# Review of Holube, Zolles, Born: “Sources of Uncertainty in Greenland Surface Mass Balance in the 21st century.” (The Cryosphere Discussion, Paper: tc-2021-128)

The manuscript of Holube and others simulate with the BErgen Snow SImulator” (BESSI) the response of the Greenland Ice Sheet (GrIS) and its Surface Mass Balance (SMB) under various warming climates scenarios. The scenarios origin from 26 climate models of the CMIP6 archive and represent four different climate scenarios. The required forcing fields of the numerous climate projection and model combinations drive BESSI in the so-called offline modus. Since the SMB of Greenland is the principal driver of the Greenland Ice Sheet's sea-level contribution, it is paramount to probe possible uncertainties of the SMB projections. The authors group the uncertainty estimates into four components:

1. the selected climate scenario that ranges from strong mitigation to business-as-usual,
2. the spread among climate model inherits from its internals that leads to diverting climatic projections under the same climate scenario (item 1),

- parameter uncertainties of BESSI,
- and the residual named internal variability

Since the sea-level contributions of the global ice sheets, such as Greenland, are still highly uncertain, this manuscript addresses an important issue. It has been a pleasure to read the well-structured manuscript, but I also confident that improvement of the language could help many readers to enjoy the work besides essential corrections.

**I recommend the publication of the manuscript after a minor revision.**

In the following, I will first discuss general concerns before I raise more specific and technical issues.

## General comments

As part of your uncertainty estimates, you are using those combinations of parameters that reproduce the SMB of the reference models RACMO. What would be needed to restrict the valid parameter space? Since you also compute the exchange of fluxes between the surface and the atmosphere within BESSI, would comparing the internally computed fluxes with references lead to a restriction of the uncertainty? Although the flux estimates coming from different regional climate models, such as RACMO, MAR, and HIRHAM, would probably differ, would you please explain a bit what could be done to reduce the uncertainties if appropriate observations could be made available? To

In some figures, the unit of matter fluxes (precipitation) or radiation fluxes (shortwave and longwave) are usually per time unit; otherwise, the numbers might be wrong. Please check, for example, Figures 1, 3, 6, 7, while the mass flux of Figures 2, 9 seem to be correct. Please also check the related text.

Since my mother tongue is not English, I know it can be hard to write English, which is nice to read and understandable. Nevertheless, I've gotten the impression that the manuscript would gain vigor with an improved language. In the more specific issue section, I provide examples for some cases. However, the list is not exhaustive.

## Specific issues

In the following, the abbreviations "L" or "l" stands for the line number of the manuscript, and "p" and "P" for page.

L1 (abstract): Please replace "that" with "which" because it is not a defining clause; see https://www.grammarly.com/blog/which-vs-that/, for instance

L61: Since much effort is put into preparing BEDMAP, for instance, how significant are the differences between ETOPO and BedMachine v3 (Morlighem et al., 2017), for example, and how sensitive are your results considering the applied height corrections?

L62: Can you please be so kind and indicate how the results would change if you use instead of daily, sub-daily forcing reproducing the daily cycle.

L67: Could you please elaborate on how the simplified horizontal mass flux impacts the results compared to entirely ignoring the flux versus a fully dynamical ice sheet model?

You might add a sentence like: "The uncertainty related to the simplified representation of the ice flow is not addressed further."

L74-75: BESSI is compared to RACMO. What went into the comparison? The integrated SMB, spatial SMB field, or even the different fields contributing to the SMB, such as precipitation, melting, refreezing, sublimation.

L81: I heard about the Pareto optimality in the relationship of economic science. Since this might not be commonly known, would you please be so kind as to add one sentence summarizing its basic concept?

P3, L71-84: I guess you only vary the following parameters: fresh snow albedo, firn

albedo, and turbulent heat exchange coefficient. Please state clearly, by adding a sentence like: "The combination of these parameters contribute to the parameter uncertainty discusses below."

P3, L71-84: You may add: “The albedo of bare ice is fixed with a value of 0.35.”

P5, L91-95: The property difference between the historical and future period is added to the reference climate property from ERAinterim. Do you use the entire historical period (1850-2014)? Would you please clarify the text?

P5, L94-95: I guess you perform the computation for each calendar day independently? How do HOW DO YOU FILL THE MISSING DAYS IF THE MODEL HAS ONLY 360 DAYS?

L104-105: Not sure, but have you swap shortwave and longwave in the text or Figure 1d+1e?

L106-107: I do not fully understand the second half of the sentence. In particular, what is meant by "model differences overlap most for different scenarios." Please clarify.

L109-110: I understand these two sentences, but initially, I have not. Would it be possible to improve them?

L 112: You mention 96 combinations, which is not the multiple of 26 climate models. I guess that some combinations of models and scenarios are not available. I suggest adding to the caption of Table B1: "For each of the listed models, we use the scenarios SSP126, SSP245, SSP370, SPP585 to drive BESSI; except for some missing model scenario combinations. XXX misses SSPxxx, YYY: SSPyyy, ZZZ: SSPzzz1 and SSPzzz2, … ." and expend the sentence of line 112: ".... 96 selected climate model-scenario combinations (Table B1)."

L120: How fast does the bias in the identical starting conditions, which may not be consistent with all parameter combinations, disappear?

L126: You state that a small amount of daily precipitation is unrealistic in the North. Could you add a reference to confirm this statement?

L130: You may replace “..., but the monthly averages are the same” by “..., but the monthly averages are identical” or “..., but the monthly averages are similar.”

L131: I guess “Therefore” is not appropriate than “thus.”

L133: You may help the reader to list the transient variables shortly by writing, for example:"... with different transit variables (air and dew point temperature, precipitation, short and longwave radiation)."

L141-143: You compare the "range in simulated SMB" with the "range in input variable" in terms of "magnitude." Since these do not necessarily have the same unit, improve the ambiguous wording to avoid comparing apples and oranges.

L149-150: Here, you describe the models' inability to reproduce atmospheric blocking. Since the horizontal resolution of most models (Table B1) prevents a representation, you may modify the sentence:"... (Fig.2, black) because the coarse horizontal resolution

hampers the representation of the observed blocking and its increased activity (Davini and D'Andrea, 2020)."

L155-156: I suggest: “There, heavier precipitation occurs under a warmer climate.”

L156: Please drop the awkward wording “greatly” or replace it.

L157-159: Please avoid greater, and the appearance of the information in the parentheses is confusing; you may turn it into an actual sentence. I suggest:" These SMB changes are much more pronounced in the high-end scenario SSP585 because of the enhanced/amplified/more robust change in the input variables."

L159: In the sentences above, you describe simulation results and now compare them with observational estimates. Please make this distinction clear, for example,": Currently observed SMB changes are dominated by amplified melting … ." Also, check the manuscript if you use termination "melting" versus "melt."

L161: You have found a 6°C warming across Greenland in SPP585. Just for curiosity, how strong is the warming in the altitude of the ablation zones, such as the altitude up to 1500 m?

L162-164: I find this sentence not clear enough, and, I guess, you talk about the actual equilibrium line that spreads across a larger area (Fig. 4) for more substantial warming. Therefore, please sharpen the sentence. I suggest: "Since ice sheet margin experiences the highest melting rates, its relative standard deviation reaches highest values near/along the actual(?) equilibrium line. Therefore, the choice of the climate model is decisive for the SMB in this region."

L164: Here, you say, "the equilibrium line varies substantially more." Since the title of your manuscript refers to uncertainty, you may rephrase "the equilibrium line position is subject to substantial uncertain."

L166: Please clarify if you mean: "... the differences between climate models driven by the same scenario increases with stronger greenhouse gas forcing (Fig. 2)."

P9, L168-175: This paragraph should be sharpened.

L169-170: There, you make the assumption that you can split the uncertainty into four components. I guess you further assume that these components are independent. Therefore I suggest rephrasing: "We assume that the total uncertainty of the simulations could be split/separated into four independent components: climate model, climate scenario to drive a chosen climate model, BESSI parameter uncertainties (albedo of fresh snow and firn, turbulent heat exchange coefficient), and internal variability.”

L170: Please add a sentence stating what internal variability is or prove an example.

L172: Do you mean:” ... the decadal running mean of the SMB at each grid point ...”?

L173: Replace "are" buy "is."

L177: You do not really talk about visibility. I suggest:”... the different uncertainty components can be clearly identified when normalised with the sum... .”

L190: Do you mean here, "This pronounced uncertainty is larger than the differences"?

L190: Unclear, what do you mean by "the difference of the model consensus between the scenarios"? Please clarify.

L191-192: The sum of all components is 99% and not 100%. Please correct.

L195: I'm unsure if "the SMB changes most" is appropriate. Would you mind checking and rephrasing if applicable?

L208: Please rephrase:"...variables on the SMB across the entire GrIS and three regions previously used by Zolles and Born (2019)(Fig. 7).

L219-222: You may rephrase and split the sentence. I suggest:"... simulation (Fig. 7) driven by the SSP585 scenario. It highlights non-linearities that amplify the SMI reduction. For example, air temperature and precipitation often covary so that the increased precipitation compensates the increased melt only partly. If heavier precipitation delivers more rain, the energy required to refreeze the additional rain in the snowpack increases its heat."

L222-224: Here, you create the impression that the combination of a transient air temperature and longwave radiation explains the non-linearities. I believe you, but you have performed only simulations where one variable is transient and not two, or? If this is the case, please formulate it more carefully. You may add at the beginning of the sentence: We conclude that when the air temperature and longwave ….".

L223: Please be very clear about the distinction between observation deduced from measurements and simulated results. Hence, replace "is observed" with "is detected."

L225: Please clarify if you mean: "on the vertical temperature gradient in the snow."

L226-228: Do you mean: "Since the sublimation is driven by the saturation pressure difference between lower atmosphere and surface, sublimation increased for a higher dew point temperature while it is reduced for a warmer surface."

L226-228: Unclear sentence. Please improve.

L243-244: You may shorten: “As a consequence, the scenario uncertainty is reduced (Fig. 8b).”

L274: Since you talk about the unknown future, I would like to suggest a slight change:" temperature changes are probably exacerbated."

L301-302: A sentence is missing stating that increased blocking leads to amplified mass loss. Would you please add an appropriate citation?

L303: I suggest rephrasing: "Therefore, our future SMB projections are conservative because the climate models do not fully represent the expected increase of the Greenland block in a warming climate."

## Appendix

L327: I suggest rephrasing: “show strong oversaturation of humidity in areas with very low temperatures while only small oversaturation occurs in nature... .”

L342: Please add “t”:” of these uncertainties contributors and time *t* as indicated … .”

### Figures

The figures are in general of high quality and well prepare. However, some technical issues remain, which are discussed below.

Some figures having a time axis do not show the evolution until 2100 (Figure 5, 8). Is this an artifact? If so, please correct it.

Figure 1: Please state the meaning of the vertical line in all subplots. Would it be possible to indicate the used EraInterim data period in the plots? Are these line plots the actual medians, or are these the climate model anomalies relative to their related historical or pre-industrial climate states? If so, please clarify. In the caption, you may state that the radiative fluxes are "at the surface." Since you use for the first time the unit "kg $m^{-2}$“ for precipitation, you may add the following note: “Please note the precipitation unit, 1 kg $m^{-2}$ equals 1 mm(WE); WE=Water equivalent.”

Figure 3: The labels indicating the subplot (a-d) are below the black ground. Please repair.

Would you please move the column labels above the top figure row? The subplot in the lowest row shows only black and grey patterns and does not resemble the values of the related colorbar. Please fix. In the figure caption, I consider the last sentence using the wording "meaningful" as jargon. Please improve.

Figure 5: Great figure, but would it be more appropriate to represent the square root of the variance/standard deviation in subplot (a)? In this case, the values could be directly compared to recent mass balance estimates and sea-level potential. If you would like to keep your variance y-axis, you may add a second axis with the square root values.

Figure 6: The subplot labels are cover by the black subfigure's background. Please fix. As mentioned for Figure 5, would it be possible to present the square root of the variance too? Why do you not use for the right column the last complete decadal period 2091-2100?

Figure 7: In the subplot (e), only the region "East" is shown. Please repair.

### Table

Table 1: Please separate the units corrected by replacing “$kgm^{-2}$“ with “kg $m^{-2}$“, for instance.

## Bibliography

Morlighem, M., Williams, C. N., Rignot, E., An, L., Arndt, J. E., Bamber, J. L., Catania, G., Chauché, N., Dowdeswell, J. A., Dorschel, B., Fenty, I., Hogan, K., Howat, I., Hubbard, A., Jakobsson, M., Jordan, T. M., Kjeldsen, K. K., Millan, R., Mayer, L., Mouginot, J., Noël, B. P. Y., O’Cofaigh, C., Palmer, S., Rysgaard, S., Seroussi, H., Siegert, M. J., Slabon, P., Straneo, F., van den Broeke, M. R., Weinrebe, W., Wood, M. and Zinglersen, K. B.: BedMachine v3: Complete Bed Topography and Ocean Bathymetry Mapping of Greenland From Multibeam Echo Sounding Combined With Mass Conservation, Geophys. Res. Lett., 44(21), 11,051-11,061, doi:10.1002/2017GL074954, 2017.