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Interactive comment on "Sensitivity of the Greenland mass and energy balance to uncertainties in key model parameters" *by* Tobias Zolles and Andreas Born

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Summary

The paper evaluates the sensitivity of output from a simple glacier surface mass and energy balance model to changes in its parameters. For this study the model has been extended from a previous version to include the description of turbulent latent heat fluxes, deemed important for cold climates. The evaluation is performed over the Greenland ice sheet for two contrasting climate states (present day:PD and last glacial maximum: LGM) and several regions with distinct surface mass balance regimes. The work provides detailed information about the importance of key model parameters for the surface mass and energy balance and confirms the importance of latent heat fluxes

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for the LGM climate.

General comments

The conclusions of the paper are fairly specific for this particular model. I was wondering if the manuscript wouldn't find a more appropriate audience if it was instead submitted e.g. as a model evaluation paper in GMD. This is an editorial decision, but I think it is worth considering.

The paper is well organised and the text is largely clear in its presentation in sections 1-2, which requires some improvement to be more precise (see detailed comments below).

My main problem with the results section (Sec. 3) is related to the challenge to present results for 9 different parameters for two different climate states, 6-12 different regions and two different analysis techniques in a concise and interesting way. I believe this section in its present form lacks focus and direction and much improvement can be made in presenting these results. More precision of the descriptions is also needed here.

I suggest the authors should look for possible generalisations across these four axes of analysis and of clear story lines that are followed throughout the discussion of results. To give an example: the manuscript discusses the notion that the Greenland margins at the LGM exhibit similar features to the interior at the PD. Maybe this can be used to generalise the results further and reduce the amount of individual cases that need to be discussed.

Overall, one possible approach could be to define a few main conclusions of the study first and then find evidence for those in the different results. If possible, consider moving less important results to an appendix or supplement.

What struck me as particularly difficult to digest are parts of the text where the description of the results happens without accompanying figures (e.g. p17.l21, p19.l17).

I strongly suggest to provide additional figures to make the discussion of results more tangible. In all cases where results are not shown in figures or tables, add 'not shown' in the text, otherwise, make a reference to the figure.

Regions. It is confusing to me that the paper apparently operates with three different sets of regions (those defined in Fig2, Fig 5 and those not shown for the LGM). If at all possible, I'd suggest that one set of regions (or at least one clear definition of regions that may then results in differences between PD and LGM) be used throughout the manuscript? In the current framework, the regions defined for the LGM should be shown (they should be different from the PD if they are based on elevation) as results are given for those. It seems that the PD analysis is limited to region 5 only, so it is a surprising choice to show all PD regions in detail, but none of the LGM regions.

As pointed out in the text, the relative importance of different parameters in the global sensitivity analysis are dependent on the sampled parameter ranges. I miss a clear motivation and argument for the plausibility of the assumed ranges beyond reference to Born et al. (2019). This seems like an important aspect of the paper, so it should get some attention in the text. This includes the question if the parameter ranges supposedly derived for PD climate hold for the LGM and what could be done to mitigate this effect, if any.

Specific comments

Up front a few points that are repeated throughout the manuscript. Some examples are given below.

- Reconsider the use of 'it' and 'this' in cases where the subject of the sentence is not clear.

- Distinguish between physical quantities and mechanisms on one hand and the parameters that influence those on the other hand.

- Be clear about what is shown in a given figure (PD or LGM) and what results you are

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discussing in a given paragraph (PD vs LGM). Possibly use section headers to make that distinction.

- Be explicit what you are comparing in a given part of the text: PD vs. LGM, one region against another or one parameter against another.

- In the context of this paper, I would always refer to the contrast between PD and LGM as 'difference' rather than 'change', since there is no time dependence here.

Title: Add 'surface' before 'mass and energy balance'

Abstract: Could add more information about the model and experimental setup.

p1.l2 remove 'climate' after 'present day'. A climate is not a period.

p1.l16 If this is supposed to be a reference for the ITM method, more appropriate references may be Bintanja et al., 2002 or Van den Berg et al., 2008

p2.l2 Add 'computationally' before 'too expensive'.

p2.l9 Maybe 'can be used', to make clear they are not used in parallel.

p3.l9 Not obvious what a 'mass following' grid is. Clarify, add a reference.

p3.l9 Add 'in the snowpack' after '15 layers' if that is the correct description.

p3.l9 Maybe 'The mass of each layer is 100 - 500 kgm-2'. Clarify if the mass is decreasing/increasing with depth or where the range originates from.

p3.l12 Clarify what happens to the other variables if they are not downscaled to the model topography. Are they just interpolated?

p3.l17 Which two? The last two? Clarify

p3.l24 Insert 'then' after 'The actual melt is'.

p4.l1 Consider adding numbers for the 4 different parametrizations below. 1. Constant, 2. Oerlemans and Krapp ...

p4.l12 We don't know yet how large the boxes are! Also, you use the term 'layers' before. Is large the right term for a layer defined by its mass?

p4.l12 The end of the sentence 'would likely already be wet if the real surface was resolved' needs further explanation to be comprehensible.

p4.l14 Consider using same notation as for the other forms (number) author: ...

p4.equ(4) Add 5d for Ts = 273K?

p4,l21 Clarify what the first 'this' refers to in 'this was adapted for this model'.

p4.l24 Clarify what 'fixed and temperature dependent' means. How can it be both at the same time?

p4.l25 Clarify what 'it' refers to in 'Keeping it constant'

p5.l7 Could explain physically what this approach is trying to mimic. Supposedly that the first snow that falls on a wet surface will get wet immediately.

p5.l21 'ice-sheet' –> 'ice sheet'

p6.l16 Typo 'fesetup' –> setup

p6.l23 'heat supplied by precipitation depends on the temperature'. Which temperature?

p6.l24 Insert 'in the snowpack' after 'grid cell'. Consider consistent use of terms 'layer' vs. 'grid cell' vs. 'grid box'.

p7.l12 'The global sensitivity analysis is a variance-based method'

p7.l13 'In contrast to other methods'

p7.l13 'all parameters are varied at the same time'

p7.l15 remove 'using' after 'hypercube'.

p7.fig1 Why is the colour over the ocean different in a and c? Why is there a contour line in the ocean? Are elevations at LGM relative to LGM sea level (as they should) or relative to PD sea-level? Suggest to plot all topographies with ocean surface at sea-level = 0.

p8.l8 'optimal model setting' implies an already tuned model which is supposedly not the case here. Clarify!

p8.l18 Specify temperatures in degree C instead.

p8.l19 'As the ice sheet has different shapes' –> 'As the ice sheet geometry differs between the two climate states' or similar.

p8.l19 Why not use the larger ice sheet area of the LGM for both to avoid biases e.g. from the large ocean area in the south-east?

p8.l25 How is the model run back and forth? Is it reversible in time?

p8.l31 Explain why the ensemble is split in two.

p9.l1 Suggest to move 'A detailed description of the algorithm can be found in (Sobol et al., 2007) and (Saltelli et al., 2010).' after 'used to estimate the model sensitivity.' to where the general description of the method ends. Also, specify k in your example.

p9.l15 Insert 'STi' after 'total sensitivity index'.

p9.l16 Clarify temporal or spatial average in 'surface mass balance and the average surface temperature'.

p9.l17 Specify which variables are averaged and which are summed.

p9.18 'reseeding' –> 'residing'

p10.fig2 Do you explain somewhere how the sensitivity is normalised? The plot of Greenland looks distorted. Can this be plotted in equal aspect ratio. Additional (white) contour lines could make the region separation clearer. Caption: Add panel for 'entire

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ice sheet' to the description. Consider adding panel indicators a-f for the boxes and g for the GrIS plot and use them in the text.

P10.l4 Maybe 'low' –> 'limited'

p10.l4 Remove 'changes' after 'SMB'

p10.l5 See general comment on relative sensitivity of parameters dependent on choice of parameter range. Should be clarified here.

p10.l6 Check consistency Eatm (here) - Eair (Figure 2)

p10.l7 Check consistency DSH (here) - Dsf (Figure 2)

p10.l9 Add 'albedo' after 'the fresh snow'

p10.l14 is 'above 2000 m' > 2000 or the region 2000-3000? Clarify

p11.fig3 Title: 'Sensitivity of the SMB at PD' Are values >1 actually defined for this analysis? If not, why is the yellow arrow on the colour bar? What does a sensitivity index above 1 mean? The colour scale with the darkest colour for the least important results is not convincing me. Contour lines are not visible on most plots. Suggest a different (lighter) colour and omitting the numbers. Caption: Mention figure is for PD. Mention colour choice for ice free land. 'mass balance' –> 'surface mass balance'. Reformulate 'are not to be taken too seriously'. If we don't take the absolute values seriously, what is left in this figure? If relative values are more important, find a way to plot those instead.

p12.l2 Reformulate 'the structure is much more complex'. What does that mean? There is more information in 2D compared to 0D?

p12.l3 remove 'glaciers' after 'west coast'.

p12.l7,8 2x 'becomes' –> 'is'. Otherwise this implies a process.

p12.l30 Reformulate 'negative ensemble member'.

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p12.l33 'interior of Greenland'

p12.l33 Clarify 'the atmosphere is more in balance with the snow surface'. What does that mean?

p12.l34 Consider adding a section header 'LGM analysis' or similar to make a clearer separation between the two climate states in the text.

p14.l8 Would an additional figure similar to Fig2 for the LGM help?

p13.fig4 Title: 'Sensitivity of the SMB at LGM' See comments for fig3 for general layout. Caption: Start with description what is shown, not with discussion of the figure.

p14.l2 'The ice sheet integrated SMB'. Do we see this somewhere? Consider adding a figure or table and refer to it here.

p14.l2 'shows sensitivity', add qualifying statement 'some', 'strong'. Depending on relative scale, all most parameters will show some sensitivity.

p14.l4 'do not impact the SMB'. Not at all? Clarify.

p14.l4 add 'the' in 'either of the two climate states'. Refer to fig 3 and 4 then.

p14.l4-7 First start discussion of LGM, then continue comparison LGM-PD.

p14.l8 'increased'. Relative to PD? Clarify.

p14.l9 Add 'surface' before 'mass balance'.

p14.l11 'intra-annual variability' –> 'seasonal variability'

p14.l12-14 'the ... impact of ... impacts the latent heat flux more than the actual exchange coefficient'?? Not clear. Reformulate. Clarify.

p14.l15 remove 'temperature' after 'surface and the air', to avoid duplication.

p14.l16 'the fewest precipitation amounts'. Is this shown somewhere? If not, add 'not shown' in the text.

p14.l18 'more important on the western than the eastern margin'. Explain why.

p14.l18 Add 'at LGM' after 'The reduced model sensitivity'.

p14.l21 'The sensitivity of ...' to what? maybe 'model parameters'?

p14.l22 'without additional figures'. Not sure this is a good idea, see general point. Maybe add a table with results instead?

p14.l23 What is 'final firn albedo'? Reformulate

p14.l24-25 Not sure I understand this conclusion. Reformulate?

p14.l26 What does 'it' refer to in 'it is most sensitive'? Clarify

p14.l28 'as are the snow albedo related ones in the north' –> 'as are the ones related to snow albedo in the north'

p14.l30 Start sentence with 'Globally' and then give specific details in the end.

p14.l31 'the framework' , maybe 'this framework', 'our framework'

p15.fig5 Add panel with regions for LGM, which are different and actually used in the analysis (unlike only region 5 for PD). Why invent new regions after what is already introduced in figure 2? Could you not do the analysis for region 1000-2000 instead of region 5? Or find a common subset to use in fig 2? Caption: Start caption with what is displayed in the figure. Results are for the text.

p15.l1 'more' or 'less' than what? Maybe 'closely linked to the SMB'?

p15.l1 'and shows similar sensitivities as have been reported for the SMB'

p15.l2 'much lower.' compared to what? Why is that expected? Explain.

p15.l4 Add 'surface' before 'mass balance'.

p15.l6 'Parameters which result in either surface heating or cooling'. More precision needed. It is not the parameters that result in heating or cooling, but the physical

process that is parameterised.

p15.l7 'require a different analysis'. So what is this analysis, describe. Consider adding this description as 2.4.

p15.l7 Add 'Conversely' before 'Albedo', as these are examples where GSA will work.

p15.l8 Add 'so that GSA gives clear results' or similar after 'mass balance'.

p15.l9 'and 13 for the LGM (2 more around Elsmere Island)'. Need to show these in a figure.

p15.l19 'based on elevation and similarity'. Similarity of what? Explain.

p16.fig6 Add yticks in column 2 and 3. Suggest to plot all results as discrete boxes. The mix between continuous quantiles and discrete outliers looks strange to me. Caption: Add that this is for PD.

p16.l1 What does 'It' refer to in 'It shows'?

p16.l4-6 According to you, parameter Eatm can be well analysed with GSA. Why does it need more detail here?

p16.l6 'accelerating manner' could suggest that the parameter should be sampled non-linearly.

p16.l7 'the variation of the SMB as a result of other parameters, increases too' and p16.l8 ' the width of the distribution decreases' Could you explain why this is the case? I would think with more available energy (l7), differences in the other parameters have a larger impact on the SMB. Similar with lower albedo (l8), differences in the other parameters are more effective in making a difference.

p16.l8 Add parameter in 'Even very low albedo parameter values'

p17.l4 'has the highest median mass balance'. Explain why.

p17.l6 'The strong impact' on what?

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p17.l7 'the other fluxes'. What kind of fluxes? Energy?

p17.l21 'During the LGM the western region between 1000 - 2000 m'. Should be shown.

p17.23 'three distinct changes' –> 'three distinct differences relative to PD'

p17.l23 'χQL results in a decrease of SMB'. Distinguish physical process and parameters.

p17.l26 'slower snow albedo decay'. This is discussed as a general result, but is not available in all albedo models, is it?

p17.l30- Make clear that the discussion is back to LGM results.

p17.l28 'sublimation ... results in a mass loss rather than a mass gain as in PD.' You should probably distinguish the opposite sign using the term 'deposition' or 'desublimation'.

p18.fig7 Panels are difficult to compare due to different vertical scale. Add xticks in row 2 and 3 Caption: Add that this is for LGM. Highest elevation at bottom is counterintuitive, consider changing order. Add figure with regions and link from here.

p19.l2 'The smallest spread of the ensemble is found in the high altitude-regions 9, 10, 11'. Difficult to judge with different vertical scales in figure. Also, this is a new point. First finish discussion of DSH?

p19.l3 'a result of higher air-temperatures than snow surface temperatures'. Needs more explanation to be clear.

p19.l4 'This shows'. What does 'This' refer to?

P19.l7 What is 'moisture differences between surface and atmosphere'?

p19.l8 '7-11' was 9-11 in the explanation above at l2. Clarify.

p19.l14 'it acts as a buffer of the SMB'. Not clear.

p19.l18 Add 'Ql' after latent heat flux.

p19.l17- Hard to follow this part without any guidance. Include a figure?

p19.l28 'the SMB decreases' with what?

p19.l29 'behavior to the GSA' –> 'behavior as shown in the GSA'

p19.l35 'Similar to the GSA' –> 'Similar to the results from the GSA'

p20.l1 'above 2500 instead of above 3000 m'. Is this comparing to PD? If so, mention it.

p20.l6 'in region 5'. And in in all the other regions? No discussion of those?

p20.l8 'the air-temperature buffers the snow temperature'. Not clear. Clarify.

p20.l14 'The model sensitivity in this study is evaluated' –> 'The model sensitivity is evaluated in this study'

p20.l15 'big' –> 'large'

p20.l17-18 I would say it is the other way around: lower atmospheric temperatures ... 'leading to fewer areas where melt and runoff occurs' and consequently 'reduce the impact of QLWin and εatm' ...

p20.l20 'This is due to the absence of melt'. I read this as complete absence of melt. Is that correct? Otherwise 'negligible amount of melt'?

p20.l25 'bigger' –> 'larger'

p20.l25 'for the surface during PD' –> 'for the surface energy balance at PD'

p20.l26 Is it correct that the long-wave radiation is twice as large as the incoming solar radiation? This is for heavy cloud cover?

p21.l1 Add 'surface' before 'mass balance'.

p21.l12 'the temporal change of the sensitivities'. What is that? The contrast between LGM and PD?

p21.l15- Try to formulate this positively to make it clearer.

p21.l18 Replace 'increased' by 'larger'

p21.l19 'during the LGM' –> 'at the LGM'. Similar for PD and in other places.

p21.l19 replace 'increase' by 'influence'.

p22.l4 Move 'climate' to after 'glacial maximum' in the next line.

p22.l5 'study the change of the model response under different boundary conditions' –> 'study the differences of the model response under LGM and PD boundary conditions'.

p22.l6 add 'for the LGM climate' after 'is a necessity'

p22.l9 'creates a SMB model uncertainty' –> 'govern the SMB model uncertainty'

p22.l9-10 'With the change in circulation during the last glacial a changing energy input from the atmosphere to the surface will result in a SMB response' –> 'With the different circulation during the last glacial maximum a changing energy input from the atmosphere to the surface will result in a SMB difference.'

p22.l11-14 I don't think this has been shown in the manuscript. This could be a discussion item, but not a conclusion of the manuscript if it is not even mentioned before.

p22.l16-18 This reads like a discussion item, not like a conclusion.

References

Revise inconsistent use of abbreviated and full journal titles. E.g. Cryosphere –> The Cryosphere. J. Geophys. Res. –> Journal of Geophysical Research.

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