

Point-by-point response to the reviewers

We thank the two reviewers for the constructive second round of comments on our manuscript. We have done our best to address the concerns raised by the reviewers and here provide a point-by-point reply to each of the reviewers' comments, including an explanation to subsequent changes to the manuscript. ("RC" stands for "reviewer comment", "AR" for "authors response".)

5 1 Answers to reviewer 1

RC: "l8. "Therefor," –typo"

AR: Corrected.

RC: "l29-31. Great addition for background. I would put the newly introduced terms "surface mass balance" and "specific mass balance" in italics"

AR: Done.

RC: "l35. "satellites able to observe Earth's surface did not yet exist for a large portion of the 20th century." Good point, but I think you can be more specific here what you mean by "large portion" (i.e. letting the reader know roughly for how long back in time we have remotely-sensed observations of glaciers)"

AR: The problem is that it depends on what kind of observations you think about. Images (e.g. for outlines) are now being used from spy satellites from the early sixties. We changed the sentence to: "satellites able to observe the Earth's surface only became available well into the second half of the 20th century".

RC: "l180. Do you mean "inaccuracy" or "uncertainty" here?"

AR: We would argue that it is actually inaccuracy, because if the observations are biased, our estimates will be, too

RC: "l199. Would rather use "elevation" than "height" here to be consistent"

AR: Changed to "elevation".

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RC: "l200-207: do you mean "scaling factor" not "scale factor" ?"

AR: It is actually called "scale factor" in the literature.

RC: "l212: Not sure what you mean by "random variable" here. Does this mean that it has to be empirically derived?"

30 **AR:** Yes. In the subsequent sentence of the manuscript this is also stated as: "[...] and scale factors empirically derived in Bahr (1997) and Bahr et al. (1997)."

RC: *"1214-215. This is important information, how do you estimate the 40% and 100% errors in the volume-area and volume-length scalings, respectively? Does these numbers matter at all for the errors derived in the global model?"*

35 **AR:** They are very rough estimates based on the scatter of the scaling relation and are taken from Marzeion et al. (2012); we added "[...], as in Marzeion et al. (2012)" to the corresponding sentence. They do matter for the individual model setups' error estimate of, e.g., glacier volume – but they matter only very little for the estimates of volume *change*. Since we show that the error estimates of the individual model setups are substantially too small anyway, especially pre-1950, they matter even less for the total (ensemble) uncertainty.

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RC: *"1307. "parameter combinations/sets"–I think it's enough to write either "parameter combinations" or "parameter sets", you don't need both"*

AR: Removed "combinations/".

45 **RC:** *"1497: Holding the temperature constant resulted in a mass change decrease of 65 %, while the constant lower precipitation increased the glacier mass change by 5 %. I would change to "Holding the temperature constant resulted in 65 % lower mass loss, while the constant lower precipitation increases mass loss by 5 %." I think this is what you mean? (looking at your new Fig A1)"*

AR: Adopted the suggestion.

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RC: *"1508: "... applied scaling and relaxation laws," -perhaps include cross-references to the relevant equations/section here."*

AR: Added "(see section 2.2.1)".

55 **RC:** *"1509-510."is the positive ice-elevation feedback: as a glacier loses mass, it's thickness, and thereby surface elevation decreases, causing it to experience higher temperatures." I think you can write this in a more concise way. I would also call it a "mass balance –elevation feedback" or "surface mass balance –elevation" feedback. Although this feedback is well known, it doesn't hurt to add a reference (e.g. Harrison et al., 2001)."*

AR: We formulated it now as follows: "[...] is the positive mass balance-elevation feedback: as a glacier's surface elevation decreases due to mass loss, it experiences higher temperatures, because of the atmospheric temperature lapse rate. This in turn enhances the initial mass loss." We already had one reference on this topic in the subsequent sentence, but added the suggested one as well.

RC: *1536-539. Great point, please add a reference if this point has been raised in the literature before."*

65 **AR:** Although there is some literature on icebergs in fjords, we were not able to find a discussion of the point raised in our manuscript in articles on GRACE-based glacier mass change estimates.

RC: "l575. "to small"—typo"

AR: Corrected.

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RC: "l610. "making it unpractical to use them in validation framework we applied."-missing "the""

AR: Added "the".

RC: "l619. I don't think using "e.g." in-text reads well, would change sentence to "...the application of a robust initialization
75 method (e.g. Eis et al., 2019;2021)... ""

AR: Adopted the suggestion.

RC: "l630. "Finally, all ensemble members agree that around the 1930s mass loss rates from glaciers were comparable
80 to those of today."—this is what you find, but something that can easily be misinterpreted by other scientists only reading the
Conclusion, as well as by the broader public/news media. I think you should clarify/add the caveat that you discuss at the end
of Section 4 (1507-512), specifically the neglected mass balance-elevation feedback, and state that, most likely, mass loss rates
are actually greater today than around the 1930s."

AR: This is a good point, thank you! We added the following now: "This finding is weakened by the lack of an explicit
mass balance-elevation feedback in the model we applied, though, and it might hence well be that mass change rates during
85 the 1930s were actually smaller than today".

RC: "l632-633. "They were followed by a phase of mass loss deceleration roughly between 1940 and 1980, which has been
accelerating since then"—this could be written more clearly. First, it is not clear what "They" refer to (the mass loss rates?).
In the last part, "which has been", this needs to be clarified as well. What has been accelerating(the deceleration? the mass
90 loss?). From reading the paper I know what you mean, but I'm being a bit picky here because these lines will be among the
most read in the paper, so it's great if they cannot be misinterpreted."

AR: Further good points, thanks! We now formulated it as follows: "According to our results, the increase in mass loss until
the 1930s was followed by a phase of mass loss deceleration until roughly 1980. The glaciers' contribution to sea-level rise has
been accelerating again since then [...]".

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RC: "l633-635. Perhaps a personal preference, but I would reduce/remove the use of i.e. in-text (similar to e.g. above), and
try to describe what you mean in words. In my opinion this makes the text flow better."

AR: We let the "[...], i.e. higher altitudes" formulation as it was, hoping that, as it comes at the end of the sentence, it does
not disturb the flow of the text in that case. The next sentence, where we also had an "i.e." was reformulated in regard to your

100 next comment.

RC: "l634. "...this is partly driven by ..."—do you mean here that reduced solid accumulation partly explains the acceleration found since the 1980s? If so this is an important point. Also Fig 8 shows that the amount of precipitation has increased since the 1980s, so I guess Fig 8 suggests that due to air temperatures being warmer, precipitation increasingly falls as rain instead of snow. So, the main driver is still air temperature, right? You don't want people to confuse your finding that air temperature is by far the main driver of global glacier mass loss (cf. your new Fig. A1). I think you can end stronger and clearer here."

AR: We changed the part you are referring to here to: "Our results also indicate that this acceleration was partly driven by decreasing amounts of solid precipitation at glacier locations from ca. 1980 onward. This implies that the enhanced atmospheric warming not only increased ablation rates, but probably lowered the amount of snow the glaciers received as well, notwithstanding a slight increase in total precipitation." This should make the final statement clearer and stronger.

1.1 Figures

RC: "Figure 1. New flowchart is great, but with the small font size hard to read, I had to zoom to 200% on my screen. Please increase font size/redesign flowchart (extend vertically?) to become more readable, also in print-out format"

115 **AR:** We substantially increased the font size.

2 Answers to reviewer 2

RC: "Line 8: Therefore"

AR: Corrected.

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RC: "Motivation for the three criteria line 11 abstract?"

AR: The motivation is laid out in section 2.3. Still, we added the following now as the subsequent sentence: "These criteria were chosen in order not to trade lower error estimates by means of the root mean squared error (RMSE) for an unrealistic interannual variability."

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RC: "Line 13: Cross-validation in abstract difficult as it is not clear what is meant with that term, to me it is not a universal known term."

AR: We think the usage of this term in the abstract is appropriate, since using only "validation" would just make it less specific. To make the kind of used cross-validation method clearer we added to the second sentence where the criticized term appears the following (in italics): "[...] than the uncertainties obtained via the *leave-one-glacier-out* cross-validation, [...]". We

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think that methods should usually not be explained in the abstract or introduction, but in the corresponding section of the article.

RC: *"Line 20/21: Last sentence to be amendment to derived from GRACE data over the period xxxx-yyyy. Because it is another period than the 1901-2018 you have to specify it."*

135 **AR:** We added the following to the last sentence of the Abstract: "[...] , which only cover the years 2002 - 2018 though."

RC: *"Line 26: remove J."*

AR: Done.

140 **RC:** *"Line 44: establish rather than establishing?."*

AR: We think "establishing" is correct in this context.

RC: *"Line 50 often? Or many times?"*

AR: Changed to "many times".

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RC: *"Line 50: The sentence The Eis, 2021). Disturbs the flow of the paragraph. I suggest to leave it out."*

AR: We moved a slightly changed version of this sentence two paragraphs down, where it fits better.

RC: *"Line 51: Unclear where this refers to. It can be either the current manuscript or the work by Eis et al.."*

150 **AR:** We changed "[...] used in this work [...]" to "[...] used in the work presented here [...]".

RC: *"Line 55: these models usually lack ice dynamics or geometric scaling rather than "the models .. scaling""*

AR: We adopted the suggestion.

155 **RC:** *"Line 59: the reasoning around energy balance models are hard to optimize is nonsense. You have already 5 parameters here. You could also develop an energy balance model with 5 parameters if you wish. I suggest you simply remove line 55-61 it does not add to the paper and only dismisses energy balance approaches which is not needed and not the purpose of your paper."*

160 **AR:** We do not dismiss energy balance approaches, but merely state that those add complexity. The number of parameters usually increases with the number of processes one wants to resolve in a model, if those are not computed from first principles. We added: "[...] not yet done routinely, but might still have the potential to enhance the accuracy of glacier modeling. That is because such models would have the ability to represent the physical mechanisms influencing a glacier in a more detailed, and thus possibly more realistic, fashion." to the end of the paragraph to point out that we do not want to dismiss such an approach, but merely point to the added complexity, which, in turn, might actually enhance such a model's capability to reproduce glacier

165 behavior.

RC: *"Line 70. I don't think it is correct to say that a comprehensive analysis is not yet possible. It has not been done but that does not mean that is impossible to do. It could be done , maybe for a shorter period or a smaller selection of glaciers. So please tune down this too firm statement."*

170 **AR:** We extended the corresponding sentence to (in italics): "This implies that a comprehensive analysis determining which modeling approach might be most appropriate is not yet possible; *at least not for all global glaciers and the whole 20th century.*"

RC: *"The paragraph starting with line 73 to line 80 should be interchanged with the next."*

175 **AR:** Done.

RC: *"Line 104: if you explains terms I suggest you also explain what you mean with cross-validation, you use it as if this is trivial and obvious but at this stage in the manuscript I have not yet any clue what you mean with it."*

180 **AR:** We added (in italics): "[...] *leave-one-glacier-out* cross-validation (see section 2.2.1 and green box in Fig. 1) [...]". In section 2.2.1 the concept is actually (briefly) explained.

RC: *"Line 105: as THE optimization.."*

AR: Added "the".

185 **RC:** *"Figure 1: It is useful but not really embedded in the text try to refer more often to the figure."*

AR: We added some references to the figure to the manuscript.

190 **RC:** *"Line 205: It looks like the scale factor is simply taken form Bahr with an uncertainty. It seems to be that the scale factor should be derived from the total volume of glaciers as it follows from the Randolph data. If you don't do that it maybe that you over or underestimate the global ice volume from glacier and this then flaws your dV calculation because you can loose more if you have more and vice versa. So I think you have to find the scale factor for a time where you know the area and the global glacier volume (or better the individual glacier volume), being present-day. I therefore would like to see volume and area information I can compare with Randolph information. What is for instance your ice volume for present-day is it comparable to Randolph derived estimates? I believe that is lacking from the manuscript now."*

195 **AR:** The problem here is that in order to empirically derive the scale factor one has to know the volume of the glaciers the scale factor is fitted to. The RGI does, unfortunately, not contain volume estimates for every glacier; only outlines/area estimates. Thus, we rely on the previously empirically derived scale factors from Bahr (et al.). To section 3.2 we added: "Comparing our results of glacier geometry to a publication that estimated contemporary global glacier volumes (Farinotti et al. 2019), though on the basis of modeling results as well, we find that our global volume estimate differs less than 1 % from their

200 result." Additionally, as stated in the manuscript and Fig. 1, we only directly model glaciers that meet the recorded RGI areas in the individual years of record.

RC: *"Line 355 how do you know it is correctly, I believe you but I suggest to leave out from the text."*

205 **AR:** We calculated it from the validation data as stated in the manuscript (section 2.3). Therefore, we see no good reason to leave it out.

RC: *"Figure 1 is a useful addition, but it should be more conceptual and better embedded in the text. If you decide to keep it so detailed you need many references to the figure in the text."*

AR: We added some references to the figure to the manuscript.

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RC: *"Figure 6 could be expanded with literature values for the GMSLR value of glaciers and this study. For the 20th century and a zoom for the satellite period"*

AR: We think this would make the figure too crowded and hence unclear. Literature values for comparison are given in Table 4.

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RC: *"Table 4 I would prefer the information which is in the footnote to be in a separate column."*

AR: We put the information that was in the footnote in a separate column now.