

Responses to Reviewer 1

We would like to thank the reviewer 1 for reviewing our manuscript and for his constructive and insightful comments. We greatly appreciated these remarks, which helped improve the overall quality of the manuscript, notably through a number of clarifications that substantially improved the readability and understanding of the study. We addressed all comments in the revised manuscript in line with the reviewer's recommendations. Our responses are provided in black, and the comments of the reviewer are presented in blue font.

General comments

This paper documents several developments implemented to the ORCHIDEE land, surface model for use over the Greenland and Antarctic ice sheets. These include (1) a new snowpack initialization routine, (2) a wind-based surface snow density parameterization, and (3) a recalibrated dry-snow densification scheme. Positive impact of these developments on the simulation of surface snow density and vertical density and temperature profiles is demonstrated, but some weaknesses are still noted in representing the Greenland ablation zones. Overall, this is a comprehensive paper that could fit either in The Cryosphere or Geoscientific Model Development. The paper has gone through one review/revision round, and accordingly, it is already overall in a good shape. I don't have very much to add to the comments on the substance of the paper made by the reviewers of the original manuscript. I do have, however, a significant number of minor comments targeted mainly at increasing the clarity of the paper, polishing its language, and correcting a few typos and other minor errors.

Minor comments

1. line 229: "several years" sounds like an understatement. Decades or even centuries?

We fully agree with this comment and replaced "several years" with "several decades":

"This procedure enables the formation of a 10 m water equivalent (w.e.) snowpack in low accumulation areas, such as the interior of AIS where several decades of simulation would be necessary to form a thick snowpack."

2. lines 258–260: Avoid giving percent differences for temperature. They are very different depending on whether temperature is expressed in Celsius or Kelvin.

Thank you for this comment, we removed the percentage differences for temperature : "Over Greenland, the parameterizations yield root mean square errors (RMSE) representing 11% of the mean accumulation logarithm ($RMSE = 0.60 \ln(\text{kg m}^{-2} \text{ yr}^{-1})$) and 11% of the mean surface density (36.4 kg m^{-3}). For the surface temperature, the RMSE is equal to 3.1°C in Greenland (compared to an observed mean temperature of -20.6°C) while over Antarctica, the RMSE reaches 4.6°C (compared to an observed mean temperature of -32.8°C). The corresponding errors over the AIS represent 12.2% of the mean accumulation logarithm ($0.56 \ln(\text{kg m}^{-2} \text{ yr}^{-1})$) and 8% of the mean surface density (29.4 kg m^{-3})."

3. lines 284–285: "The new parameterization is applied to the modeled fresh snow density ...". This is an important point, and it should be perhaps be made even more

explicit. If I interpret this correctly, the equation for surface density (Eq. 7) (and Eq. 1 for OR OLD), is only applied at time steps when snowfall adds new snow on top of the existing snowpack, and then the surface density remains constant until the next snowfall event? Rather than computing the surface snow density based on instantaneous wind speed (and temperature for OR OLD) for all time steps (also those without snowfall), which would result in fast and unphysical variations in density.

We agree that this point deserves further clarification in the manuscript. Indeed, the surface snow density equation is only applied at time steps when snowfall occurs. After deposition, the surface density remains relatively constant, and can only be modified by processes such as surface meltwater refreezing or surface snow compaction, the latter being considered negligible here. Therefore, the different surface density parameterizations described in the manuscript are applied using the wind speed at the time of snowfall (or the temperature at the time of snowfall for OR_OLD).

We added this sentence in the revised manuscript : *“The new parameterization is applied to the modeled fresh snow density in ORCHIDEE, i.e. only at time steps when snowfall occurs, in order to determine the deposited snow density.”*

4. lines 293–295: The use of words “heterogeneous” and “this heterogeneity” in these sentences gives the impression that the wind-speed dependent density parameterization is motivated by the density variations in Greenland, which is misleading. Please reformulate the wording.

Thank you for your comment, we delete the sentence : *“To account for this heterogeneity”* which indeed was misleading about the motivation of the parameterization.

We added instead : *“Here, we propose a new expression for surface snow density”*

5. line 305: As a follow-up comment, it would be honest to note explicitly that for Greenland, Eq. (7) doesn’t capture much of the surface density variations, but rather acts as a bias correction that avoids the strong negative bias resulting from Eq. (1).

Thank you for this comment. We agree that a more explicit clarification is necessary.

“Although the parameterization does not fully capture the observed spatial heterogeneity of surface snow density, particularly over Greenland, it nevertheless reproduces the observed mean surface density and thereby corrects the strong negative bias resulting from Eq. (1).”

6. lines 343 and 392. You should refer to Section 4.1 rather than Section 4.

Thank you for the comment, we updated the references to the Section in order to refer to Section 4.1 instead of Section 4.

7. line 389: also mention Eq. (4).

Eq. (4) has been added as suggested.

8. line 461: 11.9 kg m⁻³ should be 45.2 kg m⁻³

We thank the reviewer for pointing out this error. The RMSE value has been corrected in the revised manuscript.

9. Fig. 6: Colour should be used for making the figures clearer rather than for artistic purposes. There is no need to use different colours for the different models, because they are cleanly separated into different figure panels. However, using different colors for Greenland/Antarctica/refreezing /no-refreezing would improve the clarity.

Thank you for this comment. We update the figure 6 to improve the visual distinction between Greenland and Antarctica, as well as between refreezing and non-refreezing cases.

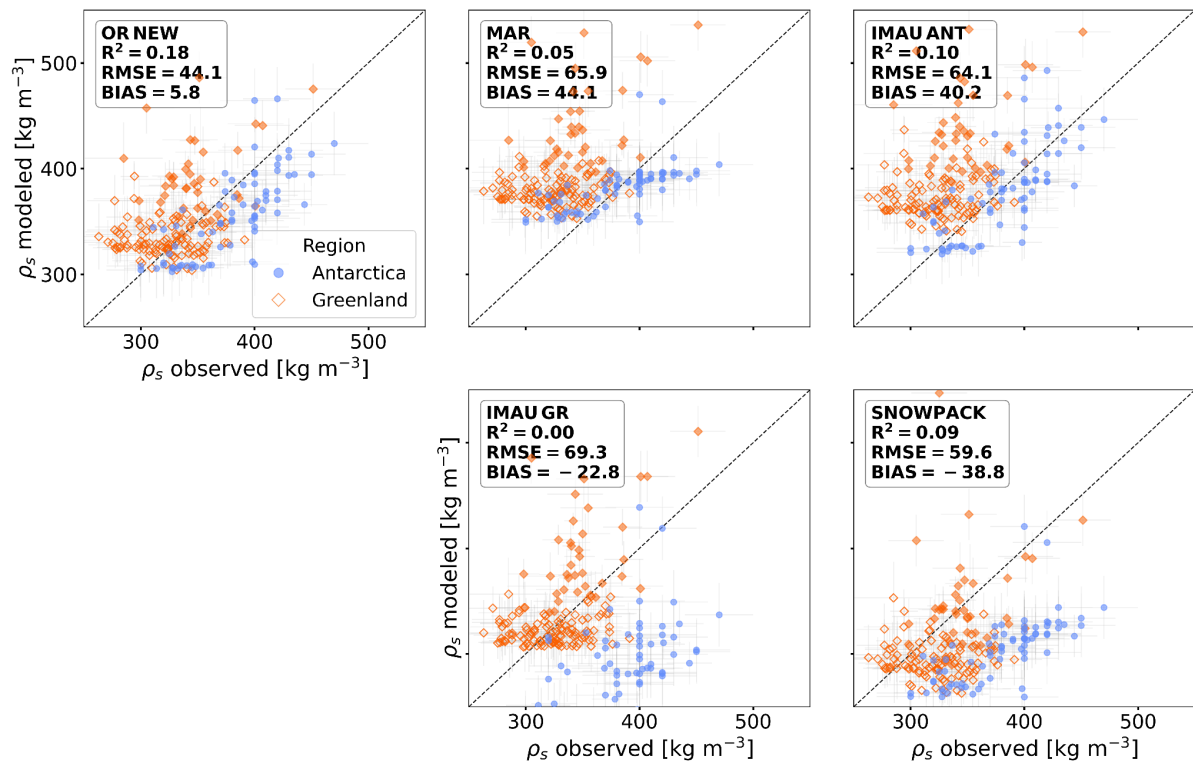


Figure 6. 40y-average surface snow density compared to observations, modeled by (a) the new wind parameterization in ORCHIDEE, (b) the wind parameterization developed for Antarctica in MAR (Kittel et al., 2021), (c) the wind and temperature parameterization developed for Antarctica in IMAU (Lenaerts et al., 2012; Veldhuijsen et al., 2023), (d) temperature parameterization developed for Greenland in IMAU (Ligtenberg et al., 2018) and (e) the wind parameterization developed in SNOWPACK (Groot Zwaaftink et al., 2013). Locations are specified with orange open diamond and blue solid circle, for Greenland and Antarctica respectively. Shaded points are locations where the 40y-averaged refreeze in the top 20 cm of the snowpack is larger than 0.1 mm d⁻¹. Error bars represent observational uncertainties (see Supplementary).

10. Fig. 6: As a very minor point, some of the numerical values given in the legends differ marginally from Table 6 (BIAS is panel (b) and RMSE in panel (d)).

We have corrected the values in Table 6.

11. line 528: add "albedo" before "parameters" to increase the clarity. When reaching this point in the manuscript, at least this reviewer could not remember what Rauolt et al. (2023) was about.

We have taken this comment into account and added "albedo parameters".

12. line 535: It would be clearer to say "...while ORCHIDEE values are lower by 2 to 3 m yr⁻¹".

We have taken the suggested correction into account.

13. line 540: "(May–June 2012, see supplementary material)". So far I can see, there are no figures in the Supplementary material showing May–June 2012.

This was a mistake. We have now added the figure showing melt and refreezing for 2012, as in panels d and e of the Figure 10 from the original manuscript. This figure is now present in the Supplementary material.

14. lines 549–551: Since you are discussing a short-term event (12 days), it might be better to use units of $\text{kg m}^{-2}\text{d}^{-1}$ instead of m yr^{-1} .

This comment has been addressed in the revised manuscript.

15. Caption of Fig. 10: Mention the use of the OPT12L albedo parameters, and that panels (d)–(g) are for year 2012.

We have added the following sentence : "The ORCHIDEE simulations were run using the OPT12L albedo parameters."

16. line 572: Fig. 11b should be Fig. 11d? Also, replace "following profiles" with "profiles 2–5".

This is indeed Fig. 11d, thank you for pointing out the typo. We have also corrected "profiles 2–5" accordingly.

17. lines 634–635: Noting explicitly that $\gamma = \gamma \ln(A)$ would help the reader to understand why the logarithm of accumulation rate is needed (on line 642).

Thanks, we added this sentence : "where $\gamma = \alpha \ln(A)$ is the correction term defined previously in Section 3.1 (see Eq. 6)"

18. line 635: Eq. (1) should be Eq. (5). Also, giving the numerical values $C_0 = 0.03$ and $C_1 = 0.07$ would help, as the symbols C_0 and C_1 are not used after Eq. (5).

We corrected this, we have also added the numerical values of parameters C_0 and C_1 .

19. lines 643–644: For completeness, also mention the parameterization of snowpack thickness in the list.

We have corrected this and added the description of the snowpack thickness parameterization : "*Finally, we introduce a varying snowpack thickness parameterization defined as a function of snow temperature. Each parameterization is defined separately for Greenland and Antarctica, with the exception of the snowpack thickness parameterization introduced for Greenland only.*"

20. lines 648–649: mention also the use of a lower lapse rate ($6.5^\circ\text{C km}^{-1}$) in the lowest 500 m.

We have reformulated the paragraph to include the lower lapse rate in the lowest 500 m : "*The lower temperature lapse rate was prescribed to $6.5^\circ\text{C km}^{-1}$ for elevations below 500 m. This value was obtained using the Broyden-Fletcher-Goldfarb-Shanno (BFGS) optimization algorithm to minimize the root mean square error between the parameterized mean surface temperature and the observed firn temperature at a depth of 10 meters.*"

Indeed, this lapse rate was obtained through minimization, in contrast to the lapse rate used for elevations above 500 m, which is taken from Feulner et al. (2013).

21. Caption of Table A1: explain the meaning of MBE (Obs), MBE (MAR), RMSE (Obs) and RMSE (MAR).

We have added this sentence in the caption of Table A1.: “*MBE and RMSE are the mean bias error and root mean square error respectively. MBE (Obs) and RMSE (Obs) correspond to the comparison between observed temperatures and the parameterized temperature using the elevation and latitude of the observations. MBE (MAR) and RMSE (MAR) are computed similarly, but using the mean 10 m snow temperature field from MAR over 1980–2019, compared to the parameterized temperature evaluated at the elevation and latitude of each MAR grid point.*”

22. Table A4: There are two rows for zsnow max.

We corrected this typo and added zsnow_min instead of zsnow_max.

23. Supplementary material, Eq. (S1): Something wrong; the units of the two terms on the right hand side don't match.

We thank the reviewer for this comment. We identified an error in the formulation reported in the Supplementary Material, which resulted from a mix-up between two parameterizations. This issue is limited to the supplementary description; the simulations correctly use the formulation of Yen (1981) and Sun et al. (1999). The Supplementary Material has been corrected accordingly.

Yen, Y.-C. (1981), Review of the thermal properties of snow, ice and sea ice, *Tech. Rep. 81-10*, Cold Reg. Res. and Eng. Lab., Hanover, N. H.

Sun, S. F., J. M. Jin, and Y. K. Xue (1999), A simple snow-atmosphere-soil transfer model, *J. Geophys. Res.-Atmos.*, 104(D16), 19587–19597, doi:[10.1029/1999JD900305](https://doi.org/10.1029/1999JD900305).

24. Supplementary material, Eqs. (S5) and (S6): What does Tsoil mean in the context of the present study?

We thank the reviewer for this comment. In this study, this corresponds to the surface snow temperature. To avoid confusion, we have replaced T_soil with T_surf in the revised manuscript.

25. Supplementary material, Eqs. (S8) and (S9). What are the units of Ts? The numerical values suggest that they might be K for (S8) and °C for (S9), but this should be noted explicitly.

Thank you for your comment. We updated the formulation to be consistent with Ts in K. We therefore updated the S9 formulation to be consistent with Ligtenberg et al. 2018 and Brils et al. 2022.

Ligtenberg, S. R. M., Kuipers Munneke, P., Noël, B. P. Y., and van den Broeke, M. R.: Brief communication: Improved simulation of the present-day Greenland firn layer (1960–2016), *The Cryosphere*, 12, 1643–1649, <https://doi.org/10.5194/tc-12-1643-2018>, 2018.

Brils, M., Kuipers Munneke, P., van de Berg, W. J., and van den Broeke, M.: Improved representation of the contemporary Greenland ice sheet firn layer by IMAU-FDM v1.2G, *Geosci. Model Dev.*, 15, 7121–7138, <https://doi.org/10.5194/gmd-15-7121-2022>, 2022.

Language corrections and typos

1. line 177: remove the comma after η .

Corrected.

2. line 193: it should be "in terms".

Corrected.

3. Caption of Fig. 4, third line: space missing after "dots."

Corrected.

4. line 412: "correlation between both". Remove "both".

Corrected.

5. line 445: add "the" before "IMAU-Firn densification model".

Corrected.

6. Caption of Fig. 6: replace "developped" with "developed".

Corrected.

7. Caption of Fig. 8, first and third line: the word "difference" should be used instead of "anomaly".

Corrected.

8. lines 527–530: Add "Because," before "As presented ...", to make this sentence grammatically correct. (Why? "As" refers to only "presented in Section 2.4", not to the last part of the long sentence).

Thank you for the explanation. We have corrected this: "*Because, as presented in Section 2.4, the albedo parameters from Raoult et al. (2023) lead to an underestimation of melt-refreeze processes ...*".

9. lines 654–655: It should be "dependency ... on latitude".

Corrected.

10. line 701: it should be "affected"

Corrected.

11. Caption of Fig. A1: replace "in function" with "as a function of".

Corrected.

12. Figure A.3: I would use "precipitation-weighted air temperature" and "precipitation-weighted wind speed".

Corrected.

13. Caption of Figures S1, S2 and S4: It should be "Dark lines represent".

Corrected.

14. Caption of Figures S3 and S5: "numeroted" should be "numerated" or "enumerated".

Corrected.

Responses to Reviewer 2

We would like to thank the reviewer 2 for their constructive and insightful comments. We addressed all of these comments in the revised manuscript to improve its overall quality in line with the reviewer's recommendations. Our responses are in black, and the comments of the reviewer are presented in blue font.

I'm happy to see that the reviews have led to a better manuscript, at least in my view. Some points remain, though minor. Besides these mentioned below, quite some spaces and commas are missing in the manuscript. Although these will be picked up when the manuscript is processed for final publication, it would be good if the authors check that themselves to before they send in the final revised version.

Thank you for this comment. We have carefully reviewed the manuscript to correct errors of typography, punctuations and other minor errors.

After reading the revised manuscript I realized that the underestimated melt in the ablation zone of the Greenland Ice Sheet likely stays when ORCHIDEE is run embedded in IPSL-CM. That is, however, possibly a topic for a next study.

Indeed, it will be the focus of our next study, in order to better understand this underestimation of melt over the Greenland ablation zone.

- Section 2.1 starts somewhat abrupt with details, consider to re-introduce the "where are we using the observations for"-sentence the initial manuscript had.

We have added the following sentence to introduce the Section : *"To improve the representation of snow densification, we use observations of snow temperature, accumulation and density in Greenland and Antarctica."*

- Section 2.3.1 is a bit odd - consider merging the content with 3.2 and leave here that the surface snow density has been changed in this study and will be discussed in 3.2. If applied, the subdivision of 2.3 into 2.3.1 and 2.3.2 is no longer needed too. [Maybe that is reverting the changes I proposed in the first review, but this isn't elegant either.]

Thank you for this suggestion. Following your previous recommendations, we revised the structure of Sections 2 and 3. In the current version of the manuscript, we find it more consistent to present the surface snow densification and snow compaction separately (Sections 2.3.1 and 2.3.2) just after the introduction of the ORCHIDEE model in Section 2.2. Indeed, surface snow densification and snow compaction correspond to distinct developments (presented after in Section 3).

Line 182: Mention here (again) that you will recalibrate these values and that the calibration method will be described later / in section X.

We added the following sentence : *"In this study (Section 4), we calibrate these parameters to represent polar snow densification using the History Matching calibration method (see Section 4)."*

Section 2.4: Thanks for the extra explanations. A question remains:

Line 195: Deriving turbulent fluxes from near-surface gradients is not trivial (I mean, choice-free), but at the other hand not the focus of this study. Therefore, can you specify how ORCHIDEE derives these fluxes in one line and refer to a/the paper where these flux relations and choices made are described in detail? Afterall, it is this SEB coupling that leads to the reduced melt production, for example as mentioned in sections 6.2 and 6.3.

We have added the following sentence to clarify this: *“These turbulent fluxes are obtained following the Monin-Obukhov turbulence theory (Monin and Obukhov, 2009) using the wind speed at 10 m, a drag coefficient and the atmosphere/surface gradient of temperature and specific humidity at 2 m (Charbit et al., 2024).”*

I think it improves the structure of the section if all information on MAR and the used MAR versions are moved to the first paragraph of 3.1. That is the information in lines 198-200 and 205-208. In this third paragraph then remains the comments on the used albedo parameterizations.

Since we use forced simulations, we feel that it is important to present the forcing data together with the experimental setup. We therefore believe that it is more consistent to keep the presentation of MAR in this section.

Section 2.5 is rather short, therefore, consider merging 2.5 with 2.1 and place the merged section on the observations after the current section 2.4.

Following this recommendation, we merged Sections 2.5 and 2.1, and moved the presentation of the observations after Section 2.4,

L228: "Deep snowpack": the actual snowpack in central Antarctica is up to 100 m thick, much thicker than the snowpack in ORCHIDEE. Replace therefore "deep" by "full", "stable", or "10 m w.e.", ... or a combination of these.

We added the following : *“This procedure enables the formation of a 10 m w.e. snowpack in low accumulation areas”*

Section 6.2: Thanks for this revision, this is more insightful in the behaviour of ORCHIDEE.

Lines 548-554: please express all melt and refreezing values concerning this melt onset event in mm per day and not in mm per year, like the refreezing rate in line 552.

This comment has been addressed in the revised manuscript.

Additional remarks:

We have updated Figure 9, which compares observed 10 m temperature in both Greenland and Antarctica, using the SUMup temperature dataset without the restriction to dates after the year 2000 for Greenland and including the grid average processing, as explained in the Observations section and as recommended in the first review. This update had been inadvertently overlooked in the previous revision. The updated figure is provided below.

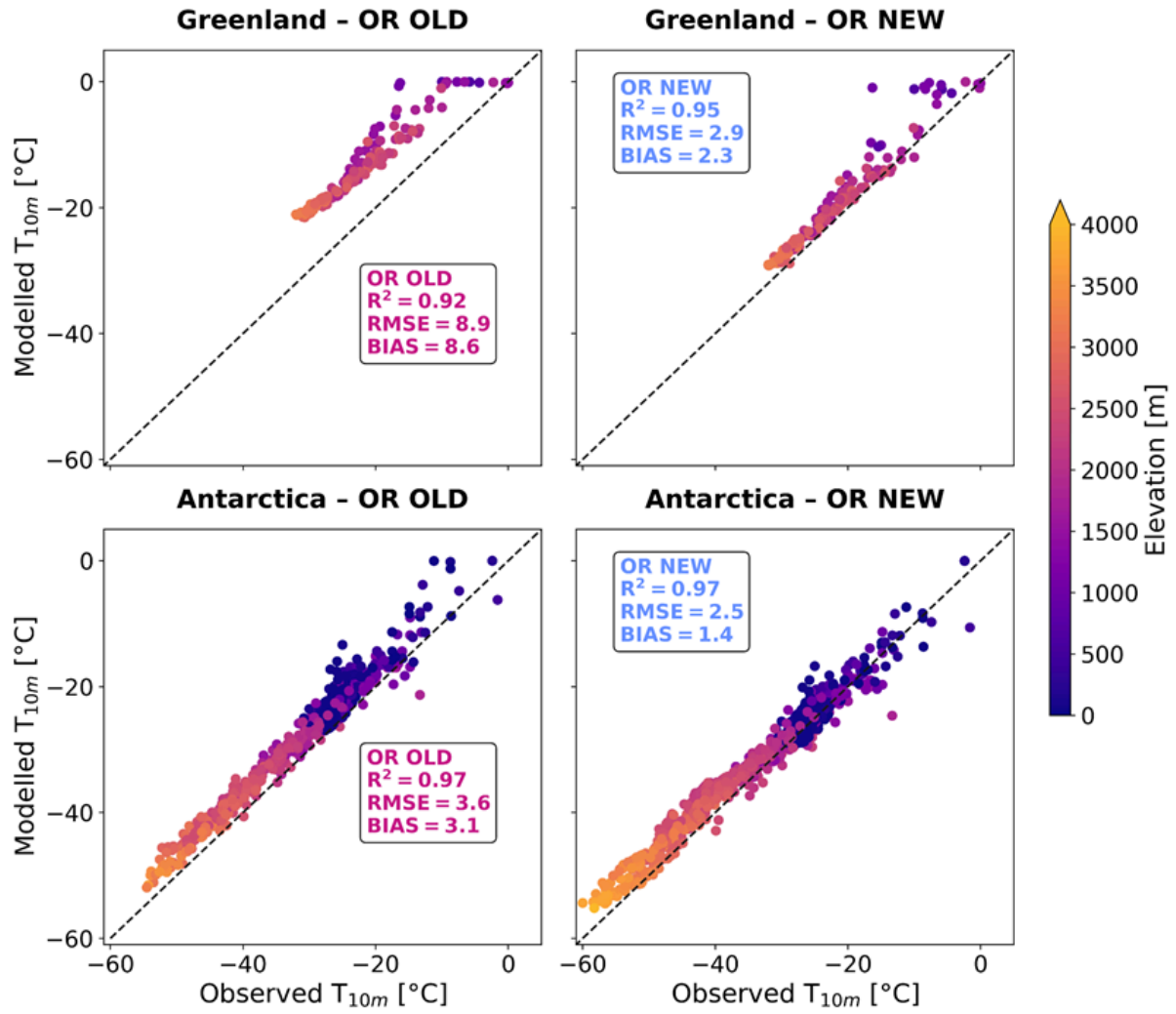


Figure 9. Comparison of observed and simulated snow temperature at 10 m depth from (a, c) the previous ORCHIDEE configuration (OR OLD) for (a) Greenland and (c) Antarctica; and from the new ORCHIDEE configuration (OR NEW) for (b) Greenland and (d) Antarctica.

We can see that the performance of OR OLD is degraded over Greenland, whereas OR NEW remains consistently good, using the updated dataset of observed temperatures.