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:

$$r^{+}_{frac,i} = 0 \tag{S3.11}$$

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.