Authors' response on "Brief Communication: Annual variability of the atmospheric circulation at large spatial scale reconstructed from a data assimilation framework cannot explain local East Antarctic ice rises' surface mass balance records"

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Response to RC1: 'Comment on egusphere-2024-3140', Anonymous Referee #1, 17 Dec 2024

Brief Communication: annual large-scale atmospheric circulation reconstructed from a data assimilation framework cannot explain local East Antarctic ice rises' surface mass balance records By Cavitte, Goosse, Dalaiden, Ghilain

This short manuscript describes the suitability of simulating the near surface wind pattern over the Dronning Maud land region from downscaled fields from an atmospheric model, in which ice core and ice penetrating radar results are assimilated.

The manuscript is reasonably well written with clear figures. The topic is appropriate for The Cryosphere and presents interesting results.

We thank the reviewer for their time in reviewing our manuscript. And we apologize for the delay in replying.

I do have some comments that I feel need to be addressed before publication.

My main concern is the clarity of the manuscript, where especially the method is not clearly described. As far as I understand, downscaled fields from an ensemble of models is taken. Then these are modified by assimilating the ice cores including information from the ice penetrating radar. This then results in time series of SMB and 10-m wind fields. I might be wrong, since it is not fully clear what is actually done, in what order, and what results from it. Also how the 10-m wind is related to or constrained by the SMB field is not clear to me, especially how the 10-m wind field is changed after assimilation of ice cores in the SMB field.

We have adapted the manuscript to clarify the processing steps to obtain the resulting new SMB and 10-m wind fields. The steps described above are correct. The way the updated 10-m wind field is obtained is through the assimilation process, in particular the update of the prior – taken from the downscaled fields – using the information from ice core records, while calculating the error from the penetrating radar observations. Only the total local snowfall is assimilated from the eight ice core sites. However, not only the snowfall is updated through the data assimilation process but the wind fields as well by using the modelled co-variance between snowfall and wind fields from the prior (i.e., the downscaled ensemble). Since the modelled downscaled 10-m winds are consistent with the modelled downscaled snowfall ensemble, the same approach for updating snowfall is applied for the wind fields.

We have now added the following paragraph at the end of the Methods/Downscaled model ensemble section: *"*One of the advantages of data assimilation methods is the use of the co-variance among all the modelled variables to not only update the variable that is assimilated (i.e., snowfall) but also all the other modelled variables, in particular the ones presenting a strong relationship with the assimilated variable. As such, the downscaled 10-m winds are updated concomitantly with the SMB field through the assimilation process. When assimilating the ice core data, a set of temporal weights for all particles are obtained to update the initial modelled state to match the assimilated observations. More specifically, during the data assimilation process, the largest weights are associated with the particles presenting the closest match with observations. Originally, all the weights are set to unity (all of the members of the prior have the same weight). The data assimilation process therefore aims at updating the weight to match the assimilated observations. These resulting weights are then applied to the modelled downscaled SMB fields to then calculate an optimal reconstructed SMB field that fits the observations while taking into account uncertainties from both modelling and observations. Since the modelled downscaled 10-m winds are physically consistent with the modelled downscaled SMB ensemble, the same set of weights can be applied to all the simulated variables. This is particularly valuable for the variables having a strong relationship with the assimilated variables.*"*

My second main point is the use of the term 'large-scale atmospheric circulation' when the 10-m wind field is described. In atmospheric terms, the large scale atmospheric circulation usually refers to the circulation that is not, or only limitedly, influenced by the surface. Usually the circulation at 500 hPa or 300 hPa is taken to represent it, not the 10-m wind since that is clearly influenced by interaction with the surface. Given the presented results you actually mean the near surface wind field on a larger spatial scale than purely local. Your title and manuscript should more clearly reflect what is actually presented.

We agree with the reviewer on this point and have changed the vocabulary used to be more precise. We indeed meant surface winds on a large spatial scale. We now use "at large spatial scales" everywhere. We also modified the title to "Brief Communication: annual variability of the atmospheric circulation at large spatial scale reconstructed from a data assimilation framework cannot explain local East Antarctic ice rises' surface mass balance records".

In relation to this, I am also curious why the SMB patters are related to changes in the flow pattern instead of the flow pattern themselves. Most logical steps would be to first try to explain the SMB pattern with the flow pattern, followed by SMB changes with changes in the flow pattern. Both are now a little bit mixed in this manuscript, with the title being different from the described research goals.

Our main goal is to analyze the temporal variability of the SMB over the Dronning Maud Land region, in particular to investigate the mechanisms that could explain different time evolution in nearby locations. The use of the data assimilation in our study aims at correcting the temporal variability of the ensemble of downscaled simulations to match the ice core observations in view of understanding the underlying mechanisms of the temporal variability from the different ice core locations, in particular the contribution of the wind variability. Ghilain et al. (2022) generated this ensemble of the downscaled simulations in a way to mimic the mean state of RACMO2.3 over the present-day conditions. Under the assumption that RACMO2.3 is perfect, this ensemble already displays an accurate mean state. This has been clarified in the revised version

We have added this sentence in the Results section discussing the wind reconstruction Fig:

“We analyse how the wind circulation has changed over the recent decade (2002-2011) with respect to the earliest decade reconstructed (1987-1996**). The goal is to determine if the temporal variability of the winds can explain the temporal variability in the ice core's SMB record, i.e. to understand why the SMB trends in the ice cores present different trends despite their relative proximity.** This comparison is a test…”

We have also updated the title of the manuscript to reflect that we focus on variability.

We have also made it more explicit that we are looking at variability when we mention ‘SMB reconstruction’, modifying this phrasing to ‘reconstruction of SMB variability’ in several places in the manuscript.

Other comments:

L9-10: rephrase this sentence: the processes that make up the surface mass balance are (reasonably) well understood, as are the processes that result in the spatial distribution. The actual absolute amounts are not well constrained, resulting in uncertainties in the details of the spatial patterns.

This sentence was removed for lack of clarity.

L17: add 'limited' before 'grid resolution'

Added

L20-21: rephrase this sentence: especially seasonal resolution is limited. The actual resolution very much depends on the accumulation rate. In L187 you also state that ice cores are rarely sub-annually resolved.

We have changed the sentence to “Ice cores provide historical records with a high temporal resolution, which strongly depends on the accumulation rate, generally annual in the first hundreds of meters of the ice sheet.”

L187 has also been modified to now read “Ice cores' temporal resolution strongly depends on accumulation, generally annual in the first few hundred meters of the ice sheet. Therefore, we need to rely on other types of SMB records such as automatic weather stations to have information on these shorter timescales..”

L24-25: rephrase sentence: it now reads as if the observations underestimate the SMB at the observation site. Since the ice cores are actual observations, they cannot underestimate

the mass balance at that site. It might result in an underestimation of the SMB of a larger region, but that is not what I read in this sentence.

The sentence has been rephrased to “Cavitte et al. (2022) have shown that, in the case of East Antarctic ice rises, this can lead to a systematic underestimation of the SMB over a larger region, but that the temporal variability of the SMB is generally well captured”

L27: replace 'offers thus' with 'thus offers'

Done

L33: rephrase sentence: not sure what you mean by 'a same area as grid points in a model'.

For the data-model comparison, the nearest grid cell (based on the centroid) from the ice core site is selected. We have rephrased to: “...and is traditionally estimated based on prior knowledge or comparing observations with the nearest grid cell (i.e., centroid) from the prior (...)”

L41: clarify: 'recent compilation' of what are you referring to?

We just meant “compilation provided in Cavitte et al. (2023)”. This has been changed.

L42-43: Suggest to replace 'These eight ice core SMB records have an annual resolution with differing trends in close proximity (~100-300 km between ice rises, Fig. 1a).' by 'These eight ice core SMB records are in close proximity (~100-300 km between ice rises, Fig. 1a) of each other, and have an annual resolution with differing trends.'

Done, thank you for the suggestion.

L44-51: Clarify the method described here.

We have clarified the processing steps used in this section and end the paragraph with: “The downscaled SMB and 10-m winds are therefore consistent and provide us with information at the adequate temporal and spatial scales to understand the different time evolution of the local ice rises' SMB over the historical period. Our approach allows us to understand the local SMB records better as we have a quantified estimate of the records' uncertainties and a framework to test the role of those uncertainties compared to a potential contribution of regional atmospheric dynamics in the difference between the records. After assimilation of the SMB records, the reconstructed winds are associated with the variability of the snowfall field through the assimilation process.”

We have also added another paragraph to describe our working hypotheses at the end of this section, following RC2.

L44: Explain on first usage of this term what you mean with 'model prior'. My guess is that it is similar to or basically a 'first guess' field.

The prior indeed consists of the first guest of the state of the system. We have added a short definition in brackets after (“first guess field”).

L46: I guess you mean that you downscale to the RACMO2.3 grid, not the resolution, which can be two different things.

Yes, we have replaced“resolution” by “grid”.

L49-51: please rephrase sentence: it is not clear to me what you wish to say with this sentence.

See response to comment above.

L55: what model do you mean with 'the model'

It now says the model prior.

L58-59: Due to my lack of knowledge of DA methods, this sentence is very unclear. What are or do the particles represent? Are they SMB fields for each year over the 165 year period? Times 10 then results in 1650. And what is the role of the prior in this?

Data assimilation methods require two main inputs, an initial guess of the state and the observations used to update this initial guest. The initial guess is commonly drawn from an ensemble of model simulations. In the case of the particle filter, each model simulation is called a particle, and the ensemble of all particles is referred to the prior. In this study, the prior is built from the ten downscaled simulations spanning the 1850-2014 period from Ghilain et al. (2022). However, in the assimilation process, we do not use only the model year corresponding to the year we want to reconstruct. First, ten simulations are too small to correctly estimate the range of potential states at a particular time. Second, because of the large internal variability of the system there is no reason that observations in one particular year are more similar to model states for the same year than 10 years before or ten years later for instance. Therefore, as in previous studies (e.g., Dalaiden and Rezsohazy et al., 2023), the size of the prior is augmented by selecting all the annual averages of the initial 10-member ensemble, under the assumption that the temporal predictability for the target variables we want to reconstruct is lower than one year. This is a reasonable assumption for the temperature and winds over our region of interest, and such a method has been shown to be highly skilful for reconstructing the hydroclimate (e.g., Steiger et al. 2017).

The whole paragraph is reworked to integrate this information.

L88: replace 'can thus provide' with 'thus can provide'

Done.

L91: rephrase sentence: better to state that melt in this region is limited and therefore the SMB is dominated by the snowfall and can be represented by it.

We have rephrased those sentences to: “In the framework of our methodology, this is a reasonable assumption for our region as the total annual melt in this region is limited (and when occuring, it mainly freezes within the firn) and therefore SMB is dominated by the snowfall and can be represented by it.”

L105: replace 'a majority' with 'the majority'

Done.

L103-1012: Do I conclude correctly that although RACMO for individual ice core sites does not correlate with the original ice cores or the reconstruction, over DML in general, there are regions where the temporal variations in the reconstructed SMB does correlate significantly with RACMO SMB?

That is correct. In Fig2, panel b shows the strong positive correlation between RACMO and the reconstruction in red.

L112: What heterogeneity do you refer to?

The fact that each of the ice cores has its own differing trend. We have reworded now to: “although the ice cores have differing SMB trends”.

L113: remove 'must'

Done

L113-114: Why would the 10m wind field reconstruction show physical validity of the reconstruction? The 10m wind field is, if I understand correctly, not independent. Furthermore, you do not look at the wind field pattern itself, but at changes in the pattern. See my comment above. I suggest to first look at the pattern itself, before looking at changes in the patterns.

See our answer below to both comments.

L116: Why is comparing changes a validity test? It only works if you know what the pattern should look like, and you do not know that.

One way to interpret our data assimilation procedure is as a constraint imposed on the model field to become closer to observations, assuming some uncertainties on both the model fields and observations. If the procedure works well, the reconstruction obtained at the end is still consistent with both observations and model results (in other words in their uncertainty range) but this reconstruction is updated and the uncertainty reduced compared to the initial values given independently by model results and observations. However, there are some cases where the difference between model results and observations is so large that it is not possible to find an optimal state after data assimilation that is still consistent with observations and model results (including their uncertainty). This might be due to a wrong estimate of the uncertainty of observations, model biases, additional processes that are not well accounted for, etc. In that case, the reconstruction using data assimilation may look unrealistic (for instance classical ‘bull-eye’ features close to each data point that appear disconnected from each other, or a very weak, homogeneous signal with an unrealistically small variance compared to available records in similar environment due to a too weak data constraint).

We have added the following sentence to make it clearer: ‘While ERA5 is constrained by observations at large scale and should provide a reasonable estimate of the wider circulation, the regional circulation is more uncertain and no clear target is available to measure precisely the skill of our reconstruction of the winds. Nevertheless, the

reconstruction should not appear to be too strongly constrained by conflicting regional records (inducing for instance very strong local patterns) or in strong disagreement at large-scale with ERA5.

L124: replace: 'Figure 3 shows the difference in wind strength between the youngest and oldest 10-year intervals of the reconstruction, so 2002-2011 versus 1987-1996.' with 'Figure 3 shows the difference in wind strength between the 2002-2011 and the 1987-1996 10-year intervals of the reconstruction.'

Done

L130: rephrase sentence: how do you know it is not realistic? It is different from RACMO. And rephrase 'large-scale', see my comment above.

We now mention that the pattern is different from RACMO. We have modified the vocabulary used to refer to large-scale, as suggested.

L143: replace 'that' with 'than'

Done

L180: check sentence, the word 'from' does not make sense to me.

Changed to “with”

Figure 1:

Caption: add the source of the 10-m wind field.

Done.

Figure 2:

Please check how you refer to RACMO2.3p

In the legend of panel a. and in panel b. it states RACMO5. Either use R5, as stated in the caption, or RACMO2.3p.

We have now changed the legend to read ‘RACMO5’.

Also check line 4 of the caption where le should be replaced by the equal to / smaller than sign. Done

Perhaps add in the description of panel b, that you present the temporal correlation.
Added “Spatial map of the temporal correlation between...”

Figure 3:

Change caption in: Difference in (a-b) SMB and (c-d) wind circulation, average over 2002-2011 minus average over 1987-1996 10-year intervals of the reconstruction.
Done

Response to RC2: 'Comment on egusphere-2024-3140', Anonymous Referee #2, 22 Jan 2025

Brief Communication: annual large-scale atmospheric circulation reconstructed from a data assimilation framework cannot explain local East Antarctic ice rises' surface mass balance records By Cavitte, Goosse, Dalaiden, Ghilain

In this short communication, the authors use eight ice core surface mass balance (SMB) records from a previous study, annually resolved over the period 1987-2011, from ice rises located in coastal Dronning Maud Land, East Antarctica. They use a downscaling method

that associate circulation patterns with surface fields (snowfall and surface wind) from the regional atmospheric model RACMO at 5.5km resolution. They apply this downscaling to the 10 ensemble members of the CESM2 Earth System Model. They use all years of this downscaled ensemble as prior for a data assimilation method, as well as a radar-based estimation of the representativeness error.

I think this article is interesting because the authors are honest with their results and with the limitations of the reconstructions. I would like to point out that it's not often that authors publish negative results, and I think this type of study is very useful for the scientific community.

We would like to thank the reviewer for their time in reviewing our manuscript, we really appreciate their reflections on its usefulness. And we apologize for the delay in our response.

However, I think the article would benefit from clarifying its objectives.

Major comments

In the introduction, the authors state that "To reconstruct SMB beyond direct instrumental measurements, which only cover the last decade or two (Wang et al., 2021), ice cores are the main in-situ observations (Lenaerts et al., 2019)." This sentence suggests that the article is about SMB reconstruction over a longer time period than the last decade or two. Then the time period of the ice rise records seems to be 1987-2011, which is covered by direct instrumental measurements.

The ice cores we use in this study indeed cover the recent instrumental period, but we meant to highlight that if the method works, it could then be extended to longer ice core records.

We have now added at the end of the introduction “The main goal of this study is therefore to test whether using a data assimilation framework with SMB constraints from East Antarctic ice cores, with added information from radar data (for estimating the observation error), can help to get a better reconstruction of SMB. Note that the ice cores used in this study cover the recent instrumental period to test the methodology and evaluate if it could be applied to longer ice core records.”

Then, the authors show that ice rises SMB records are not correlated to RACMO2 SMB, which means that either :

1. the ice rises SMB variability is not representative of a large-scale signal, or
2. RACMO2(ERA-Interim) SMB variability is wrong.

If I understood well, the authors have explored option (2), with the hypothesis that the link between large-scale circulation and SMB in RACMO2 is correct, but that it may be the large-scale circulation forcing RACMO2 that was wrong. Then they use the relationship between SMB and large-scale circulation to test whether they can obtain a SMB map more consistent with the ice rises SMB variability.

Can you tell me if I understood well or not? In any case, I think the article would need a clarification of the hypotheses that are being tested.

We actually test both hypotheses. As the other reviewer also found the setting up of the problem a little confusing, we have restructured the methods section to be as clear as possible and have detailed the hypotheses being tested up front in the introduction, as suggested (see proposed text below).

I think the authors should also give their hypotheses on why RACMO2 SMB variability might be wrong. Are they suggesting that the ERA-Interim forcing reanalysis might have a biased atmospheric circulation?

The large-scale circulation is relatively well constrained in ERA reanalysis over the period investigated but the link between large-scale and local scale variability may be biased or may misrepresent some processes that can be corrected by data assimilation. We know for instance that small-scale processes such as wind erosion and redistribution, are not that well represented (https://tc.copernicus.org/articles/18/4933/2024/).This is what we want to test. This is now specified more clearly in the revised version.

Conversely, they use the relationship between large scale circulation and RACMO2 SMB to downscale a large ensemble CESM2, which means that they trust the downscaling but not the ERA-Interim large scale circulation. It would be good to clarify if this is based on previous studies or it is a working hypothesis.

This is a working hypothesis. We assume that in the whole downscaled CESM2 ensemble we have enough samples of the potential variability of the system to reproduce the observed variability. This will be mentioned more explicitly in the revised version.

We have added the following text at the end of the introduction to explain more explicitly our working hypotheses:

“The observed differences in the signal displayed by the various ice cores could be due either to local processes and non-climatic signal noise (e.g. stratigraphic noise Dallmayr et al. 2025) that are uncorrelated between the different locations or to regional atmospheric circulation variability inducing contrasted spatial patterns in snow accumulation. We investigate those two potential origins here in the data assimilation framework. The estimate of the uncertainty based on radar measurements will give more weight in the reconstruction to the records that display a stronger climate signal (i.e., less noisy) and we will check if this helps to obtain a reconstruction which is consistent with all the records accounting for their uncertainty. The impact of the regional atmospheric circulation will be tested using the downscaled estimates of winds. We assume by this that, although model results unconstrained by data may not follow well the SMB derived from ice cores (maybe because they have some biases in simulating the regional atmospheric dynamics or the link between large-scale and regional atmospheric circulation), the physics of the model is adequate to represent the regional processes and the data constraint imposed by the assimilation of ice core records will ensure a better agreement between observed and reconstructed variability.”

Finally, I was troubled by the emphasis on "test(ing) if using the representativeness error derived from radar data improves the reconstruction of SMB" which at the end did not seem to be a center point of the article.

We are now more explicit by modifying the sentence to: “Here, we apply the representativeness error derived from radar data improves the reconstruction of SMB of the

Dronning Maud Land (DML) region over the past 25 years based on the assimilation of eight ice core SMB series by taking advantage of the compilation provided in Cavitte et al (2023)".

Minor comments

Abstract

"To evaluate if large-scale atmospheric circulation explains contrasted SMB trends at eight East Antarctic ice rises"

- -> "contrasted SMB trends" with regard to what?
  We meant that the SMB trend of the various ice cores are very different from each other, so we have modified it to "...explains the differing SMB trends at ..."

1 Introduction

"Regional climate models with a high spatial resolution (~a few km2), such as the polar-oriented Regional Atmospheric Climate Model version 2.3 (RACMO) (Van Wessem et al., 2018), struggle to capture the mean SMB state in the ice sheet interior, while they have a reasonably good fit with coastal mean SMB (e.g. Agosta et al., 2019)"

- -> I don't see this information in Agosta et al., 2019, can you clarify where it comes from?
  This is from Fig2 of the Agosta et al., 2019 paper, the panel for Dronning Maud Land is a good example.

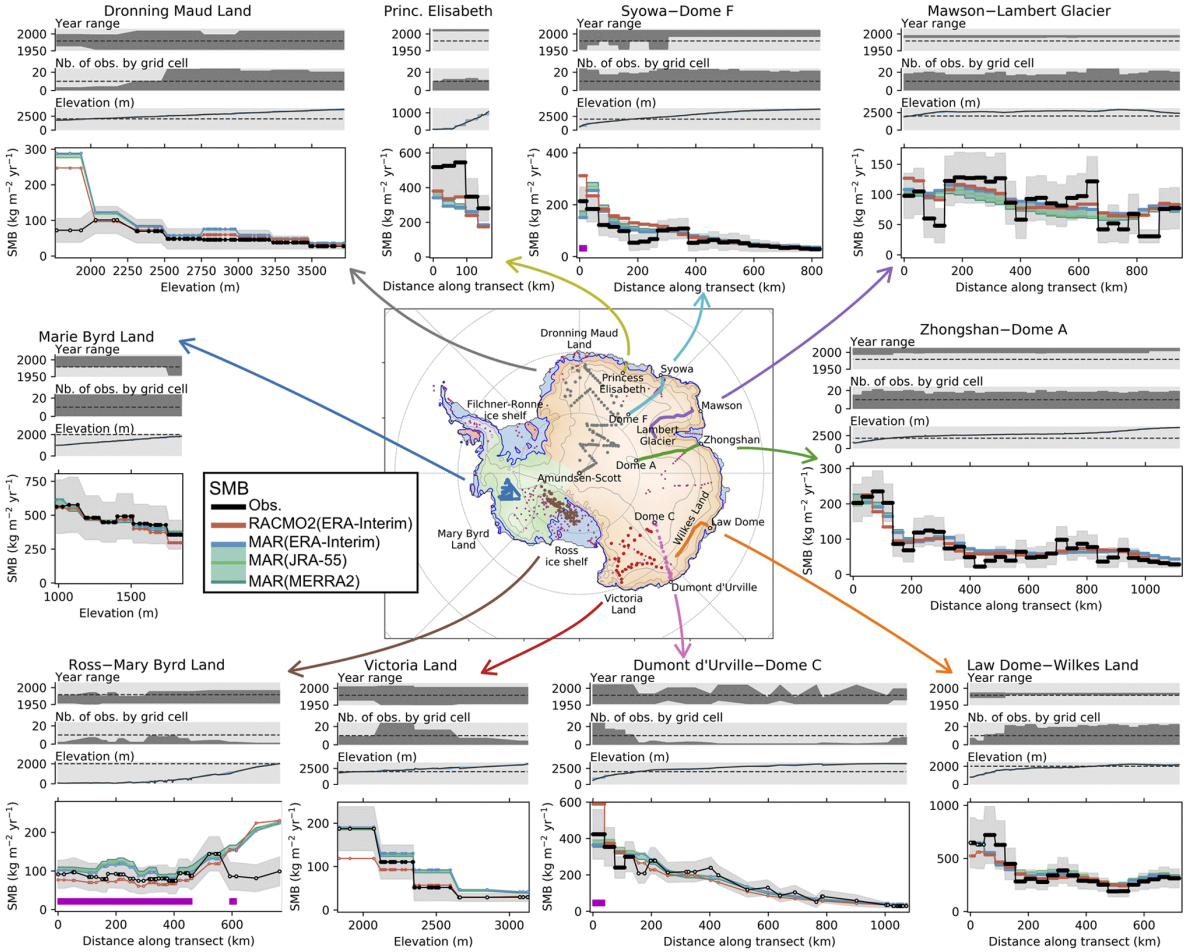

Figure 1. Figure reproduced from Agosta et al., 2019, The Cryosphere

- "Fig. 1" Nice figure. Thank you!

- "Fig. 1: Background is the RAMP RADARSAT mosaic (Jezek et al., 2013) with superimposed the Reference Elevation Model of Antarctica (REMA) v2 elevation for each site (units are meters and referenced to the WGS84 ellipsoid)." Added.

  - -> the colorbar is missing for REMA elevation maps , and I recommend to use a continuous colormap instead of the rainbow colormap. We have changed the colormap and added contours to make the coastline of the ice rises stand out, modifying the figure caption accordingly.

- "Fig. 1: (b) Mean 10-m winds over Dronning Maud Land for 1987-2011."

  - -> from which dataset? RACMO2.3p. Added.

2. Method

2.1 Data assimilation

"Particle weights are assigned based on the agreement between model results and observations, with closer matches receiving higher weights. "

- -> provide the exact metric : extract the model at the nearest grid cell? And RMSE across model-obs? Yes, this has been added explicitly. New text: “Particle weights are assigned based on the agreement between model results and observations at the nearest grid cell, with particles presenting the highest likelihood (i.e having a closer match with observations) receiving higher weights (see Dubinkina et al. 2011 for more details and the exact formulas).”
- -> Then can you provide the exact formula of weighted mean using this weight? We have now provided a reference for this. See added text above.

- "Our observation error is the root-mean-square combination of the instrumental error and the representativeness error (Supplementary Table S1)."

- -> I don't see in the short method description where the observation error is taken into account. We have clarified this in the method description:

  ‘The observation error is taken into account during the data assimilation process, in particular during the data-model comparison when computing the weight of each particle based on the likelihood. Our observation error is the root-mean-square combination of the instrumental error and the representativeness error (Supplementary Table S1).’

2.2 SMB observations

- -> add more details about SMB observations, notably the time period, time resolution and associated uncertainties with regard e.g. on ice core dating.
  We have added a table with some information on the ice cores (lat, lon, age coverage, references). We also state that all ice cores have an annual resolution .

2.3 Downscaled model ensemble

"This downscaled product has an improved spatio-temporal distribution of snowfall compared to global climate models, such as the CESM2 simulations on which it is based, and can thus provide information on large-scale atmospheric circulation patterns associated with local snowfall changes."

- -> Is the improvement quantified in this study or in a previous study? In both cases, can you give the reference to this quantification?
  This is shown in the Ghilain et al., 2022 paper in ESSD, which presents the downscaled SMB product. Based on a comparison with available ice cores and spatial reconstructions, they show that the spatio-temporal distribution of snowfall is improved in the downscaled dataset compared with the CESM2 simulations. We have added this reference in the paragraph.

3 Results

- "We highlight that the number of particles retained by the filter is quite low (about 7% on average). Retaining too few particles implies that the reconstruction may be based on too few samples and the estimate may become less accurate (filter degeneracy)."

- -> The final number of particles retained should be added in the Method section.
  We have added a few words on this in the Method section: “However, 7% of the 1650 particles available in the prior still corresponds to 115 particles on average, which provides a reasonable size for computing statistics for our reconstruction.”

  - Figure 3:

- -> I suggest that you add the difference in SMB field between the reconstruction and RACMO for the full period, and the same for winds, to assess the difference between the reconstruction and RACMO2 SMB (on top of the difference in changes in SMB).
  In the revised version of the manuscript, we now explicitly insist that we are studying variability (including in the title of the manuscript) (this was brought up by Reviewer 1 too, and is complimented in our answers to Reviewer 1) and so a panel showing the mean state would be out of context.

"Because the ice core records are rarely sub-annually resolved, due to the nature of the measurements (if we want to go back further than 10 years), we would need to turn to other types of SMB records such as automatic weather stations. The issue in that case is that such records are currently not long enough to retrieve meaningful SMB trends"

- -> Many automatic weather stations are already assimilated in reanalyses, though not for SMB. Can you clarify what you want to reconstruct or constrain with ice cores? Do you want to reconstruct circulation patterns beyond the reanalyses era? Do you want to use SMB to better constrain reanalyses?
  What we meant here is that we would like to reconstruct circulation patterns beyond the reanalysis era, beyond AWS measurements. This paper was the first step: testing it over a short recent timescale, to see if then we can extend further back in time. We have modified the sentence, see our response higher up on this.

"ML and AI emulators"

- -> replace abbreviations by full words. Done

" downscaled annual wind simulations are available at xxxx."

- -> typo. The online portal will be added upon publication.