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 ~~($x \in]0, 1]$)~~ 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 $x \in]0,1]$** ~~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 :

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