Answer to Referee #1

We thank the referee for their insightful comments. Please find our detailed response to the issues raised by the reviewer below. Referee comments are in bold while our answers appear in blue. Changes in the manuscript appear in red (lines correspond to the marked-up manuscript). Please also refer to the marked-up manuscript.

This study provided very important data by field observation for water infiltration and ice layer formation using traditional snowpack observation, SnowMicroPen, and upper GPR. Considering water transport, thermal process, preferential flow, and the freezing process is important to study ice layer formation in the snow physics. Due to the difficulty of laboratory experiments for ice layer formation, the water transport model lacked validation data considering freezing. They are useful data to collaborate with laboratory experiments and 2D or 3D models. I would like to know whether authors have a plan to open these data. The implementation of ice reservoir parameterization is also interesting. And I impressed that the ice layer was reproduced well using a onedimensional model. In my opinion, this paper is suitable to accept for The Cryosphere. I suggest several comments to make this paper more informative. But it is not necessary requirement for acceptance. Please refer to comments to make this paper be better.

minor comment

Line 123-144 Section 2.2.2 is a new parameterization and main improvement part of the model. So a more detailed expression is necessary. I guess the ice in the matrix layer block (or transport with very low permeability) for water transport. But it is unclear whether the ice in the ice reservoir also affects hydraulic conductivity or not. Please add the description about the influence of ice in ice reservoir on water transport simulation.

The influence of ice in the matrix on water transport has not been changed from the original parameterization of Wever et al. (2016). On the other hand, the ice kept in the ice reservoir has no effect on the hydraulic properties of the snow layer. It is indeed a local reservoir, mimicking a heterogeneous layer formed of snow and ice lenses. Considering its effect on water transport may be out of scope for our 1D simulations, given our limited knowledge and data about local ice lenses hydraulic effect. This point has been clarified in the revised manuscript.

Please also note the implementation of the ice reservoir in the SNOWPACK source code will be made publicly available on models.slf.ch.

--- CHANGES IN THE MANUSCRIPT (l. 154-176) ---

To better reproduce the formation of continuous ice layers from discontinuous and growing ice lenses, we developed an ice reservoir parameterization. The water normally transferred from the preferential flow domain to the matrix domain that freezes instantly is stored in an ice reservoir (step 4 in Fig. 2), instead of being added to the ice volumetric content of the matrix. The ice reservoir is representative of the volumetric content of ice lenses (i.e. spatially discontinuous ice) in a given layer. The transferred water that does not freeze goes in the matrix domain, i.e. is spread homogeneously (step 5 in Fig. 2).

Furthermore, the saturation threshold in the PF domain (Wever et al., 2016) was chosen as a simple solution to the unability of Richards equation to model the saturation overshoot present in the tip of flow fingers (DiCarlo, 2007). This simple parameterization can lead to inconsistencies due to the vertical discretization of the simulated snowpack. After water has been transferred to the matrix at the layer corresponding to the finger tip (i.e. where the saturation threshold was exceeded), the highest saturation is then reached more likely at the layer above, where no water transfer occurred, because water percolation from this layer to the finger tip layer only occurs at the next time step. Because of that, the water transfer from PF domain to matrix domain may spread over too *many layers, instead of being concentrated in the lowest layer (i.e. the tip of the flow finger). To overcome this issue, the ice reservoir was cumulated in the lowest layer. When the ice volumetric content of the cumulated ice*

reservoir added to the ice volumetric content and water volumetric content of the associated matrix layer exceeds the corresponding ice density threshold of 700 kgm^{-3} in SNOWPACK, there is enough ice to consider it as horizontally homogeneous: the ice content of the cumulated ice reservoir is then transferred to the associated matrix layer (step 6 in Fig. 2). As long as it is kept in the ice reservoir, the forming ice has no effect on the water transport in the matrix domain that still follows the RE/PF scheme (Wever et al., 2014, 2016). Furthermore, we neglect any impact the ice reservoir, which is interpreted as ice lenses, may have on hydraulic properties (e.g. local hydraulic barrier effect). Simulations with the ice reservoir parameterization are called RE/PF/IceR hereafter.

The implementation of the ice reservoir parameterization in the SNOWPACK source code is publicly available (see Code and data availability Section).

Line 164-166 Is the SNOWPACK simulation reproduced this water front observed by upGPR, runoff and temperature profiles well?

As visible on Fig. 11b for the RE/PF configuration, the matrix water flow reaches deeper layers of the snowpack than the observed water front. For example, the water front is observed at around 100 cm in the beginning of April, while the simulated matrix flow reaches the ground at that time. The matrix flow for RE/PF/IceR simulations (Fig. 13b) is very similar to the RE/PF simulations. A reference to the water front observations has been added in that part of the text in the revised manuscript.

(Note that the y axis title of Fig. 11b and Fig. 13b was wrong: it is indeed the LWC in the *matrix* domain for the 15 Mar - 15 Apr period, as correctly formulated in the text and in the legend. It has been corrected.)

--- CHANGES IN THE MANUSCRIPT (l. 269-271) ---

Matrix flow reaches the ground and the snowpack is entirely isothermal on 31 March (Fig. 11b), i.e. 9 days before the observations (Sect. 3.1.2). On 31 March, the water front was actually observed at around 100 cm (Fig. 4), hence a too early simulated water front progression.

--- CHANGES IN THE MANUSCRIPT (l. 297-298) ---

The matrix water flow reaches the ground on 30 March (Fig. 13b), i.e. 10 days before the observations (Sect. 3.1.2). The water front progression occurs too early, similarly to the RE/PF simulations.

Line 186-188 Fig.6 showed the mean SMP resistance. Can you explain the heterogeneity of SMP resistance other than layer 1 and 2 briefly?

Some details have been added in the text to describe the penetration resistance heterogeneity in dry snow. We also added boxes indicating the approximate location of layers 1 and 2, so that the reader can relate more easily to Fig. 3.

--- CHANGES IN THE MANUSCRIPT (l. 219-225) ---

Daily SMP measurements enable to more clearly identify the temporal and spatial variability of ice formation. Figure 6 represents the evolution of penetration resistance from 1 February to 19 April, with a scale from 0 N to 2 N to highlight variations in dry snow. The deep MFcr is visible in the middle of a low resistance depth hoar layer, at approximately 20 cm. In February and March, the highest values in the middle of the snowpack correspond to dense layers of faceted crystals (Fig. 3). In March, the buried surface hoar of layer 1 is marked by a lower penetration resistance than the surrounding faceted crystals. Layer 2 exhibits less heterogeneity with surrounding layers. Overall, the penetration resistance increases substantially from the end of March on with the progressive wetting, particularly at the top of the snowpack where many melt-freeze crusts form.

Line 196-199 Confirmation of melt-freeze crust on buried surface hoar seems valuable observation result. Considering the theory, a capillary barrier forms on surface hoar due to low suction of surface hoar and froze later. Is it confirmed past study or observations? If so, please add the reference.

As highlighted by the reviewer, our observation of ice formation at a layer interface corresponding to buried surface hoar is consistent with the theory of capillary barriers. However, we have no knowledge of past studies reporting such observations.

Fig 10-13 Please add a and b in the figure.

Done.

Line 247. I felt that the Fig. 12b is strange. In Fig. 10b, water ponds at 70-80cm height (on the freezing layer) on 11 February. On the other hand, despite the frozen layer was not shown in Fig 12a, water ponds at the same place. I guess that ice exists in the ice reservoir which was not shown in Fig. 12, and it affects this ponding. If my guess is correct, ice content in the ice reservoir had better be shown in some way. Also, can you describe the influence of the ice content in the ice reservoir on water percolation? In 2.2.2, formation of ice in ice reservoir is described. But influence of it on water transport should be also explained.

Indeed, Fig. 10b (RE/PF configuration) and Fig. 12b (RE/PF/IceR configuration) show similar water ponding in the preferential flow domain. The water ponding at this layer interface is due to the fine-over-coarse grain structure. The melt-freeze crust in the RE/PF simulation is a consequence of the water ponding, with water transferred and freezing in the matrix. This ice goes into the ice reservoir in the RE/PF/IceR simulation, which explains the different grain types (Fig. 10a and 12a). The ice reservoir, however, does not affect the water transport. More generally, the microstructural changes in SNOWPACK are assessed via the ice and liquid water content in matrix domain, independently of the water in the preferential flow domain and the ice kept in the ice reservoir. This point has been clarified in the revised manuscript.

About the influence of the ice reservoir on water transport, please also see our answer to your first comment.

--- CHANGES IN THE MANUSCRIPT (l. 279-289) ---

Simulations were also performed with the ice reservoir parameterization (RE/PF/IceR) to assess its ability to improve the simulation of ice layer formation compared to the previous simulations. Figure 12 shows the grain shape and liquid water content in the PF domain for the month of February. Similarly to the RE/PF simulation, the fine-over-coarse grain structure leads to water ponding in the PF domain at layer 1. But contrary to the RE/PF simulation, no melt-freeze crust forms at layer 1 (Fig. 12a): the water leaving the PF domain and refreezing is in too low quantity to be considered as representative of the mean state of the snowpack in this layer, it is thus stored in the ice reservoir. The fine-over-coarse grain transition forming a capillary barrier is preserved. Note that liquid water content in the PF domain (Fig. 12b) is almost not modified compared to the RE/PF simulation (Fig. 10b). Liquid water transport is similar, and in particular the vertical spreading of water ponding, but ice in the reservoir is concentrated at the capillary barrier. The ice kept in the reservoir has indeed no effect on water transport and microstructural changes in the matrix. At the end of February, less melt-freeze crusts are formed than in the RE/PF simulation, even though the ones surrounding layer 2 are also thicker than observed.

Line 325 (4 discussion): This study is attractive for researchers of water transport mechanisms using laboratory experiments and 2D or 3D models. Also, collaboration with them enhances the value of this study in terms of cover some assumptions and make physical evidence. I expect the observation data will be opened. Also, during conducting this study, if the author came up with the idea that could be done by a laboratory experiment or a 2D or 3D model, suggesting ideas in discussion will be a good information.

As stated in the “Code and data availability” section: the dataset used in the paper will be available on the EnviDat database (doi will be provided). The ice reservoir parameterization for SNOWPACK will be available on models.slf.ch. Deposits will be ready with the final manuscript version.

Ice reservoir simulations call for other experiments on large snowpack samples, similar to Yamaguchi et al. (2018), focusing on the formation of heterogeneous ice lenses due to preferential water flow, and possibly providing further accurate validation data. These suggestions have been added in conclusion of the revised manuscript.

--- CHANGES IN THE MANUSCRIPT (l. 399-406) ---

These simulations highlighted the relevance of detailed snow-cover models for the modelling of complex phenomena like deep ice layers formed by preferential water flow, since an accurate representation of the snow microstructure is necessary. Recent advances in preferential flow observations and modelling could contribute to strengthen water transport representation. This study also underlined the importance of comprehensive observation datasets for the validation of complex snow models. Collecting high-resolution data over more winter seasons will further improve the understanding of deep ice layer formation, particularly concerning their density, their impermeability and their evolution in the late melting season. Ice reservoir simulations also call for further experiments on large snowpack samples, similar to Yamaguchi et al. (2018), focusing on the formation of discontinuous ice lenses due to preferential water flow.