Dear Editor,

We would like to thank you and the reviewers for the time and effort dedicated to reviewing our manuscript. The constructive feedback has been invaluable in improving the quality and clarity of our work.

Following the review process, please find below our detailed responses to each reviewer's comments. As outlined in these responses, we have moved all appendices to the Supplementary Material to provide more appropriate space for presenting and discussing the technical details previously included in the appendices.

During the revision process, we also identified and corrected an error in the Supplementary Material (Section S2, Table S1). A snowfall episode of approximately 50 cm (equivalent to 0.1 m w.e.) was not measured by the instruments in September 2021 due to a malfunctioning incident. Consequently, this snowfall event is missing from the forcing data. To ensure a fair comparison between simulations and observations, we have adjusted the mass balance value from GLACIOCLIM (last row of Table S1) by subtracting 0.1 m w.e. to exclude this unmeasured event. The correction is indicated below:

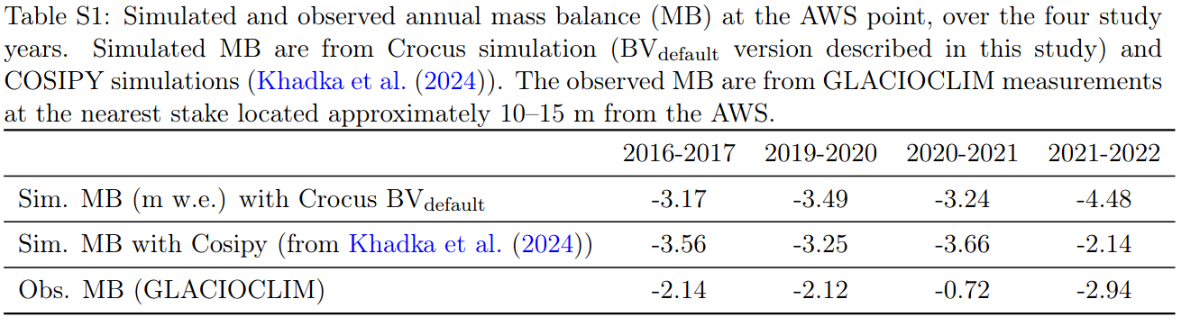

Table S1: Simulated and observed annual mass balance (MB) at the AWS point, over the four study years. Simulated MB are from Crocus simulation ($BV_{default}$ version described in this study) and COSIPY simulations (Khadka et al. (2024)). The observed MB are from GLACIOCLIM measurements at the nearest stake located approximately 10–15 m from the AWS.

	2016-2017	2019-2020	2020-2021	2021-2022
Sim. MB (m w.e.) with Crocus $BV_{default}$	-3.17	-3.49	-3.24	-4.48
Sim. MB with Cosipy (from Khadka et al. (2024))	-3.56	-3.25	-3.66	-2.14
Obs. MB (GLACIOCLIM)	-2.14	-2.12	-0.72	-2.94

We also provide a revised version of the manuscript, as well as a version with tracked changes.

Below, we provide our detailed responses (in blue) to each reviewer's comments (in black), with corresponding changes in the revised manuscript highlighted in **bold blue**.

Detailed responses to the comments from reviewer #1

Explicit representation of liquid water retention over bare ice using the SURFEX/ISBA-Crocus model: implications for mass balance at Mera glacier (Nepal)

by Audrey Goutard et al.,

R1.1. The manuscript addresses the issue of missing representation of water bodies (e.g., melt water ponds, supra-glacial lakes) in current mass balance models. They used the CROCUS model and added an extra layer above the surface layer of the glacier that can fill with melt water if certain conditions are fulfilled. This layer (buffer) can act like a liquid water reservoir storing melt and rain water and can modify the surface energy balance as well as the glacier mass balance.

In the model implementation, the manuscript presents the performance of the CROCUS model without and with the buffer layer. The buffer layer can achieve improvements in the mass balance, and modulates the vertical temperature profile of the glacier interior due to altered percolation processes. Further, they show results of sensitivity tests.

The manuscript is well-written and delivers a clear message. It addresses most aspects and presents an advancement in glacier mass balance modelling. The effect of liquid water bodies on top of glacier and ice sheets have rarely been considered in models, therefore there is a novelty in the approach.

There are some minor questions, that can be addressed/discussed for more clarity.

We thank Manuel Tobias Blau for their careful reading of our manuscript and their comments. Below, we provide our detailed responses (in blue) to each comment (in black), with corresponding changes in the revised manuscript highlighted in **bold blue.** We also provide a revised version of the manuscript, as well as a version with tracked changes. Additionally, we have moved all appendices to the Supplementary Material, to have more appropriate space to present and discuss the technical details previously included in the appendices.

R1.2. The model was executed in combination with CROCUS. Was it offline linked or implemented as a parameterization in the model feeding back to the base model?

The buffer layer, in other words the impact of liquid water at the ice surface, was implemented as a parameterization scheme within the SURFEX/ISBA-Crocus model. It operates as an optional scheme that can be activated or deactivated through model configurations. By activating this routine, it is possible to explicitly account for the presence of liquid water, its thermal effect, its impact on albedo, and on the surface mass balance. Thus, a feedback exists between the surface energy balance and the thermal profile of the model layers at each time step. When deactivated, the model runs identically to the standard version of Crocus with no impact on the simulation. This point has been clarified in the revised version of the manuscript in Section “3.2.1. Buffer description”, as follows:
“**The buffer layer is implemented as an optional parameterization within Crocus that can be activated or deactivated through model configuration. When activated, it allows explicit consideration of the thermal influence of liquid water on the underlying ice, its effects on surface albedo, and its contribution to the surface mass balance. This implementation introduces a feedback between the surface energy balance and the thermal profile of the underlying layers at each time step. When deactivated, the model runs in its basic configuration.**”

R1.3. Is there a minimum value of Mbuff when it is considered for the simulations to have effect on the surface energy fluxes and the mass balance? Further, what would happen to the water content of Mbuff when the water content exceeds the maximum threshold (when the reservoir is full)?

We thank the reviewer for this important question regarding the buffer activation and overflow management.

a) *Minimum threshold for buffer impact:*

The thermal conduction between the water layer and the first ice layer is activated as soon as M_{buff} is non-zero (with numerical zero defined as 10^{-17} kg m^{-2} in the code implementation). Once activated, the magnitude of the conductive flux between the buffer and the ice surface depends on the temperature difference and thermal properties, and not on the water quantity itself.

The information about the minimum threshold has been clarified in the revised version of the manuscript, in Section "3.2.1. Buffer description" as follows :

"A maximum threshold, $z_{max,buff}$ (in m), is set for the buffer to prevent unrealistic water storage. Once the water content in M_{buff} exceeds this threshold, any additional meltwater or rainfall is transferred directly to the runoff variable exiting the glacier without further interaction with the ice surface. By default, $z_{max,buff}$ is set to 1 cm but can be adjusted by the user without restriction. **On the other end, when M_{buff} equals zero, the buffer's thermal and radiative effects are deactivated by setting the fraction parameter x to zero (see Section 3.2.2 for details on the energetic impact), while the mass remains in the buffer."**

However, the intensity of this thermal impact on the overall energy balance is moderated by the fraction parameter x, which appears in both the thermal conduction and albedo formulations. The parameter x is specified as a model input (x = 0.2 by default in our simulations) and represents the fraction of the representative surface area affected by the buffer, thereby weighting the buffer's contribution to the total energy balance. When M_{buff} equals 0, x is effectively set to 0, deactivating any energetic impact of the buffer. It has been clarified in the manuscript in Section "3.2.2. Impact of liquid water on ice thermal profile" as follows:

"The fraction x ~~(x ∈]0, 1])~~ was introduced to modulate the buffer's influence on the thermal profile and albedo, since water only covers part of the surface. **When the buffer scheme is activated and liquid water is present (M_{buff}>0 kg m^{-2}),** x is ~~a fixed parameter that does not depend on the water quantity in the buffer,~~**set by the user to a constant value in the range x∈]0,1]** ~~and remains constant throughout the entire simulation. It cannot be zero, as this would decouple the buffer's mass effects from its thermal interactions. x is set by the user and is arbitrary fixed to 0.2 in this study, a value above 0 to~~**. This user-defined value represents the fraction of the representative surface area affected by the buffer and must be greater than zero to** ensure that the buffer's thermal contribution is integrated into the heat diffusion equation's conduction term ~~but also not too high,~~ **and its radiative effects are included in albedo calculations. When the buffer scheme is deactivated (either through model configuration or when buffer conditions are not met) or when M_{buff} equals 0, x is effectively set to zero in the calculations, decoupling any thermal and radiative effects. In this study, x is set by default to 0.2 when the buffer is active, a**

value chosen to allow significant thermal contribution while keeping ice as the dominant surface ~~in albedo calculations~~ component. This choice and its impact are discussed in Sect. 5.2.1."

b) *Overflow management:*

When the water content in M_{buff} exceeds the maximum threshold z_{max} (maximum buffer capacity), the excess water goes immediately into runoff. The buffer mass M_{buff} is then maintained at its maximum capacity, and any additional meltwater or rainfall that would exceed this threshold directly contributes to runoff. This overflow mechanism ensures physical consistency and prevents unrealistic water accumulation while maintaining the buffer's role in temporarily storing meltwater during active melt periods.

In agreement with your comment, the information about the maximum threshold has been clarified in the revised version of the manuscript, in Section "3.2.1 Buffer description" as follows:

"A maximum threshold, $z_{max,buff}$ (in m), is set for the buffer to prevent unrealistic water storage. ~~When this limit is reached,~~ **Once the water content in M_{buff} exceeds this threshold,** ~~excess water~~ **any additional meltwater or rainfall** is transferred directly to the runoff variable **leaving the glacier without further interaction with the ice surface** ~~in the model~~. By default, ~~it~~ $z_{max,buff}$ is set to 1 cm, but can be adjusted by the user.

R1.4. How sensitive is the model to temporal and spatial resolution?

a) *Spatial resolution*

SURFEX/ISBA-Crocus operates as a 1D column model at point locations. There is therefore no spatial resolution in the model structure itself. This point has been clarified in section 3.1.1 as follow:

"Originally developed for seasonal snow cover in alpine environments, SURFEX/ISBA-Crocus (hereafter referred as Crocus, **Lafaysse et al. (2025)**) is a physically based~~, one-dimensional (1D)~~ model designed to simulate the microstructural evolution of snowpacks using a multilayer approach. **Crocus is a one-dimensional column model and is used at the point scale. For spatial applications, the model is run at multiple independent grid points (i.e. without lateral transfers). In this study, the simulations are limited to a single-point configuration.**"

However, we understand that this information might be confusing regarding the implementation of the parameter x in the buffer scheme and the term "grid cell" used in the initial version. Indeed, x represents the fraction of a representative surface area of the simulation point which is affected by the buffer, but this does not constitute a spatial discretization of the model domain.

Thus, in agreement with your comment and the comment R2.2 L 167 made by the reviewer 2, this is now clarified in the revised version of the manuscript as follow:

“where x is the fraction of ~~the grid cell~~ **a representative surface area of the grid point which is** impacted by the buffer (i.e. the fraction of ice covered by water on Figure 2c),”

b) *Temporal resolution.*

In general, Crocus is not very sensitive to the time step as soon as the diurnal cycle of incident radiation is sufficiently detailed (time step < 1h), because the implicit numerical scheme used to solve heat diffusion (Eq. 88 in Lafaysse et al., 2025) is unconditionally stable. However, the uncoupling between heat diffusion and phase change (Sections 2.4.12 and 2.4.13 in Lafaysse et al., 2025) is known to be responsible for a slight time-step sensitivity of simulations especially for the highest values of incident radiation (Southern slopes). Alternative formulations were suggested by Fourteau et al., 2024 for a better coupling between heat transfers and surface melting and should be explored in the future to reduce this issue.

Following the publication of Lafaysse et al. (2025) since the initial submission, the reference at line 92 has been updated accordingly, as this publication provides a more up to date description of the model version used in this study.

R1.5. Further, the implementation was tested in a glacier in the Himalayas. Can this model also capture the buffer layer in other climatic conditions (e.g., Polar regions or tropical glaciers)?

This is an interesting and useful question.

Regarding the implementation of the buffer layer, it has been designed to be as transferable as possible, regardless of climatic conditions. On the one hand, the physical processes involved (water accumulation, thermal exchange, albedo modification, drainage, and refreezing) have been developed without any calibration specific to a given climatic region.

However, it is important to keep in mind that the model calibration related to the buffer implementation (see the parameters listed below), remains site-specific (depending not only on climatic conditions, but also on glacier geometry, topography, etc.) and therefore requires careful tuning to ensure reliable model performance. Although default values are provided, these parameters are left free for the user to adjust.

1. *Buffer-specific parameterization:* The buffer scheme parameters introduced in this study are z_{max}, D, x, and albedo values. The maximum buffer capacity (z_{max}) may vary depending on local surface roughness and microtopography. The drainage parameter (D) should reflect site-specific permeability and drainage efficiency, which can be influenced by surface characteristics such as slope, crevasse density or supraglacial channel development. The albedo values for liquid water and refrozen ice are also expected to vary between sites, as they depend on factors such as sediment concentration, ice crystal structure, and impurity content, which differ across climatic zones. And the parameter x can be adjusted to reflect varying degrees of surface water coverage depending on very local conditions and climatic characteristics, with the constraint that $x < 0.5$ to maintain the assumption that ice remains the dominant surface component.

2. For polar regions specifically, additional considerations may be necessary. The prevalence of superimposed ice formation, the potential for seasonal water storage in englacial systems (e.g. Cooper et al., 2018), and the distinct surface roughness characteristics of polar ice surfaces may require modifications to the buffer scheme or its parameterization. Similarly, for tropical glaciers at different elevations or with different exposure to monsoon conditions, the frequency and intensity of rainfall events may require adjustments to buffer parameters such as maximum storage capacity (z_{max}) and drainage rate (D) to account for rapid water accumulation during intense precipitation events, while the prevalence of liquid precipitation versus snowfall throughout the year may necessitate different albedo values than those identified for Mera Glacier.

Furthermore, the question of transferability arises more generally when using Crocus in regions other than the one in which it was developed (the Alps). Previous studies have demonstrated its application in the tropical Andes (e.g. Lejeune et al., 2007; Wagnon et al., 2009) or the Arctic (Royer et al., 2021), meaning under various other climatic conditions. However, these studies sometimes highlight the need for additional developments or careful calibration in certain regions (e.g., the Arctic). More details about the parameterization and examples are cited below.

3. *Base model parameterization:* The underlying CROCUS model contains several parameters that must be adapted to the local climatic context. For example, fresh snow density parameterization differs significantly from site to site, reflecting differences in precipitation characteristics and temperature regimes (e.g., Lejeune et al., 2007; Wagnon et al., 2009 for tropical applications). Application to polar regions would likely require further adjustments to parameters such as fresh snow density, snow metamorphism rates, and albedo aging schemes, as polar conditions (e.g., extremely cold and dry environments, low solar angles, persistent katabatic winds) differ substantially from the alpine and tropical contexts where the model has been primarily validated (e.g. Royer et al., 2021).

In conclusion, while the buffer scheme is physically based and theoretically transferable to other climatic regions, it is important not only to carefully calibrate the parameters listed below using local observations, but also to ensure that the Crocus schemes are appropriate for the specific conditions of the region.

Due to the importance of the point, we decided to add a dedicated section discussing the transferability of the approach and the use of the model in different climatic contexts. This section now reads as follows:

“ 5.3 ~~Implications for glacier in a warming climate~~ **Model transferability and glacier evolution under climate change**

5.3.1. Transferability of the model development to other glaciers

The buffer layer implementation is based on physical representations of water retention at the ice surface (water accumulation, thermal exchange, albedo modification, drainage, and refreezing) and was developed without region-specific calibration to remain broadly transferable. However, buffer parameters still require

site-specific tuning, as they depend on local conditions (e.g. glacier geometry, surface topography, climate conditions). For instance z_{max} varies with surface roughness and microtopography, D reflects local drainage efficiency influenced by crevasse density or channel development, x adjusts for surface water coverage (constrained to $x < 0.5$ to maintain ice dominance), and albedo values depend on sediment concentration, ice crystal structure, and impurity content (e.g. Gardner and Sharp (2010); Dadic et al. 2013). Additional care may be needed for instance for polar regions due to the prevalence of superimposed ice formation and the potential for seasonal meltwater storage within ice layers (Cooper et al., 2018), which differ from the surface-only water storage represented by the buffer. Consequently, parameter calibration requires careful tuning to ensure reliable model performance and parameters are intentionally left free for users to adjust, preferably calibrated with local observations to ensure the proper functioning of the buffer approach.

More generally, the question of model transferability applies to Crocus beyond its original alpine context (Vionnet et al., 2012). Although built on a robust physical basis, Crocus still requires calibration when applied in contrasting climatic environments. Previous studies have demonstrated its use in regions such as the tropical Andes (e.g. Lejeune et al. (2007) and Wagnon et al. (2009)) and the Arctic (e.g. Royer et al., 2021) where adjustments to some key processes (e.g. fresh-snow density or thermal-conductivity parameterizations) were necessary. In the present study, however, only the ice surface is considered, which makes the approach more easily transferable for the specific case of surface meltwater retention.

5.3.2. Glaciers mass balance evolution in a warming climate. "

R1.6. Finally, one reference appeared as "?" (L. 492) and there is a typo in "need" (L. 498)

We thank the reviewer for pointing out these errors. The missing reference at L. 492 has been added, and the typo in "need" at L. 498 has been corrected in the revised manuscript.

References :

Lafaysse, M., Dumont, M., De Fleurian, B., Fructus, M., Nheili, R., Viallon-Galinier, L., Baron, M., Boone, A., Bouchet, A., Brondex, J., Carmagnola, C., Cluzet, B., Fourteau, K., Haddjeri, A., Hagenmuller, P., Mazzotti, G., Minvielle, M., Morin, S., Quéno, L., Roussel, L., Spandre, P., Tuzet, F., and Vionnet, V.: Version 3.0 of the Crocus snowpack model, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2025-4540, 2025.

Fourteau, K., Brondex, J., Brun, F., and Dumont, M.: A novel numerical implementation for the surface energy budget of melting snowpacks and glaciers, Geosci. Model Dev., 17, 1903–1929, https://doi.org/10.5194/gmd-17-1903-2024, 2024.

Cooper, M. G., Smith, L. C., Rennermalm, A. K., Miège, C., Pitcher, L. H., Ryan, J. C., Yang, K., and Cooley, S. W.: Meltwater storage in low-density near-surface bare ice in the

Greenland ice sheet ablation zone, The Cryosphere, 12, 955–970, https://doi.org/10.5194/tc-12-955-2018, publisher: Copernicus GmbH, 2018.

Lejeune, Y., Bouilloud, L., Etchevers, P., Wagnon, P., Chevallier, P., Sicart, J.-E., Martin, E., and Habets, F.: Melting of Snow Cover in a Tropical Mountain Environment in Bolivia: Processes and Modeling, Journal of Hydrometeorology, 8, 922–937, https://doi.org/10.1175/JHM590.1, 2007.

Wagnon, P., Lafaysse, M., Lejeune, Y., Maisincho, L., Rojas, M., and Chazarin, J. P.: Understanding and modeling the physical processes that govern the melting of snow cover in a tropical mountain environment in Ecuador, Journal of Geophysical Research: Atmospheres, 114, https://doi.org/10.1029/2009jd012292, 2009.

Royer, A., Picard, G., Vargel, C., Langlois, A., Gouttevin, I., and Dumont, M.: Improved Simulation of Arctic Circumpolar Land Area Snow Properties and Soil Temperatures, Frontiers in Earth Science, 9, https://doi.org/10.3389/feart.2021.685140, 2021.

Detailed responses to the comments from reviewer #2

Explicit representation of liquid water retention over bare ice using the SURFEX/ISBA-Crocus model: implications for mass balance at Mera glacier (Nepal)
by Audrey Goutard et al.,

R2.1. General comments

This study presents a new approach to include a liquid water buffer on top of bare ice surfaces in a (near-)surface energy balance model, SURFEX/ISBA-Crocus. This allows to explore the impact of short (hours) surface retention of meltwater on two key processes: (i) albedo (and hence melting), and (ii) how water which remains on the surface (rather than running off instantaneously as is commonly modelled) impacts the surface mass balance.

The scope of this study is well within the scope of TC and presents substantial conclusions into the impacts of explicit treatment of liquid water on bare ice surfaces. I found the case study choice of Mera Glacier, which undergoes monsoon forcing, to be particularly instructive; for me such an approach is clearer than a purely synthetic case, so I appreciated this design decision. Overall I found the study well-written and very clear - thanks for submitting such a mature piece of work to review.

We thank the reviewer for their careful reading of our manuscript, their encouraging comments and the very positive feedback. Below, we present our detailed responses (in blue) to the comments (in black). Changes made to the manuscript are highlighted in **bold blue.** We also provide a revised version of the manuscript, as well as a version with tracked changes. Additionally, we have moved all appendices to the Supplementary Material, to have more appropriate space to present and discuss the technical details previously included in the appendices.

R2.2. Specific comments

L38-40: I'm of the understanding that low-density weathering crusts form when internal melting by shortwave radiation penetration exceeds surface lowering by other energy sources (e.g. turbulent fluxes). It's not melting and refreezing per-se that produces the weathering crusts. See also e.g. Muller and Keeler 1969, Schuster 2001, Cooper et al. 2018.
We apologize for the error, indeed there was a confusion in the vocabulary and “weathering crust” is not the phenomenon described in this study. We should have called the created refrozen ice “superimposed ice”, the sentence was changed in the manuscript as : “~~The process of melt and refreezing can result in the formation of an ice layer referred to as "weathering crust" or "white ice" in Greenland (Cook et al., 2016), which is a porous layer of ice characterized by its white appearance and higher albedo (Traversa and Di Mauro, 2024).~~ **This diurnal melt-refreeze cycle can create thin layers of superimposed ice on the surface that exhibit a higher albedo (e.g. Volery et al., 2025).**”

L41: 'glacier models' -> would 'surface energy balance models' be more appropriate?
Indeed, ‘glacier models’ is not the best suited name. However, we wanted to point out that this process is generally missing in glacier mass balance studies, regardless of the approach used. We have therefore changed ‘glacier models’ by ‘surface mass balance models’ in the

following sentence: “Despite clear observational evidence of these processes, most current **surface mass balance models** do not explicitly represent the impacts of supraglacial liquid water”.

L46-47: Work by Buzzard et al. 2018 might also be relevant here.

We thank the referee for this additional pertinent reference. It has been added in the revised version of the manuscript.

L167: What is the size of a grid cell? Presumably this refers to the horizontal dimension? (I am not familiar with SURFEX).

We agree that the term "grid cell" may be confusing given that SURFEX/ISBA-Crocus operates as a 1D column model. In SURFEX/ISBA-Crocus, there is no intrinsic horizontal grid cell size as simulations are performed at point locations. The parameter x represents the fraction of a conceptually defined representative surface area that is affected by the buffer process. This representative area does not correspond to a physical horizontal dimension inherent to the model but is rather a conceptual spatial domain considered representative of the point simulation.

In agreement with your comment and also the comment R1.4. made by the reviewer 1 we clarified this point in the revised version of the manuscript as follows:

In section 3.1.1 you can now read:

“Originally developed for seasonal snow cover in alpine environments, SURFEX/ISBA-Crocus (hereafter referred as Crocus, Vionnet et al. (2012)) is a physically based~~, one-dimensional (1D)~~ model designed to simulate the microstructural evolution of snowpacks using a multilayer approach. **Crocus is a one-dimensional column model and is used at the point scale. For spatial applications, the model is run at multiple independent grid points (i.e. without lateral transfers). In this study, the simulations are limited to a single-point configuration.**”

In section 3.2.2. you can now read:

“where x is the fraction of ~~the grid cell~~ **a representative surface area of the grid point which is** impacted by the buffer (i.e. the fraction of ice covered by water on Figure 2c),”

L201-205: does this mean that there is melting which can occur below the surface (i.e. internal melting)? Please clarify.

We thank the reviewer for requesting clarification on this point.

Yes, internal melting below the surface can occur in the model. The buffer accumulates meltwater from all layers in the ice column where melting occurs, regardless of depth. However, in our simulations and under the conditions at Mera Glacier, melting is confined to the uppermost layers (typically the first few centimeters) due to two main factors: (1) the absence of basal melt flux and (2) the attenuation of penetrating shortwave radiation with depth, which limits subsurface energy absorption. We have revised the text (L201-205) to clarify this point:

"Meltwater from all layers in the **ice** column is accumulated in this buffer, regardless of depth. ~~This approach avoids to define a fixed~~ **As melting is confined to the uppermost layers (typically the first few centimeters in our simulations) due to the absence of basal flux and attenuation of penetrating shortwave radiation, this approach avoids the need to define an arbitrary** depth threshold in the code~~, given that melting only occurs within the first few centimeters, as basal flux is null~~."

L228-252: this is a very extensive technical description. I'm not sure this level of detail is necessary to comprehend the messages of the paper. Might be better suited as an Appendix, or somewhat summarised?

We understand the reviewer's concern about the level of technical detail in this section. To improve readability and in agreement with your comment, all technical details have been moved and clarified in Supplementary Material, Section S3 (see above). In the revised manuscript, lines 228–252 have been streamlined and condensed to retain only the information essential for understanding, as follows:

“The **model determines whether to create a new surface layer or aggregate the refrozen mass with the** existing surface layer. If the **refrozen mass M_{refrz}** is thick enough (greater than 1/10 of the first layer **thickness)**, a new refrozen ice layer is created at temperature T_0 with a density of 917 **kg m^{-3}. Otherwise, M_{refrz} is aggregated into the existing surface layer at its temperature. To track the proportion of refrozen ice within the upper layers and properly compute albedo,** a refreezing fraction **variable** $r_{frac,i}$ **is introduced for layers $i \in [1, 2]$. This variable ranges** between 0 (bare ice) and 1 (**fully** refrozen ice) **and is calculated differently depending on the refreezing scenario: when a new layer is created, the new surface layer receives $r_{frac,1} = 1$, while when refrozen mass is aggregated with an existing layer, $r_{frac,1}$ is calculated as a weighted average based on the relative thicknesses of the refrozen and existing ice. The variable $r_{frac,i}$ remains stored between time steps, allowing the albedo calculation to account for the presence of refrozen ice in the surface layers. When melting occurs in layer i, $r_{frac,i}$ is reset to 0, assuming the refrozen layer melts first.**

A detailed description of the layer management strategy, numerical thresholds, and the mathematical formulation of $r_{frac,i}$ can be found in the Supplement, Section S3."

The supplementary information now reads as:

S3 Layer strategy management and refrozen fraction

S3.1 Overview of layer management

The layer management strategy aims to maintain optimal discretization for heat diffusion resolution by preserving finer resolution near the surface while respecting constraints on the total number of layers (50 by default) and avoiding thickness variations of several orders of magnitude between successive layers.

When buffer refreezing occurs, the model must integrate the refrozen mass into the vertical discretization. The subroutine *upgrid_glacier* evaluates whether a new layer is formed or if the refrozen water is merged with an existing layer (see workflow in Appendix S1). This decision depends on the magnitude of the refrozen mass M_{refrz} and the current layer structure.

S3.2 Refreezing scenarios and layer creation

S3.2.1 Negligible refreezing

If M_{refrz} is lower than 3 J m^{-2} (equivalent to 1×10^{-8} m), it is added to the first layer without further updates to other variables, to avoid numerical instabilities associated with extremely thin layers.

S3.2.2 Layer aggregation

If the potential new layer would be thinner than 1/10 of the first layer thickness, M_{refrz} is aggregated into the existing surface layer. This maintains a reasonable vertical discretization and avoids creating excessively thin layers that would compromise numerical stability.

S3.2.3 New layer creation

If the refrozen mass is thick enough (greater than 1/10 of the first layer thickness) and the total number of layers in the model is below the maximum limit (50 layers by default), a new refrozen ice layer is created at the surface with temperature T_0 (273.15 K) and a density of 917 kg m^{-3}.

S3.2.4 Layer creation with column reorganization

If the model has already reached the maximum number of layers, it first identifies two similar layers within the column (based on temperature and density proximity) and merges them. This creates space for the new refrozen ice layer, which is then added at the surface at temperature T_0 with density 917 kg m^{-3}.

S3.3 Continuous layer management

Even when refreezing occurs slowly, the surface layer thickness remains controlled because the *upgrid* routine is called at the start of each time step (see workflow in Appendix S1). This routine automatically subdivides layers that become too thick relative to adjacent layers, ensuring consistent discretization throughout the simulation.

S3.4 Refreezing fraction calculation

S3.4.1 Definition and purpose

The albedo of the first and/or second layer must be updated when buffer refreezing occurs. Because refreezing can either form a new layer or aggregate with an existing one, a refreezing fraction variable $r_{frac,i}$ is introduced to track the proportion of refrozen ice within layers $i \in [1, 2]$. This variable varies between 0 (bare ice) and 1 (fully refrozen ice) and is used to compute the layer albedo as a weighted average between bare ice and refrozen ice albedo values.

S3.4.2 Calculation formulas

The refreezing fraction is calculated differently depending on whether a new layer is created or the refrozen mass is aggregated:

$$\begin{cases} \text{if creation of new layer:} & \begin{cases} r^{+}_{frac,2} = r^{-}_{frac,1} \\ r^{+}_{frac,1} = 1 \end{cases} \\ \text{if aggregation to existing layer:} & r^{+}_{frac,1} = \dfrac{z_{refrz} + r^{-}_{frac,1} z_1}{z_{refrz} + z_1} \end{cases} \tag{S3.1}$$

where z_1 (in m) is the thickness of the first layer and z_{refrz} (in m) is the thickness of refreezing, computed as:

$$z_{refrz} = \frac{M_{refrz}}{L_m \rho_i} \tag{S3.2}$$

where L_m is the latent heat of fusion for ice and $\rho_i = 917$ kg m^{-3} is the ice density.

S3.4.3 Temporal evolution and reset conditions

The variable $r_{frac,i}$ is maintained from one time step to the next to preserve information about refreezing for albedo calculations. When melting occurs in layer i, $r_{frac,i}$ is reset to 0, based on the hypothesis that the refrozen layer at the surface melts first. The refreezing fraction is also updated whenever changes in layering occur (aggregation or separation of layers) according to the scenarios detailed below.

S3.5 Additional layering scenarios affecting r_{frac}

S3.5.1 Surface regrid (layer 1 aggregation)

Surface regridding occurs when the first layer becomes too thin and must be aggregated with the second layer. The new first layer thickness becomes:

$$z_1^{+} = z_1^{-} + z_2^{-} \tag{S3.3}$$

The refreezing fractions are aggregated using depth-weighted averaging:

$$\begin{cases} r^{+}_{frac,1} = \dfrac{z_1^{-} r^{-}_{frac,1} + z_2^{-} r^{-}_{frac,2}}{z_1^{-} + z_2^{-}} \\ r^{+}_{frac,2} = 0 \end{cases} \tag{S3.4}$$

S3.5.2 Splitting of layer 2

Layer splitting occurs when layer 2 exceeds the maximum thickness threshold and must be divided into two layers. The layer is split into equal thicknesses:

$$\begin{cases} z_2^+ = \frac{1}{2} z_2^- \\ z_3^+ = \frac{1}{2} z_2^- \end{cases} \tag{S3.5}$$

When layer 2 splits, the refrozen fraction is divided equally between the two new layers. Since r_{frac} is only defined for layers 1 and 2, the new layer 2 retains half of the original fraction while layer 3 receives no fraction:

$$\begin{cases} r_{frac,2}^+ = \frac{1}{2} r_{frac,2}^- \\ r_{frac,1}^+ = r_{frac,1}^- \end{cases} \tag{S3.6}$$

S3.5.3 Splitting of the first layer

First layer splitting occurs when the surface layer exceeds the maximum thickness threshold. An optimal thickness value $z_{1,\text{opti}}$ is calculated based on column-wide optimization principles. The new layer thicknesses are:

$$\begin{cases} z_1^+ = 1.5 z_{1,\text{opti}} \\ z_2^+ = z_1^- - z_1^+ \end{cases} \tag{S3.7}$$

The refrozen fractions are redistributed using depth-based weighting:

$$\begin{cases} r_{frac,1}^+ = \frac{z_1^+}{z_1^-} r_{frac,1}^- \\ r_{frac,2}^+ = \left(1 - \frac{z_1^+}{z_1^-}\right) r_{frac,1}^- \end{cases} \tag{S3.8}$$

S3.5.4 Aggregation of layer 2 with layer 3

Layer aggregation occurs when layer 2 requires regridding and must be combined with layer 3. The new layer 2 depth becomes:

$$z_2^+ = z_2^- + z_3^- \tag{S3.9}$$

Layer 1 remains unchanged while layer 2 receives a weighted fraction based on the original depth of layer 2:

$$\begin{cases} r_{frac,1}^+ = r_{frac,1}^- \\ r_{frac,2}^+ = \frac{z_2^-}{z_2^- + z_3^-} r_{frac,2}^- \end{cases} \tag{S3.10}$$

S3.5.5 Melt reset

When melting occurs in layers 1 and/or 2, the process initiates at the surface. This surface melting removes the refrozen ice, returning the affected layers to bare ice conditions. Consequently, the refrozen fraction resets to zero:

$$r^{+}_{frac,i} = 0 \qquad \text{(S3.11)}$$

for layer i where melting occurs.

Fig. 9 and L450: the caption lists this figure as being produced from BV_tests, in which x varies from 0 to 1; the text makes a note about liquid water over 60% (therefore 0.6?). But I'm not clear which value of x is used in the figure? Presumably it is showing results from only one value of x? How does this reconcile with L471 which says that water cover remains minor relative to ice cover (i.e. < 20 %), and L479 which says the model is not adapted for x > 0.5? Maybe I've just misunderstood something here, but this suggests that the communication could be a bit clearer.

We thank the reviewer for pointing out this lack of clarity, which highlights a confusion between the spatial fraction parameter x and the temporal coverage of surface states.

We agree that the communication was unclear. The figure was produced using fixed buffer parameters ($x = 0.2$, $D = 0.995$, $z_{max} = 0.01$ m) while varying only the albedo values. The mention of "60%" in the text refers to temporal coverage, not the spatial fraction x. Specifically, during the subperiod shown in Figure 9c, liquid water over ice was present as the dominant surface state for more than 60% of the time, which is independent of the spatial fraction parameter x (fixed at 0.2 for this analysis).

To clarify this distinction, we have:

1. Updated the figure caption to explicitly state: "A contour plot showing the effect of broadband albedo values for refrozen ice (vertical axis) and liquid water on ice (horizontal axis) on the annual (a) or subperiods (b and c) mass balance (colour scale) for BV_{tests} version **with $x = 0.2$, $D = 0.995$, and $z_{max} = 0.01$ m.**"
2. Modified the text (L567) to better explain the temporal nature of this coverage: “During periods when liquid water over ice dominates (Figure 9c), ~~covering~~ **which means that liquid water over ice occurs for** more than 60% of the ~~surface~~ **time during this subperiod**, the variation is similar to the annual graph, with liquid water albedo showing an even more dominant influence (up to 18% variation over the period).” clarifying that the 60% refers to temporal, not spatial, coverage.

L567: do the authors really mean 'non-porous ice'? I thought Cooper et al 2018 showed porous ice.

We thank the reviewer for catching this error. The reviewer is correct as Cooper et al. (2018) demonstrate meltwater storage in porous ice.

We have corrected the text (L567) to: "Existing literature on surface water depths provides context but from very different glaciological settings. Sneed and Hamilton (2011) report depths of 0.2-3 m **of supraglacial melt ponds**, while Cooper et al. (2018) suggest approximately 15 cm of meltwater storage in ~~non-porous~~ **porous** ice in Greenland."

In order to clarify that our buffer implementation refers only to surface water storage without percolation nor water storage within ice layers, we added in the Section 3.2.1. Buffer description:

"Surface water retention is modeled using a virtual surface layer called a buffer, that holds liquid water between time steps, representing water accumulated in surface ice rugosity (Figure 2). **This buffer explicitly accounts for liquid water at the surface only, without representing percolation into or water storage within the underlying ice layers.**"

R2.3.Technical corrections

All technical corrections mentioned below have been considered in the revised manuscript.

L128: 'rugosity' is used twice.

Removed duplicate use of 'rugosity' and changed it to irregularities

L132: hold -> holds

Corrected 'hold' to 'holds'

Fig. 3: I would find longer and extra ticks/grids useful, also identifying midday. Note also that panel c is referred to in the text before panel b.

We have improved the readability of the figure by adding longer ticks/grids to better identify midday and midnight, and a yellow background was added as well to identify daytime. We have also reordered the panels order to match the references in the text (panel b is now mentioned before panel c).

L381: remove first comma (after 'days')

Removed the first comma (after 'days')

L381: refreezed -> refrozen

Corrected 'refreezed' to 'refrozen'

Fig 7a: x-axis labels should also have hour?

Applied the same improvements as Fig. 3 (longer ticks/grids and yellow background for better identification of midday and midnight)

L474: missing reference

L492: missing reference

Missing references in L474 and L492 have been added

L610: facilitating -> facilitates

Corrected 'facilitating' to 'facilitates'

Fig. A1: please provide key for boxes B92, V12 etc.

The boxes were removed, as this level of detail was unnecessary on this graph.

Fig. B1a: please clarify the daily time period over which observed albedo is shown/averged?

Clarified in the caption that the observed albedo is averaged over the complete daily period. We also corrected the x-axis labels which were in French.