Responses to Reviewer #1

The authors updated the parameterizations for glacier ice and snowpack within the land surface model and carried out validation over the Greenland Ice Sheet. The updated model demonstrated comparatively strong performance on the Greenland Ice Sheet and yielded valuable outcomes for the future development of ecLand. However, there remain several unclear aspects and areas lacking sufficient validation. I hope that the following comments will help improve the manuscript.

Major comments:

1. The differences between the existing model (CTL) and the updated model (GLA) are not clearly explained. For example, it is not clear what parameterizations the CTL used. Since this is a key part of the manuscript, I suggest showing the differences between the two models in a table to enhance clarity.

Following the recommendations from the reviewer we have amended the Methodology section to better describe the differences between CTL and GLA:

- To highlight the current parameterisations used for glacier points, we have modified Section 2.1 and added a new subsection, 2.1.1, named “Current treatment of glacier points in ecLand”.
- Section 2.2 has been further divided in subsections to highlight the modified snow process that is discussed.
- A table has been added to better clarify the differences in each component of the snow scheme, see below:

Table 1. Summary of the differences in the representation of glacier grid points between the current model version (CTL) and the new glacier parameterisation (GLA).

Parameter / Parameterisation	CTL	GLA
Sub-grid ice tile	None	Explicit ice tile with sub-grid fraction
Ice Thermodynamics	None	Included (4 layers)
Ice Albedo	None	Fixed, 0.4
Ice Melting	None	Included (bare-ice exposure)
Snow Mass Balance	Fixed to 10 m SWE	Dynamic and capped to 10 m SWE, see Sect. 2.2.2 Snow Mass
Snow Albedo	Fixed, 0.82	Dynamic, see Sect. 2.2.2 Snow Albedo
Snow Density	Fixed, 300 kg m^{-3}	Dynamic, see Sect. 2.2.2 Snow Density

2. The transition from validating against the Greenland Ice Sheet to evaluating river discharge in the Northern Hemisphere feels somewhat sudden. Validation using in-situ albedo may be challenging, but would it be possible to compare the land surface albedo in CTL or GLA with MODIS albedo across the Northern Hemisphere? At least, the authors should discuss whether the GLA experiment also shows a decrease in albedo outside of Greenland.

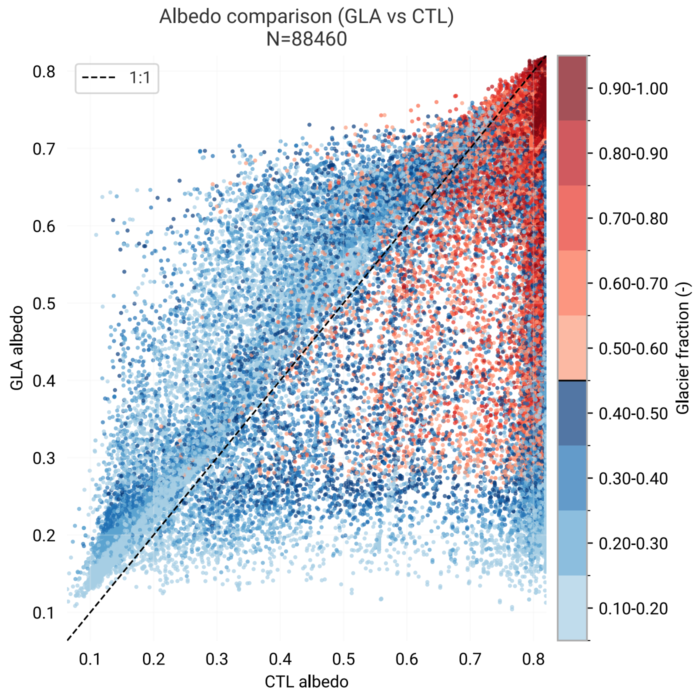
As suggested, we have examined the albedo differences between GLA and CTL (see Figures below). The first scatter plot compares grid-box average albedo for the boreal summer months over 2000–2019, considering only grid points with glaciers/land ice (glacier mask > 0.1). The spatial map shows the composite albedo differences for the same period and season, providing context to the scatter plot.

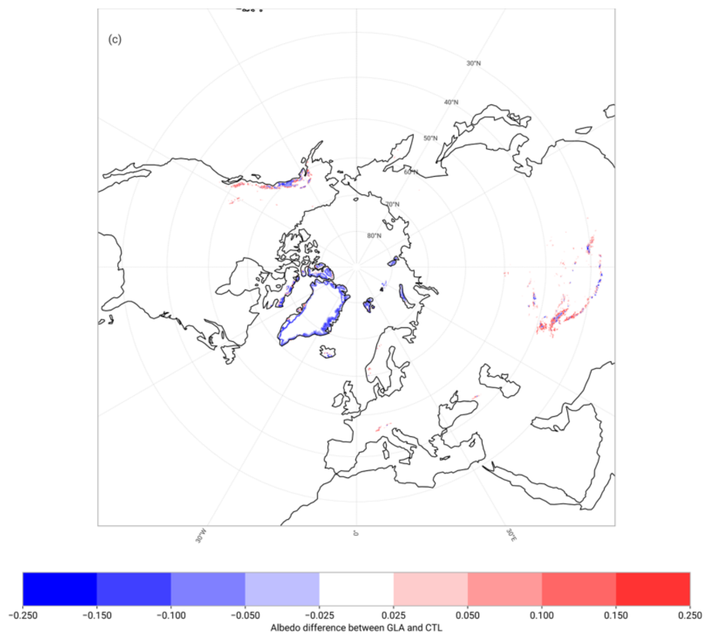
Overall, at grid points where the glacier mask exceeds 0.5 the albedo is reduced. This reduction is due to the new dynamic albedo parameterization for snow over land ice in GLA, in contrast to the fixed value of 0.85 used in CTL. Things are more complex at grid points where the glacier mask is below 0.5: for grid points located in high altitude regions, the new sub-grid representation of ice leads to an increase in the grid-box average albedo; however coastal points show a reduction of albedo.

Because of the above, the associated increase in river discharge within the analysed basins is primarily linked to the exposure of bare ice, either fully resolved or sub-grid, which can melt during summer and thus contribute to runoff.

This discussion has been included in the revised manuscript, in Sect. 3.3, to interpret the changes in the river discharge as follows: "Changes in the river discharge may stem from a general reduction of snow albedo over glaciated surfaces in the Northern Hemisphere and the exposure of bare ice. For grid points located in high altitude regions and with sub-grid glaciers, there is a general increase in the grid-box average albedo in GLA compared to CTL (see Supplementary Figure Sx). Therefore, the increase in river discharge within the analysed basins is primarily linked to the exposure of bare ice, either fully resolved or sub-grid, which can melt during summer and thus contribute to runoff."

The plots have been added as supplementary material.





Specific comments:

Title: In my impression after reading this manuscript, the use of the term “global” feels somewhat excessive. Since the river discharge validation is conducted only for the Northern Hemisphere, it might be better to change the title to “local and regional impact,” or remove the phrase “: local, regional and global impact.”

> We have amended the title to better reflect the content of the manuscript as follows: “Enhancing the Representation of Glaciers and Ice Sheets in the ecLand Land-Surface Model: Impacts on Surface Energy Balance and Hydrology Across Scales.”

L35 (Surface processes…): Add melting and refreezing processes.

Thanks, done.

L67: What do you mean by "physical capping"? Please add a clearer explanation.

Mottram et al. (2017) have introduced a hard limit to the surface temperature solver over ice and snow so that it does not exceed the melting point. This has been clarified in the revised version of the manuscript.

2 Methodology: It is better to briefly describe the difference between the GLA parameterization and the other LSM parameterization. Lee et al. (2024) might help you to compare GLA with LSMs (land surface models).

Thanks. This has been done as part of the revision of the "Methodology" section (see major comment).

L87: Does "fully coupled" mean "Atmosphere, land and Ocean coupling"?

The IFS runs by default as an atmosphere-land-ocean coupled model, but in the context of this paper we mean the coupling between the land-surface component, ecLand, and the atmospheric component ("IFS"). We have clarified this in the manuscript.

2.2 New glacier parameterisation: Although the GLA parameterizations are described, it is not clear what has changed compared to the CTL parameterizations. I would like to understand the differences between the two models before seeing results, so I suggest summarizing the characteristics of both models in a table.

We have addressed this suggestion by adding additional material to the Methodology Section.

L157-158: Previous studies have suggested that new snow density in the polar region exceeds 300 kg m-3 (Greuell and Konzelmann, 1994; Lenaerts et al., 2012; Niwano et al., 2018), so I have no objection to your assumption for the Greenland simulation. However, you should be careful if you apply the assumption to midlatitude areas. New snow density in midlatitudes is typically around 100 kg m-3 as indicated by previous studies (e.g., Niwano et al., 2012). Regarding this point, it should be stated whether changes in snow density parameterization affect snow albedo.

We thank the reviewer for this comment and acknowledge that using a limited dynamical range for the density of new snow over glaciers in the midlatitudes can be a limitation. However, we believe that this is still an improvement compared to the previous scheme, for which a resolved glacier point would have a constant snow density of 300 kg m-3, with no variability in time. We are currently working on spatialising the parameters of ecLand, to allow a more flexible use of parameter values across different climate conditions. This work will allow us to use different values of new snow density depending on the region and will be evaluated in future work. We have included part of this discussion in the revised manuscript, see new Sect. 2.2.2 Snow Density.

L169-170: Please add the references for the values you used for Eq. (3). If the values are not based on previous studies, please add the rationale why you set the values.

The values were selected based on a preliminary parameter tuning experiment conducted prior to the analysis presented in the paper. In this experiment, the parameters were adjusted to achieve the best compromise between their impact on snow processes (as evaluated in this study) and on near-surface weather variables when the model is coupled to IFS for numerical weather predictions. We have clarified this aspect in the revised version of the manuscript, see new Sect. 2.2.2 Snow Albedo.

L192: If there is no alternative to the spatial SMB data other than RCM, it should be mentioned.

We use this product because it allows a comparison of the current scheme with state-of-the-art RCMs used to produce SMB estimates. A comparison with in situ observations would be valuable, for instance the observations compiled by Machguth et al. (2016). However, this would require a higher horizontal resolution, and consequently a more detailed glacier/ice-sheet mask, as most of the in situ observations compiled by Machguth are near the ice-sheet margin. In addition, the altitude difference between the observation location and the model grid point could further affect the SMB. We have clarified this in the revised manuscript, in Sect. 2.3, as follows: "*However, given that this product is based on RCMs, it will be used as a reference for comparison with current state-of-the-art models for SMB studies, rather than a validation dataset. A detailed comparison with in situ observations (see for instance Machguth et al., 2016) would require a high horizontal resolution and a more refined glacier/ice-sheet mask. Such analysis is beyond the scope of the present study, which is primarily focused on global 2D simulations in a close-to-operational setting (see Sect. 2.4.2).*"

L205 (different periods for each site): This is vague explanation. Please describe clearly. It would be helpful if you could make a table summarizing the experimental setting, including other experimental settings. A supplemental material might be good.

Thanks, we have added a table as supplemental material (Table S1) to summarise the experimental setting. The paragraph on the different periods has been reformulated as follows: *"The point scale simulations over the PROMICE stations described in Sect. 2.3 are run for different periods for each site, depending on the availability of observations at each location. To minimise spin-up effects, each site is simulated repeatedly over its available period until at least 30 years of spin-up are achieved, before performing the final simulation used for evaluation. Three types of experiments are run to evaluate the impact of the new glacier parameterisation depending on the forcing used to drive the model, as well as the glacier mask used to identify the glacier points, as summarised in Table S1."*

L220: Did you apply elevation correction to ERA5?

No, an elevation correction was not applied. This choice was made to better reflect the conditions of a coupled model run. While we acknowledge that applying such a correction could qualitatively affect the results (see also response to Reviewer #2 comment on “differences due to elevation difference”), it would not represent the specific conditions we intended to investigate. We have clarified this point in the revised manuscript, see Sect. 2.4.1.

2.4.2 2F global simulations: Please add an explanation regarding spinup simulations.

The model is initialised in 1970 in order to spin up thoroughly. Snow variables across the five layers are initialised using data from ERA5, following the "warm-start" procedure described in Arduini et al. 2019. The four-layer ice temperature is initialized based on the temperature of the lowest snow layer and is allowed to evolve dynamically. Given the relatively limited total thickness of the ice layers (10.86 m), they are expected to reach thermal equilibrium within approximately 20 years prior to the period used for evaluation (1990 onwards). We have included this discussion in the revised manuscript, see Sect.2.4.2.

Figure2 (skin temperature): “Skin temperature” and “surface temperature” are mixed up in the main text. If they mean the same thing, please unify either.

We have unified the terminology using surface temperature across the revised manuscript.

Figure2: What period does the analysis in this figure cover? Please add the period and season for the analysis.

Thanks, done.

Results: The Results section should be nominally limited to new results from the current observation or calculation and not include a literature review (L264, 281. 334…). I found that the authors' interpretations are included within this section (e.g. L280-284, L332-340). I suggest that you change “Results” section to “Results and Discussion” section.

We have modified the Section title to “Results and Discussion” following the reviewer’s suggestion.

Line 242: Could you tell me about the specific scheme you improved?

We have amended the methodology section to better clarify the differences between GLA and CTL in order to provide a solid foundation for the reader throughout the manuscript.

Figure 3 (c): In the OBS experiment, temperature from PROMICE is used as an atmospheric forcing, yet panel (c) shows a bias of nearly 3°C during winter. The result looks strange. Please verify that there are no errors in the simulations or analyses. If no errors are found, the bias may be due to ERA5 precipitation used in the OBS experiment. Additionally, I could not locate the CLIM experiment lines in the figure.

The land-surface component of the IFS, ecLand, generally struggles to simulate extremely cold wintertime surface temperatures over ice sheets. This issue has been documented in several studies over Antarctica (see for instance Dutra et al. 2015) and similarly applies to Greenland. The two contributing factors are: the excessive thermal inertia of the snowpack when vertical discretization is too coarse; excessive turbulent mixing in stably stratified conditions. We have added two supplementary figures illustrating the different components of the surface energy balance. In addition, the revised manuscript now includes a physical interpretation of the biases in Figure 3 and 4 (see Sect. 3.1.1).

Regarding the CLIM experiment in Figure 3c, this is underneath the ERA5 experiments, as those are equivalent for the accumulation sites. We have clarified this in the revised manuscript.

Figure 4 caption: Add the specific season you analyzed.

Thanks, done.

Line 270: Add the specific months.

Thanks, done.

Line 280: This paragraph is clearly a discussion.

Following the reviewer's suggestion we have renamed the section "Results and Discussion".

Figure 5: Please modify the legend. It looks like an old version. It is better to make the texts about the bias values larger.

Thanks, done.

Figure 6: I could not find the red dashed line at first. Please add that the red dashed line can be seen at 0 kg m-2.

Thanks, we have improved the quality of this figure following the reviewer's suggestions.

Line 310: It is better to add the explanation regarding snow layers in the models to the method section.

Following previous comments from the reviewer, we have moved the details on the discretisation to the Methodology section, focussing only on the discussion of the results in this paragraph.

Figure 8: As the color bar in the upper panels and the map in the bottom panels are close to each other, the labels on the color bar were misunderstood for the titles of the lower panels. In addition, please describe the difference between CTL and the validation dataset you analyzed to the labels of Figure 8a and c (for example, difference between Glacier minus CTL, like Figure 8b and d).

This figure has been modified and improved following comments from Reviewer #1 and Reviewer #2.

Figure 11(a): The text for CTL and GLA is cluttered, so why not red and blue text for CTL and GLA, respectively?

Thanks, we have modified the text accordingly to reviewer's suggestion.

Figure 11(b-e): It is hard to see each line. How about changing the line style to a dashed line for CTL and GLA?

Thanks, done.

Line 393: Could the cause of this overestimation be the decrease in albedo in the GLA experiment? In the validation over the Greenland Ice Sheet, the GLA experiment showed a significant reduction in albedo. It is necessary to compare the land surface albedo from MODIS, CTL, and GLA across the Northern Hemisphere and discuss whether the new parameterization leads to a decrease in albedo over the Northern Hemisphere.

This has been addressed as part of the reviewer's "Major comment" #2.

References:

https://www.ecmwf.int/sites/default/files/elibrary/2015/15262-understanding-ecmwf-winter-surface-temperature-biases-over-antarctica.pdf