Response to Review 1 of egusphere-2025-444

We are thankfull Richard Essery for taking the time to review our manuscript and for his constructive review. Please find below our point by point response to the review. The comment of the referee are shown in blue and our response in black below. Proposed modifications of the manuscript are shown in green with page and line numbering corresponding to the preprint version of the article.

This is a good paper, and I suggest that it will be publishable with corrections that are merely clarifications or editorial.
1 Vapour transport can also be important; it is only in line 79 that we learn that it is neglected here.
We propose to explicitly say at the beginning of Section 2 that we focus our analysis on liquid water percolation and thus neglect some of the physical processes at play in snowpacks, such as metamorphism or water vapor transport. We will remove the mention to water vapor **L79** concerning the energy equation, and we will add at the start of Section 2 **L72**:

"As we focus this article on liquid water percolation, we neglect several processes at play in snowpacks, such as metamorphism or water vapor transport, in order to simplify our analysis."

2 The highly relevant paper by Wever et al. (2014) is almost "in the last decade", but modelling percolation of water in snow under gravity and capillarity goes back at least as far as Colbeck (1974). https://doi.org/10.3189/S002214300002339X
27 Between bucket schemes and solving the Richards equation, an intermediate approach of calculating water percolation under gravity without capillarity is used in some models (e.g., SNTHERM).
Following the comments from this review and that of the second referee, we propose to rewrite this section of the introduction to better describe the different representation of liquid water flow that have been proposed in models, i.e. with or without capillary pressure gradient, with or without preferential flow, and in 1D or multi-D. We will also specify at the end of the introduction that we restrict our study to the case without preferential flow.
We propose to rewrite the paragraph starting **L27** to:

"A simple and largely employed way of representing liquid water percolation in 1D snowpack models is the so-called bucket-scheme. In this picture, snow layers are expected to retain liquid water until a certain threshold, after which all liquid water is instantaneously transferred downward (Bartelt and Lehning, 2002, Vionnet et al., 2012, Sauter et al., 2020). While this implementation is numerically efficient, it cannot capture certain effects, such as capillary barriers, capillary rise, or the finite dynamics of the percolation process. On the other hand, a more detailed description of liquid water flow in snowpacks can be achieved by explicitly solving the liquid water budget under gravitational and capillary forces, i.e. Richards' equation (Richards, 1931capillary, Colbeck, 1974, Illangasekare et al., 1990, Daanen and Nieber, 2009). Richards' equation has notably been implemented in the detailed 1D models SNOWPACK (Wever et al., 2014) and Crocus (d'Amboise et al., 2017). This more advanced description has notably been shown to better capture the timing associated with the wetting of the snowpack (Wever et al., 2015). In the case of significantly wet snow, capillary forces become negligible and the driving force of liquid water flow reduces to gravity only (Colbeck, 1972). This offers a simplified version of Richards' equation, for instance implemented in the SNTHERM 1D model(Jordan, 1991). However, note that implementations based on the standard 1D

Richards' equation cannot represent preferential flow, which is crucial to fully capture the complexity of liquid water percolation in snowpacks (Marsh and Woo, 1985, Schneebeli, 1995, Waldner et al., 2004). Explicit representations of preferential flow in snow have been proposed in the literature. A first broad class of strategies is based on modelling the snowpack in multi-dimensions, allowing the formation of fingering flows in response to snow heterogeneities (Hirashima et al., 2014, Leroux et al., 2017, Leroux et al., 2020) and/or instabilities in the wetting front (Moure et al., 2023). These studies offer valuable insights on the physical mechanisms responsible for the formation of preferential flow in snow. A second strategy, which is compatible with a 1D framework, is the use of a dual-domain percolation model (Wever te al., 2016, Queno et al., 2020)."

74 Is this transposition to 2D or 3D arrays of 1D columns? Inclusion of lateral flows is not so straightforward.

We did not have an array 1D columns in mind to construct a 2D or 3D version, but really the writing of Richards' equation in a multi-dimensional setting, as done for instance in rock sciences. The translation into the general 3D case requires to change the gravity term *cos γ* to the vertical vector z in Richards equation and to potentially change the scalar conductivities into tensor in the case of an anisotropic material. Lateral flow is handled based on the gradient of water potential, similarly as to vertical flow. But this picture requires to treat the whole 2D or 3D at once, rather than splitting it connected 1D columns (spatial decomposition of the domain is always possible, but requires some additional techniques not discussed in the manuscript). This will be precised in the manuscript **L73**

"Note that while this article assumes a 1D framework, as usually done in snowpack models, it could be transposed to a 2D or 3D configuration similar to what is done in several rock, soil, or even some snospack models (Vauclin et al., 1979, Hirashima et al, 2014, Leroux et al., 2017, Cockett et al., 2018). Therefore, we tried to keep the notation used in this article as general as possible."

We will also add L**127**

"Note that in the multidimensional case, the gravity term cos γ should be replaced by the unit vector orientated with gravity"

81 If wanting to retain *F*cond as a vector for generality, GMD guidelines require it to be printed in boldface. Alternatively, as it is a scalar in the 1D framework, the divergence could simply be ∂z*F*cond.

We will write $\mathbf{F}_{\mathrm{cond}}$ (and other vectors) in boldface to make it explicitly a vector. On a similar note, we will also modify the writing convention of the fluxes in Appendix A from "J" to "**F**" so it is consistent with the main part of the article.

Figure 1 Does the inset serve any useful purpose? Mention it in the caption if so, and remove it if not.

The goal of the insert was to have a better view of the regularization and of the plateau of the WRC. We will mention it in the caption:

"Examples of the regularized water retention curves used in this work, for three different snow density and surface specific area (SSA). The zoomed insert focuses on the regularization and the associated plateau below the retention point."

234 There are models that allow liquid water in snow below the fusion temperature, e.g., https://doi.org/10.1175/2010JHM1249.1 https://doi.org/10.1002/2016WR019672

We will mention in the manuscript that some models assume that the ice/liquid water translation in snowpack occur on a temperature range rather than at a single temperature.

This will be inserted in Section 2.4, where we will rewrite the discussion on the assumption of thermodynamical equilibrium between the ice and the liquid water. We will rephrase the manuscript to

"As most snowpack models (e.g., Jordan, 1991, Bartelt and Lehning, 2002, Vionnet et al., 2012detailed, Sauter et al. 2020) we assume (i) that liquid water and the snow are in thermodynamical equilibrium (which means that the melting/freezing dynamics can be assumed as infinitely fast) and (ii) that this equilibrium occurs at the single temperature T_0. However, we note that these assumptions are not systematic in snowpack models. […] Also, due to capillary effects, the thermal equilibrium between the ice and liquid water phases technically occurs on a temperature range rather than at a single temperature. This effect is commonly taken into account in soil models through a so-called soil Freezing Characteristic Curve (soil FCC; Devoie et al. 2022). Some snowpack models have proposed to introduce a similar FCC for snow (Daanen and Nieber 2009, Dutra et al., 2010, Clark et al., 2017). While the FCC of snow could in principle be computed from the WRC of Sect. 2.2 (as done for instance in Daanen and Nieber, 2009, Li et al., 2023), this would represent a significant increase in the complexity of the snow representation. Indeed, the simple equilibrium condition that ice and liquid water can only coexist at T_0 would have to be replaced by an implicit equation relating the temperature to the matric potential. However, we note that the computation of a FCC from a diverging WRC implies that thermodynamical equilibrium cannot be reached with a LWC below the divergence point (Daanen and Nieber, 2009), and thus that regularizing the WRC is a necessary step to model a dry material."

326 The harmonic average seems to be the natural choice, corresponding to adding the conductances in adjacent layers in series.

This indeed amounts to having the conductances in series. This will be mentioned in the manuscript **L326**

"This is consistent with the idea that the conductances corresponding to adjacent cells are placed in series. It notably ensures that the heat flux vanishes when the thermal conductivity of one of the two cells vanishes (Kadioglu et al., 2008)."

344 Models 4 and 5 have not yet been introduced.

We propose to rephrase **L344** to

"In two of the implementations that will be presented below (denoted models 4 and 5), this criterion is complemented with a criterion on mass conservation, as these numerical scheme are not naturally mass-conservative."

Also we will remove the mention to models 4 and 5 at the end of the paragraph and rephrase **L361** to:

"As a test, we also run some simulations using the modified Picard rather than the Newton method."

397 It would be good to show temperature, density and SSA for this stratigraphy.

We will add a figure presenting the initial state of the snowpack in terms of density, SSA, and temperature introduced **L425**

"The initial conditions for the density, SSA, and temperature are displayed in Figure 2."

with caption

“Initial conditions of the snowpack used in the simulation, in terms of density (panel a), SSA (panel b), and temperatures (panel c). Note that the initial temperatures are lower in test cases 1 and 3 in order to simulate liquid water infiltration withing a colder snowpack.”

Something that we forgot to mention in the first version of the manuscript is that the test cases have the same initial density and SSA, but different initial temperature field. The idea was to perform simulations with more or less cold snowpack (and thus with potentially more or less deep refreezing). This will be mentioned **L398**
“For the initial state of the simulation, the initial temperature was decreased compared to the Crocus output in order to obtain a cold and dry snowpack near its peak snow water equivalent.”,

L413

“The initialization is the same as in case 1, based on the output of the same Crocus simulation, but with a higher temperature in order to have a snowpack close to its melting point.”

and **L420**

“The initialization is also based on a Crocus simulation, with a temperature field intermediate between test case 2 and 3.”

Figure Where is the water that appears at the base of the snow before the surface melt water arrives coming from?
The formation of liquid water at the base results from the heat flux used as a bottom boundary condition meant to emulate a warm ground. In the case of a zero heat flux condition this melting is not present. This will be mentioned in the manuscript **L426** alongside a more detailed description of Figure 3:

“In these three cases, liquid water is produced directly at the bottom of the snowpack in response to the 10 W m-2 heat flux from the warm ground. In the absence of such heat flux, the bottom of the snowpack would remain dry until liquid water percolates through the whole snowpack.”

Figure 4 Why do increasing timesteps run right to left on the x axis? – not wrong, but unconventional if there is not a clear reason.
There was no specific reason for that choice. We will redo the figure with increasing timesteps running left to right. Note that there are two other modifications to the figure:
- As noted by the second referee, rain was missing from the forcing of Experience 2. This was changed and the figure updated with the new results.
- Moreover, we were not able to reproduce the results for model 5 in Experiences 1 and 3, even after re-running all the simulations (the results for the other models were reproduced). We do not know what was the error in the results of model 5 we used for the initial submission. However, it does not change the conclusion of the manuscript.

505 “internal ice layers” sounds like horizontal layers are being discussed, whereas I think it is actually vertical columns.
In this part we wanted to mention the idea that internal horizontal ice layers can be formed by the injection of liquid water through percolation chimneys down to a capillary barrier where the water can then horizontally spread. When excavated after refreezing, there indeed is a structure composed of vertical ice columns connecting horizontal crusts (as

illustrated by picture #58 of Fierz et al., 2009). We propose to clarify this point by rephrasing **L503** to

"While the exact mechanisms, and therefore description, of preferential flow in snowpacks remain unclear at this point (Hirashima et al., 2014, Hirashima et al., 2019, Moure et al., 2023), the presence of fast flowing, and out-of-equilibrium with the rest of the snow layer, liquid water appears as a prerequisite for the formation of internal horizontal ice layers. In this picture, the preferential flow transports liquid water through cold snow layers down to a capillary barrier, where the liquid water can then horizontally spread and refreeze as a horizontal crust (Queno et al., 2020). This is illustrated by the close relation between refrozen preferential paths (i.e. ice columns) and internal horizontal crusts, for instance illustrated in picture #58 of Fierz et al. (2009)."

Minor corrections:

Below are a few responses to some specific comments. For the rest of the comments, the modifications proposed by Richard Essery will be directly followed.

The text uses both "Richard's equation" and "Richards' equation", and it is often "the Richards equation" in literature. Pick one!

We will make the naming consistent throughout the manuscript as "Richards equation".

22 I'm not sure of the authors' intended emphasis, but "likely" is not the right word here.

We will rephrase "likely" by "similarly".

336 1/cos *γ*

We will remove the parentheses in Eq. 19 and will add the forgotten *cos* **L336**. Unless we made a mistake computing the vertical projection of a length d perpendicular to the slope, we believe it is cos γ d.

457 "can be efficiently cheapened" (or "can be made more efficient" would be better)

We have replaced the end of the sentence with "can be made more efficient".

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