

## Reply on Review 1 (Kappelsberger et al., 2023)

Thank you very much for the very detailed and helpful review of our manuscript. The comments are very helpful in improving and shortening the manuscript. Below we respond to each comment and describe how we plan to revise the manuscript to make it more concise and thus easier to read. Reviewer comments are marked in italics.

### 1 Major comments

**1.1** *Overall this paper is very dense/wordy, it reads more like a report than a scientific paper. Some sentences and paragraphs seem to just be added as filling without a clear purpose. I suggest heavily cutting the text, especially in the introduction and data section. See some specific suggestions further down.*

- We fully agree that the paper will benefit greatly from being shortened. The following parts of the manuscript will be significantly shortened or even deleted:
  - L55-63 (introduction)
  - L66-70 (introduction)
  - L72-79 (introduction)
  - L91-101 (introduction)
  - L195-231, Fig. 2 (data)
  - L320-326 (methods)
  - L414-419, Fig. 6 (results)
- In addition, we plan to change our methods slightly for ease of presentation and explanation.
  1. Data section: Here, we will describe that, we remove the offset, linear, quadratic and seasonal signals from the altimetric elevation changes,  $h^A$ , and from the modelled firn thickness changes,  $f^M$ , to obtain the altimetric variations,  $hv^A$ , and the modelled firn thickness variations,  $fv^M$ . Thus,  $hv^A$  and  $fv^M$  will represent our “input data sets” for our methods below.
  2. Methods section: Based on this, we will use  $hv^A$  as the input to our regression approach. This will simplify Eq. (1) to

$$hv^A(t) = \sum_{n=1}^N e_n^A PC_n^M(t) + r^A(t).$$

Thus, Eq. 2 and its accompanying text will no longer be needed at this stage as we will remove the offset, linear, quadratic and seasonal signals before. Likewise, Eq. 4 and its text are also no longer needed at this stage. We might change the order of the subchapters 3.1 and 3.2 due to the planned changes.

We note that by splitting the regression approach (Eq. 1) into two separate steps of parameter estimation (one for the offset, linear, quadratic and seasonal part, and a second one for the interannual patterns), we will imply a slightly different treatment of correlations between those parameters than in our original manuscript. However, the effect on the results will be small. Our conclusions will not be affected. With these changes the methods section will be shorter and we believe, much easier to read and understand.

**1.2** *There are a lot of sentences where you use a full stop rather than a comma.*

- Thank you for your detailed and specific suggestions below to improve the readability of our manuscript. We will take all these suggestions into account and rephrase or combine the relevant sentences in accordance with punctuation guidelines (Purdue OWL, 2024).

Originally, we have frequently chosen to write two shorter sentences rather than one longer sentence because less convoluted sentences are easier to write and read, especially for non-native English speakers. Nevertheless, we admit and agree that some of our short sentences may read a bit odd and we will improve those based on your suggestions.

**1.3** *Furthermore, there are a lot of grammar errors, like Line 94/95 “Nevertheless, discrepancies still remain. (See Section 2.3 for further details on comparisons between altimetry and firn models.)” It is not grammatically correct to start a new sentence with a paraphrase. All these things are disrupting the reading flow. This paper could really benefit from a proofread! See some specific suggestions further down.*

- We will go through all these sentences, remove the parentheses and rephrase the sentences if necessary.

**1.4** *There are a lot of inconsistencies in the figures, especially with the colour bars (spatial plots). It seems random if the colour bars have a min or max arrow extension, or both arrow extensions. These colour bar inconsistencies are seen throughout the paper. Also, in Figure S13 red is negative and blue is positive, just below in Figure S14 purple/blue is negative and brown/red is positive. Please go through them all and double-check if all the colour bars are correct.*

- The min and max arrow extensions of the colour bars are not random. We only use the arrows when there are values beyond the colour scale range. To avoid confusion and to clarify that there are no inconsistencies, we will add the following sentence to each figure that has a mixture of no arrow extensions and arrow extensions: “Colour bar arrows indicate that the value range exceeds the limits of the colour scale.”
- The colour scale in Fig. S13 is indeed inconsistent to the other similar figures. We will change the Fig. S13 colour bar accordingly.

**1.5** *Snow and firn are mentioned many times but the terms are not well defined here. The manuscript could benefit from a clear distinction between snow and firn. Further, sometimes it says snow/firn layers in plural and sometimes the layer is singular, and firn pack is also used. It seems like the terms are used interchangeably, please make sure to be consistent, as they have different meanings.*

- These terms should indeed be clarified and consistently used, thank you. For the most part, we have used the term ‘firn’ to refer to both snow and firn. For example, we use ‘firn thickness changes’ rather than ‘snow and firn thickness changes’. Also, the top layer of the firn model, which could be considered a snow layer, is already considered part of the firn layer.

The first time the terms ‘snow’ and ‘firn’ are used in the Introduction, we will define/clarify: “Snow is typically used for the seasonal snow cover, i.e. less than a year old. Firn refers to multiyear snow and is defined as the transition from freshly fallen snow to glacier ice (van den Broeke, 2008). However, we do not consider a separate snow layer, it is also referred to by the term firn layer.”

## 2 Minor comments

**2.1** *In section 2.4 it seems like you start to present and discuss results (Fig. 1 and 2), this feels out of place in the method sections.*

- Section 2.4 presents the original input data sets, without applying any of the methods described afterwards in Section 3. This is done to ensure that the reader is familiar with the original data sets used. In Fig. 1 (dash-dotted lines) and Fig. 2, we show the basin-mean time series and rms maps because this kind of presentation is commonly used when comparing results from altimetry and firn modelling. However, we acknowledge that this section feels out of place as we are already discussing the data. We will remove Section 2.4 as the content mentioned is either provided elsewhere in the manuscript or, as the data sets used have been published and discussed, can be assumed to be known. We will also remove Fig. 2 and we will modify Fig. 1.

**2.2** *In Section 2.1 you refer to the two altimetry datasets as “TUD altimetry” and “JPL altimetry” in lines 124-126. But in the section, you also call them “TUD” and “JPL”, or “TUD product” and “JPL product”, or “Schröder et al. (2019a)” and “Nilsson et al. (2022)”. When you make a definition in the beginning you should consistently use that. Likewise in section 2.2, you refer to the two firn models as IMAU firn model and GSFC firn model, within the same section you call them “IMAU”, “IMAU model”, “GSFC”, and “GSFC model”. When you make a definition in the beginning you should consistently use that.*

- In fact, we use many abbreviations. This may be overwhelming rather than helpful for clarity. We therefore suggest that we no longer use the abbreviations TUD, TUD altimetry, JPL, JPL altimetry, IMAU, IMAU model, GSFC and GSFC model. Instead, we will use the references of the data sets.

**2.3** *In the caption of Figure 2, you write “Color” which is American English other places you write “metre” which is British English. Please choose one way and be consistent.*

- We will change it to “colour” as we are using British English.

## 3 Specific comments

**L21:** *The references “(Horwath et al., 2022; IPCC, 2021)” are here in alphabetical order, the rest of the references are in timely order oldest first.*

- Absolutely, that is not consistent. To be precise, the first reference refers to the first part of the sentence and the second reference refers to the second part. We will change this accordingly: “Ice-mass loss from Antarctica contributed ~6 % to this rise (Horwath et al., 2022), and is likely to continue (IPCC, 2021).”

**L33:** *“in the snow and firn layer” This reads like there is no difference between snow and firn*

- We will change this to “in the firn layer” according to our definition in 1.5.

**L44:** *“statistically significant trends in the Antarctic (surface) mass balance” this statement needs a reference.*

- We will add the reference King and Watson (2020).

**L52-53:** *“Earth system models have recently caught up in this regard (Lenaerts et al., 2019)”. Is this sentences relevant? ESMs are not mentioned anymore.*

- We will delete this sentence.

L53: Suggest change “They are forced” to “They can be forced”, because not all RCMs use reanalysis data.

- We will combine this sentence with the previous sentence as follows: “When the main goal of RCMs is to realistically simulate the ice sheet weather, as is the case here, they are forced by atmospheric reanalysis products (van Wessem et al., 2018; Agosta et al., 2019).”

L54: “data from 1979 onwards” I guess you refer to ERA-interim but we have ERA5 now starting in 1950

- Thanks for this note. In order to keep the manuscript shorter, we will delete this part of the sentence.

L58: “However, spatial variations in SMB show a poorer agreement. On a basin scale, the largest...” remove the full stop after “agreement” use a comma instead as the following sentence is a continuation.

- This part will be shortened and reworded.

L81: “They” who?

- The observations from satellite altimetry. We will replace "They" with "These measurements".

L87: Here you have snow/firn layers in plural in L33 the layer is singular.

- According to our definition above (see 1.5), we will change this to: „(...) while radar signals penetrate into the upper firn layer.“ Here, and everywhere else we will use the singular.

L87: “If elevation changes due to changing ice flow can either be neglected or subtracted...” Please argue where or when they can be neglected.

- We will rephrase: “Altimetric elevation changes can be compared to modelled firn thickness changes in regions where changes in ice flow are either insignificant or are known and can be subtracted”.

L94: “Nevertheless, discrepancies still remain. (See Section 2.3 for further details on comparisons between altimetry and firn models.)” Incorrect grammar, suggest rewriting to: Nevertheless, discrepancies between altimetry and firn models still remain and are discussed.

- This sentence is not part of the revised manuscript anymore.

L98-99: “The reason likely lies in errors in the involved altimetry and modelling results” Is that not always the case? either the errors are from the altimetry or the model.

- In the revised manuscript, we plan to delete this sentence and much of the paragraph to which it belongs.

L99: “Therefore” what?

- Because of the large errors, the models cannot be used in a rigorous, deterministic manner to derive altimetric ice mass changes. Therefore, a simplified approach is commonly applied. However, in the revised manuscript that sentence will be deleted.

L99: What is meant by a “Steady-state” density model?

- A steady-state density model refers to a spatially but not temporally resolved density "map". Thus, only a single density "map" is used to translate all time slices of surface elevation change "maps/grids" into mass change "maps/grids". This implies the assumption that the density to which the elevation changes refer is steady/constant over time. However, in the revised manuscript this sentence will be deleted.

L118-119: “For the first time, the entire spatial information present in both the altimetry products and modelling outputs, together with the high (monthly) temporal resolution of gridded altimetry products, is jointly exploited.” This is a convoluted sentence, e.g. “altimetry products” is mentioned twice, please rewrite.

- We will rewrite: “For the first time, the entire spatial and temporal information present in the altimetry products is exploited together with the modelling results.”

L140: Here you write firn pack and firn layer as earlier.

- We will change this to: „(...) reduce the sensitivity to variations in the properties of the upper firn layer.“

L177-178: In SMB components you are missing refreeze/runoff

- The IMAU firn model is not forced with all SMB components, but with the fluxes and boundary conditions at the top of the firn layer. Refreezing is a process happening in the firn itself, so this is calculated within the IMAU-FDM model, same as runoff.

L179: “dynamically downscaled with RACMO2.3p2” does that mean that you have run the RACMO model?

- No, this is just a description of the data we used. The reference for the RACMO model is van Wessem et al. (2018). We will clarify this in the revised manuscript.

L182: “firn layer” singular

- We will keep it in the singular, the “firn layer”.

The following comments (L201-230) refer to Sections 2.3 and 2.4, which will be deleted. For this reason, we provide only some explanation, but no proposed changes:

L201: Missing reference to ERA-Interim.

- The reference of ERA-Interim, Dee et al. (2011), was already mentioned in L55.

L204: Define the sign of rates, is a positive rate making the surface go up?

- Positive: +; negative: -. Yes, if the ice sheet surface is going up, the rate is positive.

L207: “more positive” does that mean thicker firn or a faster thickness rate?

- “More positive rates” means larger/faster thickening rates (not faster densification rates);  
e.g.: modelled rate v1.1: +2 cm/yr; modelled rate v1.2A: +5 cm/yr

L208: “less negative” slower thickness rate, or slower thinning rate?

- “Less negative rates” means lower/slower thinning rates;  
e.g.: modelled rate v1.1: -5 cm/yr; modelled rate v1.2A: -2 cm/yr

L210: Do you mean the average ice sheet-wide seasonal amplitude in firn thickness? Or are you talking about ice sheet seasonal amplitude?

- The estimates of the average ice-sheet-wide seasonal amplitude give discrepant results.

*L211-213: It is unclear what these numbers are, Are they seasonal differences in firn thickness? Are they integrated over the entire ground AIS?*

- These numbers are the seasonal amplitudes in firn thickness averaged over the ice sheet and based on the various altimetry products and firn models.

*L215: Which basin definition?*

- The basin definition used in this study.

*L220: "Agreement between hA1 and fMa is generally good on interannual scales. Differences appear in the long-term trends." these are two very short sentences, I suggest removing the full stop.*

- Deleted.

*L225: Here you say the entire period is 1993-2017, does it not start in 1992?*

- Indeed, it starts in May 1992.

*L230: put s on "model" since you are referring to both models.*

- Deleted.

*L262: Replace full stop after regression with comma*

- We will rephrase these sentences on the basis of your comments and those of the second reviewer: "The stochastic model of our regression is represented by a different weighting of observations from two time periods. As results from the older altimetry missions generally have a higher noise level (Schröder et al., 2019a; Nilsson et al., 2022),  $h\nu^A$  after 2003 are weighted by 1, while  $h\nu^A$  before 2003 are given a different (usually lower) weight."

*L306: Suggest remove " ('R squared')"*

- Instead of removing "R squared", we plan to remove "the coefficient of determination" and refer to  $R^2$  as R squared throughout.

*L328: Shouldn't you also refer to  $fvE1$ ?*

- $fv^{E1}$  would be equal to  $fv^M$  since we do not adjust/scale anything.

*L330: "These alternative variations are called scaled firn thickness variations. We refer to them by  $fvE2$ ", replace full stop with a comma.*

- We will replace the full stop with ", and".

*L332: "These alternative variations are called modified adjusted firn thickness variations. We refer to them by  $fvE3$ ", replace full stop with a comma.*

- We will replace the full stop with ", and".

*L345-355: Please add references for the Kolmogorov-Smirnov test*

- We will add Massey (1951), Miller (1956) and Marsaglia et al. (2003).

L610: What is meant by “ measurement noise”?

- This refers to random errors in the altimetry results caused by the measurement (method) itself. We will briefly introduce that different effects can be responsible for errors in altimetry.

L731: Changes the full stop between noted and By to a comma, as it is the same sentence

- We will combine these sentence and the sentences in L726: “However, it is important to note that (...)”.

#### 4 Figures

Fig3 caption: you write “. Drainage basins of the EAIS and WAIS used in this study (thick black lines) following Rignot et al. (2011a, b).” but then in L298-299 you talk about regions and multiple Rignot basins forming one basin. Please clarify when you talk about Rignot basins, “your” basins or other regions

- In Fig. 3 we will clarify: “Drainage basins of the EAIS and WAIS used in this study (thick black lines), slightly modified from the definition of Rignot et al. (2011a, b).”
- In L298-299 we will change “regions” to “basins”: “We individually apply the PCA to  $fV^M$  for 10 selected basins (Fig. 3). To define the basins, we make use (...)”

Fig3: I suggest that you put all the areas/regions which you mention in the text

- Good idea, thanks. We will incorporate the following modified figure:

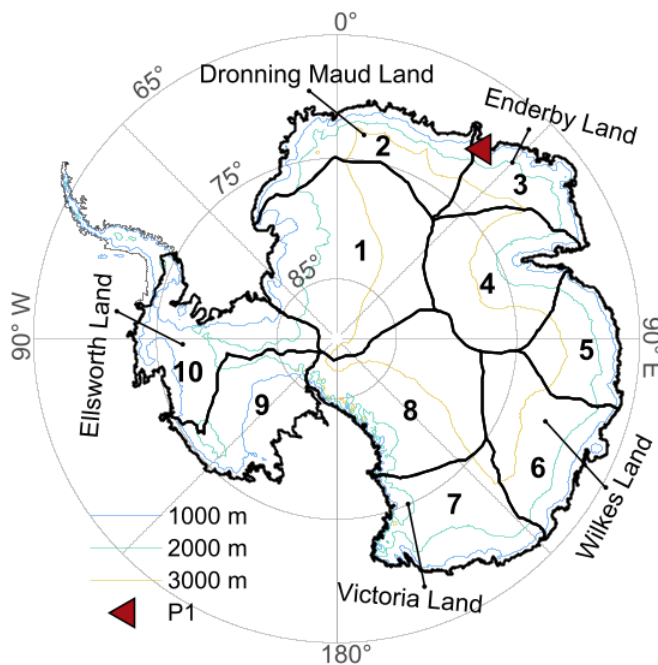


Fig10: The left colour bar has only max extend while the right has both min and max extend. Also are there even Coefficients of determination for the regression that are negative, like the min extend suggests?

- The arrow extensions are correct: (a, b) max extension only, (c) min extension only. Yes, there are very few grid cells where the coefficients of determination for the period after 2003 are negative. This is due to the different weighting of altimetry observations before and after 2003. Without weighting, the coefficients of determination would all be positive. However, due to the different weighting, it is possible that the adjusted firm thickness variations describe less of the variance of

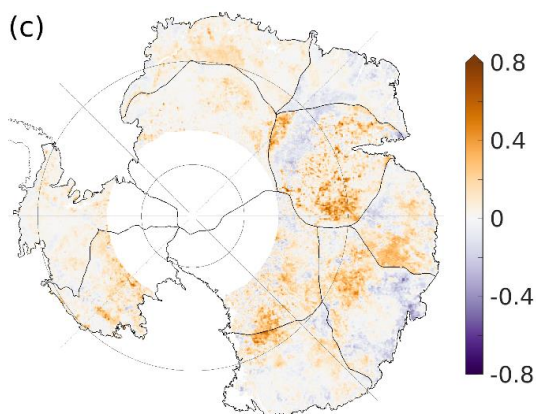
the altimetric variations for one of the two periods. This is more likely for the period before 2003, as altimetric observations before 2003 are usually weighted lower (see Fig. S21). We have tried to explain this in L406-409. In the revised manuscript we will explain this more clearly.

*Fig11: Shouldn't there be a min extension on the colour bar?*

- No, there are no values below  $-3$  because kappa values by HECTOR are always greater than or equal to  $-3$ . This is explained in L486. We will rephrase.

*Fig A1: Shouldn't there be a min extension on the colour bar?*

- There shouldn't be a min extension. However, we actually made a mistake when labelling the colour scale. The labels were in the wrong place. The correct labelling is shown below.



**All the following comments will be revised as suggested. Thank you for your scrutiny which will help us to improve many details of the manuscript.**

- L57-63: This could be written much shorter, it is not a review in Mottram et al 2021.
- L64-70: Again this could be written much shorter, it is not a review in Verjans et al 2021. I do not think all the numbers are necessary
- L71-79: In my opinion, this paragraph could be removed, as gravimetric mass balance is not the topic of this paper.
- L80: Remove "By contrast"
- L83: Change "utilise(d)" to utilise
- L84: Change "(ICESat-2)" to (ICESat), as your time period ends in 2017 and ICESat-2 was first launched in 2018.
- L86: "laser signals are reflected at or near the ice sheet surface". I think you mean "laser signals are reflected at or near the surface".
- L102: I suggest merging sections 1.2 and 1.3 and removing the text about gravimetry in Sec. 1.3
- L104: Remove "(Section 1.2)"
- L111: I suggest also merging sections 1.2, and 1,4 and then writing the "purpose part" in the last paragraph in Sec. 1.2.
- L113: Remove "(Section 1.1)"
- L131-132: Suggest changing the full stop to a comma between "differs. Thus,"
- L162-163: Why mention the Shepherd et al 2019 data when you are not using it? I suggest removing these lines.



- L172-173: you write “In accordance with the altimetry data, we involve firn thickness changes from the grounded AIS excluding the Antarctic Peninsula and the period May 1992 to December 2017” This sentence says that you exclude the AP and the period 1992-2017, it should likely say that you use the period 1992-2017
- L192: “ Medley et al. (2022a) built a new model” should it not say parameterisation instead of model?
- L198: Suggest to delete this line, it sounds like a rapport.
- L199: Again “TUD, JPL”
- L206: Remove “section 2.2”
- L215: Remove “ In this section” it sounds like a rapport.
- L219: “. (For the JPL altimetry, h A2, and the GSFC firn model, f Mb, similar time series are shown in Fig. S1.)” using the parentheses is incorrect grammar.
- L230-231: Using the parentheses is incorrect grammar.
- L247: “. It is explained in Section 3.1.1” maybe change to “, this is explained in Section 3.1.1”
- L284-286: “Comprehensive and general references....” this feels like it is a bit misplaced perhaps to put in the references after “respectively”
- L305: Suggest to merge section 3.1.1 and 3.1.2 as sec. 3.1.2 is very short.
- L311: Label eq 5a er 6 instead. It is a bit strange to have Eq 5 followed by eq 5a
- L360-361: “. (For example, power-law with  $\kappa = -1$  and  $\kappa = -2$  represents flicker and random walk noise, respectively.)” using the parentheses is incorrect grammar
- L365-366: “. (Note that the residuals may additionally contain signals related to variations in ice flow dynamics or subglacial hydrology.)” using the parentheses is incorrect grammar
- L398: “standard deviation” => std, the abbreviation is already introduced.
- L402:“(In the case of data gaps in the altimetry time series, this equality holds approximately.)”
- L409: Remove “(Section 3.1)”
- L431: “(The rms of all versions of fvA and fvM is illustrated in Fig. S17a–d and Fig. S18a, b, respectively.)”
- L441:“(Corresponding rms maps of differences are displayed in Fig. S17–S19).”
- L448: Section 4.2.4, you already have a section with the same title, this is confusing.
- L456-457: “(Fig S20 and Fig. S21 further shows maps of the residuals rms and of R2 for different versions of regression and both time periods. Table S1 lists basin averages of R2 for the period before 2003.)
- L472: “(Basin-mean time series of all regression results and versions are presented in Fig. S22–S24.)”
- L478-479: “(For the larger subset of selected grid points, Fig. S25 and S26 display the psd of the regression results from A1a and A2a, respectively.)”
- L485-486: “(HECTOR only yields numerical stable results for -3.)”
- L495: “(For all versions and both PCA, the original and rescaled patterns are illustrated in Fig. S27–S29).”
- L507: “power spectral density (psd)” => psd, the abbreviation is already introduced.
- L510-511: “(Unlike our analysis, they did not co-estimate a quadratic or seasonal term.)”
- L548-549:“(The histograms and cumulative histograms for all basins are shown in Fig. S30 and S31, respectively.)

- L556-557: “(See also Table 2 for an overview of the various differences in firm thickness variations fv and their description.)”
- L595: “also high” please put a number on that.
- Fig1: I suggest to refer to Fig3 in the caption for basin locations.
- Fig9 caption: Replace full stop with and “Histograms. Vertical”

Additional references:

- Marsaglia, G., Tsang, W., and Wang, J.: Evaluating Kolmogorov’s Distribution, Journal of Statistical Software, 8, 1–4, <https://doi.org/10.18637/jss.v008.i18>, 2003.
- Massey, F.: The Kolmogorov-Smirnov Test for Goodness of Fit, Journal of the American Statistical Association, 46, 68–78, 1951.
- Miller, L.: Table of Percentage Points of Kolmogorov Statistics, Journal of the American Statistical Association, 51, 111–121, 1956.
- Purdue OWL: Identifying Independent and Dependent Clauses. [https://owl.purdue.edu/owl/general\\_writing/punctuation/independent\\_and\\_dependent\\_clauses/](https://owl.purdue.edu/owl/general_writing/punctuation/independent_and_dependent_clauses/), last access: 29 January 2024.