Reviewers comments in black

*Author's response in red*

# Summary of major changes

**Figure 1 and 2.** The *m* and *r* have been added to each panel, in addition RACMO2.3 and CESM1.0 in text are annotated to the first figure in colors corresponding to their scatter and lines. Y-axis is changed to show the same range for the same units.

**Figure 2.** Added an additional panel containing snowfall.

**Figure 3.** Added an additional row with SMB vs elevation for each of the lapse rates.

**Figure 4**. Added a spatial map of the RACMO2.3 reference data. Changed panel (b) to show EC-1K minus EC-6K.

**Supplementary figure.** A supplementary figure similar to Figure 1 has been added showing the incoming and outgoing solar and longwave components.

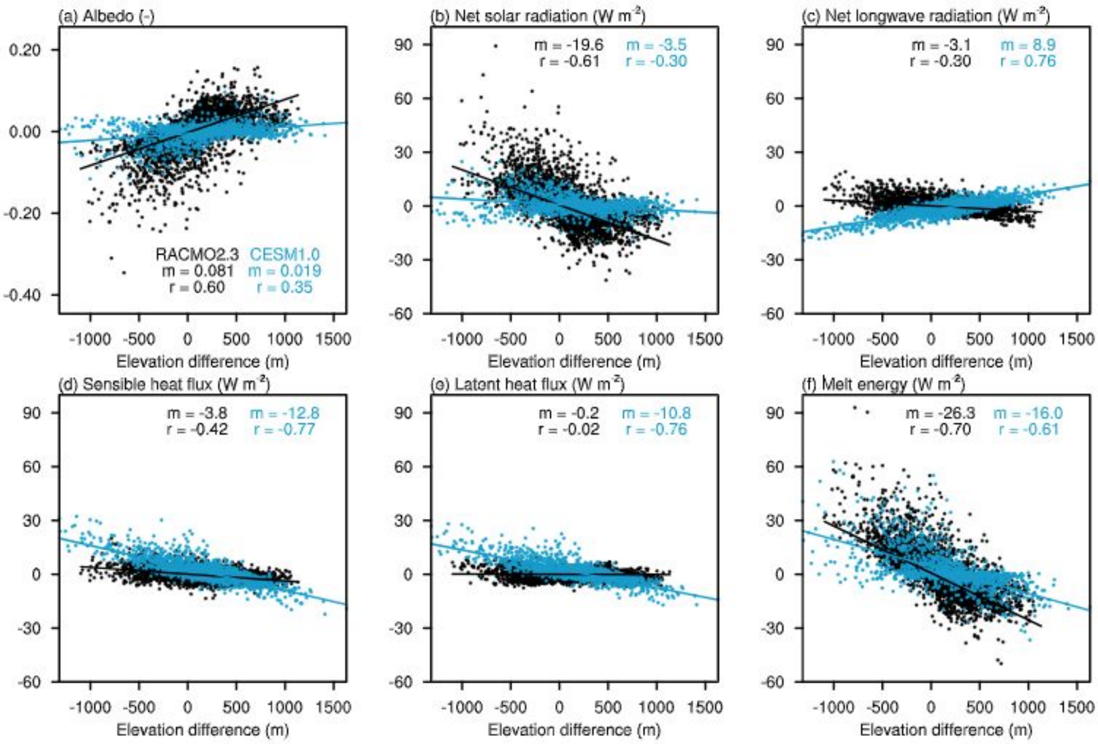
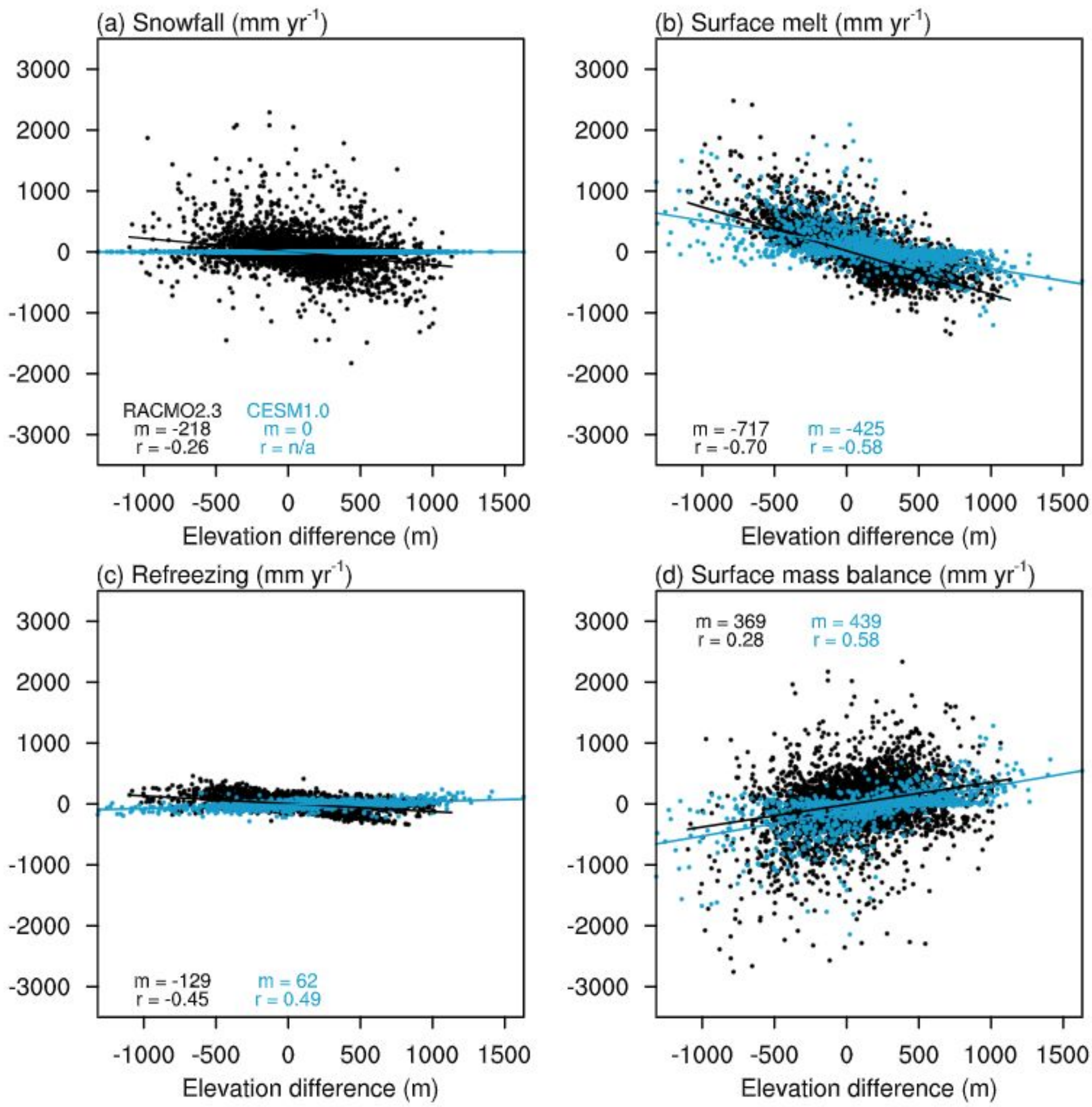



Figure 1



(a) Snowfall (mm yr-1)
RACMO2.3
m = -218
r = -0.26
CESM1.0
m = 0
r = n/a
(b) Surface melt (mm yr-1)
m = -717
r = -0.70
m = -425
r = -0.58
(c) Refreezing (mm yr-1)
m = -129
r = -0.45
m = 62
r = 0.49
(d) Surface mass balance (mm yr-1)
m = 369
r = 0.28
m = 439
r = 0.58
Elevation difference (m)


Figure 2

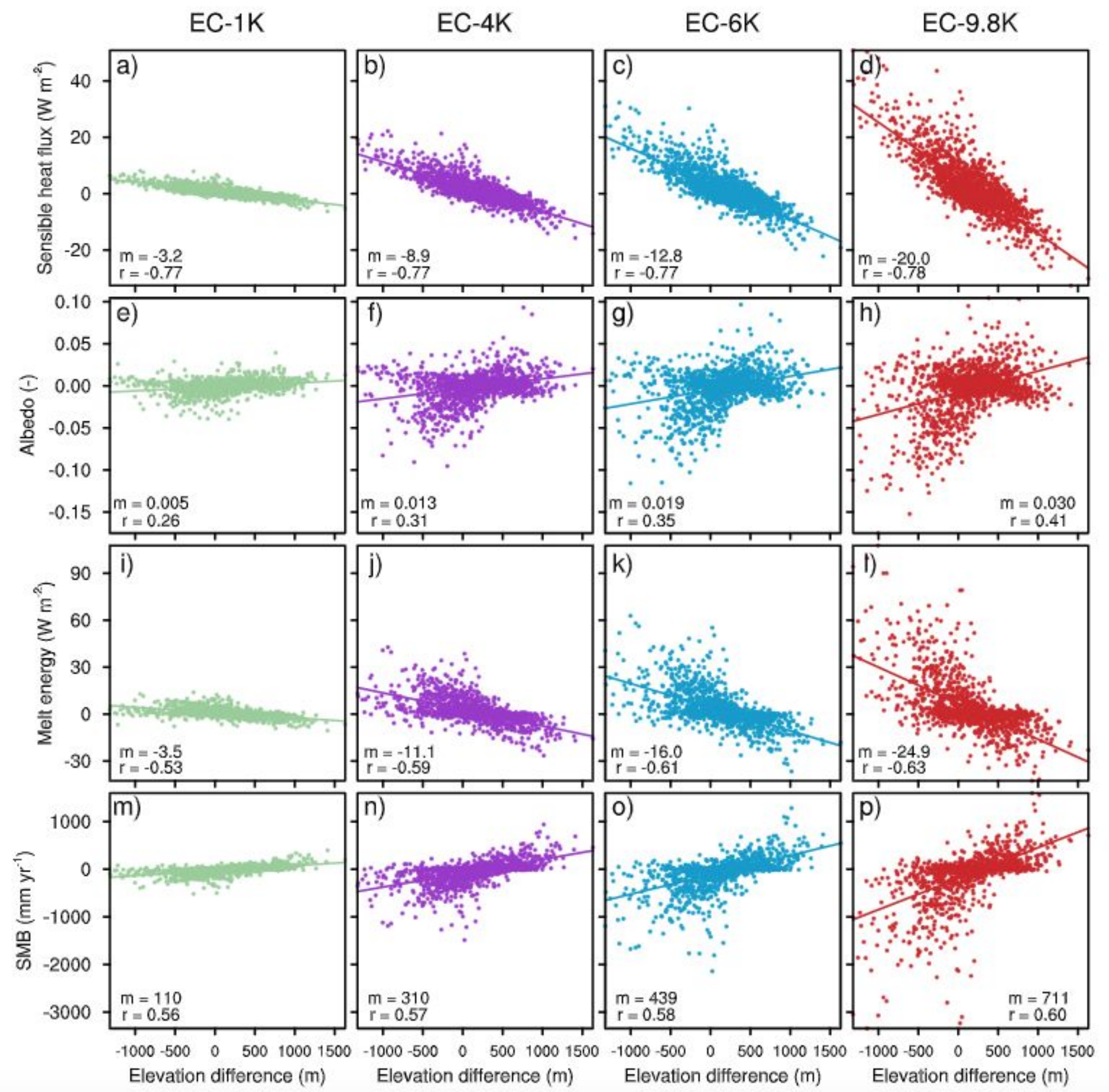

EC-1K
EC-4K
EC-6K
EC-9.8K
Sensible heat flux (W m-2)
Albedo (-)
Melt energy (W m-2)
SMB (mm yr-1)
Elevation difference (m)
a)
m = -3.2
r = -0.77
b)
m = -8.9
r = -0.77
c)
m = -12.8
r = -0.77
d)
m = -20.0
r = -0.78
e)
m = 0.005
r = 0.26
f)
m = 0.013
r = 0.31
g)
m = 0.019
r = 0.35
h)
m = 0.030
r = 0.41
i)
m = -3.5
r = -0.53
j)
m = -11.1
r = -0.59
k)
m = -16.0
r = -0.61
l)
m = -24.9
r = -0.63
m)
m = 110
r = 0.56
n)
m = 310
r = 0.57
o)
m = 439
r = 0.58
p)
m = 711
r = 0.60

Figure 3

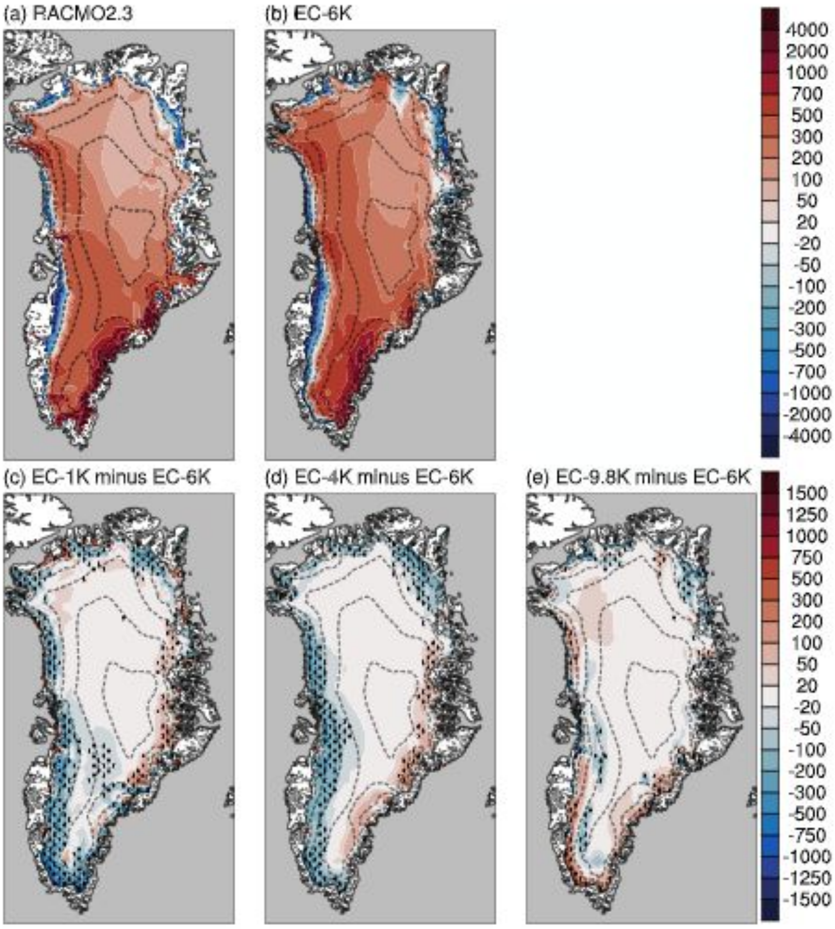

(a) RACMO2.3
(b) EC-6K
(c) EC-1K minus EC-6K
(d) EC-4K minus EC-6K
(e) EC-9.8K minus EC-6K
4000
2000
1000
700
500
300
200
100
50
20
-20
-50
-100
-200
-300
-500
-700
-1000
-2000
-4000
1500
1250
1000
750
500
300
200
100
50
20
-20
-50
-100
-200
-300
-500
-750
-1000
-1250
-1500

Figure 4

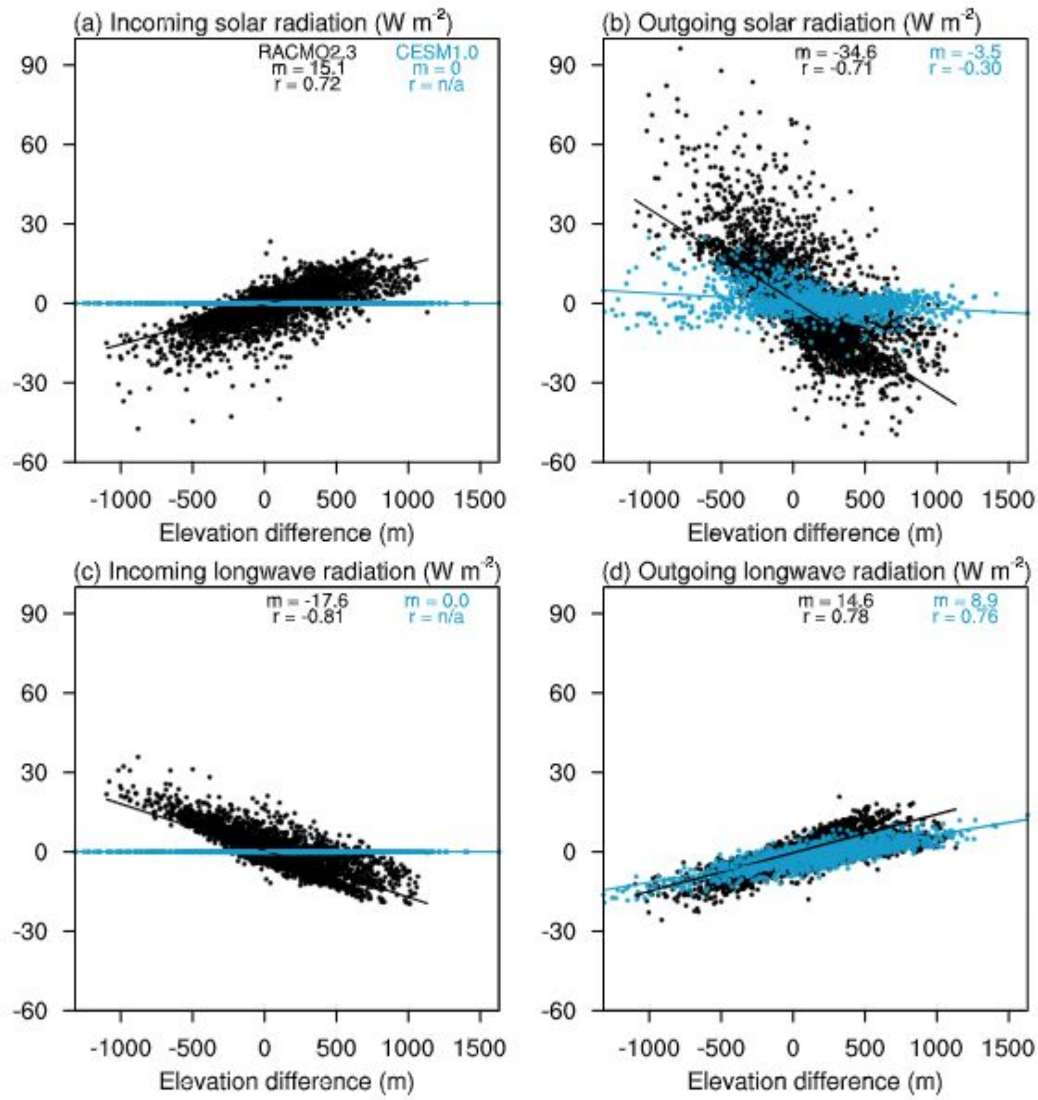



Figure S1

# Reviewer #1:

**General comments**

This paper describes an analysis of the online climate downscaling scheme used over the Greenland ice sheet in an older version of CESM, alongside a limited study of how sensitive it is to the temperature lapse rate specified, one of the scheme's key parameters. The topic is timely, although I don't think it's totally clear that this belongs in The Cryosphere rather than Geosci. Model Dev., seeing as it doesn't purport to research anything about the real world, rather evaluate the emergent behaviour of a model parameterisation. That's not meant to imply that I don't think it's an important subject, and it is valuable to highlight these results to a wider audience than those who work on the development of climate models, as it directly bears on the interpretation of model results that are used widely in the cryospheric community. In general I liked it, and as someone working in this area, I found it practically useful.The paper is well structured and clearly written - my main recommendation for an improvement would simply be to show more figures.

*We thank the reviewer for this feedback, and we will expand on the figures in the manuscript, in addition to adding more figures to the supplementary material. We submitted this manuscript to TCD instead of GMD, as the study is more focused on physical analysis of surface fluxes and climate impacts resulting from the method.*

One might suggest a number of improvements to the downscaling scheme itself, of course, but those would be outside the scope of the work actually presented here.

**Detail**

title: the editor's initial comments have already touched on the title, but I'm not convinced the current title is as clear as it could be. The quantities being actively downscaled are "climate" variables, not the SMB itself.

The authors' replies to this comment from the editor also say they'd prefer to leave "Greenland" out of the title, as the scheme is general. Personally I'd put it in. The other obvious ice sheet application for this is for Antarctica, but circumstances there are rather different. Sub-gridscale variation in SMB components there is more dominated by dynamic weather considerations rather than pure elevation, and temperatures are such that the lower, melt/bare ice albedoes - the only means by which sub-grid variation in shortwave radiation can really enter in this scheme - should play a much smaller role. That being the case, the analysis and component gradients here probably *are* only really applicable to Greenland. Additionally, no comment is made of how the scheme might perform for other ice sheets - perhaps if the authors wanted to leave the title as it is they could include some discussion about how the scheme might be expected to perform on Antarctica, or if applied to paleo ice sheets in other regions?

If they wish to keep the scope to just modern-day Greenland, how about "Downscaling climate through elevation classes for Greenland ice sheet surface mass balance in an ESM: analysis [etc...]"?

*We consider we are downscaling the SMB and surface energy fluxes and not the climate, as the downscaling is done in the land component of the CESM as opposed to e.g., grid refinement in the atmospheric component or statistical downscaling of climate variables.*

*We are aware of the current application of the EC method to some other ice sheets, but we prefer not to speculate about how adequate it would be for those. Instead, we think future work can use our study as to guide the evaluation to other (paleo) ice sheets.*

*The title of the manuscript is changed to "Surface mass balance downscaling through elevation classes in an Earth System Model: application to the Greenland ice sheet".*

page 1, line 5: it would be clearer if you note that RACMO is an RCM

*Changed to "from the regional climate model RACMO2.3"*

p1,l20: "leading" would be better as "which would lead"

*Changed accordingly*

p1,l21: "is losing" would be better as "has lost" if you start the sentence with "Since"

*Changed accordingly*

p2,l6: I'd say "ESM" deserved a wider definition than 'a climate model with a carbon cycle'. There are many possible physical components in an ESM, and for certain applications I don't think you would necessarily have to have the carbon cycle part active to still call the model an ESM

*Changed to: "... (ESMs; coupled climate models capable of simulating the Earth's chemical and biological processes, in addition to the physical processes)".*

p2,l8: does the "SMB" contraction need defining in the Introduction proper rather than just in the abstract, which can sometimes stand alone from the main paper?

*SMB is defined in the introduction now (p.2, l.7)*

p2,l10-25: I didn't think the distinction between methods 2. and 3. was terribly clear, or that the "hybrid" variant used by CESM doesn't really sit within method 2. or 3. The section also suggests it's going to list "state of the art downscaling techniques" in general, but this is a wide field and this list seems far from comprehensive - pattern scaling, EOF methods etc

*This is a good point, and it will be too much to go through all of the state of the art downscaling methods. Therefore it is changed to "Most common downscaling techniques for the GrIS SMB are".*

*The distinction between method 2 and 3 is that method 2 only allows for applying statistical corrections to output of a model. This is, as you mention, a very large field containing EOF methods and pattern scaling, in addition to the rapidly growing toolbox of machine learning techniques. However, for a method to qualify for the hybrid approach the SEB/SMB needs to be explicitly calculated after some statistical downscaling of the atmospheric variables involved.*

p3,l1: since CESM1 was superseded by version 2 more than a year ago, I think that somewhere in the introduction it would help if you explicitly noted that you're not using the current release version of CESM, and said why. Perhaps in the Discussion you could also note what, if anything, readers might expect to be different in CESM2, based on what you've learnt and what has changed in the model in the meantime

*This study was based on CESM1.0 as the elevation classes were first introduced in this model version. We are preparing a short follow-up study using CESM2. CESM2 uses some of the recommendations made in the text (e.g., a lapse rate for incoming longwave radiation, a lower ice-albedo, and precipitation phase corrections based on surface temperatures).*

p4,l24: Why did you use a "minimal", 1K/km lapse rate as a control rather than 0K/km which would effectively deactivate the scheme properly and revert to the type of behaviour seen in most ESMs?

*We feared that using a lapse rate of 0 K km$^{-1}$ could have unwanted consequences: the model was designed to have activate elevation class with a certain lapse rate, so completely disabling this feature would potentially lead to model artefacts.*

p5,l4: I think it's noted later in the analysis, but you're effectively comparing two (likely completely different) realisations of climate variability during a specific historical period by using an ERA-forced RCM vs the GCM. I think it's worth flagging this up, and anticipating the possible impacts here already.

*Have added: "As we are only comparing CESM1.0 simulations with identical initial conditions, we are likely to sample a different realization of climate variability than the reanalysis forced RACMO2.3." in section 2.3.*

p5,l9 The framework used from here on does rely rather on fitting simple linear relationships to scatter plots of " vs elevation" from all of Greenland. The apparently wide scatter in the figures often make it look like such a simple relationship really isn't a good way to approach the RACMO data being compared with, although the r values given look higher than the scatter shown in the plot might suggest, so perhaps this is more a presentational issue? Since a universal linear gradient is the paradigm being used in CESM - and the CESM fits do often *look* much more linear - it's not an unjustified way to proceed, but some kind of cautionary note should be put in here that this is a potentially over-simplistic way of looking at regionally heterogeneous data from a much higher resolution study, and that for some variables the scatter makes the fits and gradients reported perhaps more qualitative than quantitative.

*This is a very valid point. We believe the scatter itself might appear as larger than it statistically is, especially for RACMO, and the reason for the r-values to look higher than the scatter shown is due to the very high number of points in this plot (13,311 for RACMO and 1,551 for CESM as stated in p5,l17). Also, the temperature forcing itself is a linear regression onto the elevation, which makes seeing how (non-)linear different quantities respond to such a forcing an interesting point in itself through the linear correlation coefficient with elevation.*

p5,l17: I think some 2D plots so that readers can see the regional differences between the RACMO2.3 reference fields you use in this study and your CESM1 SMB would be very useful here. The choice of which figures to put in the main paper in which should be supplementary material will need to be thought about, but in general I think this is the first of a couple of areas in this paper where it would just be useful to be able to see more information than is currently there.

*We have added a map of the RACMO2.3 data to Fig. 4, and made EC-1K to an anomaly map wrt. EC-6K.*

p7,l29: it wasn't immediately obvious to me why the subset of fluxes shown in figure 3 were the "most relevant"

*It is because we focus on the fluxes that are controlling the downscaling: the turbulent fluxes (sensible), net shortwave (albedo), and melt energy. We will also add a fourth row with SMB in the final version, as this might be the most relevant of all to show here.*

p7,l33: the CESM albedo does not look very sensitive to the lapse rate - probably worth noting that even at the maximum lapse rate you don't even get to half of the RACMO value.

*The numerical difference in albedo gradient is not very large indeed. However, we feel that it is still sensitive to the forcing lapse rate, as even a small change in the albedo gradient leads to a much larger change in $SW_{net}$ gradients.*

*Added: "Even with the maximum lapse rate forcing, CESM1.0 is only able to produce an albedo gradient that is 35 % of the RACMO2.3 gradient."*

p8,l9: why not actually do the SMB scatter plots and show the gradients? Surely they're important enough to show explicitly?

*Fig. 3 will be updated to also show the SMB scatter plots.*

p8,l31: I really didn't understand the description of the prognostic temperature, or how it was calculated

*The prognostic temperature is calculated at each EC in CLM as a result of the calculated energy fluxes and exchanges. Therefore, it is different from the forcing temperature.*

p9,l9: I still don't understand why you used a 1K/km experiment as the control, rather than 0K/km?

*Please see answer before.*

p9,l14: it's not clear in which topography the "mean elevation is lower"

*In this part, we mean that the atmospheric grid cell elevation is lower than the land grid cell elevation, even though both are on a 1° grid cell as the atmospheric model requires a more smoothed topography to not force the highest wavenumbers that can cause noise. We have changed the sentence to: "First, because the atmospheric topography is more smoothed than the topography in the ice-sheet covered land grid cell, the atmospheric mean elevation per grid cell is lower than the land model mean elevation per grid cell."*

p9,l29: the Supplementary info figure is labelled A1 here, but as S1 in one of the links I was given to download

*It appears as S1 in my PDF. It was labelled A1 during the initial submission, but was corrected and now appears as S1 in the public discussion paper.*

p9,l30: the large discrepancies in the comparison with the reanalysis may be a place where the fact that the reanalysis and the GCM will have different realisations of internal climate variability really plays a role

*We agree. We have added: "As we are only comparing CESM1.0 simulations with identical initial conditions, we are likely to sample a different realization of climate variability than the reanalysis forced RACMO2.3" to section 2.3 so this difference is already expected earlier.*

*We have also changed this part to: "However, the differences between EC-1K and EC-6K are small compared to the difference between these simulations and ERA-Interim, likely due to different realizations of internal climate variability. This precludes a robust conclusion."*

p10,l29: as previously noted, I think it's worth flagging up differences between your CESM1 and the new CESM2, which is the version new users will likely pick up. Can you say which, if any, of the recommendations you make have been implemented in the current CESM?

*Of the recommendations made in this paper, the following were implemented in CESM2:*

- *Lowered albedo*
- *Downscaling of incoming longwave radiation with a fixed elevation dependent gradient*
- *Downscaling of precipitation phase based on surface temperature*
- *More advanced firn simulation*

*We decided not to include references to CESM2, both to avoid confusing reader and as the effects of these different parameterizations have on the downscaled SMB is not yet documented.*

p11,l20: "certain lapse rates score better for some metrics than others" is a little disingenuous, really. You've done a great job of showing that that the components being directly downscaled via the lapse rates generally cannot be made to match the physical elevation gradients for any value of the lapse rate, and that the final SMB you get only scores well because of fortunate cancellation of these significant errors. At this point, the "lapse rate" you specify almost loses a physical meaning - it's no longer a parameter you might desire to constrain directly through observations to match reality, rather a model control you can tune directly to get the final (SMB) result you want without worrying about the fidelity of the underlying components that go into that result. Something along these lines should be noted in this paragraph, I think

*Yes, we agree in that the lapse rate is the tuning control to redistribute energy within a grid cell. We have removed the statement: "certain lapse rates score better …".*

p11,l24: implies that it's hard to distinguish between the EC6K and EC9.8K SMB gradients, yet two sentences before states that EC6 has a better SMB gradient but EC9 has the best melt. I'm confused as to whether you can really make a robust distinction between the SMB gradients in the two cases - especially since the SMB vs height scatter plots are not shown for cases other than EC6. Does the r value on the SMB gradient actually justify distinguishing between the two cases? If, in fact, you're only basing that recommendation on the top line of total GrIS SMB in Table 2, given the size of the standard deviation on the RACMO numbers it would seem difficult to justify saying one is better than the other.

*We will add an additional row to Fig. 3 with SMB gradients which clearly show that the SMB gradient in EC-9.8K is very steep compared to RACMO.*

**Figures**

On the whole I feel that the paper could be usefully improved by tweaking the presentation of the figures. Above I've noted that it would be good if 2d plots of the EC6k vs the RACMO2 reference data could be shown, and the actual SMB scatter plots and fits for EC1, EC4.5, EC6 and EC9.8 rather than only summarising this data in a table. It may be that the authors or editor take a view on which figures belong in the main body of the paper and which in Supplementary information, but I do think it would be uesful to show them.

*We have followed the recommendations of the reviewer and will add the SMB scatterplots to Fig. 3.*

Of all the panels of scatter plots, only Figure 3 includes the useful gradient and r values on the scatter plots themselves - it would be useful if Figures 1 and 2 could show this information as well. In Figure 4, why is the absolute value of SMB shown for the EC1K experiment rather than the more useful difference from EC6K, which is how the information for the EC4K and EC9.8K experiments is shown in panels c) and d)?

*We follow the reviewers recommendation of adding the m and r values directly to the plots.*

# Reviewer #2:

**Summary**: The authors present an evaluation of an elevation class scheme applied in the Community Earth System Model 1.0 (CESM1.0). The elevation class scheme allows CESM to simulate surface processes at a sub-grid scale, and allows for interaction between the surface and the atmosphere on the CESM gird scale after surface fluxes are integrated on the CESM grid. The authors mainly focus on comparing gradients of energy and mass balance components at the sub-grid scale with gradients from the RACMO2.3 RCM, a leading RCM used to simulate surface mass balance (SMB) over the Greenland ice sheet. CESM captures gradients of SMB effectively as compared with RACMO2.3 but SMB and surface energy balance (SEB) components are not captured as effectively. Biases in these components tend to compensate for each other, resulting in the effective simulation of SMB gradients. The authors also find that implementing the elevation class scheme influences the simulation of regional climate around Greenland in CESM.

**General Comments**

I feel that this paper represents an important contribution to our understanding of simulating ice sheet surface mass balance in global climate models. Implementing such simulation is essential for capturing SMB-climate feedbacks in future climate projections with earth system models, which the authors also briefly address in the study. The paper is well argued and the analysis and interpretation of results is straightforward and logical. Sometimes the text becomes a bit wordy and difficult to understand; some suggestions are provided below. I feel the paper can be excepted with relatively minor revisions. Some general comments:

*Thank you for your positive feedback, we have addressed individual comments below.*

1. There is a recent study by Alexander et al. (2019) that builds on work of Fischer et al. (2014), which evaluates the impact of elevation classes on simulation of Greenland SMB in the NASA GISS ModelE GCM. This study was similar in comparing GCM outputs to an RCM, but differs in that the EC simulation was not evaluated at a high resolution as is done here. These studies should be mentioned and the authors may be interested in exploring similarities or differences in the conclusions at the ESM grid scale.

Alexander, P., LeGrande, A. N., Fischer, E., Tedesco, M., Fettweis, X., Kelley, M., Nowicki, S. M. J., and Schmidt, G. A.: Simulated Greenland ice sheet surface mass balance in the GISS ModelE2 GCM: Role of the ice sheet surface, Journal of Geophysical Research, 124, 750-765, https://doi.org/10.1029/2018JF004772, 2019.

Fischer, R., Nowicki, S., Kelley, M., and Schmidt, G. A.: A system of conservative regridding for ice-atmosphere coupling in a General Circulation Model (GCM), Geoscientific Model Development, 7, 883-907, https://doi.org/10.5194/gmd-7-883-2014, 2014.

*We include references to these papers in the revised manuscript.*

2. The authors discuss some gradients for which scatter plots are not included. It would be helpful if the authors could provide additional figures for e.g. downward and upward shortwave and longwave radiation, snow accumulation and refreezing. These figures could be included as additional panels in Figures 1 and 2 or supplemental figures at the authors' discretion.

*We agree that these figures would provide the readers with additional insight, and will add them to the supplementary material.*

3. It is not clear in the text that the SEB terms are computed for JJA, while SMB terms are computed annually. The authors should make this difference clear in the methods and results sections.

*In the model, both the SEB and SMB terms are computed every 30 minutes. However, our analysis focuses on JJA for SEB terms (as melt on the ice sheet is generated in summer) and annual SMB. As we see this is a point of confusion, we have changed in the description of the SEB calculation: "At each EC, an energy balance model is used to calculate the surface energy balance every 30 minutes" and: "SMB (...) is calculated at each EC, with the same frequency as the SEB calculation, as".*

**Specific Comments**

1. Figure 1: Though not essential, it would be helpful if the authors add text or a legend on one of the figures to show that black is RACMO2.3 and blue is CESM1.0. Also it would be helpful if the authors specify the sign convention (+ down) in the legend and text. Mention y-axis scale

differences in the legend. Also, what is meant by “several summer SEB components”. Is only a subset of years used to calculate the gradients? If so this should be made clear in the text.

*All SEB components plotted are the multi-year means from the full simulation (1965-2005). Several refers to showing more than one SEB component. Rather than mentioning the y-axis scale, we will update the figures to use the same y-axis where quantities are of the same unit. We will also include annotated text on the plot to show which is RACMO and which is CESM.*

2. Figure 2: Again, include a legend on the figure if possible. Mention difference in y-axis scales in the legend.

*This figure is updated with a legend, and the y-axis are changed to be the same for every panel.*

3. Table 2: Are the standard deviation values annual values? Please specify.

*Yes, the standard deviation are annual values, except for the prognostic temperatures where the standard deviations are JJA and DJF.*

4. P. 1, Line 5: Change “from RACMO2.3” to “from the RACMO2.3 regional climate model.” The model has not been introduced yet.

*We will change accordingly.*

5. P. 1, Lines 11-12: The topographic smoothing affects the atmospheric simulation, while the elevation class technique cools the surface by another means. It seems the technique doesn’t really “correct” the bias, but rather “compensates” for it by correcting a bias associated with the coarse ESM resolution. Is this the case? Please clarify here.

*Yes, compensates is a more appropriate word. Changed “corrects” to “compensates for” at p.1, l.11 and p.11, l26.*

6. P. 2, Lines 24-25: Here the authors might mention that a benefit of the “online” approach is that it is able to capture feedbacks between the downscaled surface simulation and the atmospheric component of the ESM.

*Added: “A benefit of this "online" approach is that it is able to capture feedbacks between the downscaled surface simulation and the atmospheric component of the ESM.”*

7. P. 2, Lines 26-30: As noted above, an elevation class scheme has also been implemented in the NASA GISS ModelE GCM in an “online” manner as discussed by Fischer et al. (2014) and evaluated on the ModelE grid by Alexander et al. (2019). However, I believe the authors are correct that the effects of downscaling on the finer resolution grid representation of SMB and SEB has not been evaluated in detail. These studies should be mentioned and the authors

should make clear the distinction between evaluation on the coarse resolution model grid, and at the finer scale.

*This is clearly relevant literature that should be reviewed in this section, so we will add references to the articles.*

8. P. 3, Line 19: I believe the authors are referring to downscaling using elevation classes, but this is not entirely clear. Perhaps the sentence can be revised to read something like "A static ice sheet surface that corresponds to present-day observations (Bamber et al., 2013) is used to downscale SMB and other quantities through the elevation class scheme."

*A modified version of this sentence is added: " A static ice sheet surface that corresponds to present-day observations (Bamber et al., 2013) is used to downscale SMB, energy fluxes and other quantities at the land/atmosphere interface through the EC scheme."*

9. P. 3, Line 21 – P. 4, Line 21: This section is a bit confusing. The steps in the elevation class scheme are not entirely clear. I believe the steps are as follows: 1. A set of elevation classes is defined and for each grid cell containing ice. 2. Some atmospheric quantities are downscaled by elevation. 2. The surface model is run for each elevation class, forced with the downscaled quantities. 3. Surface model outputs are averaged to the ESM grid, weighting for the percentage of each elevation class within each ESM grid cell, and these integrated quantities feed back to the atmosphere. Perhaps these steps can be clarified in the paragraph on P. 3, lines 21-24, and this will make the following material clear, or the text can be revised to mention one step at a time.

*We follow the reviewers suggestions, and have added the steps:*
*"The steps for of the EC calculation in an ESM are roughly as follows*

1. *A set of elevation classes are defined for each (partially) glaciated grid cell in the land model*
2. *A selected set of atmospheric variables are downscaled by applying simple elevation corrections (typically, prescribed lapse rates)*
3. *The land model calculates the SEB and SMB per EC*
4. *EC outputs are area-averaged per grid cell, and these averages are coupled to the atmospheric component*

*In the following, the EC calculation is described in more detail."*

10. P. 3, Line 27: How is the weight of each elevation class within a grid cell determined?

*The weight of each elevation class within a grid cell is determined by the area of the high-resolution topography dataset that lies within an elevation class. This clarification has been added this clarification to the revised manuscript.*

11. P. 3, Line 28: I believe "average" is referring to the average surface to atmosphere fluxes, and outputs such as SMB and SMB components, but this is not clear.

*This is correct, and text is changed to: "These weights are used to calculate the grid cell average that will be output of CLM4.0 and coupled to CAM4, as well ..."*

12. P. 3, Line 33: Clarify to read "all ECs within a grid cell."

*Changed according to reviewers suggestion.*

13. P. 4, Lines 2-8: It would be helpful if the authors can reiterate here which terms are common to all ECs within a grid cell, and which terms vary by EC as a result of downscaling. In particular it should be mentioned that albedo is calculated interactively within the model for each EC based on snow properties / snow depth over ice.

*This is explained on p3, l31-33. We have added: "Snow albedo is calculated based on snow grain size, depth, density, and other properties."*

14. P. 4, Lines 11-12: Note that these quantities are calculated on the ESM grid. Also, aren't these quantities calculated by the atmospheric model CAM4 and not CLM4?

*These quantities, as mentioned here are calculated by CLM. Take for instance the temperature. It is first calculated in CAM (taken into account e.g. advection), then passed to CLM. CLM simulates exchanges of moisture and heat with the surface, whereafter the temperature is passed on again to CAM.*

15. P. 4, Line 30: Although the details of the setup are described by Vizcaino et al., the authors should mention briefly what forcing is applied (e.g. sea ice/ocean temperatures/ atmospheric nudging).

*Added: "All CESM1.0 model components are allowed to vary freely.".*

*Have added: "*

16. P. 5, Line 15: Make clear why it is necessary to subtract the average CESM grid value from the RACMO2.3 grid cell values. I think this is to only capture gradients within grid cells, and not at the coarser resolution.

*This was to illustrate the scatter as deviations from what is simulated at the grid cell mean, due to different climate realizations in the two models.*

*For clarification, we have added: "We subtract these averages to only capture gradients within each grid cell, and to reduce the effect of internal climate variability."*

17. P. 5, Line 19: "mean elevation" is confusing. Perhaps use "on the CESM grid".

*Changed to: "on the CESM1.0 grid".*

18. P. 5, Line 23: "..comparison of the downscaled SEB components via EC and RCM" is confusing. It is the gradients that are being compared. Revise to something like "…comparison of SEB component gradients for CESM1.0 ECs and the RACMO2.3 RCM."

*Changed accordingly.*

19. P. 6, Line 10: Change "opposite gradient" to "opposite elevation gradient" for clarity.

*Changed accordingly.*

20. P. 6, Lines 16-18: The difference in sign here makes this a bit confusing. Including the longwave components in Fig. 1 or in a supplemental figure would help the reader to easily visualize this.

*We are including this in a supplementary figure.*

21. P. 6, Lines 22-23: Suggest changing "null gradients of incoming radiation in the model and weaker albedo gradients" to "a null gradient of incoming radiation in CESM1.0 and weaker albedo gradients than in RACMO2.3, leading to a smaller gradient in net shortwave radiation." Also, I believe this sentence is only referring to shortwave radiation, but this is not mentioned. Please clarify.

*We do refer to both.*

22. P. 7, Lines 11-12: What is the value of the gradient for CESM1.0?

*The value of the refreezing gradient in CESM1.0 is 62 mm $yr^{-1}$ $km^{-1}$ as mentioned on p7, l3.*

23. P. 7, Lines 14-15: Again, it would be interesting to see the figures for snowfall and refreezing.

*Panel for snowfall is be included in Fig. 2, figure for refreezing is already there (Fig. 2b).*

24. P. 8, Lines 1-3: Not sure what is meant by “non-null variations”. It would be clearer to simply note that the albedo gradient increases with increasing lapse rate, as shown in Figure 3.

*It means that more EC points respond to the forcing in form of albedo change.*

25. P. 8, Lines 14-15: Any idea why there is a reversal for the 9.8K/km case?

*It becomes opposite in the 9.8K $km^{-1}$ case as this is stronger than 6 K $km^{-1}$ (whereas 1 K $km^{-1}$ and 4K $km^{-1}$ are weaker) forcing leads to higher amounts of energy being transferred to the lowest areas.*

26. P. 8, Line 19: This is the first time interannual variability is mentioned. Perhaps introduce this with a separate sentence, explaining why interannual variability is interesting in this case and not elsewhere in the study.

*We would argue interannual variability could be interesting in the first part of the study as well. On the other hand, we find the gradients and correlation to be more informative for analyzing the downscaled fluxes, as interannual variability is connected to atmospheric variability which is somewhat taken out when the grid cell mean is subtracted from each EC.*

*See previous answers on internal variability: we have now introduced it in the methods section, where we have also added text to clarify why we do not look at internal variability in the first part.*

27. P. 9, Lines 13-15: This is confusing and should be clarified. I think the authors mean that the mean grid cell elevation is lower than the elevation of the ice sheet, so without ECs, the simulated ice sheet is higher in elevation. This effect was also observed by Alexander et al. (2019).

*Yes. Within each CESM grid cell, there is a range of elevations from the 5 km ice sheet topography. The mean of the elevations from the 5 km topography dataset is higher than the elevation that the CESM atmosphere “sees” both due to smoothing of the atmospheric topography, and that the atmosphere can “see” both ice sheet and vegetated parts of a grid cell. As the lapse rate correction is only applied to elevations corresponding to the ice sheet, this causes a higher areal weight of ice sheet points being forced with a temperature that is lower than the atmosphere simulates. The result of this is cooling of the grid cell.*

28. P. 9, Line 27: Any idea as to why incoming longwave radiation changes?

*Not only does the near-surface heat up, the entire lower part of the atmospheric column warms which is probably leading to the increased incoming longwave radiation.*

29. P. 9, Lines 29-34: It seems ERA-Interim is used for locations outside of the RACMO2.3 domain? Please make this clear. Also specify here which fields are compared.

*ERA-Interim is used for the entire area when calculating the averages for Fig. S1. To clarify, we have added: "Figure S1 compares near-surface temperature, turbulent heat fluxes, net longwave radiation and sea ice extent in EC-1K and EC-6K with ERA-Interim over the entire area …".*

30. P. 9, Line 33: change "as with RACMO2.3" to "as differences with RACMO2.3" for clarity.

*Changed accordingly.*

31. P. 10, Lines 4-5: Other studies (e.g. Vizcaino et al., 2013; Alexander et al., 2019) have evaluated the EC method at the coarse resolution but not at a higher resolution as done here. This should be clarified here.

*Added for clarity.*

32. P. 10, Line 6: "Linear fits" of what? Please clarify.

*Changed to: "These gradients are obtained by linear regression of the components on sub-grid elevations in all GrIS grid cells"*

33. P. 10, Line 22: Change "enables to explore the interaction with" to "enables exploration of the interaction between the high-resolution surface simulation and…"

*Changed accordingly.*

34. P. 10, Line 25: Change "to RCM" to "to the RACMO2.3 RCM".

*Changed accordingly.*

35. P. 11, Line 25: It could be that improving representation of physical processes at the elevation class scale will allow for a better identification of the optimal lapse rate. This could be mentioned here, if the authors agree.

*Yes, that is a good point, and we have added here: "Further improvements of the physical representation of SMB processes at the EC scale might allow for a better identification of an observationally constrained optimal lapse rate."*

36. P. 11, Line 32: Clarify "for radiation", e.g. "for apparent biases in gradients of net radiation"

*Changed to: "compensate for absence of incoming radiation downscaling."*

37. P. 12, Line 11: Clarify "more adequate".

*By adequate we mean to represent snow compaction, firn, refreezing etc. more adequately.*

*Added : "for realistic representation of e.g., snow compaction, firn, and refreezing"*

**Technical corrections**

1. P. 1, Line 2: Remove "the" before "surface mass balance (SMB) modeling"

2. P. 1, Line 4: Change "elevation dependent" to "elevation-dependent"

3. P. 1, Line 20: Change "leading" to "which would lead".

4. P. 1, Line 21: Change "is losing mass" to "has been losing mass".

5. P. 2, Line 9: Perhaps change "seem required" to "are likely required"?

6. P. 2, Line 12: The van Kampenhout paper year can be changed to 2019, with the reference to the final revised paper updated in the reference list

7. P. 2, Line 17: Revise "Statistical downscaling, which uses elevation corrections on…" to "Statistical downscaling uses elevation corrections to…"

8. P. 5, Line 23: Change "r-value" to "r-values".

9. P. 5, Line 25: Change "…solar radiation is not downscaled so that all ECs receive…" to "…solar radiation is not downscaled. As a result, all ECs within a grid cell receive…"

10. P. 6, Line 4: Change "more correlated" to "better correlated".

11. P. 6, Lines 20-21: Change "The net radiation gradients…" to "The net radiation gradient in CESM1.0 is 5.4 W m-2 km—1 and in RACMO2.3 is -22.6 W m-2 km-1 (Table 1)."

12. P. 7, Line 5: Change "low ECs" to "low elevation ECs"

13. P. 7, Line 24: Change "compensates the biases" to "compensates for the biases"

14. P. 7, Line 26: Change "compensates this" to "compensates for this"

15. P. 8, Line 27: Change "therefore not only reflecting" to "therefore reflect more than just"

16. P. 8, Line 30: Change “high ECs” to “high elevation ECs” and “low ECs” to “low elevation ECs”

17. P. 8, Line 34: Change “lower than the magnitude of the respective” to “lower in magnitude than the respective”

18. P. 8, Line 35: Change “gradient is less” to “gradient is also less”

19. P. 9, Line 27: Change “overcompensated by” to “overcompensated for by”

20. P. 10, Lines 11-13: Suggest revising the sentence to read: “However, one of the limitations of comparing with an RCM is that unlike an ESM, the RCM is laterally forced with reanalysis. Also, there are fundamental differences in the physical schemes and simulated climate components between the ESM and RCM compared here.”

21. P. 10, Lines 13-14: Change “net longwave” to “net longwave radiation”

22. P. 11, Line 1: Change “although it varies” to “despite the fact that it varies”

23. P. 12, Lines 2-3: Change “efficient to generate” to “efficiently generates”

Thank you, these suggestions are taken into account for the revised manuscript.

# Reviewer #3:

**General synopsis** This is a useful contribution about the novel application of using Earth System Models (ESM) with downscaling, via sub-gridcell elevation classes, to simulate Greenland Ice Sheet surface mass balance. Although it is fairly model-specific (based on the CESM1.0 ESM), this paper should be of broad interest to the GrIS SMB modelling and Greenland climate communities.

Some previous highly relevant literature is missing or can be better acknowledged (see comments below).

I wonder whether the CESM results can be compared with MAR as well as RACMO, for an independent RCM model check (and since MAR is the main alternative RCM currently used for Greenland)?

**Specific comments**

Page 1, lines 15-16 re. strong Arctic warming: Please add the following reference to those cited: Overland, J.E. and Hanna, Edward and Hanssen-Bauer, I. and Kim, S.-J. and Walsh, J.E. and Wang, M. and Bhatt, U.S. and Thoman, R.L. (2018) Surface air temperature. Arctic Report Card , NOAA.
https://www.arctic.noaa.gov/ReportCard/Report-Card-2018/ArtMID/7878/ArticleID/783/Surface-Air-Temperature

*This reference is added.*

P1, L21 re. “GrIS is losing mass at an accelerated rate”: please add the following highly relevant references to those cited: Edward Hanna, Francisco J Navarro, Frank Pattyn, Catia M Domingues, Xavier Fettweis, Erik R Ivins, Robert J Nicholls, Catherine Ritz, Ben Smith, Slawek Tulaczyk, Pippa L Whitehouse, H Jay Zwally (2013) Ice sheet mass balance and climate change. Nature 498, 51-59. Bamber, JL et al. (2018): The land ice contribution to sea level during the satellite era. Environmental Research Letters, 13(6), 063008,

*These references are added.*

P2, L8: should also add there is a significant disparity between different model estimates of GrIS SMB (Fettweis 2018): Fettweis, X. (2018) The SMB Model Intercomparison (SMBMIP) over Greenland: first rlts. AGU Fall Meeting talk archived at:
https://orbi.uliege.be/handle/2268/232923.

Reference for the SMBMIP is added, in addition to: “Also,  there is a significant disparity between different model estimates of GrIS SMB even for models with higher resolution”

P2, L19: re. statistical downscaling please add the following highly relevant references: Hanna et al. (2011) AND Wilton et al. (2017) DJ Wilton, A Jowett, E Hanna, GR Bigg, MR Van Den Broeke, X Fettweis, ...(2017) High resolution (1 km) positive degree-day modelling of Greenland ice sheet surface mass balance, 1870–2012 using reanalysis data. Journal of Glaciology 63 (237), 176-193

*This reference is added.*

E Hanna, P Huybrechts, J Cappelen, K Steffen, RC Bales, E Burgess, ...(2011) Greenland Ice Sheet surface mass balance 1870 to 2010 based on Twentieth Century Reanalysis, and links with global climate forcing. Journal of Geophysical Research: Atmospheres 116 (D24)

*This reference is added.*

P2, L32: While the motivation for the study is good as stated, can you make it clear in this sentence/paragraph whether you investigated precipitation downscaling as well as temperature downscaling?

*Yes, we will make it clear by adding "(it must be noted that our model does not downscale precipitation)"*

P3, L26: How was this number of elevation classes chosen? Would having a greater number of classes improve the results?

*The choice was motivated by a compromise between computing time and increased (vertical) resolution. Offline test showed this number is appropriate, and is the default for CESM1.0. We will add this to the revised manuscript.*

P3, L34 "Incoming radiation, precipitation and wind are kept constant across all ECs" - Is this a potential limitation of this study or could improvements be made here?

*This is discussed in detail in section 4 (p.11, l1-11)*

P5, L8 "snow when near-surface temperatures are between -7ˆoC and -1ˆoC" – the latter value (-1C) seems quite a low upper threshold for snow?

*This is the limit of where precipitation falls as snow only, mixed precipitation can occur at higher temperatures. This will be added to the revised manuscript.*

P10, LL4-5 "the first time the EC method for downscaling from a global climate model of ~100 km to the much higher resolution (5 km) of an ice sheet model" – point out that this kind and magnitude of statistical downscaling has been previously successfully used in downscaling meteorological reanalysis data from ~100-km resolution to 5-km resolution (Hanna et al. 2005 & 2011, Wilton et al. 2017). E Hanna, P Huybrechts, I Janssens, J Cappelen, K Steffen, A Stephens (2005) Runoff and mass balance of the Greenland ice sheet: 1958–2003. Journal of Geophysical Research: Atmospheres 110 (D13) (Other two references details are above.)

*This reference is added.*

P11, LL9-11: The recommended implementation of a precipitation phase downscaling scheme doesn't really solve the great challenge of overall elevation correction for precipitation. This paragraph therefore sounds a little weak as currently stated – can the authors strengthen their argument here?

*Yes, this wouldn't solve the difficulty of resolving the complex spatial patterns of precipitation over the GrIS. However, we do believe that changing the phase could improve the SMB as it would not allow for e.g., unrealistic rain at higher elevations.*

P12, L4 “Our sensitivity experiments reveal that a larger lapse rate for the temperature correction results in higher melt energy gradients” – isn’t this rather an obvious and unsurprising result? – perhaps rephrase?

*We will rephrase to: “our sensitivity experiments show that a larger lapse rate for the temperature correction results in higher melt energy gradients, as expected.”*

# Surface mass balance downscaling through elevation classes in an Earth System Model: ~~analysis, evaluation and impacts on~~ application to the ~~simulated climate~~Greenland ice sheet

Raymond Sellevold[1], Leonardus van Kampenhout[2], Jan T.M. Lenaerts[3], Brice Noël[2], William H. Lipscomb[4], and Miren Vizcaino[1]

[1]Geoscience and remote sensing, Delft University of Technology, Delft, the Netherlands
[2]Institute for Marine and Atmospheric Research Utrecht, Utrecht University, the Netherlands
[3]Department of Atmospheric and Oceanic Sciences, University of Colorado Boulder, Boulder CO, USA
[4]Climate and Global Dynamics Laboratory, National Center for Atmospheric Research, Boulder CO, USA

**Correspondence:** Raymond Sellevold (R.Sellevold-1@tudelft.nl)

**Abstract.** The modeling of ice sheets in Earth System Models (ESMs) is an active area of research with applications to future sea level rise projections and paleoclimate studies. A major challenge for ~~the~~ surface mass balance (SMB) modeling with ESMs arises from their coarse resolution. This paper evaluates the elevation classes (EC) method as an SMB downscaling alternative to the dynamical downscaling of regional climate models. To this end, we compare EC-simulated ~~elevation dependent~~ elevation-dependent surface energy and mass balance gradients from the Community Earth System Model 1.0 (CESM1.0) with those from the regional climate model RACMO2.3. The EC implementation in CESM1.0 combines prognostic snow albedo, a multi-layer snow model, and elevation corrections for two atmospheric forcing variables: temperature and humidity. Despite making no corrections for incoming radiation and precipitation, we find that the EC method in CESM1.0 yields similar SMB gradients as RACMO2.3, in part due to compensating biases in snowfall, surface melt and refreezing gradients. We discuss the sensitivity of the results to the lapse rate used for the temperature correction. We also evaluate the impact of the EC method on the climate simulated by the ESM and find minor cooling over the Greenland ice sheet and Barents and Greenland Seas, which ~~corrects~~ compensates for a warm bias in the ESM due to topographic smoothing. Based on our diagnostic procedure to evaluate the EC method, we make several recommendations for future implementations.

## 1 Introduction

During the 20th century, the Arctic has warmed much faster than the rest of the world ~~(e.g., Serreze and Francis, 2006; Screen and Simmond~~ (e.g., Serreze and Francis, 2006; Screen and Simmonds, 2010; Hartmann et al., 2013; Overland et al., 2018) due to shrinking sea ice cover (Serreze and Stroeve, 2015), associated positive albedo-temperature feedbacks (Pithan and Mauritsen, 2014), and increased moisture and heat transport from the mid-latitudes (Screen et al., 2012). The Greenland ice sheet (GrIS) lies within this fragile and rapidly changing environment. The GrIS is the world's second largest ice sheet, after the Antarctic ice sheet, and has an estimated volume of 2.96 $\times$ $10^6$ km$^3$ of ice, ~~leading~~ which would lead to an increase in global mean sea level by 7.36 m if it were all melted (Bamber et al., 2013). Since the 1990s, the GrIS ~~is losing~~ has lost mass at an accelerated rate

(Shepherd et al., 2012; Kjeldsen et al., 2015; Mouginot et al., 2019)(Shepherd et al., 2012; Kjeldsen et al., 2015; Hanna et al., 2013; Bam
. This mass loss is projected to be sustained and contribute 0.04-0.21 m sea level rise by the end of the 21st century, depending on the climate scenario (Church et al., 2013). The range of uncertainty is due to uncertainties in climate scenarios, climate sensitivity and simulated mass balance of the GrIS by ice sheet models (ISMs). This latter uncertainty is currently being targeted by the Ice Sheet Model Intercomparison for CMIP6 (ISMIP6; Nowicki et al., 2016), a major international effort to investigate future ice sheet evolution, constrain estimates of future global mean sea level and explore ice sheet sensitivity to climate forcing.

State-of-the-art Earth System Models (ESMs; coupled climate models capable of explicitly representing the carbon cycle, Flato, 2011) (ESMs; coupled climate models capable of simulating the Earth's chemical and biological processes, in addition to the physical processes typically operate at a resolution of 1° (∼ 100 km), which poses a challenge for studies with a regional interest, such as GrIS SMBsurface mass balance (SMB). For instance, the extent of GrIS ablation areas may be underestimated (Cullather et al., 2014). Downscaling techniques seem Also, there is a significant disparity between different model estimates of GrIS SMB even for models with higher resolution (Fettweis, 2018). Downscaling techniques are likely required to capture realistically the sharp gradients of SMB with elevation in the GrIS ablation zone (Lenaerts et al., 2019). State of the art downscaling techniques Most common downscaling techniques for the GrIS SMB are

1. Dynamical downscaling, as is done in regional climate models (RCMs, e.g., Box and Rinke, 2003; Noël et al., 2018; Fettweis et al., 2017) and recently as regional grid refinement within ESMs (van Kampenhout et al., 2019). This type of downscaling allows for explicit modeling at relatively high resolution for a region of interest. Physical parameterizations need to be readjusted over the fine grid (Hourdin et al., 2017; Schmidt et al., 2017), and in some cases, the model physics can be better tuned for this region. A major disadvantage of this downscaling method is the computational cost and the dependency on another model for lateral forcing in the case of RCMs.

2. Statistical downscaling , which (Hanna et al., 2005, 2011; Wilton et al., 2017) uses elevation corrections on either SMB or components of SMB (e.g., runoff). This type of downscaling is successful when realistic topographic gradients of SMB or melt are captured in the model (Helsen et al., 2012; Noël et al., 2016). However, in an ESM these gradients are typically not well-captured (Cullather et al., 2014), making this technique unsuitable.

3. Hybrid downscaling, where elevation corrections are applied to components of SMB or surface energy balance (SEB), and the full SEB and/or SMB are explicitly calculated offline at a higher resolution. This method was used by Vizcaíno et al. (2010) to construct an SMB field from a global climate model for coupling to an ice sheet model.

A variant of the hybrid approach with "online" (that is, within the ESM) implementation has been developed recently. This method is based on the use of elevation classes (ECs) (Fyke et al., 2011; Lipscomb et al., 2013)(Fyke et al., 2011; Lipscomb et al., 2013; Fi
. It simulates the SEB and SMB over glaciated surfaces, with specific albedo and snowpack evolution for each EC. A benefit of this "online" approach is that it is able to capture feedbacks between the downscaled surface simulation and the atmospheric component of the ESM. This method has been successfully applied to the simulation of historical and RCP8.5-scenario projections of the GrIS SMB and mass balance evolution (Vizcaíno et al., 2013; Lipscomb et al., 2013; Vizcaino et al., 2014; Fyke

et al., 2014a, b) with the Community Earth System Model version 1.0 (CESM 1.0). However, the EC downscaling in itself and its effects on the downscaled SMB and SEB components in CESM1.0 or other models have not been analyzed or evaluated before. Our study aims to fill this gap in three steps. First, we compare the simulated EC gradients of SMB and SEB components with gradients simulated by an RCM. Second, we investigate the sensitivity of the GrIS surface mass balance simulation to the main EC downscaling parameter, i.e., the temperature forcing lapse rate (it must be noted that our model does not downscale precipitation). Third, as the downscaling of SMB in the ECs takes place online within the climate model, we investigate how the EC implementation impacts regional climate.

Although we analyze the particular EC implementation in a specific ESM (CESM1.0), we aim to provide an evaluation and diagnostic framework to guide future implementation of EC downscaling in other climate models, for offline SMB estimates, and/or forcing of ice sheet models.

The paper is structured as follows: Section 2 describes the modeling setup as well as the regional model used for evaluation. In Section 3 we present the results. The discussion (Section 4) addresses the strengths and limitations of the EC implementation in CESM1.0. Section 5 gives the main conclusions and outlook.

## 2 Methods

### 2.1 CESM1.0 and EC downscaling scheme

The model used for this study is the Community Earth System Model 1.0.5 (CESM1.0) (Hurrell et al., 2013) with all components active. The atmospheric model is the Community Atmosphere Model 4 (CAM4; Neale et al., 2013) which is run at a horizontal resolution of 0.9° × 1.25° and has a finite volume dynamical core. The land model is the Community Land Model 4.0 (CLM4.0; Lawrence et al., 2011) which is run at the same horizontal resolution as CAM4. Within a CLM4.0 grid cell, different land cover types can exist. The grid cell average passed to the atmosphere is calculated with an area-weighted average of the fluxes. The ocean is simulated with the Parallel Ocean Program 2 (POP2; Smith et al., 2010) with a nominal resolution of 1°. The ocean model grid is a dipole with its northern pole centered over Greenland to prevent numerical instabilities, implying a higher effective resolution around Greenland. Sea ice is modeled with the Los Alamos Sea Ice Model 4 (CICE4; Hunke et al., 2010; Jahn et al., 2012) which runs on the same grid as the ocean. The ice sheet model in CESM1.0 is the Glimmer Community Ice Sheet Model 1.0 (CISM1.0; Rutt et al., 2009; Lipscomb et al., 2013), with a default resolution of 5 km. For the simulations performed in this study, the GrIS ice thickness and extent does not evolve. ~~The SMB is downscaled to a~~ A static ice sheet surface that corresponds to present-day observations (Bamber et al., 2013) is used to downscale SMB, energy fluxes and other quantities at the land/atmosphere interface through the EC scheme.

The steps for of the EC calculation in an ESM are roughly as follows

1. A set of elevation classes are defined for each (partially) glaciated grid cell in the land model

2. A selected set of atmospheric variables are downscaled by applying simple elevation corrections (typically, prescribed lapse rates)

3. The land model calculates the SEB and SMB per EC

4. EC outputs are area-averaged per grid cell, and these averages are coupled to the atmospheric component

In the following, the EC calculation is described in more detail. SMB calculations in CESM1.0 are done in CLM4.0 through ECs using the CLM4.0 snowpack mass balance scheme. EC downscaling accounts for sub-grid elevation variability. SMB is explicitly calculated at multiple surface elevations to force the higher resolution ice sheet model. The EC calculation is activated in the glaciated fraction of any grid cell with total or partial glacier coverage within a pre-defined region of interest (e.g., Greenland for the present study).

The EC method takes sub-grid surface elevation from the ice sheet model and bins them into $n$ ECs. In this study, $n$ is 10 and the $n+1$ boundaries are fixed at 0, 200, 400, 700, 1000, 1300, 1600, 2000, 2500, 3000 and 10000 m elevation a.s.l. The choice of $n$=10 was motivated by a compromise between computing time and increased (vertical) resolution. Offline test showed this number to be appropriate, and is the default for CESM1.0. After this binning, CLM4.0 calculates the relative weight of each EC within a given grid cell, as well as the mean topography for each EC. The weight of each EC within a grid cell is determined by the area of the high-resolution topography dataset that lies within an EC. These weights are used to calculate the grid cell average that will be ~~used in~~ output of CLM4.0 and coupled to CAM4, as well as for the interpolation of SMB and ice sheet surface temperature (which is equivalent to the temperature at the bottom snow/ice layer in CLM), which are standard forcings for ice sheet models (Goelzer et al., 2013).

Through the coupling with the atmosphere model, CLM4.0 receives surface incoming shortwave and longwave radiation, precipitation, 10-m wind, relative and specific humidity, surface pressure, and 2-m air temperature. Incoming radiation, precipitation, and wind are kept constant across all ECs within a grid cell. In contrast, the method downscales near-surface (2m) air temperature to the ECs with a default lapse rate of 6 K km$^{-1}$, and specific humidity is downscaled by assuming the relative humidity to be constant with elevation (Lipscomb et al., 2013). At each EC, an energy balance model is used to calculate the surface energy balance every 30 minutes (SEB; W m$^{-2}$) as

$$M = SW_{in}(1-\alpha) + LW_{in} - \epsilon\sigma T^4 + SHF + LHF \cancel{-} + GHF \qquad (1)$$

where $M$ is the melt energy [W m$^{-2}$], $SW_{in}$ is the incoming solar radiation [W m$^{-2}$], $\alpha$ is the surface albedo [-], $LW_{in}$ is incoming longwave radiation [W m$^{-2}$], $\epsilon$ is surface emissivity [-], $\sigma$ is the Stefan-Boltzmann constant [W m$^{-2}$ K$^{-4}$], $T$ is the surface temperature [K], $SHF$ is the sensible heat flux [W m$^{-2}$], $LHF$ is the latent heat flux [W m$^{-2}$], and $GHF$ is the subsurface heat flux into the snow or ice [W m$^{-2}$]. For these surface fluxes, positive values indicate energy transfer from the atmosphere to the land surface, and from the ~~surface to subsurface~~ subsurface to surface for $GHF$. Snow albedo is calculated based on snow grain size, depth, density, and other properties (Flanner and Zender, 2006). The first term on the right-hand side of Eq. (1) is the net solar radiation, and the sum of the second and third term on the right-hand side is the net longwave radiation. As a result of the SEB calculation, CLM4.0 calculates prognostic temperature, wind, relative humidity, and other quantities, taking into account the simulated exchanges of heat and moisture and surface roughness.

Additionally, the SMB (mm water equivalent yr$^{-1}$, referred to as mm yr$^{-1}$ in this paper) is calculated at each EC, with the same frequency as the SEB calculation, as

$$SMB = SNOW + REFR - MELT - SUBL \quad (2)$$

where $SNOW$ refers to the snowfall rate, $REFR$ is the refreezing rate of snowmelt and rainfall, $MELT$ is the sum of snow and ice melt rates, and $SUBL$ is the rate of sublimation/evaporation minus deposition/condensation. Rain and meltwater that do not refreeze are routed to runoff. For further details on the calculation of SEB and SMB, see Vizcaíno et al. (2013). Total snow mass is limited to 1 m water equivalent.

The resulting SMB is linearly interpolated onto the ice sheet grid, in two steps: first, with a bilinear horizontal interpolation per EC, and second with a vertical linear interpolation between two ECs (above and below), based on the ice sheet model high-resolution topography.

### 2.2 Simulations design

We perform four CESM1.0 simulations with an identical setup, except for a different temperature lapse rate forcing to each of the $n$=10 ECs. These four lapse rates are 1 K km$^{-1}$, 4 K km$^{-1}$, 6 K km$^{-1}$ (default) and 9.8 K km$^{-1}$, and we refer to the corresponding simulations as EC-1K, EC-4K, EC-6K, and EC-9.8K, respectively. EC-1K is chosen to represent minimal activation of the EC calculation. EC-4K is chosen as a lapse rate forcing between EC-1K and EC-6K that is close to the summer lapse rate over the Greenland ice sheet as estimated from observations (e.g., Fausto et al., 2009). As the upper limit of the magnitude of the lapse rate, 9.8 K km$^{-1}$ (dry adiabatic lapse rate) is used.

All simulations start in 1955 from a CMIP5 historical run that is evaluated in detail in Vizcaíno et al. (2013) (which also describes the spinup procedure and the setup for the EC-6K) and run to 2005. All CESM1.0 model components are allowed to vary freely. The first 10 years are used for model adjustment to the new lapse rate, leaving the period 1965-2005 for analysis.

### 2.3 RACMO2.3 and evaluation procedure

For evaluation of the EC downscaled simulation of SEB and SMB, we compare with the dynamical downscaling in the Regional Atmospheric Climate Model version 2.3 (RACMO2.3; Noël et al., 2015) with a horizontal resolution of $\sim$ 11 km, and forced by the ERA-Interim reanalysis (Dee et al., 2011). We analyze the period between 1965 and 2005 for both RACMO2.3 and CESM1.0. As we are only comparing CESM1.0 simulations with identical initial conditions, we are likely to sample a different realization of climate variability than the reanalysis forced RACMO2.3. RACMO2.3 has been successfully evaluated in multiple studies by comparison with in-situ and remote sensing observations (Ettema et al., 2009, 2010; Ran et al., 2018). Version 2.3 includes updates in cloud microphysics, surface and boundary layer microphysics, radiation and precipitation (Noël et al., 2015). For the latter, precipitation falls exclusively as snow when near-surface temperatures are between -7°C and -1°C.

For the comparison, we use SEB and SMB components simulated at each EC with those simulated at the native grid of RACMO2.3. For CESM1.0, this results in between 1 and 10 values per CLM4.0 grid cell, depending on sub-grid elevation heterogeneity. We subtract each EC value of SEB or SMB component from the grid cell average, as well as the corresponding

EC topographic height from the CLM4.0 mean height. We subtract these averages to only capture gradients within each grid cell, and to reduce the effect of internal climate variability. With these differences, we calculate a gradient or linear function with elevation. To generate these gradients for RACMO2.3, we first cluster RACMO2.3 model output from the 11 km native grid onto the CLM4.0 grid ($\sim$ 100 km). We then calculate averages for each RACMO2.3 SEB/SMB component and surface elevation over the coarse CLM4.0 grid cells. We subtract these averages from the native original values, and we construct the gradients via a linear fit. In this way, up to 56 RACMO2.3 grid cells are mapped into each CLM4.0 grid cell giving a total of 13,311 points for evaluation. For CLM4.0, the resulting number of points is 1,551.

For comparison of the overall downscaled SMB in CESM1.0 to a previous RACMO version (2.1), and an evaluation of the simulation at the mean elevation, see Vizcaíno et al. (2013).

## 3 Results

### 3.1 Process-based comparison of EC and dynamical downscaling

We use CESM1.0 output from a simulation using the default lapse rate forcing of 6 K km$^{-1}$ (EC-6K). Figure 1 illustrates the comparison of the downscaled SEB components via EC and component gradients for CESM1.0 ECs and RACMO2.3 RCM. Regression slopes $m$ (gradients) and $r$-value -values (correlation with elevation) are given in Table 1.

In CESM1.0, incoming solar radiation is not downscaledso that all ECs . As a result, all ECs within a grid cell receive the same amount as simulated by the atmospheric component. In reality, however, incoming shortwave radiation generally increases with elevation as a result of thinner clouds (Van den Broeke et al., 2008; Ettema et al., 2010). RACMO2.3 simulates the incoming shortwave elevation gradient as 15.1 W m$^{-2}$ km$^{-1}$ (Table 1, Fig. S1a), giving less energy with decreasing elevation. On the other hand, for the absorbed solar radiation (Eq. 1), albedo variations generally dominate over the variations in incoming solar radiation. The albedo gradient (Fig. 1a) is underestimated in CESM1.0 (0.019 km$^{-1}$, lower albedo with decreasing elevation) when compared to RACMO2.3 (0.081 km$^{-1}$). Part of this difference may be explained through CESM1.0 not being able to capture the anomalies (-0.35 to -0.20, Fig. 1a) corresponding to very low albedos in RACMO2.3. These differences in the models arise from the treatment of albedo during bare ice exposure. Both models treat snow albedo in a sophisticated fashion (Flanner and Zender, 2006). On the other hand, CESM1.0 and RACMO2.3 treat bare ice albedo quite differently. CESM1.0 uses a fixed value of 0.50 (0.60 for visible light and 0.40 for near-infrared radiation) while RACMO2.3 prescribes albedo from satellite observations (Noël et al., 2015), which can be as low as 0.30 for the simulated period. The albedo in RACMO2.3 is more better correlated with elevation ($r$=0.60) than CESM1.0 ($r$=0.35). As a result of the underestimated gradients in both downwelling shortwave and albedo in CESM1.0, the net solar radiation gradient is also underestimated: -3.5 W m$^{-2}$ km$^{-1}$ (CESM1.0) compared to -19.6 W m$^{-2}$ km$^{-1}$ (RACMO2.3), as illustrated in Fig. 1b. In other words, the absorbed solar energy increases strongly with decreasing elevation for RACMO2.3, but only weakly for CESM1.0.

The downscaled net longwave radiation (difference between incoming and outgoing longwave radiation, Eq. 1) in CESM1.0 has an opposite elevation gradient (8.9 W m$^{-2}$ km$^{-1}$) compared to RACMO2.3 (-3.1 W m$^{-2}$ km$^{-1}$) as shown in Fig. 1c. That is, the net longwave energy available for melting increases with lower elevation for RACMO2.3, but decreases with lower elevation for CESM1.0. The reason for this difference is that CESM1.0 does not downscale the incoming longwave radiation, while RACMO2.3 simulates a gradient of -17.6 W m$^{-2}$ km$^{-1}$ with a relatively high correlation with elevation ($r$=-0.81, Fig. S1c, Table 1). This negative correlation in RACMO2.3 is caused by thicker clouds as well as higher water vapor and atmospheric temperatures at lower elevations (Van den Broeke et al., 2008; Ettema et al., 2010). As the outgoing thermal radiation depends on the surface temperature, both models simulate negative gradients (Fig. S1d). The result is a positive gradient for the net longwave in CESM1.0. In RACMO2.3, the magnitude of the outgoing longwave gradient is smaller than the incoming longwave gradient, resulting in a net negative gradient. Due to the complex relationship between the different components of the longwave radiation, the net longwave has a low correlation with elevation in RACMO2.3 ($r$=-0.30). In contrast, CESM1.0 simulates a high correlation ($r$=0.76) as the surface temperature gradient directly controls the net longwave gradient. The net radiation ~~gradients in both models are~~ gradient in CESM1.0 is 5.4 W m$^{-2}$ km$^{-1}$ ~~(CESM1.0) and~~ and in RACMO2.3 is -22.6 W m$^{-2}$ km$^{-1}$ (~~RACMO2.3,~~ Table 1).

In summary, biases in the downscaling of net radiation in CESM1.0 are due to null gradients of incoming radiation in the model, and weaker albedo gradients. As a result, the gradient is dominated by the outgoing longwave gradient in CESM1.0, and by the albedo and incoming longwave gradients in RACMO2.3.

Next, turbulent fluxes of latent and sensible heat are examined, as well as their contribution to the available melt energy with respect to radiation. The gradients of sensible and latent heat fluxes are negative in both models (Table 1); more energy is available for melting at lower elevation. The sensible heat flux gradient is stronger than the latent heat flux gradient and shows a larger spread of values (Fig. 1d,e.). In CESM1.0, this is a result of the elevation correction applied to the near-surface temperature (lapse rate). This correction increases atmospheric temperature and specific humidity at lower ECs and decreases them at higher ECs within each coarse grid cell. In RACMO2.3, these heat flux gradients are smaller and less correlated with elevation ($r$=-0.42 and $r$=-0.02, for sensible and latent heat fluxes, respectively) than in CESM1.0 ($r$=-0.77 and $r$=-0.76). Stronger sensible and latent heat gradients in CESM1.0 appear to compensate for most of the underestimation of the radiation gradients (Fig. 1c,d,e.), resulting in a melt energy gradient (-16.0 W m$^{-2}$ km$^{-1}$) which is similar in magnitude and sign as RACMO2.3 (-26.1 W m$^{-2}$ km$^{-1}$; Fig. 1f, Table 1).

Figure 2 compares snowfall, surface melt, refreezing, and SMB gradients between the two models. While CESM1.0 does not downscale snowfall, RACMO2.3 simulates an elevation gradient of -218 mm yr$^{-1}$ km$^{-1}$ that has little correlation with elevation ($r$=0.26), possibly due to the competition of the dominant effect of height-desertification (less snowfall at higher elevations due to colder and drier air), orographic forcing of snowfall, and small scale atmospheric circulation features (Ettema et al., 2009). Consistent with the melt energy gradients, the surface melt gradient in RACMO2.3 is -717 mm yr$^{-1}$ km$^{-1}$ while for CESM1.0 it is -425 mm yr$^{-1}$ km$^{-1}$ (Table 1).

On the other hand, the CESM1.0 refreezing gradient (62 mm yr$^{-1}$ km$^{-1}$) is in disagreement with RACMO2.3 (-129 mm yr$^{-1}$ km$^{-1}$ and Fig. 2~~b~~c). CESM1.0 simulates a positive gradient, implying increasing refreezing at higher ECs despite reduced melt rates. We hypothesize that at low elevation ECs, this is due to limited refreezing capacity in CLM4.0, as a result of the limited snow depth (Section 2.1). On the contrary, at the higher ECs, where the melt is lower, refreezing is favored due to lower snow temperatures, more available pore space and thicker snowpacks. The overestimation of rainfall at higher elevation

(Vizcaíno et al., 2013) may also be an important factor. In contrast to CESM1.0, RACMO2.3 simulates a negative gradient of -129 mm yr$^{-1}$ km$^{-1}$ (Table 1), suggesting a dominant control from the increased melting at lower elevation. As the refreezing gradient results from the combination of opposite gradients, i.e., available meltwater and available refreezing capacity, the correlation with elevation is low in RACMO2.3 ($r$=-0.45, Table 1). It is similarly low in CESM1.0, in part due to lower correlation for the melt gradient than in RACMO2.3.

Regardless of substantial differences in melt gradients in both models, the SMB gradient is relatively close (Fig. 2~~e~~d; CESM1.0: 439 mm yr$^{-1}$ km$^{-1}$ and RACMO2.3: 369 mm yr$^{-1}$ km$^{-1}$, Table 1). CESM1.0 compensates for underestimation of the melt gradient with the snowfall and refreezing gradients (in order of importance, see Table 1). ~~While CESM1.0 does not downscale snowfall, RACMO2.3 simulates an elevation gradient of -218 mm yr$^{-1}$ km$^{-1}$ that has little correlation with elevation ($r$=0.26), possibly due to the competition of the dominant effect of height-desertification (less snowfall at higher elevations due to colder and drier air), orographic forcing of snowfall, and small scale atmospheric circulation features (Ettema et al., 2009).~~ In addition to the snowfall contribution of +218 mm yr$^{-1}$ km$^{-1}$ to the CESM1.0 SMB gradient difference with RACMO2.3, the difference in the refreezing gradient contributes with +191 mm yr$^{-1}$ km$^{-1}$. The higher elevation correlation of SMB with elevation in CESM1.0 ($r$=0.58) compared to RACMO2.3 ($r$=0.27) is due to the null precipitation gradient in CESM1.0.

In summary, the EC method in CESM1.0 with the default lapse rate of 6 K km$^{-1}$ (EC-6K) is approximately reproducing SMB gradients of RCM RACMO2.3. The EC method partially compensates for the biases in radiation downscaling with an overestimated turbulent heat flux gradient. The resulting melt energy gradients, however, are still lower than in RACMO2.3. However, the EC method compensates for this in the net SMB gradient due to lack of snowfall downscaling (leading to a more positive gradient relative to RACMO) and a positive bias in the refreezing gradient.

### 3.2 EC downscaling sensitivity to lapse rate of temperature forcing

Figure 3 shows how the most relevant energy fluxes and SMB respond to different lapse rate forcings. With a larger lapse rate forcing, the simulated sensible heat flux gradient is stronger, from -3.2 W m$^{-2}$ km$^{-1}$ in EC-1K to -20.0 W m$^{-2}$ km$^{-1}$ in EC-9.8K (Fig. 3 a-d). This implies that the stronger the lapse rate forcing, the more heat is redistributed from upper to lower elevations. The correlation with elevation only increases marginally when increasing the lapse rate forcing (Fig. 3 a-d).

Albedo gradients are sensitive to lapse rate forcing, from close to zero gradients in EC-1K to 0.029 km$^{-1}$ in EC-9.8K (Fig. 3 e-h). Even with the maximum lapse rate forcing, CESM1.0 is only able to produce an albedo gradient that is 35 % of the RACMO2.3 gradient. Albedo gradients are triggered by surface temperature and melt gradients resulting from turbulent heat flux gradients. In the case of EC-1K, the turbulent heat flux gradient is not sufficient to trigger substantial albedo-melt feedback. Downscaled albedos have a variation range of similar magnitude in EC-4K and EC-6K, however more points in EC-6K have non-null variations.

The combined effects of the turbulent heat flux gradients and the associated albedo gradients result in higher melt energy gradients with higher lapse rate forcing (Fig. 3 i-l). The melt energy gradient in EC-1K is -3.5 W m$^{-2}$ km$^{-1}$ which is very similar to the sensible heat flux gradient (-3.2 W $m^{-2}$). With higher lapse rate forcings, the difference between melt energy and sensible heat gradients becomes larger, which is interpreted as an effect of the albedo-melt feedback.

The melt energy gradient as simulated by RACMO2.3 is best matched with EC-9.8K (Figure 3, Table 1). However, EC-6K matches the SMB gradient best (SMB gradients for EC-1K, EC-4K, and EC-9.8K are 110, 310 and 711 mm $yr^{-1}$ $km^{-1}$, Fig. 3, compare with Table 1). This is explained by compensation from the snowfall and refreezing gradients.

Figure 4 compares the downscaled SMB maps on the ice sheet model grid (5 km resolution) for the four lapse rates and RACMO2.3 (11 km resolution). Spatially, the largest responses to a varying lapse rate occur along the margin of the ice sheet, and close to the equilibrium line (Fig. 4c,d,e). At the margins, a low lapse rate leads to a higher SMB with respect to EC-6K in a very narrow band of only 10-20 km, due to the aforementioned relatively low turbulent fluxes and weak albedo-temperature feedbacks. In the EC-9.8K, this effect becomes opposite resulting in a similarly narrow band of lowered SMB (blue rim). Further inland, this extreme lapse rate leads to larger areas with higher SMB, as higher melt energy gradients reduce melt at high elevation ECs.

Larger lapse rates result in reduced ablation area, from 16.4% of the GrIS in EC-1K to 13.0% in EC-9.8K (Table 2. This reduction is due to an enhanced melt gradient (Fig. 3 i-l), reducing melt at higher ECs and resulting in a lower equilibrium line altitude (ELA, where SMB equals zero), and reduces interannual variability (although only mildly, from 4.0% to 3.0%). Due to this expansion of the accumulation area with higher lapse rates, the total SMB of the accumulation area increases (Table 2), although within the standard deviations. For the SMB of the ablation area, the area reduction is partially compensated with higher specific (local) ablation rates for higher lapse rates, resulting in the most negative SMB in the ablation area for EC-4K. The total SMB is the sum of the SMB for ablation and accumulation areas, and it is maximum for EC-6K. The SMB for EC-6K is at the same time the closest to RACMO2.3, also for the standard deviation. However, the range of variation of the mean total SMB across the four simulations is not large and is within the standard deviations. As an additional note of caution, the values in Table 2 result from four simulations with independent atmospheric simulation, perhaps sampling different segments of, e.g., multidecadal precipitation variability (Bromwich et al., 2001), and therefore ~~not only reflecting~~ reflect more than just the effect of the lapse rate choice.

To summarize, lapse rates lower than EC-6K result in larger ablation areas and lower integrated SMB. These results indicate a dominant effect on the CESM1.0 ELA simulation of higher melt rates at high elevation ECs versus reduced melt rates at low elevation ECs.

To complete this sensitivity investigation, we compare “prognostic” near-surface temperature gradients across the four simulations (Table 2). This prognostic temperature is calculated per EC within each CLM4.0 time step and is a result of heat and moisture exchange between surface and atmosphere. Therefore it differs from the prescribed lapse rate forcing. The prognostic temperature gradients are lower ~~than the magnitude of~~ in magnitude than the respective lapse rate forcing for all CESM1.0 simulations. The magnitude of the June-August (JJA) gradient is also less than for December-February (DJF) and is approximately half of the forcing lapse rate. The former is also the case for RACMO2.3. The simulation EC-9.8K gives the prognostic temperature gradient closest to RACMO2.3, which is in between the EC-6K and EC-9.8K gradients. It is remarkable that the simulation EC-4K with the lapse rate forcing that is closest to the observational summer gradient (4.7 K km$^{-1}$, Fausto et al. (2009)) and RACMO2.3 (4.3 K km$^{-1}$) is however not the simulation with the closest prognostic gradient.

### 3.3 Impact of the EC calculation on regional climate simulation

Next, we examine how the EC calculation in the land component (CLM4.0) affects the simulation of Arctic climate in CESM1.0. If the EC method is active in CLM4.0, sub-grid gradients in the ice sheet surface budget are coupled to the atmosphere model (and via the atmosphere to other components) during runtime. We compare two simulations for this analysis. The EC-1K simulation serves as the control as it represents the simulation closest to non-active EC downscaling, which is the standard for most CMIP5 ESMs. The EC-6K is used to assess the climatic effect of using the EC method. Figure 5 shows differences in selected climate variables between EC-6K and EC-1K.

Near-surface temperatures decrease over large parts of the GrIS and on average by 0.9 K in EC-6K with respect to EC-1K (Fig. 5a,b and Table 3). This relative cooling in EC-6K is due to two factors. First, because the atmospheric topography is more smoothed than the topography in the ice-sheet covered land grid cell, the atmospheric mean elevation is lowerper grid cell is lower than the land model mean elevation per grid cell. This gives higher ECs a higher areal weight per grid cell. Second, the characteristic quasi-parabolic shape of the ice sheet contributes to this areal effect. This results in the dominance of the net (negative) energy anomalies from high elevation ECs. Maximal cooling coincides with areas of rapid change in slope in the SE and NW. Downwind advection of colder air masses from the eastern side of the ice sheet causes mild cooling in the Greenland and the Barents Sea, which is amplified by the growth of sea-ice (Fig. 5h).

Turbulent heat fluxes respond most strongly over the Greenland ice sheet, the Labrador Sea and along the sea ice edges in Greenland and Barents Sea (Fig. 5c,d, and table Table 3). Significant differences over the Greenland ice sheet are collocated with areas showing a significant decrease in air temperature. In these simulations, the atmosphere transfers turbulent heat to the surface on average (Fig. 5c). The reduction in air temperature, and consequently air humidity (not shown), results in decreased turbulent heat transfer. Over the Barents Sea, larger sea-ice covered areas cause a reduction in the heat transfer from the ocean to the atmosphere.

Net surface longwave radiation increases over the Greenland ice sheet where the near-surface temperature decreases (Fig. 5f). Over these areas, incoming longwave radiation decreases; however, this is overcompensated for by a reduction in emitted longwave radiation due to surface cooling.

Figure S2 compares near-surface temperature, turbulent heat fluxes, net longwave radiation and sea ice extent in EC-1K and EC-6K with ERA-Interim over the entire area in Fig. 5, with the tentative goal of assessing whether the EC method improves or deteriorates the climate simulation. However, the differences between EC-1K and EC-6K are small compared to the difference between these simulations and ERA-Interim, precluding likely due to different realizations of internal climate variability. This precludes a robust conclusion. For Greenland, on the other hand, an assessment is more reliable as the differences between the EC-1K and EC-6K simulations are of the same magnitude as differences with RACMO2.3. The simulation of the GrIS-averaged annual and summer near-surface air temperature is improved in EC-6K, using RACMO2.3 as a reference, as well as the net longwave radiation, melt energy, and (only annual) turbulent heat flux (see bold values in Table 3). The simulated cooling partially counteracts the temperature overestimation in the ESM due to topographic smoothing, resulting in a close fit to RACMO2.3.

## 4 Discussion

This study has evaluated for the first time the EC method for SMB downscaling from a global climate model of ∼ 100 km resolution to the much higher resolution (5 km) of an ice sheet model. Other studies (e.g., Alexander et al., 2019) have evaluated the effect of implementing ECs on the coarse grid cell, but not at the sub-grid resolution as done here. This evaluation uses gradients of SEB and SMB components as a primary metric. These gradients are obtained with linear fits of by linear regression of the components on sub-grid elevations in all GrIS grid cells. While this provides a systematic framework of comparison, it does not account for relevant non-linear relationships for SMB gradients (e.g., Helsen et al., 2012; Noël et al., 2016) and SMB components (e.g., precipitation); or heterogeneity arising from different Greenland climate sub-regions, local influences on climate (e.g. proximity of tundra, valleys, fjords), or proximity to the ELA.

We justify our comparison with the RCM as dynamical downscaling is the most advanced downscaling technique as shown in numerous evaluations (e.g., Ettema et al., 2010; Noël et al., 2015). However, one of the limitations of comparing with an RCM is it being laterally-forced by reanalysisand has that unlike an ESM, the RCM is laterally forced with reanalysis. Also, there are fundamental differences in the physical schemes and simulated climate components relative to the ESM between the ESM and RCM compared here. Additionally, RACMO2.3 has some well-documented biases, e.g., an underestimation of net longwave radiation, which is compensated by the sensible heat flux (Ettema et al., 2010; Noël et al., 2015). Further, the RACMO2.3 model was forced at its lateral boundaries by ERA-Interim reanalysis (Dee et al., 2011), which limits the "intrinsic" or "natural" climate variability compared to an ESM. Therefore, a more systematic comparison could be made by forcing an RCM with the same ESM where the EC method is implemented.

As a result of the combination of EC downscaling and advanced snow physics (Lipscomb et al., 2013), CESM1.0 shows high skill in simulating GrIS climate compared to same-generation global climate models/earth system models (Cullather et al., 2014). The ability to realistically represent GrIS SMB in ESMs has been utilized for projections of future SMB change (Vizcaino et al., 2014; Fyke et al., 2014a, b), without an RCM for additional dynamical downscaling. Reliable simulation of the GrIS surface climate at ESM resolution enables to explore the interaction with exploration of the interaction between the high-resolution surface simulation and other climate components (e.g., atmosphere, ocean, sea-ice).

While the EC method in CESM1.0 realistically simulates SMB gradients, we have shown here major deficiencies in the simulation of individual gradients of surface energy and mass balance components compared to the RACMO2.3 RCM. This is an important caveat for modelers who may need to calculate the SMB from individual components of the energy or mass balance, e.g., to perform corrections for one atmospheric forcing field. It also limits the possibility to investigate individual processes at a higher resolution. In the following, we discuss the relative importance and possible fixes of the biases in these individual processes as identified for CESM1.0.

1. CESM1.0 does not capture low enough albedo values due to the use of a single fixed ice albedo, while bare ice has a broader range of albedos (Alexander et al., 2014). We recommend therefore the use of spatially varying ice albedos, e.g., to simulate the impacts of impurities on ice "darkening" (Wientjes et al., 2011; Ryan et al., 2018).

2. The EC scheme in CESM1.0 does not downscale incoming radiation, although despite the fact that it varies over small scales at the GrIS surface (Van den Broeke et al., 2008; Van Tricht et al., 2016). The lack of downward longwave downscaling leads to an underestimation of net radiative energy at low elevation ECs and an overestimation at high elevation ECs. We recommend downscaling of incoming radiation to reduce over-compensation from the turbulent heat fluxes gradients and more realistically capture radiation-snow-ice interactions such as shortwave-generated subsurface snowmelt.

3. Since snowfall has no elevation corrections in CESM1.0, small-scale orographically induced precipitation, height-desertification effects, and small scale variations in the rain to precipitation ratio are not captured. Designing realistic and effective elevation corrections for precipitation is a challenging task as the precipitation's correlation with elevation is spatially highly variable over the GrIS (Noël et al., 2016). To account for fine-scale variations in the rain to precipitation ratio with a simple parameterization, we propose the implementation of a scheme relating the phase of precipitation with atmospheric near-surface temperature, similarly as in Noël et al. (2015).

4. CESM1.0 does not realistically simulate the refreezing gradient, mainly due to limited snow mass in the CLM4.0 snow-pack and biased high rainfall rates at high elevations. A realistic simulation of refreezing is key in modeling the response time of an ice sheet to a changing climate (van Angelen et al., 2014) as it acts as a buffer for meltwater to run off the ice sheet surface. A more physically based treatment of snow could be used with a snow densification scheme that does not impose a maximum allowed snow depth. An intermediate approach is using relatively large snow and firn depths. As an example along this line, the maximum snow depth can be increased, as in the version 5.0 of CLM, with respect to CLM4.0 due to the further development of the snow scheme to allow for realistic firn simulation (van Kampenhout et al., 2017).

Assessing the optimal choice of lapse rate forcing proves challenging, as certain lapse rates score better for some metrics than others. In this study, the EC-1K results in the turbulent heat flux gradients closest to RACMO2.3 (Fig. 3a), but almost null melt energy and SMB gradients. EC-4K does not stand out in any way. EC-6K results in the most realistic SMB gradients, despite EC-9.8K comparing the best with RACMO2.3 for the melt gradient. This discrepancy is because CESM1.0 does not downscale snowfall which has an opposite slope to the melt gradient. For the downscaled SMB, EC-6K and EC-9.8K give fairly similar results, making it hard to distinguish one or the other as the best choice. Further improvements of the physical representation of SMB processes at the EC scale might allow for a better identification of an observationally constrained optimal lapse rate.

Global climate models often have warm biases over high areas like the ice sheets, due to topographic smoothing. Here we showed that the EC implementation in CESM1.0 results in moderate cooling over Greenland, which fully corrects compensates for the warm bias with respect to the RCM. The cooling pattern from the EC method is similar to that of Franco et al. (2012) who explored the sensitivity of the simulated GrIS surface climate to horizontal resolution with an RCM.

## 5 Conclusions

The EC downscaling as implemented in CESM1.0 results in realistic GrIS SMB gradients as shown through comparison with a state-of-the-art RCM. In CESM1.0, high turbulent heat flux gradients compensate for ~~radiation, which is not downscaled~~absence of incoming radiation downscaling. Explicit simulation of snow albedo enables the albedo-melt feedback which is shown to contribute to realistic melt gradients and consequently realistic SMB gradients. Therefore, we conclude that the EC classes method in CESM1.0 ~~is efficient to generate~~ efficiently generates a realistic downscaled SMB, despite the fact that only temperature and humidity are downscaled.

Our sensitivity experiments ~~reveal~~ show that a larger lapse rate for the temperature correction results in higher melt energy gradients, as expected. As a consequence of these gradients, ablation areas narrow in CESM1.0, although this result may be different for other models or ice sheet topographies. In turn, this leads to a general cooling downwind of Greenland and an increase in sea ice cover over the Greenland Sea and the Barents Sea. For future implementations of the EC classes within ESMs, we recommend evaluation of the effects on regional climate simulation.

Future improvements of the EC method could be headed towards realistic downscaling of the individual surface energy and mass budget components. Some concrete examples include, (1) a lower and/or spatially varying albedo; (2) downscaling of incoming radiation; (3) downscaling of precipitation phase; and (4) development of more adequate snowpack parametrizations for realistic representation of e.g., snow compaction, firn, and refreezing, fit for polar conditions.

This study aims to guide future implementation of the EC method, providing diagnostic metrics and evaluation methodology. We recommend in any case that these metrics are adapted to the particular targets of scientific research to be conducted with each model.

*Code and data availability.* The model CESM1.0.5 can be downloaded from http://www.cesm.ucar.edu/models/cesm1.0/.The output from the CESM1.0 simulations, together with code for processing the data and creating the figures for this manuscript is available at https://doi.org/10.5281/zeno

*Author contributions.* The idea of the study and simulations design came from RS and MV. RS carried out the model simulations, data analysis and writing of the manuscript, under the supervision of MV. LK contributed to the development of the analysis software and BN provided RACMO2.3 data. All authors read and commented on the manuscript.

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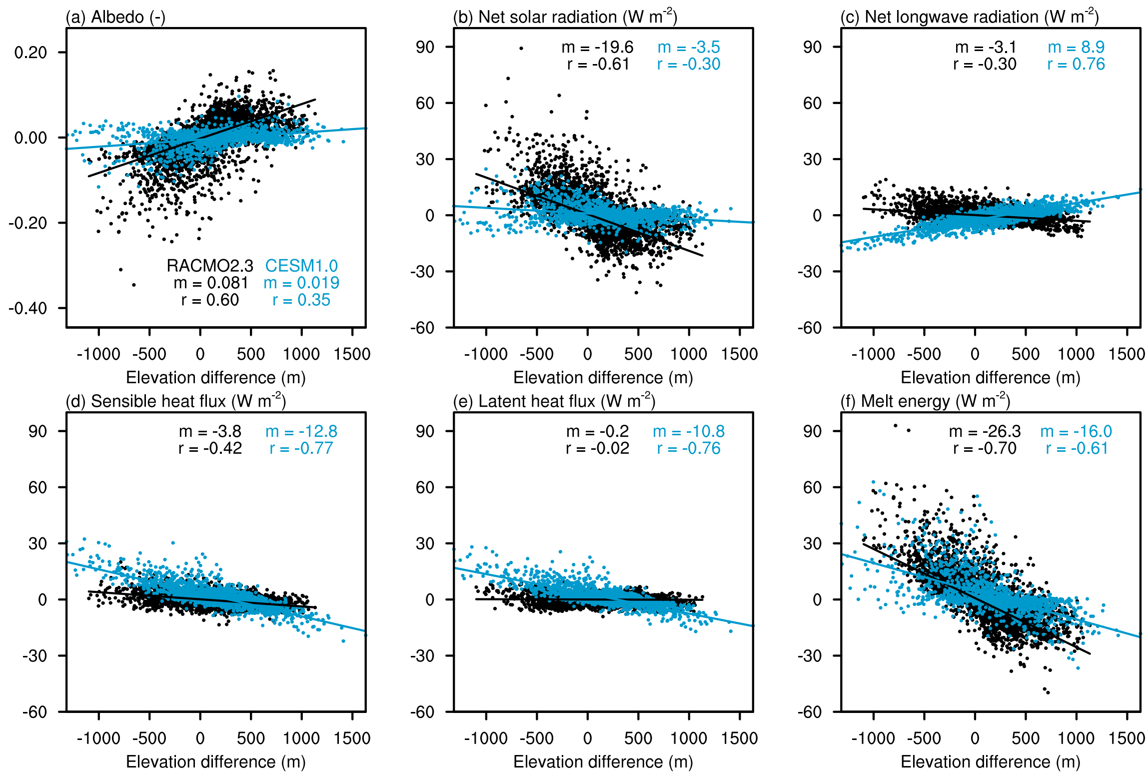


**Figure 1.** Comparison of EC downscaling (simulation EC-6K, blue) versus dynamical downscaling in a RCM (RACMO2.3, black) for several summer (JJA) SEB components and near-surface climate, a) albedo, b) net solar radiation (W $m^{-2}$), c) net longwave radiation (W $m^{-2}$), d) sensible heat flux (W $m^{-2}$), e) latent heat flux (W $m^{-2}$) and f) melt energy (W $m^{-2}$). The x values show deviation of surface elevation (m) from the coarse grid cell ($\sim$ 100 km) mean, and the y values show deviation of the physical quantity from the grid cell mean. In plots (b) through (f), positive y values indicate more energy available for melting. Melt energy (f) is the sum of the radiation and turbulent flux in terms in (b) through (e), plus the ground heat flux (not shown). The lines represent least-squares linear regression. The annotated $m$ is the least-squares linear regression gradient (W $m^{-2}$ $km^{-1}$ or $km^{-1}$ for albedo), $r$ is the correlation coefficient.

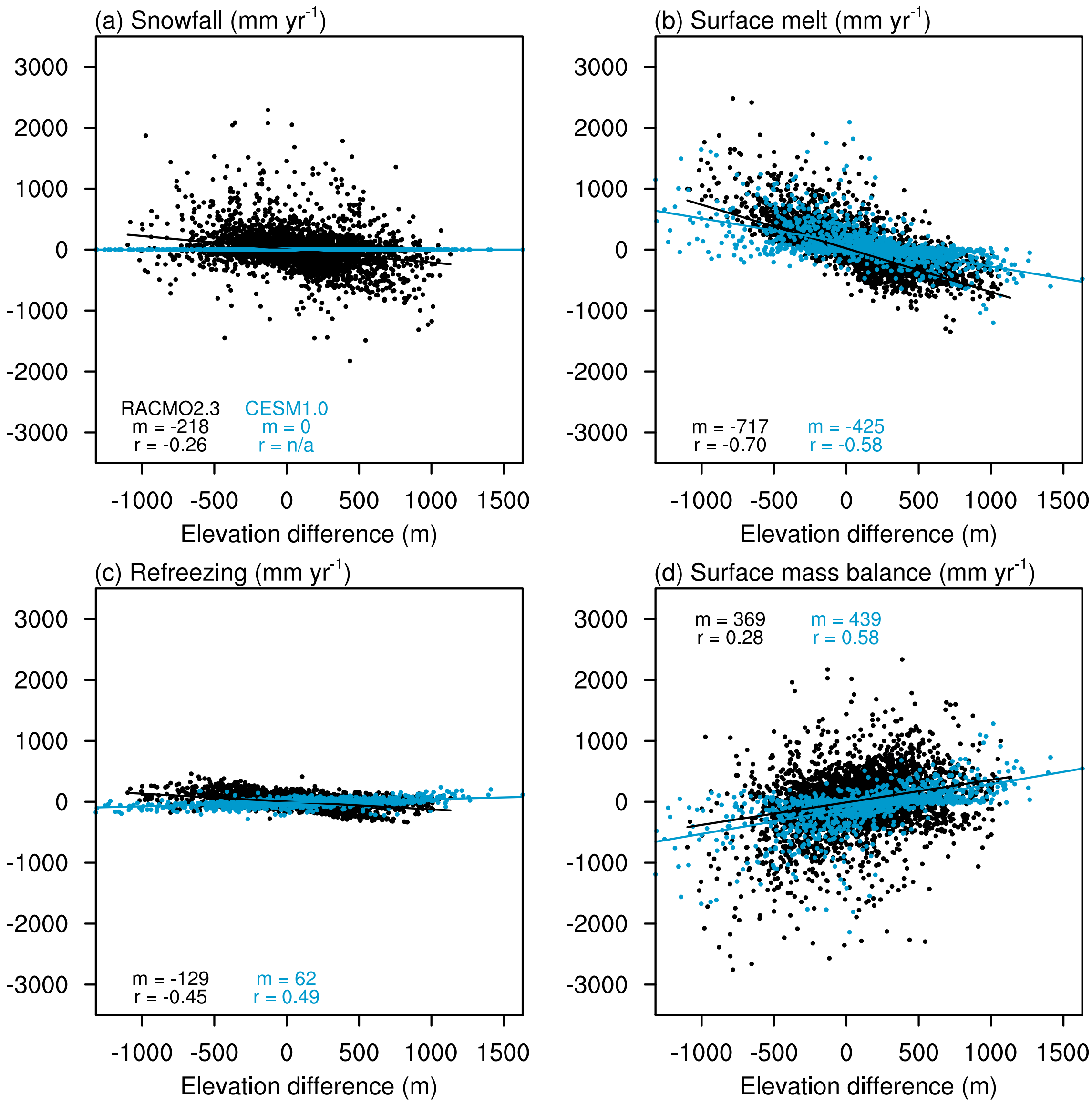


**Figure 2.** Same as figure 1, for annual SMB components from EC-6K (blue) and RACMO2.3 (black). a) Snowfall (mm yr$^{-1}$), b) Surface melt (mm yr$^{-1}$), ~~b~~c) refreezing (mm yr$^{-1}$) and ~~c~~d) surface mass balance (mm yr$^{-1}$). Surface mass balance is the sum of snowfall (~~not shown~~a) and refreezing (~~b~~c), minus the surface melt (~~a~~b) and sublimation (not shown). The lines represent least-squares linear regressions. The annotated $m$ is the least-squares linear regression gradient (mm yr$^{-1}$ km$^{-1}$), $r$ is the correlation coefficient.

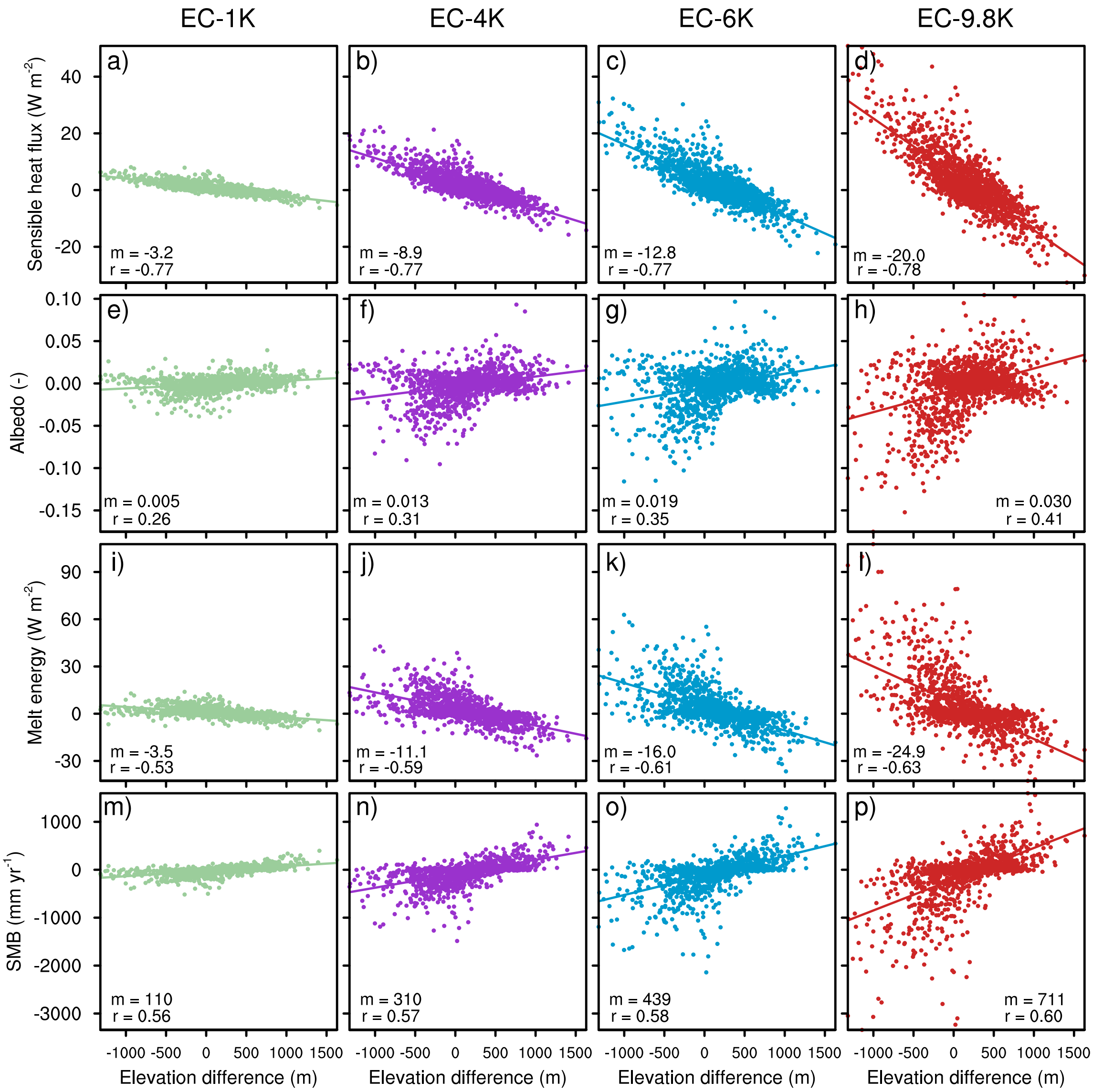


**Figure 3.** Comparison of 1965-2005 summer (JJA) downscaled energy fluxes among four simulations with different elevation corrections for the atmospheric temperature forcing. The first column corresponds to EC-1K, the second to EC-4K, the third to EC-6K and the last to EC-9.8K for a-d) sensible heat flux (W $m^{-2}$), e-h) albedo (-)~~and~~ , i-l) melt energy (W $m^{-2}$), and m-p) surface mass balance (mm $yr^{-1}$). The x- and y-value represent deviation of surface elevation and energy component for each data point with respect to the climate model grid ($\sim$ 100 km) mean. The lines represent least-squares linear regressions. The annotated $m$ is the least-squares linear regression gradient (W $m^{-2}$ $km^{-1}$ or $km^{-1}$ for albedo), $r$ is the correlation coefficient.

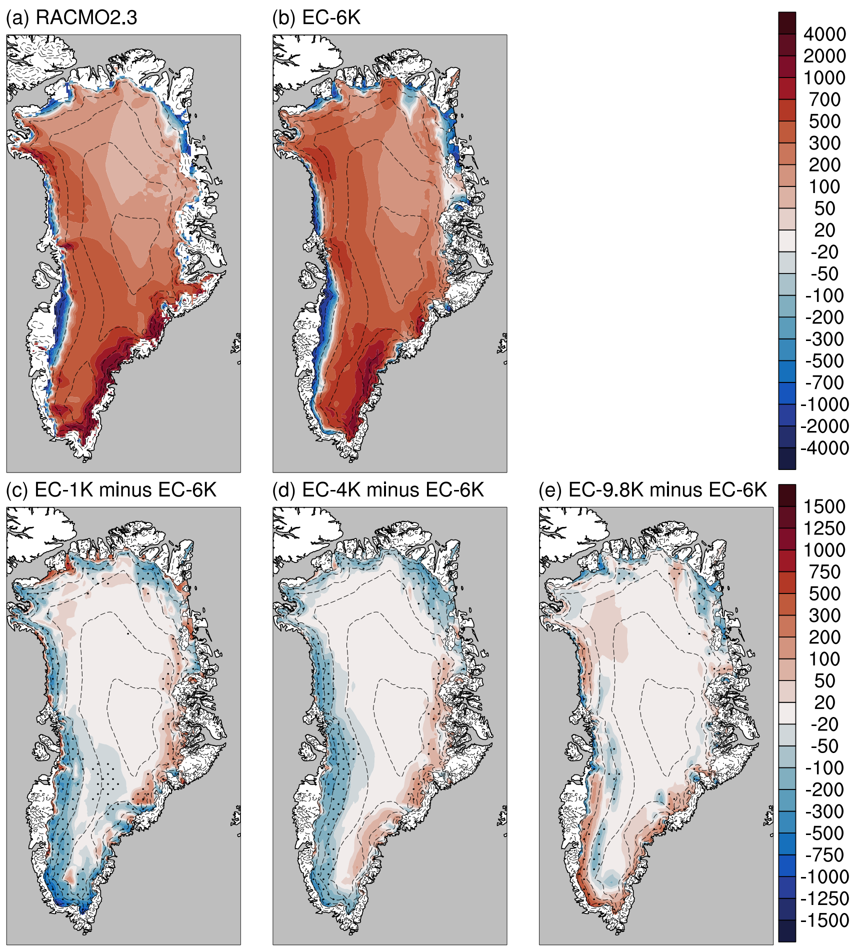


**Figure 4.** Climatological (1965-2005) ~~downscaled (5 km)~~ SMB for RACMO2.3 (a), CESM1.0 downscaled to 5 km (b), and SMB anomalies (c, d, e) (mm yr$^{-1}$) using lapse rates ~~a) 6 K km$^{-1}$, b~~c) 1 K km$^{-1}$, ~~c~~d) 4 K km$^{-1}$ and ~~d~~e) 9.8 K km$^{-1}$. Anomalies are with respect to the default lapse rate of 6K km$^{-1}$. Solid black contour shows the ice sheet margin. Elevation contours (dashed) are plotted every 500 m. The black line shows the ice sheet margin. Black dots show where differences are significant at the 95% level according to a student t-test.

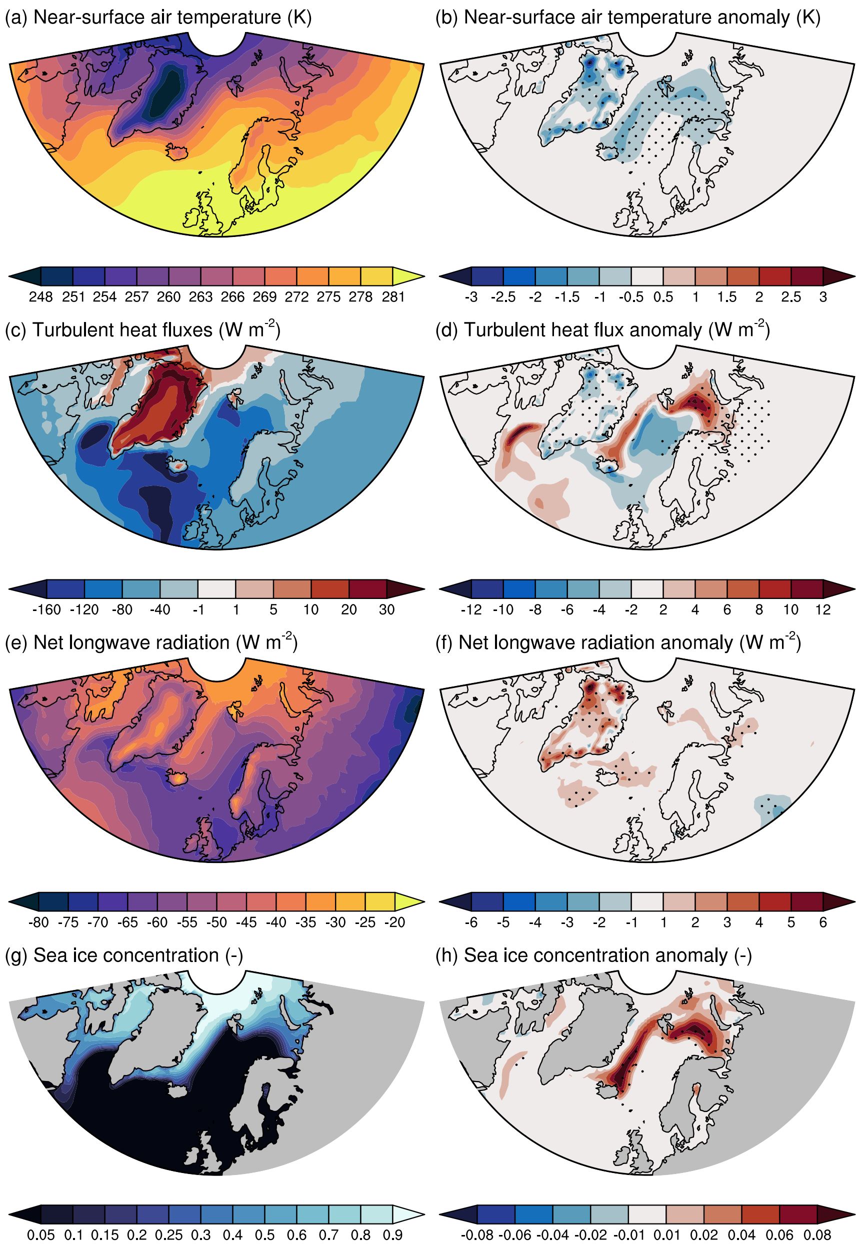


**Figure 5.** Annual climatology (1965-2005) of EC-1K (left column) and anomalies of EC-6K with respect to EC-1K, which approximate the EC imprint (right column). a,b) near-surface air temperature (K), c,d) turbulent (sensible+latent) heat fluxes (W $m^{-2}$), e,f) net longwave radiation (W $m^{-2}$) and g,h) sea ice concentration (-). Black dots indicate significance at the 95% level according to a students t-test. Positive signs for a-f indicate energy transfer from atmosphere to the surface.

**Table 1.** Gradients ($m$) and correlation with elevation ($r$; unitless) of surface energy and mass balance components as simulated through EC downscaling in CESM1.0. Values correspond to JJA (energy) and annual (mass) averages for the period 1965-2005. Melt energy is the sum of the net shortwave and longwave radiation and the heat fluxes. Surface mass balance is the sum of snowfall and refreezing, minus melt and sublimation.

| | RACMO2.3 | | CESM1.0 | |
|---|---|---|---|---|
| | $m$ | $r$ | $m$ | $r$ |
| *Surface energy balance components* | | | | |
| Incoming solar radiation (W $m^{-2}$ $km^{-1}$) | 15.1 | 0.72 | 0.0 | - |
| Albedo ($km^{-1}$) | 0.081 | 0.60 | 0.019 | 0.35 |
| Net solar radiation (W $m^{-2}$ $km^{-1}$) | -19.6 | -0.61 | -3.5 | -0.30 |
| Incoming longwave radiation (W $m^{-2}$ $km^{-1}$) | -17.6 | -0.81 | 0.0 | - |
| Net longwave radiation (W $m^{-2}$ $km^{-1}$) | -3.1 | -0.30 | 8.9 | 0.76 |
| Sensible heat flux (W $m^{-2}$ $km^{-1}$) | -3.8 | -0.42 | -12.8 | -0.77 |
| Latent heat flux (W $m^{-2}$ $km^{-1}$) | -0.2 | -0.02 | -10.8 | -0.76 |
| Ground heat flux (W $m^{-2}$ $km^{-1}$) | 0.4 | 0.05 | 2.1 | 0.46 |
| Melt energy (W $m^{-2}$ $km^{-1}$) | -26.3 | -0.70 | -16.0 | -0.61 |
| *Surface mass balance components* | | | | |
| Snowfall (mm $yr^{-1}$ $km^{-1}$) | -218 | -0.26 | 0 | - |
| Melt (mm $yr^{-1}$ $km^{-1}$) | -717 | -0.70 | -425 | -0.58 |
| Refreezing (mm $yr^{-1}$ $km^{-1}$) | -129 | -0.45 | 62 | 0.49 |
| Sublimation (mm $yr^{-1}$ $km^{-1}$) | 13 | 0.27 | 47 | 0.75 |
| Surface mass balance (mm $yr^{-1}$ $km^{-1}$) | 369 | 0.28 | 439 | 0.58 |

**Table 2.** Simulated whole-ice-sheet SMB, ablation area, total SMB in the ablation and accumulation areas, and prognostic near-surface temperature gradients for the four simulations performed in this study with varying lapse rates, and for the reference regional model RACMO2.3. Values correspond to the climatological (1965-2005) average with the standard deviation in parentheses.

| | RACMO2.3 | EC-1K | EC-4K | EC-6K | EC-9.8K |
|---|---|---|---|---|---|
| Surface mass balance (Gt $yr^{-1}$) | 382 (102) | 326 (122) | 326 (128) | 372 (101) | 367 (125) |
| Ablation area (% of total GrIS area) | 10.9 (2.4) | 16.4 (4.0) | 15.6 (4.1) | 13.4 (3.0) | 13.0 (3.0) |
| SMB in ablation area (Gt $yr^{-1}$) | -138 (45) | -142 (68) | -153 (75) | -128 (50) | -142 (48) |
| SMB in accumulation area (Gt $yr^{-1}$) | 520 (71) | 468 (68) | 480 (78) | 500 (63) | 509 (92) |
| Prognostic temperature lapse rate [JJA] (K $km^{-1}$) | 4.3 (0.2) | 0.5 (0.0) | 2.0 (0.1) | 3.0 (0.1) | 5.0 (0.2) |
| Prognostic temperature lapse rate [DJF] (K $km^{-1}$) | 4.6 (0.2) | 0.8 (0.0) | 2.5 (0.0) | 3.6 (0.0) | 5.8 (0.0) |

**Table 3.** Simulated annual (ANN) and summer (JJA) GrIS averaged components of the surface energy with the standard deviation in parentheses. The period considered is 1965 to 2005. Closest values to RACMO2.3 are given in bold.

| | RACMO2.3 | | EC-1K | | EC-6K | |
|---|---|---|---|---|---|---|
| | ANN | JJA | ANN | JJA | ANN | JJA |
| Albedo (-) | | 0.81 (0.01) | | 0.78 (0.02) | | 0.78 (0.01) |
| Near-surface air temperature (K) | 252.0 (0.8) | 265.6 (0.8) | 252.9 (0.8) | 266.5 (0.9) | **252.0** (0.8) | **265.9** (0.8) |
| Turbulent heat flux (W $m^{-2}$) | 19.1 (0.5) | 2.7 (0.7) | 23.2 (0.8) | **3.0** (1.3) | **21.1** (0.6) | 0.5 (1.0) |
| Net longwave radiation (W $m^{-2}$) | -43.9 (0.9) | -52.4 (2.0) | -45.9 (1.2) | **-47.5** (3.4) | **-43.9** (1.0) | -44.9 (2.7) |
| Melt energy (W $m^{-2}$) | 2.8 (0.5) | 10.2 (1.9) | 3.5 (0.8) | 12.4 (3.1) | **3.2** (0.6) | **11.6** (2.4) |

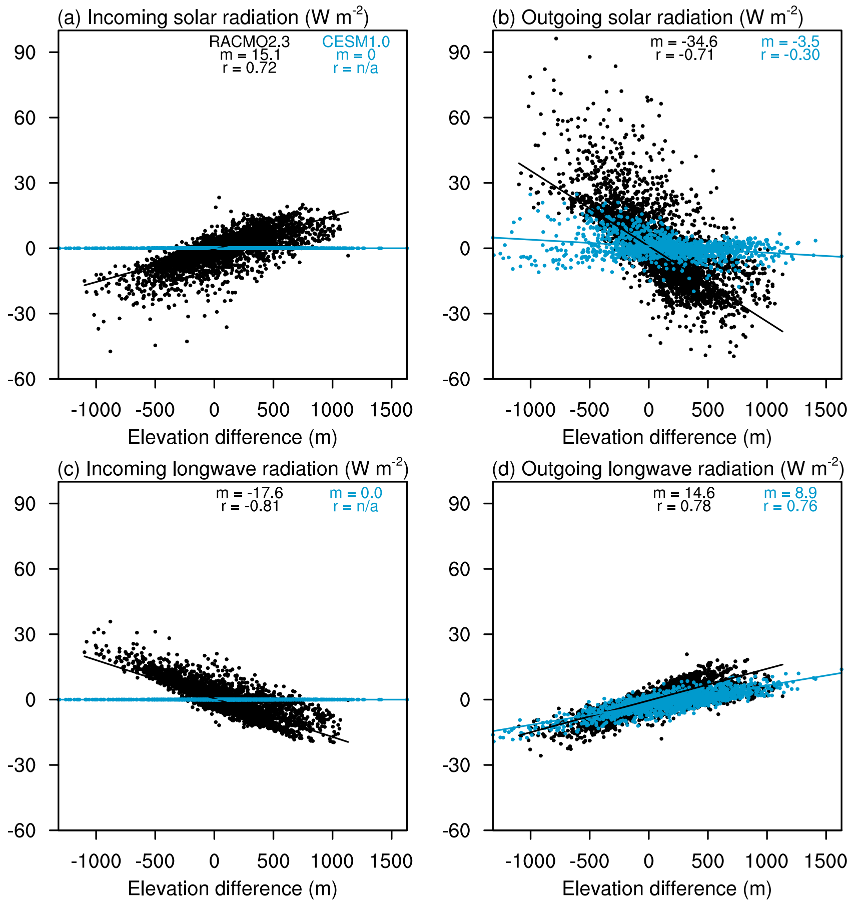


**Figure S1.** Same as figure 1, for summer SEB components from EC-6K (blue) and RACMO2.3 (black). a) Incoming solar radiation (W m$^{-2}$), b) outgoing solar radiation (W m$^{-2}$), c) incoming longwave radiation (W m$^{-2}$) and d) outgoing longwave radiation (W m$^{-2}$). The lines represent least-squares linear regressions. The annotated $m$ is the least-squares linear regression gradient (mm yr$^{-1}$ km$^{-1}$, $r$ is the correlation coefficient.

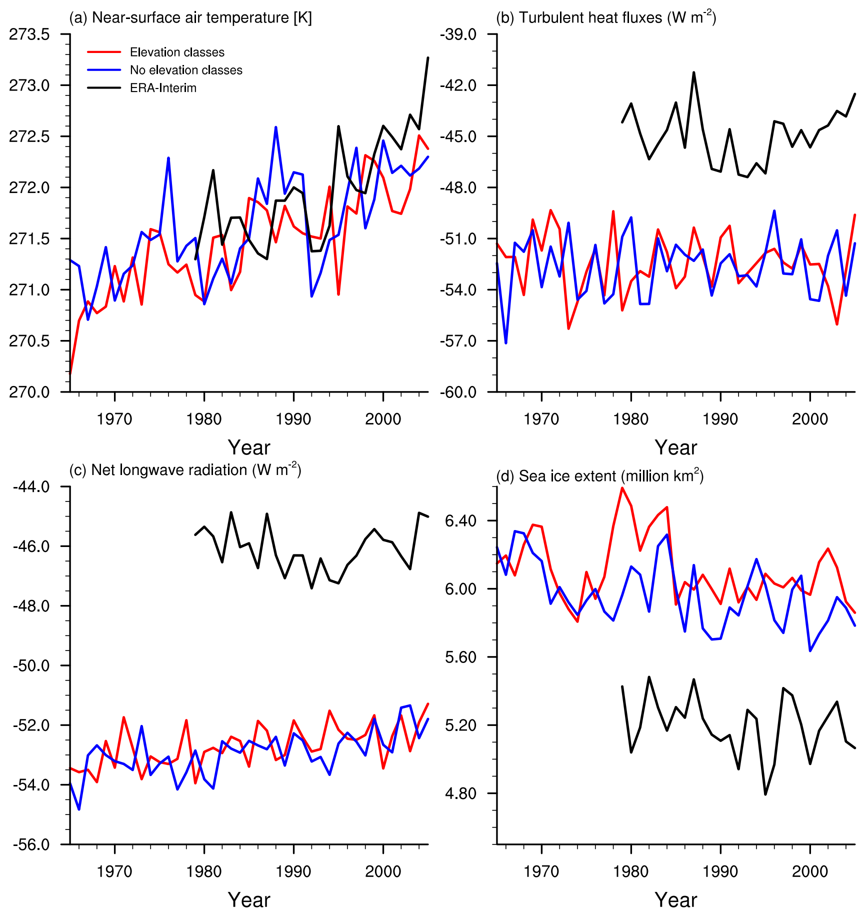


**Figure S2.** Annual means of selected climate variables in the simulations EC-1K ("No elevation classes", blue) and EC-6K ("elevation classes", red), and ERA-Interim (only 1979-2005, black) for reference. The data are area-weighted averages (integrated for sea-ice) for the region in Fig. 5.