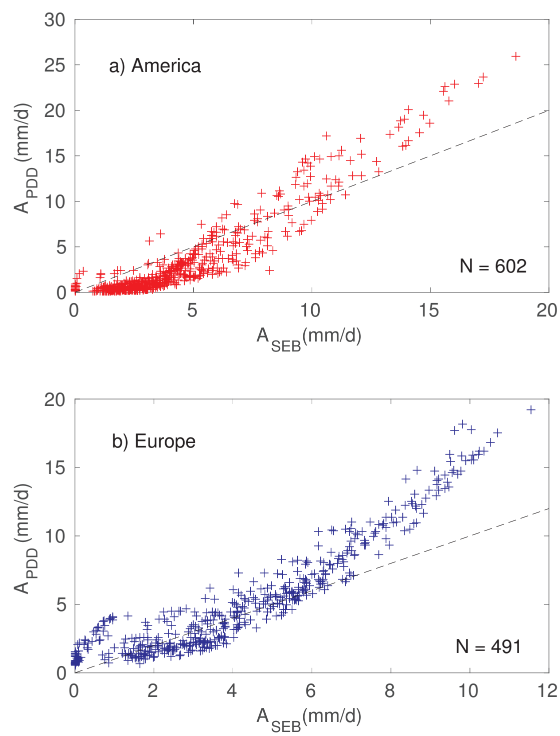


Figure 8. Scatter diagram of ablation rates by PDD method (offline) and SEB method from **(a)** American and **(b)** European ice sheets at 15 ka with equal NH ablation from both methods as shown in Fig. 7. N is number of SICOPOLIS grid cells with non-zero ablation rate.

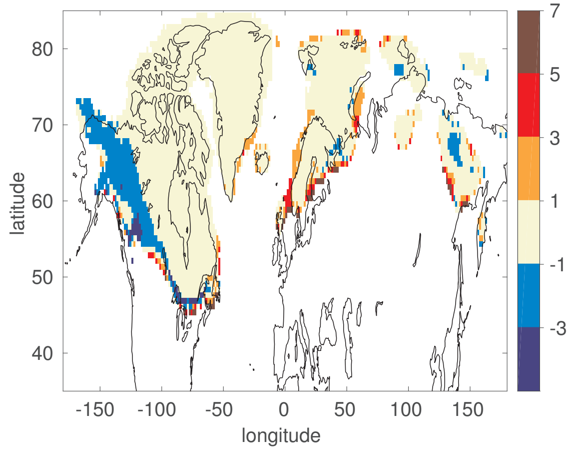


Figure 9. Geographic distribution of ablation differences (in $\mathrm{mm\,d^{-1}}$) obtained from PDD offline simulation using σ=3 °C and $(\alpha_S\ \alpha_I)$= (9, 16) $\mathrm{mm\,°C^{-1}\,d^{-1}}$ relative to reference simulation at 15 ka, where NH total ablation from PDD and SEB methods agree closely (see Fig. 7). Thin black lines are present day ~~topography~~coastlines.

Table 3. Global surface air temperature (T) and sea level (sl) at 21 ka (LGM) and 0 ka (MOD) from reference simulation (RS) compared with PDD-online simulations using σ in °C and $(\alpha_S,\ \alpha_I)$ in $\mathrm{mm\,°C^{-1}d^{-1}}$. PDD-online simulations are selected to fulfill the target windows glacial inception (I3, I5), glacial termination (T3, T5) and LGM (L3, L5) as shown in Fig. 10. Note, simulation I5 uses standard PDD parameter values (**bold**).

name	σ	(α_S, α_I)	T (°C)		sl (m)	
			LGM	MOD	LGM	MOD
RS			8.7	14.2	-122	-3.3
I3	3	(5, 16)	7.1	10.6	-263	-189
T3	3	(9, 16)	9.2	14.4	-94	-0.5
L3	3	(7, 20)	8.7	13.9	-121	-7.5
I5	**5**	**(3, 8)**	7.1	9.2	-255	-223
T5	5	(6, 8)	10.5	14.4	-31	-0.3
L5	5	(4, 7)	8.5	13.1	-120	-45

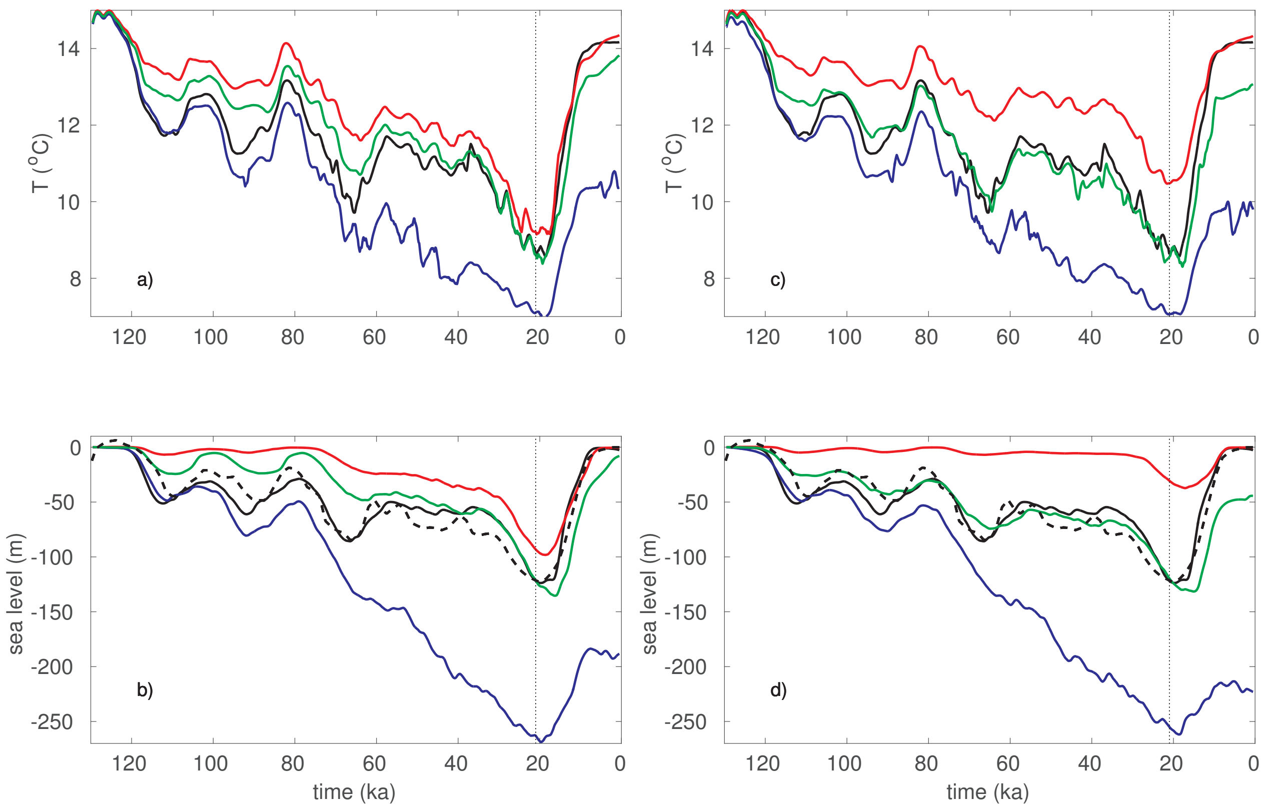


Figure 10. Glacial cycle simulations with online PDD method (**colored lines**) compared to reference simulation (**black continuous line**, cf. Fig. 1). **(a, c)** show global mean temperature and **(b, d)** show sea level together with reconstructed sea level **(black dashed line)**. PDD-online simulations in **(a, b)** with σ=3 $^\circ$C and in **(c, d)** with σ=5 $^\circ$C reproduce climate closely either at inception (**blue lines**) or at termination (**red lines**) or at LGM (**green lines**). Melt factors (α_S, α_I) in $\mathrm{mm}\,^\circ\mathrm{C}^{-1}\,\mathrm{d}^{-1}$ used in **(a, b)** for simulations I3 (**blue**), T3 (**red**) and L3 (**green**) are (5,16), (9,16) and (7,20), respectively, and used in **(c, d)** for simulations I5 (**blue**), T5 (**red**) and L5 (**green**) are (3,8), (6,8) and (4,7), respectively. Note, simulation I5 uses standard PDD parameters and generates excessive cooling without recurrence to Holocene climate. Vertical dotted line marks 21 ka. See Tab. 3 for global mean T and sea level at 21 and 0 ka.

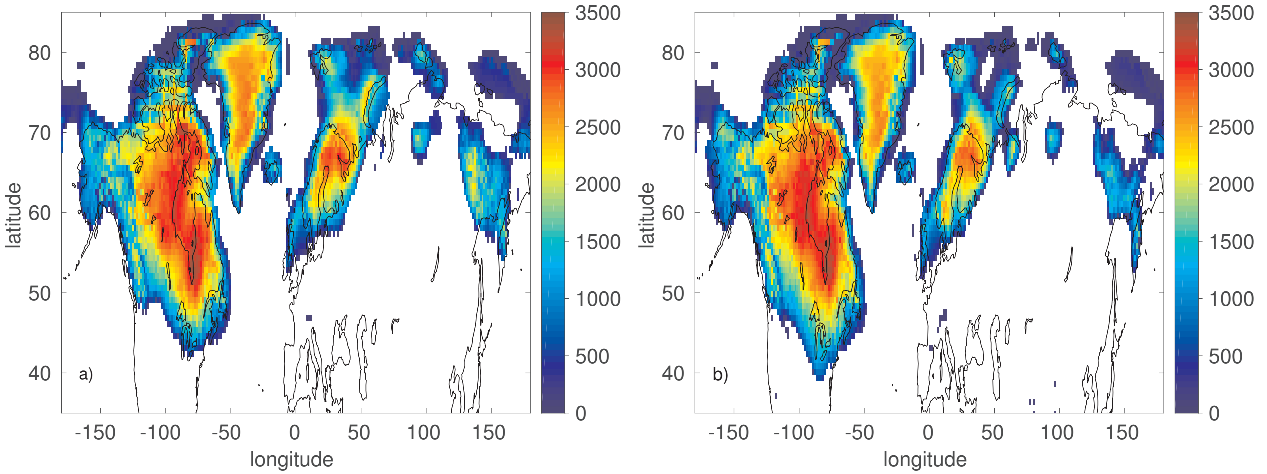


Figure 11. Simulated ice sheet thickness (in m) at ~~15~~21 ka from **(a)** reference and **(b)** PDD-online simulation L3 which fulfills the LGM target window (see Tab. 3 and Fig. 10 for PDD parameter values). Thin black lines are present day ~~topography~~coastlines.

Table 4. Global surface air temperature (T) and sea level (sl) at 21 ka (LGM) and 0 ka (MOD) from reference simulation (RS) with dust deposition ($Dust$), pure snow aging (Age_p) and aging of impure snow (Age_i) compared with online simulations using in C1 pure snow without pure snow aging (where simulation collapsed), in C2 snow with dust deposition without snow aging, in C3 pure snow with pure snow aging and in C4 snow with dust deposition and only pure snow aging. Note that simulation C1 collapsed.

name	$Dust$	Age_p	Age_i	T (°C)		sl (m)	
				LGM	MOD	LGM	MOD
RS	Y	Y	Y	8.7	14.2	-122	-3.3
C1	N	N	N	–	–	–	–
C2	Y	N	N	5.9	8.8	-322	-276
C3	N	Y	N	5.4	8.5	-356	-325
C4	Y	Y	N	7.2	10.7	-259	-151

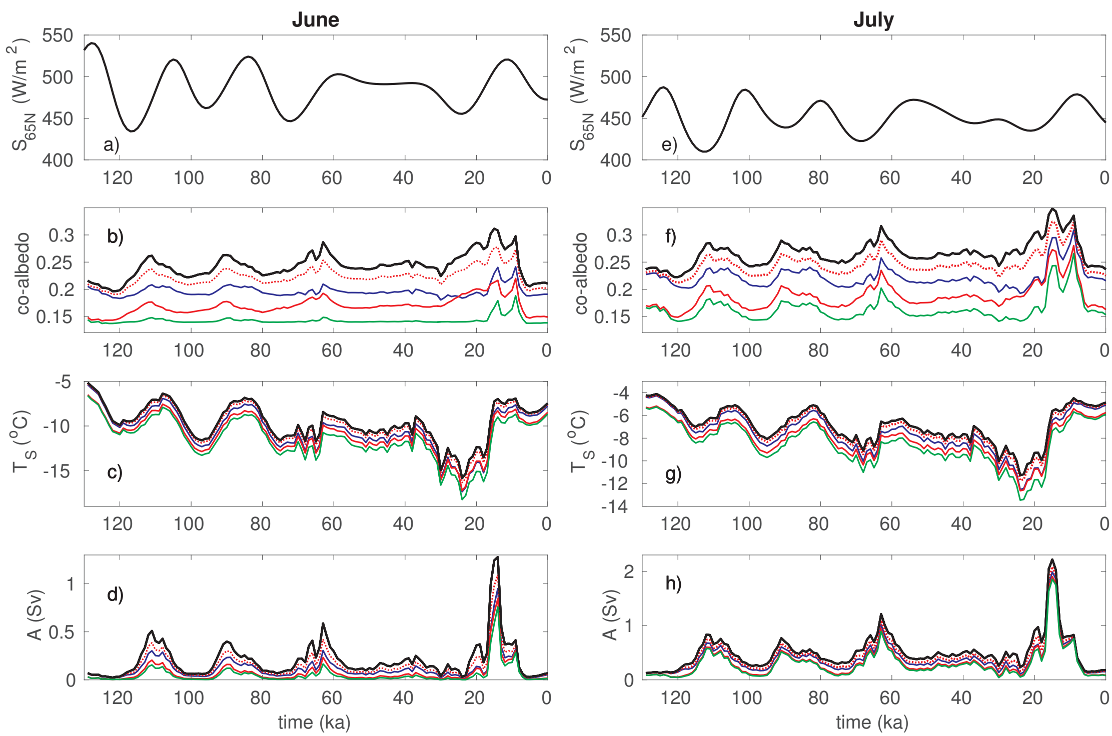
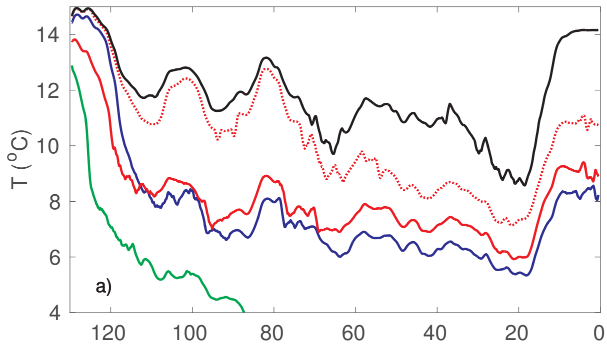


Figure 12. ~~Comparison of characteristic dependencies of fine-resolution ablation rates~~ Monthly mean time series for June (~~in) showing in~~ ~~(~~**a - d**) and July (**e - h**~~A_{SEB} as function~~) of ~~SEB~~ top-of-atmosphere insolation at 65 °N and ~~P,~~ of simulated averages over NH ice sheets of co-albedo at surface in (~~(~~**b**~~)~~, **f**~~A_{PDD} (offline)~~)~~as function of PDD and P and~~ , surface temperature in (~~(~~**c**~~)~~, **g**~~A_{PDD} (offline)~~)~~as function of SEB~~ , and ~~P~~ablation in (**d, h**). ~~A_{SEB}~~ **Black lines** represent references of standard model and ~~A_{PDD}~~ **colored lines** are ~~from NH ice sheets at 15where NH total ablation from~~ offline simulations with modified snow albedo used in SEB approach ~~and PDD offline method agree closely~~ (see ~~Fig~~Tab. ~~7~~4) showing C1 with pure snow and no snow aging in **green**, C2 with dust deposition and no snow aging in **red**, C3 with pure snow and snow aging in **blue** and C4 with dust deposition and only pure snow aging in **red, dotted**. Note ~~that~~ y-scaling in (~~(~~**c**~~)~~, **g**~~A_{PDD} values between 5~~) and ~~15vary irregular with corresponding SEB values. N is number of ice-covered grid cells~~in (**d, h**) differ.



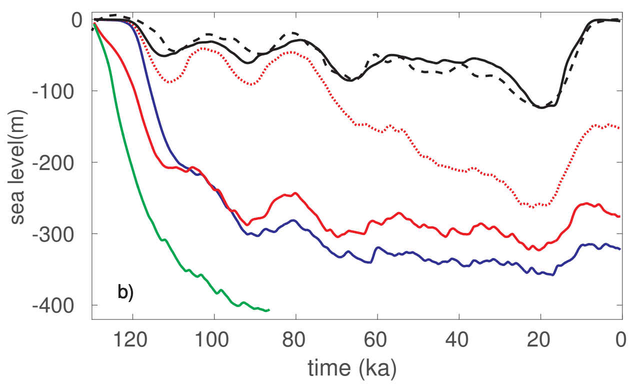


Figure 13. Glacial cycle series of temperature (**a**) and sea level (**b**) from online simulations with modified snow albedo as in Fig. 12.