Response to the review of the manuscript "Analysis of the Surface Mass Balance for Deglacial Climate Simulations" submitted to The Cryosphere.

We thank both reviewers for their comprehensive reviews and very useful suggestions to improve the manuscript. We have addressed all of their comments and believe that the changes will significantly improve the manuscript. In the following, reviewer comments are highlighted in blue, author responses in black.

Anonymous Referee #2

Major comments:
My only slightly larger comment has to do with a lack of discussion and references of literature on atmospheric circulation changes at the LGM and through the deglaciation. You mention several times that the atmospheric circulation changes over this time period, but no previous studies are cited. Atmospheric circulation changes is arguably not a main focus of your study, but it is a nice gesture to acknowledge work that has been done on this topic in the last several years, not least since it is relevant for your overall modeling approach and for the interpretation of your results. It is generally accepted that the North Atlantic jet stream and storm track was quite different at the LGM than it is today. Specifically, modeling simulations suggest that the large scale circulation was more zonally oriented than today. Several explanations for this has been proposed, but the most recent explanation (that links all previous interpretations into one theory of the zonal North Atlantic jet stream and stormtrack is described in:
https://www.sciencedirect.com/science/article/abs/pii/S0012821X20300248
A recent overview paper on the PMIP4 LGM simulations:
https://cp.copernicus.org/preprints/cp-2019-169/
Circulation changes in the North Atlantic and over Greenland over the last deglaciation: https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2017GL074274
https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2015GL066042
https://cp.copernicus.org/articles/15/1621/2019/
We fully agree with the reviewer and thank him for referring to the literature. The atmospheric circulations plays an important role in our simulations and we find similar changes in the atmospheric circulation during the LGM, as described in Löfverström and Lora (2017). In a study currently under preparation for publication, we also find that uncertainties in the ice sheet reconstructions lead to significant differences in the atmospheric circulation. As we focus on the SMB and drivers of SMB changes in the current manuscript, we will mainly touch on these processes in the revised manuscript (see detailed response below).

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Line comments:
Page 1, line 3: comprehensive -> high complexity?
We change to state-of-the-art as we believe that these models are both comprehensive (in their sub-model components) and have a high complexity.

Page 1, line 5: "downscale atmospheric processes" I assume that you mean radiation?
In this case we downscale the energy balance at the surface, more specifically the SMB, accumulation and melt, not just radiation. We changed the sentences to *"An energy balance model (EBM) is used to calculate and downscale the SMB on higher spatial resolution and allows the resolution of SMB variations due to topographic gradients not resolved by the ESM"* for clarity.

Page 1, line 6: Here and elsewhere. Maybe more appropriate to say "satellite era" or "recent past" instead of historical period. The latter is used to describe 1850 – present in CMIP6.

This is correct, but they are also labeled as historical in the CMIP experiments. We believe that defining the years of our analysis and introducing the period as historical is sufficient here.

Page 1, line 7: “from regional modeling” — add that this is constrained by reanalysis data at the lateral boundaries
We did not add this in the abstract, but into the introduction, as it is an important information that we did not mention throughout the manuscript. Thanks for the suggestion.

Page 1, line 10: Specify that you refer to Northern Hemisphere summer insolation
Thanks for pointing this out. We changed this.

Page 1, line 19: Here is a relatively recent, comprehensive review that may be worth mentioning in this context: https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2018RG000600
Thanks for pointing us to this review. We added the reference to this review in the beginning of this section in response to another comment.

Page 2, line 35-36: Good place to mention some work on atmospheric circulation changes in the last deglacial period
Thanks. As mentioned before we extended this paragraph and included some information on circulation and climate changes as well as some of the proposed references: *“The collapse of the ice sheets also resulted in significant changes in the atmospheric and oceanic circulation as well as associated climate features (e.g. Lofverstrom et al. 2017). Orographic changes, induced by the decrease of the Laurentide and Cordilleran ice sheets, led to changes in the Northern Hemispheric stationary waves and thereby the North Atlantic jet stream, which significantly affected the northern hemispheric climate (e.g. changes in precipitation and temperature patterns; Andres and Tarasov, 2019; Lofverstrom et al. 2020, Kageyama et al. 2020).”*

Page 2, line 36: “Atlantic Meridional Overturning Circulation”
Thanks. We will change this.

Page 2, line 42: “Mainly” is repeated. Maybe change the latter to “employed”?
Thanks! Changed.

Page 3, line 53: Two kind -> Two kinds
Thanks. Changed.

Page 3, line 54: Again, not sure if “historical” is the best word here
Please see comment above.

Page 3, line 56: SMBs to SMBs — awkward wording
We rephrased to *“...compare obtained SMBs to output from the regional climate model MAR”.*

Page 3, line 60: Meaning here is not clear. How do you use an EBM to downscale SMB? Do you mean that the radiation from the EBM is downscaled, or something else?
We rephrased the sentence to *“We use an EBM to calculate and downscale”*... Surface fields from the MPI-ESM simulation are used to calculate the SMB, which is then interpolated on a higher resolution ice sheet topography. Note that we not just correct radiation but also precipitation, pressure, etc.

Page 3, line 60: What influence of clouds? SW radiation? LW radiation?

We are not sure what is meant here, as clouds are not mentioned in this sentence. We assume that the reviewer is talking about Line 69, where we can add *"The main improvements are 1) an advanced broadband albedo scheme considering aging, snow depth dependency, and the influence of the cloud coverage on the thermal radiation,..."*

Page 3, line 70: Meaning of "movement of the snow/ice properties and compaction" is not clear

We rephrased to "the consideration of snow compaction and the vertical advection of snow/ice properties".

Page 3, line 71: Explain what elevation classes are

Page 3, line 72: It was technically Lipscomb et al, 2013 that introduced elevation classes in the model https://journals.ametsoc.org/jcli/article/26/19/7352/34179/Implementation-and-Initial-Evaluation-of-the

We addressed both comments by changing: *"We further adopted the scheme by introducing elevation classes, following Lipscomp et al. (2013). Calculating the SMB on fixed elevation classes, has the advantage that the model becomes computationally cheaper, as the SMB is computed on the native and coarse resolution atmospheric grid instead of the high-resolution ice sheet topography."*

Page 3, line 80: How is the lapse rate for these factors determined? Also, do you use the same lapse rate in summer and in winter? If yes, is this a valid assumption? What is the sensitivity to this choice?

The lapse rate for the corrections is constant over time and space, which is a caveat in our method. As we are using a global model it is challenging to incorporate different lapse rates for summer and winter, as it would require lapse rate values that depend on the location (e.g. southern and northern hemisphere). As we have a very different ice sheet configuration during the LGM as compared to present day we would not like to make variables location dependent. Also, it is not certain how these values would change for different climates and over different ice sheets. Here, we use values based on present-day estimates with a bias towards summer values (see also comment to Page 4, line 87).

Page 4, line 85: Not sure if I understand this description. How do you conserve water if this is the case?

Note, that we only use the MPI-ESM output as forcing for the EBM. Hence, we do not need to conserve water and it is irrelevant here. In a fully coupled simulation, where interactive ice sheets are included, this would lead to discrepancies but can be corrected through run-off.

Page 4, line 87: This lapse rate is quite a bit lower than the ICAO value of -6.5 K/km. Explain this choice, and did you test the sensitivity to this value?

The lapse rate is used in the model as tuning parameter and we have chosen a value that results in realistic SMBs for the present-day Greenland ice sheet. In the current version of the model it is considered as relatively low (4.6K/km), which certainly is at the lower end for Greenland temperatures. However, it has been shown that over ice sheets near-surface lapse rates are significantly lower than the ICAO values, specifically during summer (e.g. Gardener et al., 2007). As we only use one lapse rate for the entire year and over all ice sheets we have chosen a relatively low value that still lies within observational values.

Page 4, line 97: Technical detail but what happens to (latent and sensible) energy fluxes if the atmosphere model simulates liquid precipitation, but the height corrected temperature is below freezing (and vice versa)?

The energy fluxes are calculated from the height corrected variables, so this should not be an issue here. We added *"Latent and sensible heat fluxes are parameterized and calculated from the height-corrected variables."*

Page 5, line 136: It is a bit clunky to define WE at the end of the sentence. Can this definition be moved earlier in the sentence?
Thanks for pointing this out. We moved this part of the sentence further up.

Page 5, line 141: brighten -> increase (?)
Thanks, we changed this.

Page 6, line 165: “Once: : :” — Meaning here is not clear. Do you mean that it is removed?
We rephrased the entire paragraph for clarity according to the comments of reviewer #1.

Page 6, line 180: Technical detail, but please specify that this is the horizontal resolution
Changed.

Page 7, line 189: Acronym “ka BP” is not defined
According to the comments of the first reviewer we changed all the year definitions throughout the entire manuscript.

Page 7, line 195: Not sure if I fully understand this modeling strategy. Do you run 10 years with a constant forcing before updating the boundary conditions, or do you advance the orbital clock, topography, etc. by 10 years every model year?
The first! In our setup the model is run synchronous in time but the forcing fields are updated only every 10 years. We changed ‘updated’ to ‘prescribed’ to clarify.

Page 7, line 196: What happens to vegetation in areas that are deglaciated?
We added a sentence to explain this: “*Land cells that are deglaciated are covered with the same vegetation form as the adjacent grid cells.”*

Page 7, line 203: “it is a good proxy” –> "hence, it is a proxy for..."
We changed this.

Page 8, line 214: “ for a long enough adjustment” is a bit colloquial
We changed to ‘sufficient’.

Page 8, line 232: Why did you use ERA-Interim instead of the newer ERA5? Do you expect different results with a newer reanalysis product?
We used ERA-Interim, as the regional models used for comparison here are all forced with ERA-Interim. Using the same background climate allows us to assess the uncertainties due to the downscaling techniques (regional modeling vs. EBM_ERAI). The derived SMB can only be as good as the forcing. As observations and assimilation over the Arctic regions are still sparse we do not expect a significantly better climate for another reanalysis product.

Page 9, line 250: : : :historical climate conditions -> recent past
See earlier comment.

Page 9, line 254: remind the reader that this is the "coarse" and "low resolution" simulations
We added a reminder.

Page 9, line 264: Say something about how these numbers change over Greenland (latitudes of interest). Should be a factor of 2-3 difference from the equator
Thank you - it is a good idea to write the values for Greenland instead.

Page 10, line 286: Good reference https://tc.copernicus.org/articles/13/1547/2019/
Thanks for this reference. We added this reference and changed the paragraph according to the suggestions by reviewer #1.

Page 10, line 287: Sentence starting “The overestimation” is a bit clunky and can be simplified
Changed.

Page 11, line 316: What figure(s) are you discussion here?
We added a reference to Fig. 1 and 2.

Page 12, line 344: Good place to cite some work on atmospheric dynamics /circulation in the deglaciation. See major comment
Thanks, we did that! See comments above.

Page 12, line 354: shrinks -> recedes
Thanks! Changed.

Page 12, line 357: Further, it points towards the fact -> Further, it suggests
Thanks.

Page 13, line 380: typo: his -> its (?)
Yes.

Page 14, line 416: Even though the AMOC probably plays an important role for this response, it is the atmosphere that primarily interacts with the ice sheets. I would suggest extending this discussion with changes in the atmospheric circulation in mind, and perhaps cite a few papers that have looked at these interactions before
This is true, but we do believe that the AMOC changes are the trigger. Slowdowns of the AMOC lead to a significant cooling over the North Atlantic and the adjacent regions. Hence, they drive the changes in the surface temperatures that affect the SMB changes. All of this interaction is of course not possible without changes in the atmosphere. We tried to clarify this chain of processes and added references. We specifically added *“Another possible contributing factor to the pronounced SMB and ELA variability over the northern hemispheric ice sheets during this time period are changes in the atmospheric circulation. Lofverstrom et al. (2017) found that elevation changes of the North American ice sheet around the saddle collapse, defined by the separation of the Laurentide and Cordilleran ice sheets, caused significant changes in the stationary wave patterns. An amplifying factor for atmospheric circulation changes is the southward extension of the sea-ice cover due to the AMOC slowdown and reduced North Atlantic sea-surface temperatures. Such changes have a significant influence on downstream precipitation, evaporation and temperature patterns over the North Atlantic and adjacent areas.“ in the end of this paragraph.*

Page 15, line 467: What about regional and large scale atmospheric circulation?
We added feedbacks due to the ice sheet height, which includes atmospheric circulation changes.

Page 15, line 468: You could cite this paper when talking about other feedback processes: https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2018RG000600
Thanks, we added this reference here.

Page 16, line 491: Can you end with a slightly more comprehensive future outlook? Where do you want to take this in the future, and how will this new modeling capability be used in e.g. simulations of the future climate evolution, and/or other paleo-climate states?
We added some information of the future path of our research here: *“Utilizing the SMB data set presented here as forcing for ice sheet model simulations will allow for an investigation of ice sheet dynamics during the last deglaciation. In the future, we will utilize the EBM in simulations with an interactive ice sheet model, which is currently employed within the MPI-*

ESM setup in the scope of the project PalMod (Latif et al., 2016, Ziemen et al. 2019). This will allow to investigate feedback processes between ice sheets and the other climate components (see e.g. Fyke et al., 2018, for a recent review). It will also allow to investigate processes and test hypotheses arising from the deglaciation simulations for other climates, such as e.g. the last glacial inception, Marine Isotope Stage 3 as well as the future.“

Table 2: This simulation contributed to CMIP6
Thanks. We changed this.

Figure 1: Here and elsewhere. Spectral colorbars are bad for people with color blindness. Please us a non-spectral color scale if possible
We have revised all figures and changed the colorbar.

Figure 4: Here and elsewhere. The SMB colorscale is a but crowded. If possible, use fewer intervals.
We have revised all figures and changed the labels, according the ones used in van Kampenhout et al., 2019.