Manuscript title: A computationally efficient statistically downscaled 100 m resolution Greenland product from the regional climate model MAR

Authors: Marco Tedesco, Paolo Colosio, Xavier Fettweis, Guido Cervone

General comments

This study uses a statistical downscaling technique to enhance the horizontal resolution of the Mod.le Atmosph.rique R.gional (MAR) regional climate model and produce an improved surface mass balance (SMB) product. The authors use an impressive breadth of datasets and tools both for statistically downscaling and for evaluating the final product. The product itself is clearly an improvement, is of notably high spatial resolution, and likely has many valuable applications. The high resolution over such a large area is computationally remarkable. The manuscript is well-organized and the flow of ideas is very logical.

My main concern is the final step of the methodology, which leaves the reader wondering how well the statistical downscaling works without applying physical constraints. I have also described two minor comments and several line-by-line comments that are mostly concerned with improving the writing itself. Some clarity of the research is lost due to longer/confusing sentences, so I have suggested some improvements below.

Major comments

Description of final step of methodology: There is an insufficient description of the "physical constraints" applied in the final step of the downscaling in section 3.1 This needs further elaboration, especially since it differs from No.l et al. (2016) and is later referred to in section 4.1. The authors should

(1) provide a reason as to why the mass conservation issues did not arise in No.l et al. (2016)

R: We thank the reviewer for this comment. We are not sure, however, how to answer to the first question as we did not author the paper in object and are not sure neither why mass conservation was not considered nor why this is not discussed in the paper. As the reviewer can imagine, we think this is an important step of the methodology because it assures that the downscaling (which is very simple in its own nature) does not alter the outputs of the MAR model. The coefficients used for the downscaling , indeed, use such values and we want to preserve consistency between the two datasets (coarse and fine) so tha there is also compatibility between the two products. After all, the downscaling technique is not supposed to introduce any further information to the computed values (e.g., differently of how it would be in the case, for example, of a machine learning model or any dynamical model that accounts for changes in the state of the system). Rather, the goal is to provide a downscaled product from the MAR model outputs. To reiterate, we are not sure why this issue was not raised in the paper by Noel et al. but we think it is important.

, (2) describe exactly what these physical constraints are,

There are two physical constraints: the first constraint is on temperature. The downscaled outputs of the temperature are such that the mean average temperature of the pixels at the finer spatial scale is equal to the temperature of the original MAR pixel at 6 km; the second constraint is on the SMB. In this case, the sum of the SMB values at finer spatial scales is set to equal the SMB value for the coarser corresponding MAR pixel.

and (3)
report on how they affect the final product. Without any additional information, the application of the physical constraints could be interpreted as forcing the final product to fit within the expectations. As this is likely not the case, a description of these steps will give the reader more confidence in the methodology.
R: We ran the downscaling previously without applying the physical constraints (which are now better explicit in the paper) and found small differences between the two products (<0.1 %).

Minor comments
Scale break: I am unsure of the meaning of "scale break" (first used in section 4.1). Is that a term used in variogram analysis? If so, please describe it in the methods, as I (and I imagine many people) are not very familiar with variograms. I see the term "sill" has been used in section 3.2—is that what the scale break is? If so, please only use one term, define it, and then explain what different values may mean. For example, in Figure 5, what is the significance of the different scale break values?

R: thank you for the suggestion. We introduced the term "scale break' when we present the variogram in Section 3. The scale break is, indeed, the spatial scale at which the autocorrelation changes, indicating that different processes might be dominating (e.g., large scale atmospheric processes vs. local wind effects). We point that the *range* can be seen as a scale break but there can also be several scale breaks before the sill is reached, depending on the drivers controlling the modeled process. We added this in the manuscript and thank the reviewer for the comment.

SMB units: Throughout the manuscript, SMB is reported in units of millimeters (mm). However, SMB is generally reported as a unit of mass change over time such as mm w.e. yr^{-1}, m w.e. yr^{-1}, or Gt yr^{-1} (Lenaerts et al., 2019). In the manuscript, SMB units of mm should instead be reported as mm w.e. Yr^{-1}.
R: Done.

Line-by-line comments
Comments are numbered as "[page number].[line number]". For example, "1.12" refers to line 12 on page 1.
Abstract
1.12: Change "over next decades" to "over the next decades"
R: Done , thanks

1.12: Change "evolution surface mass loss" to either "evolution of surface mass loss" or "evolving surface mass loss"
R: Done, thanks

1.19: Please also mention the other variables that are assessed and mentioned later in the manuscript (air temperature and surface temperature)
R: Done, thank you

1.21: Specify which variable is being discussed here (SMB?)

R: Yes, we changed the sentence based on another reviewer's comment. We hope the new version clarifies that we are referring to SMB

Introduction
2.1–2.2: The use of "extension and persistency" is confusing here. I understand what the authors mean by "persistency" but not by "extension." If this refers to the surface melt increasing in strength and duration, consider rewriting this sentence as: "The persistency and intensity of surface melting has also been increasing since 1979, as measured by passive microwave satellite observations [citations]."
R: Thanks, we changed that

2.4: Change "evolution surface mass loss" to either "evolution of surface mass loss" or "evolving surface mass loss"
R: Done, thanks

2.5–2.6: Specify what is meant by "actual mass loss." As compared to what? The authors could specify that remote sensing observations can provide information about surface height changes but are unable to attribute height change to a mass change without more information about snow/firn compaction (e.g., Smith et al., 2023).
R: We changed that, thanks !

2.11–2.16: These statements could benefit from references to specific examples where a finer spatial resolution would have improved results. Several broad examples are mentioned, but citing papers that specifically mention the limitations of the spatial resolution could be helpful.

R: Thanks, We have rewritten and modified those sentences.

Datasets
3.6–3.7: Change "Greenland ice sheet" to "GrIS"
R: Done. We also changed it on other occurrences.

3.27: Specify what type of dataset is being referred to in "we used the dataset collected by Machguth". In other words "…the PROMICE dataset…" or "…the SMB dataset…" Though this section (2.3) contains "PROMICE" in its title, nowhere in the text of this section does it say "PROMICE".

R: We added "SMB" to specify that is the same dataset

4.8: What is meant by "SMB variable"? I thought there were only two model outputs (original and downscaled), but this reads as if there are three.
R: apologies, we removed the word "variable". There are indeed two SMB modeled outptus.

4.13: Change "Greenland ice sheet" to "GrIS"
R: Done.

Methods
3
5.3–5.5: Consider rewording these first two sentences for clarity; the phrases in parentheses feel disjointed. Something like: "We adopted the approach used by No.l et al. (2016), in which a

statistical downscaling method was applied to RACMO to achieve a 1-km horizontal resolution. Here we use a similar methodology applied to MAR, but instead downscale the product to 100 m horizontal resolution."
R: Thanks , we did that

5.8: Change "Greenland ice sheet" to "GrIS"
R: Done

5.15–5.17: The specific description of the pixel and line colors is unnecessary in the text. I suggest either removing these sentences ("The local linear…" and "The dashed red…") or moving them to the figure caption if not already mentioned in the caption.
R: We removed it , thanks.

5.28–5.31: Consider editing this sentence for concision and removing/rewording "embarrassingly parallel problem".
R: thanks we removed that portion and rewrittent the sentence.

6.2: Consider changing "I/O" to "input/output" to avoid computer science jargon/abbreviations that may be unfamiliar to some.
R: Done.

6.13–6.16: Modify or move this to the Figure 2 caption (see early comment on lines 5.15–5.17).
R: We moved the text to the caption.

6.20: Change "constrains" to "constraints"
R: Done

6.20–6.21: Please expand on this statement. Why was this not necessary in No.l et al. (2016)? What exactly are the physical constraints are how are they applied?

R: As we explained to the other reviewer, We are not sure how to answer the first question as we did not author the paper in object and are not sure why mass conservation was not considered. There are two physical constraints: the first constraint is on temperature. The downscaled outputs of the temperature are such that the mean average temperature of the pixels at the finer spatial scale is equal to the temperature of the original MAR pixel at 6 km; the second constraint is on the SMB. In this case, the sum of the SMB values at finer spatial scales is set to equal the SMB value for the coarser corresponding MAR pixel.

6.23: Is the citation referring to this manuscript? If so, I believe it is unnecessary to add.
R: That citation was a mistake. Thanks for pointing this out

6.25: Change "slop" to "slope"
R: Done

7.1–7.2: Please reword the sentence beginning with "The knowledge of…" I am confused by its Meaning.
R: Apologies, we rewrote that sentence.

7.22: Change “th” to “the”
R: Done

Results and discussion
8.21: Change “remains unvaried, being equal to 2.6 ÅãC” to “remains unvaried at 2.6 ÅãC”
R: Done

8.24–8.25: Please reword or expand on this sentence in order to clarify the meaning. Specifying the actual physical constraints applied (either here or in the methods as earlier mentioned) could help with clarity and thoroughness.
R: We modified that sentence following another reviewer’s suggestion.

8.30: I believe this is the first use of “semi-variogram” in the manuscript. How does this differ from just “variogram”? The prefix “semi“ is also used in Figure 5 and 6 but not mentioned in the methods section describing variograms. Please either define it or only use “variogram”.
R: thanks, we will be consistent.

8.32–9.1: Please refer to Figure 5 at the end of this sentence, especially since Figure 3 was just mentioned. Additionally, are the numbers reported here meant to match those shown in Figure 5 (13,373, 11,384, and 24,171 km)? If so, the rounded values should be reported as “13.4 km”, “11.4 km”, and “24.2 km”, respectively.

R: Done, thanks.

9.12: Is “break scale” correct or should it be “scale break”?
R: scale break is the appropriate version, thanks

10.1: Remove “from a quantitatively point of view”
R: Done

11.4: Should “negative” instead be “positive”? Or should the equation be flipped? As it is written, if $RMSE_{100m}$ is smaller than $RMSE_{6km}$ (and thus the downscaled product shows improvement), ΔRMSE would be positive, not negative. Based on Figure 8 and its caption, I believe the equation should be flipped so its $RMSE_{100m}$ - $RMSE_{6km}$

R: Yes, thanks for noticing the typo, the equation is ΔRMSE=RMSE100m-RMSE6km.

Conclusions
12.5–12.11: Please reword these sentences since they are very long. Splitting each sentence into two would help.

R: thanks, We shortened and reworded that sentence.

12.17-19: Reword for clarity.
R: Done, thanks

Figures
Figure 1: Consider changing the northing/easing values to latitude/longitude. This is not a

necessity for publication, but would be more helpful for the reader if it is not too much trouble, especially since Table 1, Table 2, and Figure 8 all use lat/lon. Also, if the range of the color bar is adjusted to 0–3200 m, it will show more contrast on the map. As it is now, it all looks like one shade of grey. Summit is at an elevation of ~3200 m, so extending the color bar to 4000+ m is Unneeded.
R: Thanks. We replaced the figure.

Figure 2: Either change "Latitude" and "Longitude" to "Northing" and "Easting" or report values of lat/lon in panel (a). The caption needs further details and should mention all of the features in the figure itself. The small black dots in (a) and the the blue circles in (a) and (b) need to be described in the caption. The text from the body of the manuscript that describes the blue dots (see earlier comment) could be moved here.
R: Done

Figure 3: Either change "Latitude" and "Longitude" to "Northing" and "Easting" or report values of lat/lon. The color bar needs to be larger so it's easier to see and should be labeled as "surface temperature". The caption should also specifiy "surface" temperature. Also, where (geographically) is this figure showing? Please either include an inset map of the ice sheet or refer to where it is in the caption. If it is one of the regions in Figure 1, please indicate so in the Caption.
R: Done.

References used in this review
Lenaerts, J. T., Medley, B., van den Broeke, M. R., & Wouters, B. (2019). Observing and modeling ice sheet surface mass balance. Reviews of Geophysics, 57(2), 376-420. https://doi.org/10.1029/2018RG000622
Smith, B. E., Medley, B., Fettweis, X., Sutterley, T., Alexander, P., Porter, D., & Tedesco, M. (2023). Evaluating Greenland surface-mass-balance and firn-densification data using ICESat-2 altimetry. The Cryosphere, 17(2), 789-808. https://doi.org/10.5194/tc-17-789-2023