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Hydrology and Earth System Sciences
Discussions

Interactive comment on "Liquid water infiltration into a layered snowpack: evaluation of a 3D water transport model with laboratory experiments" *by* Hiroyuki Hirashima et al.

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Response for reviewer 1

General: This paper shows a very interesting model analysis of water transport in a snow sample. Both the experimental data and the model have been presented earlier and this paper now compares the model with the data set. This new comparison offers interesting insight into the process and offers a technically correct analysis. The presentation is concise, state of the art is presented in a balanced way and conclusions supported by the analysis. The paper is in scope and quality suitable for HESS.

One major suggestion concerns the SNOWPACK simulations. I understand that the reason for using the SNOWPACK version without preferential flow parameterization in order to show the differences caused by the preferential flow. However, I don't understand why not additional simulations are shown, which use the SNOWPACK preferential flow parameterization. This would add value to the paper and increase its impact for two reasons: i) The 3D model is (computationally) limited to small domains (see also next comment below) and if the reader is provided with an analysis that allows to judge how much of the effect is covered by the SNOWPACK parameterization, then this has a lot of practical value for scientist that need to do larger-scale simulations. ii) The analysis would already give a first indication on how the slightly different treatment of preferential flow path initiation (entry suction) in the 3D model vs. SNOWPACK compares and would therefore add substance to the discussion of the entry suction problem, which is well executed in the paper otherwise. My suggestion is further supported by the fact that the current paper has not already too many new elements or this too long and this additional analysis should be easy to execute.

Response: Thank you for these constructive comments. The second reviewer also suggested to add SNOWPACK simulations with the dual domain approach and we agree with both of you that including this scheme would enhance the impact of the work. We have already performed such simulations, which will be included in our revised manuscript. The variables of interest of this new comparison will be water content profiles and liquid water arrival at the snow base. The discussion section will be modified accordingly.

One additional (major) comment concerns the missing discussion of the domain size effect. While domain sizes have been chosen congruently between measurements and simulations, the generalization of the results may still be suffering from the small lateral extent in both. The dye experiments we know from snow (e.g. the ones from Schneebeli mentioned in the paper) show very significant lateral spreading of flow paths much beyond the scale of the experiments presented here. This aspect should be properly discussed.

Response: We agree with you. In the revised manuscript, we will add a discussion about the domain size effect. This discussion is here reported as a reply for minor comment at P4 l32 (see below)

Detailed (minor) comments:

p.3 l.27ff: Maybe mention additional snow characteristics (grain type) and how you produced the snow samples?

Response: The details about production of snow samples are already reported in Avanzi et al (2016). However, we will add some information about the preparation method and grain type.

"In these experiments, snow samples were prepared in a cold room at -20 âŮęC using refrozen melt forms. Snow was packed in a cylindrical container composed of several acrylic rings, the height and diameter of which being equal to 20 mm and 50 mm, respectively. Each sample was made by two layers: while the upper layer was 10 cm thick, the lower layer was either 8 or 10 cm thick (see Avanzi et al., 2016). Then, samples were moved to a second cold room at 0 âŮęC and stored for at least 12 h to reach initial conditions of dry snow at 0 âŮęC. All samples were characterized by a finer-over-coarser layering (i.e., the upper layer was created using a smaller grain size than the lower one), which aimed to reproduce capillary barriers. The three classes of snow grain size included fine (0.25–0.5 mm), medium (1.0–1.4 mm), and coarse snow (2.0–2.8 mm)."

p.4 l.14: "of" breakthrough on breakthrough

Response: We clarified the sentence as reported below:

"The evaluation of simulations focused on the thickness of the ponding layer at the textural interface, on the liquid water distribution, on the wet snow fraction at different heights, and on different timings that are relevant for liquid water movement in snow.

These include water arrival at the interface between layers, breakthrough of preferential flow in the lower layer, and arrival of liquid water at sample base."

p.4 l.19: Maybe grid points or elements instead of "meshes"

Response: We clarified the sentence as reported below. Also, in revised manuscript, we will check words and replace, "meshes" with "elements" in the entire manuscript.

"The simulated timings of water arrival at the interface, entering the lower layer, and arrival at the snow base refer to the lowest elements in the upper layer, the top 3 elements in lower layer, and the lowest elements of the sample, respectively."

p.4 l.21: "expended" ?

Response: We clarified the sentence as reported below:

"The water content in the top three elements of the lower layer was used to determine the timing of breakthrough because preferential flow began immediately after the water content of one of these elements became larger than zero."

p.4 l.29: "anticipated" measured

Response: We clarified the sentence as reported below:

"As an example, some images of the development of capillary barrier and preferential flow for FC1 are shown in Fig. 1. These figures show the front surfaces after 20 sec from the beginning of the experiment (a and e), at the arrival time of water at the interface between layers (b and f), at the time of breakthrough of preferential flow into the lower layer (c and g) and at the arrival time at the snow base (d and h). The simulation results showed faster than measured arrival of water at the boundary (Table 2), which implied an overestimation of vertical velocity in the model's preferential flow for this experiment (Fig. 1)."

p.4 l.32: Here you could add some discussion on the effect of domain size (see above)

Response: We agree with you and have included some discussion on this point as reported below:

"The size of laboratory experiments was restricted by the time needed to prepare and perform each of them. Also, the diameter of samples looks consistent with the thickness of similar experiments in soils (see e.g. Hill and Parlange, 1972), whereas Avanzi et al. (2017) show that preferential flow may be intrinsically coupled with wet-snow metamorphism at grain scale. This suggests that small scales experiments are appropriate to understand the physics of this process in snow. Nonetheless, the relatively small scale of these experiments may introduce some domain size effect as well. In natural snow, water flow shows lateral spreading, especially at capillary barriers, whereas experiments with small size may partially perturb the natural flow on snow and therefore change vertical flow due to artificial edges. This may increase the ratio of preferential flow path area, decrease the arrival time at the base, and decrease natural ponding amount at capillary barrier. In terms of comparison between simulations and experiments, this effect was offset by using same domain conditions."

p.5 l.4: "85" add minutes

Response: This information was added to the manuscript.

p.5 l.7ff: By comparing to Walter I think you compare two different things: Velocity of water in an existing preferential flow path (Walter) vs. propagation speed of path initiation. Please discuss appropriately

Response: As you suggested, the velocity in an existing preferential flow path is likely different from propagation speed of path initiation. This difference makes this comparison unsuitable. Therefore, we removed the sentence "This is one order of magnitude …. supply rate (3600 mm/h). " from the manuscript. Thank you.

p.5 l.14: Please mention the reason of why it could not be determined

Response: We were not be able to measure the exact timing of preferential flow initiation using a frontal movie when preferential flow formed at the posterior side of samples with respect to the position of the camera. On the other hand, horizontal spreading of water at sample base always allowed to detect the arrival time with a reasonable precision. We clarified this in the manuscript.

"As timings were measured using frontal movies, we were sometimes unable to evaluate the timing of preferential flow formation within a sample. For example, in the case of MC1, preferential flow formed on the side of the sample which was not visible from the frontal position of the camera. Thus, the frontal movie did not show preferential flow path in lower layer, whereas horizontal spreading of water at the sample base allowed to detect the arrival time with a reasonable precision. It follows that for this sample we cannot determine the timing of preferential flow initiation. Therefore, estimated timings from laboratory experiments may contain a delay."

p.7 l.1ff: I would suggest to add a general comment that deviations of both models from measurements have the same order of magnitude

Response: We agree with your opinion. We will quantify the magnitude of deviation for each simulation in the manuscript.

"Note that the magnitude of deviation for each model is similar (RMSE of water content at measured arrival time are 0.109 and 0.094 in SNOWPACK and 3D model, respectively)"

p.7 l.21: Why "in practice"?

Response: "In practice" is not suitable to use here. So it was removed.

p.8 l.8: "too vertically strict" is a funny expression and I suggest to try to explain it (maybe domain size as mentioned above?)

Response: As we replied to your major comment, we expect domain size effects to possibly perturb real dynamics of liquid water flow by increasing wet snow area. This effect is, nonetheless, in contrast with the observed underestimation of wet snow area by the model. We elaborated on this sentence and connected it to the next paragraph.

“Nevertheless, the simulated mean wet snow area was small even for fine snow (e.g. 4.8% in FC1 and 22% in FC3, excluding the ponding area). Because simulated wet snow area is smaller than the measured one, this model may still underestimate the effective cross-sectional section of infiltration. This will be subject of future research.”

p.8 l.13ff: Here you should discuss that the model does not predict any structural changes in the snow grains. This is discussed further below but this is not sufficient. In reality, grains will grow quickly in contact with water at the walls of preferential flow paths and this will also promote lateral spreading of water, I think

Response: Although this model includes grain growth following Brun et al. (1989) and Tusima (1977), modeling some specific conditions such as wet snow metamorphism at the boundaries between preferential flow paths and drier snow is still an open issue. This is important to improve the model. Thank you for this advice. We will add a discussion about it.

“Neglecting quick metamorphism in preferential flow paths (Avanzi et al. 2017) may represent another cause of underestimation of preferential flow path size as grain growth promotes lateral spreading of water and expansion of paths. Although this model includes grain growth following Burn et al. (1989) and Tusima (1977), modeling some specific conditions such as wet snow metamorphism at the boundaries between preferential flow paths and drier snow is still an open issue. Also, existing observations of wet-snow metamorphism have been mainly performed in static conditions, which means that the coupling between grain growth and flowing water is still poorly understood. This represents a further unknown for models of liquid water in snow.”

p.9 l.4ff: Metamorphism could help to explain lateral spreading

Response: We agree with your opinion. We will add the following discussion at the end of Section 4.3.

“Extending the existing parameterizations of wet snow metamorphism for small timescales will improve simulation accuracy with regards to the development and disappearance of water ponding by capillary barriers. Also, a correct simulation of grain growth will lead to correctly estimate lateral spreading of water, which will improve the accuracy of the prediction of preferential flow path size.”

Figure 1 legend: Explain the term “front grid”

Response: We thought using phrase “front elements” is better than “front grid”. So we replaced it in the manuscript. Also, we will improve the figure to explain the term “front elements” (see below). This will also be mentioned in the caption.

“Figure 1. Development of capillary barrier and preferential flow path for FC1 during experiments (a–d) and simulations (e–h). A blue dye tracer was used in the experiment. In the simulation images, blue denotes the liquid water content at the front elements (see: right figure), while grey denotes that the front elements are dry, but some liquid water is present within the sample at that position. The grey-scale represents the maximum liquid water content for each location. Captured times were at: (a) 20 s, (b) 35 min, (c) 1 hour 25 min, (d) 1 hour 29 min, (e) 20 s, (f) 17 min, (g) 1 hour 19 min, and (h) 1 hour 20 min.”

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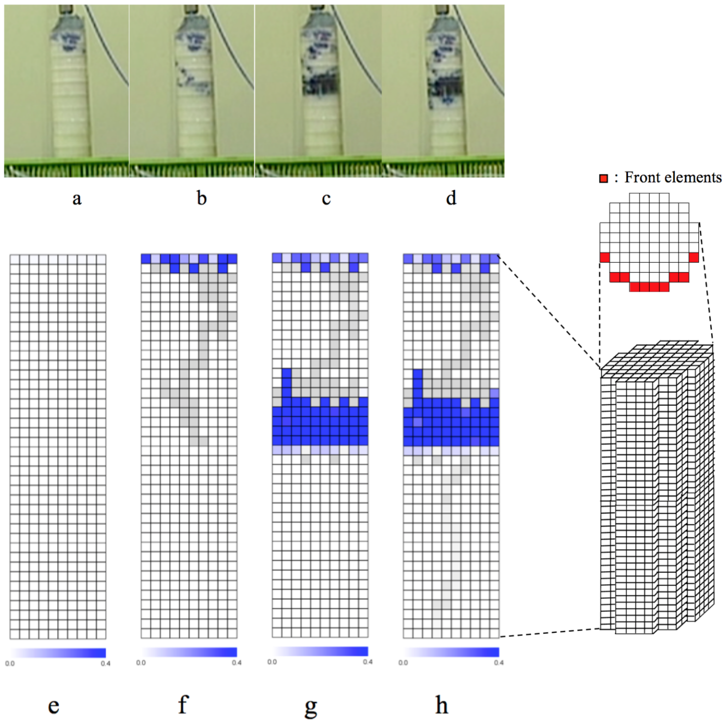

Fig. 1.