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

We thank the reviewer for reviewing our manuscript a second time and his detailed explanations where and how to improve the manuscript. In the following, reviewer comments are highlighted in blue, author responses in black.

Anonymous Referee #1

General comments

The responses to initial review comments are all fine, and I think the paper has been improved as a result. There were a still a number of parts of the model description that I still found unclear, especially the albedo and density evolution sections - clarifying those further would be the main thing I would suggest at this point. I was reasonably happy enough with what science analysis there is of the simulations in my first review, I've not really added anything additional to what I said first time on that part of the paper.

We have addressed all the comments and specifically tried to clarify the section including the albedo and density evolution.

Detailed comments:

line 5: add "northern hemisphere ice sheets" into "for the last deglaciation"?

We changed the sentence to *'study changes in the SMB and equilibrium line altitude (ELA) for the Northern Hemisphere ice sheets throughout the last deglaciation'.*

line 6: it's not clear here what this spatial resolution is higher than

We added *'The EBM is used to calculate and downscale the SMB on higher spatial resolution than the native ESM grid and…'.*

line 13: the meaning of "SMB/ELA" might be clearer as "SMB and ELA"

Thanks, we changed this.

line 26: there are RCM studies for future ice sheet SMB too of course, eg Fettweis et al 2013 doi:10.5194/tc-7-469-2013

This is of course true and these studies were not meant to be excluded here! We revised the sentence to *'as well as simulations with high-resolution regional climate models (RCMs), which are constrained by reanalysis or ESM data at the lateral boundaries, and cover the last century and near future only'* and added the reference. We also added this information to the abstract.

line 42: there's inconsistent capitalisation of Northern Hemisphere here (and elsewhere?), compare line 39

Thanks for pointing it out. We have unified it through the entire manuscript.

line 53: this last sentence is rather long and unwieldy. It's not obvious there's a direct "resemblance" between the deglacial climate changes just described and "expected future climate change"

Thanks for pointing this out. We changed the sentence as following 'The significant climate changes and variability associated with the changes in the Northern Hemisphere ice sheets emphasize the need for a realistic representation of the SMB for past and future stand-alone ice sheet and coupled climate-ice sheet model simulations (Fyke et al., 2018).' We do believe that this argument stands for itself. The resemblance to the future in terms of the rate of sea-level rise was mentioned earlier in the paragraph.

line 62: (and other places the future study is referred to) can this be cited as "Author et al, (in prep)" or similar, to give future readers a clue how to go looking for this companion paper in the literature when it has been published.

We added *'(Kapsch et al., in preparation)'* in all places that we refer to this study but are not fully aware how it is handled by the journal.

line 84: further "adapted" the scheme, perhaps? I'm not sure these sentences would adequately explain what elevation classes/levels are to a reader that didn't already know. If they are not clear on that it then makes it very confusing to then be told, having started the paragraph by saying the EBM downscales melt and accumulation onto the high resolution ice sheet topography, that you now *want* to calculate SMB on the coarse resolution atmosphere grid.

This might indeed be confusing. We changed the sentences to *'We further adapted the scheme by introducing elevation classes, following Lipscomb et al. (2013). Calculating the SMB on fixed elevation levels, has the advantage that the model becomes computationally cheaper and that the obtained 3-D fields can be interpolated onto different ice sheet topographies (see Section 2.3).'* We believe that people not familiar with elevation classes can refer to Section 2.3 or Lipscomb et al. 2013.

line 113: I didn't understand "is accumulated" before "and falls as snow"

We changed the paragraph slightly to *'Accumulation and melt determine the SMB. Accumulation is controlled by precipitation and takes place if precipitation falls as snow. In the EBM precipitation is considered as snow with a density of 300 kgm^{-3} when the height-corrected near-surface air temperature is lower than the freezing temperature of 273.15 K. Otherwise, precipitation falls as rain.'*

line 118: "includes", instead of "consists of", since the SBM does more than just snow layer modelling?

Thanks for the suggestion.

line 123: "fluxes are parameterised" - if you say this, do you need to say how?

As we use standard bulk aerodynamic formulas we changed the sentence to *'Latent and sensible heat fluxes are calculated from the height-corrected variables using bulk aerodynamic formulas'* and believe it is not necessary to include formulas.

line 127: you've given what look like one end-member of the density-dependent conductivity, it would be clearer to say what the other is too perhaps

We have removed part of the sentence, as the heat conductivity is calculated following the density, hence, changes over time. We agree with the reviewer that giving one end-member does not give more insight on the function itself without an additional equation (see reference to Schwerdtfeger, 1963).

line 130: "observations" needs a reference

We added a reference.

line 152: can a darker background "shine" through? "Show", maybe.

Yes, that is a good suggestion. Thanks.

line 156: why does snowfall only increase thickness when it's snowing faster than a certain rate?

We have chosen a rate dependence to allow for the fact that only a closed snow cover will alter the albedo. E.g. if little snow falls in an ablation area it will melt almost immediately. To account for this we chose this threshold.

line 157: "all depths presented here [..]" is repeated from line 144

Thanks, an over left of the last revision.

line 161: add "surfaces" to "melting and refreezing have different albedo values". I still don't understand the description of the refreezing albedo evolution, I'm afraid. A surface that is simply accumulating snow has an albedo set by eqs 1 and 2, right? If the temperature rises and the surface starts melting, it gets given the constant fixed value of alpha_{snowmelt} or alpha_{icemelt} (line 162) - what determines which of these is used, a density threshold in the top layer? If temperatures drop and the surface can refreeze, the albedo jumps up to alpha_{snowrefrz} or alpha{ice_refrz} - this time you do say the choice depends on the snowdepth (the d_{snow} defined on line 152?), but not how. Aging is now said to start again, I assume using eq1 with alpha_{Xrefrz} instead of alpha_{frsnow} - but since the alpha_{Xrefrz}s are lower than alpha_firn}, does aging now make the surface brighter again as eq1 pulls alpha_{snow} toward alpha_{firn}, or is a different target albedo used?

If the snow depth is larger than a threshold alpha_snowmelt is chosen, otherwise we use alpha_icemelt. We have revised the paragraph accordingly. To the last question: this is correct. Refreezing starts again with Eq. 1 in which we replace alpha_frsnow with alpha_refrz for snow and ice. Alpha_firn is replaced by alpha_refrzold, which is defined as alpha_refrzold=(2 x alpha_refrz + alpha_melt)/3. So we are aiming for a different target albedo here than simply firn. In the case of ice the target albedo lies by 0.55, in case of snow by 0.63. Hence, the surface does not get brighter but darker, as we are aiming for another target albedo as alpha_firn. Accordingly we changed the text to *'Depending on the snow depth, melting and refreezing surfaces have different albedo values (Table 1). If the snow depth lies above or below a snow depth threshold of 0.25 cm the albedos for snow and ice are used, respectively. When the surface experiences melt, the albedo drops to the albedo of snow or ice melt (alpha_{snowmelt/icemelt). When the surface refreezes, the albedo potentially increases (alpha_snowrefrz or alpha_icerefrz) and the aging process starts. The aging process is similar to that for snow processes as described in Eq.~1, but the albedos for refrozen surfaces are smaller (alpha_snowrefrz/icerefrz, the reference albedo alpha_firn reduces to alpha_refrz = (2 alpha_snowrfz/icerefrz+alpha _snowmelt/icemelt)/3 for refrozen snow or ice, respectively). Additionally, the process is slower (tau_*ar). *Only melted surfaces and the background do not experience any aging.'*

line 171: I found this phrasing confusing - cloud cover can't physically affect the surface reflectivity itself, you let it do so in your scheme to compensate for a lack of spectral resolution. "Furthermore, as part of our broadband albedo parameterisation we let varying cloud cover affect [...]"

Thanks for this good suggestion.

line 180: I still don't understand the description of the density evolution after ablation, I'm afraid! I may have a completely incorrect paradigm in my head for how your snow pack works. To take an extreme example: say there's been an extended period of ablation. Density profiles are shifted upwards, "an inflow of ice through the bottom layer closes the mass budget". Does the total mass in the snowpack remain the same, with the same number of layers (of different thickness), or do you lose layers entirely? If the influx of ice at the bottom means you keep the same number of layers in your snowpack, but shift the densities everything has, you end up with an entire set of layers at the density of solid ice. What happens to the density profile when fresh snow starts to fall on this case? The accumulation paragraph above only talks about increasing a layer's density until it reaches the appropriate reference density - but if you still have all the layers, just at ice density, the top layer is already above this reference state. Do you actually lose layers, and then fresh snow starts making new ones on top? This all comes back to my question in the first review that you give mechanisms for increasing density above the target/reference profile, but none that look like they can reduce density again.

We thank he reviewer for his feedback to this paragraph and his examples, which helped to identify the ‘missing pieces’ in this section. We have entirely revised this section in order to address the concerns raised by the reviewer. One cause for the misunderstanding is probably the lack of explaining how the vertical advection of mass works within the model, which we have now included. The revised paragraph now reads as following *‘For a non-zero SMB, the thickness of the uppermost layer of the snow model would change. To compensate for that, a simple 1-d advection scheme conserving heat and mass is applied. In case of surface ablation, the densities and temperatures are advected upward. As lower boundary condition, we assume an inflow of ice with a density of 917kgm^-3 and a temperature of the lowest model layer. In case of accumulation, an inflow of snow with a density of 300 kgm^-3 and a temperature of the height corrected near-surface air temperature is assumed as upper boundary condition. To account for snow compaction we introduce the aforementioned reference density profile Cuffey, (2010). If the downward advected snow into a layer is smaller than the reference density in that layer the density of the in flowing snow is set to the reference density and the flow to the layer below is reduced accordingly to conserve mass. Once the reference density is reached in all layers, mass flows out of the bottom layer and is removed from the system. As a consequence of this procedure the density in each layer lies always between the reference density (in case of permanent snow accumulation) and the density of pure ice (in case of permanent ablation)’.*

line 197: "Pfeffer" citation missing a year

Thanks!

line 224: Is JSBACH is allowed to interactively evolve the vegetation distribution once the ice sheet has receeded from a grid box, or do you stick with whatever is prescribed from the neighbouring cells when the ice disappears?

If the ice sheets recedes from a grid cell the vegetation is set to bare soil. It can then evolve freely depending on the climate within JSBACH. We changed the sentence to clarify this to *“Land points that are deglaciated are covered with bare soil Ocean cells that become land due to changes in the sea level are initialized with the same vegetation form as the adjacent grid cells while. After this initialization the vegetation of the grid cells evolves interactively within the dynamical vegetation model JSBACH.”*

line 392: I think "should not always" would be better than simply "cannot" here.

Thanks, we changed this.

line 526: I'd start a new paragraph at "Utilizing"

Good suggestion.

Table 1: the comments on alpha_{bg} refer to "snow aging, Equation 1", but alpha_{bg} is used in equation 2, and does not seem directly related to aging

This is a mistake. We changed this and refer to Equation 2, which refers to the modulation of the surface albedo due to the background albedo, as well as Equation 3 for the definition of alpha_bg. Thanks for pointing this out.