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Interactive comment on "Laboratory-based observations of capillary barriers and preferential flow in layered snow" *by* F. Avanzi et al.

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Summary

The authors present a set of nine laboratory experiments analysing the flow behaviour of water in a column of layered snow in order to obtain better insights into the evolution of capillary barriers and preferential flow paths in snow. During their experiments the authors used various types of grain sizes and layering and influx rates. In a second step the experimental results are compared to modelled water flow using the 1-D physically based snow cover model SNOWPACK. The model was setup to reproduce the settings of the laboratory experiments. Results show that similar to other porous media (e.g. sand) the water entry suction plays a vital role in the evolution of capillary barriers.

The water entry pressure itself is driven by the layering of different grain sizes. The results on the role of layering concerning the triggering of preferential flow paths remain very qualitative but agree to some extent to other measurements made earlier by a part of the authors team. The only difference observed is that now, the authors do not observe any dependency between preferential flow paths and influx rates. The modelling approach can reproduce the measurements. At the end the authors present experimental difficulties.

Evaluation

In this manuscript the authors present valuable work toward the greater understanding of the very complex behaviour of water flow in snow. Parts of the manuscript are extremely meaningful as it is expected that wet-snow avalanches will become more important in future. In addition, snow as a resource is getting less available and therefore its effective management will become very important in the near future. However, my feeling is that both, analysis and manuscript are still not mature for publication. There are several approaches which I believe are impropriate or need a more in depth re-analysis and/or discussion. Especially the modelling part and the interpretation of the experimental limitations need to be clarified and reassessed. Therefore, I encourage the authors to put more effort into the presented work since the experimental setup has the potential for a new, solid and fundamental contribution on the field of wet snow and water flow in snow.

Please recheck the references and check the entire manuscript for stray commas and other minor grammatical inconsistencies. Please put equations into numbered equations, which contrast from the text. In addition add descriptions of the symbols used within the equations.

General comments

There are three large issues within the manuscript:

- The use of SNOWPACK to better explore preferential flow paths.
- The presentation of the sections Introduction, Theoretical background and the discussion of the results.
- The interpretation of the experimental limitations.

The use of SNOWPACK to better explore preferential flow paths

It is questionable, why the authors decided to use SNOWPACK with the water transport scheme by Hirashima et al. (2010) to reproduce the experiments. SNOWPACK has at the moment the possibility to either use the mentioned and from the authors used approximation of Richards Equation (Hirashima et al., 2010) or to solve explicitly Richards Equation based on different parameterisations (Wever et al., 2014; Wever et al., 2015; Yamaguchi et al., 2010). It is still a matter of debate whether Richards Equation (RE) is applicable when preferential flow patterns prevail and that's what most of the experiments are showing after the capillary barrier. Before the observed flow instabilities or during the evolution of a capillary barrier, Richards Equation might be applicable. Results by a part of the authors team and Wever et al., (2014; 2015) underline this fact, but as soon as preferential flow is prevailing water routing is not well represented by SNOWPACK. This fact is also confirmed by the discrepancy between the arrival times of fast experiments with coarse grain sizes vs. the results of SNOWPACK (Figure 5g-i). Recently, Wever et al. (2015) concluded based on comparisons with upGPR data and manual snow profiles that their RE scheme would unintentionally mimic preferential flow effects. The reason, however, remained unclear. So, if the authors want to use SNOWPACK for exploring their experimental results in more detail, I suggest to use at least the water transport scheme of SNOWPACK implemented by Wever et al. (2015).

In my opinion, however, it would be even more logical and interesting to compare the now obtained experimental results with the multi-dimensional modelling approach of Hirashima et al. (2014). Since there is to some extent a mismatch between the results

presented in this manuscript and the statements and finding of Hirashima et al. (2014) and Katsushima et al. (2009a; 2009b; 2013), it would make sense to explore more in detail the reasons for the differences. In fact, Hirashima et al. (2014) mention that heterogeneity alone was not sufficient for the development of preferential flow paths. When both, water entry suction and heterogeneity, were implemented, the model could simulate the formation of a preferential flow paths, which represents again parallels to your experimental results. Additionally, the observations that infiltration rate did not show any correlation to flow behaviour is very different to observations in sand or the results by Katsushima et al. (2013).

I highly recommend elaborating on the above points. In this way the manuscript would gain much more relevance, since at the moment it represents only incremental knowledge gain on the field of water movement in snow.

The introduction, theoretical background and presentation and discussion of the results

The red thread in this story is missing. The Introduction section is not specific enough for the presented analysis. The authors present on the one hand a too broad summary on water movement in snow and on the other hand miss to mention some very decisive results for the presented topic (capillary barrier and preferential flow). Similar problems arise within the Theoretical Background section. The authors should work more on what are the problems in numerically describe water movement for stable and unstable flow conditions and how their work might help to overcome a long lasting debate on this topic.

The Results section is too short and represents at most a quick overview of the results. I suggest either combining both sections in a "Results and Discussion" section or describing in more details the relevant results and then discuss them with a broader context.

The interpretation of the experimental limitations

I suggest rewriting the entire Experiments limitations section. At the moment this section is very misleading and the interpretation of the authors ruins the outcome of the experiments. Following the statements of the authors, mass balance between measured water influx and measured liquid water content using a portable calorimeter differed up to 434%. As explanation for the mismatch the authors hypothesize that undesired melting may have taken place during the warming of the snow column from -20° C to 0°C. If this was really the case, all experimental results would be questionable, since this fact means that controlled conditions did not prevail during the experiments. Consequently, no conclusions can be drawn. However, I believe that the explanation for the discrepancy is due to the way the authors measured liquid water content and the inherent measurement error resolution. Absolute measurement errors for the calorimetric method in determining LWC range according to literature from 1%-5% (Kinar and Pomeroy, 2015). By estimating the values of measured LWC with the calorimetric method (Fig. 5) and comparing these values to the mass of water taken from Table 1 and 2, absolute differences in per cent by mass are 0.04 ± 0.03 (for per cent by volume slightly smaller) and thus slightly higher than the values reported in literature (However, values were only estimated for this calculation! [see xls-file in the supplement]).

The second argument, why the errors seem to be in an acceptable range is that modelled and measured values at least for the experiments with slow and medium velocity are in fair agreement. Since SNOWPACK will not produce any water without additional energy input, I believe that the expected measurement error is the explanation for the differences. The most accurate method to determine LWC so far is the dilution method (Kinar and Pomeroy, 2015). So, if the authors aim for another series of experiments, I suggest using this method, since the measurement errors have to be small in case of fast flowing experiments with MC layering.

For the updated version of the manuscript, I would be very nice to see a mature discussion on the experimental limitations and their meaning for the results.

Specific comments

Abstract

- P. 6628, L. 15-16: Ponding is defined as presence of water with no flow; please change the wording in this sentence and/or define this term more precisely
- P. 6628, L. 18: There is no thickness = 0cm
- P. 6628, L. 18: Delete “extensive”

Introduction

- General remark: I was missing some important conclusions and summaries of topic relevant results from parts of the authors team, e.g. Hirashima et al. (2014) and Katsushima et al. (2009a; 2013).
- P. 6629, L. 3-4: I suggest rewording; especially the term snow porous matrix has only limited meaning; better porous ice matrix
- P. 6630, L. 1-2: I suggest rewording of this sentence.
- P. 6630, L. 21-22: I think the community is aware of the vital role of capillary effects, so please reconsider this sentence. The limited knowledge is purely based on the very high difficulties in measuring and modelling water in snow.
- P. 6631, L1: add “flow” in front of “instability”, otherwise it is not clear which type of stability you mean.

Theoretical backgrounds: Capillarity in snow

- General remark: Please use Equations with numbering and symbol description. In addition, I would expect a more specific theoretical background on capillarity in snow; your explanations are partly very basic and might rather fit into a textbook than into a manuscript with a very specific topic.
- P. 6632, L. 22-24: I think that Daanen presented in his doctoral thesis a similar relation of alpha and n to grain size.
- P. 6633, L. 1-2: I think this sentence makes no sense here. Just before, you explain the hysteresis in snow and now you talk about the conversion of pressure head and pressure potential.

Theoretical backgrounds: Ponding and water flow instability

- General remarks: You sometimes use capillary barrier and ponding as interchangeable terms, however, I think that there are subtle differences, i.e. you might have a capillary barrier and will get ponding on that barrier, but there can be also ponding without capillarity involved e.g. above a melt-freeze crust.
- Please state more clearly why the saturation overshoot found by Katsushima et al. (2013) is so important.

Laboratory experiments: Preparation of samples and experiments

- General remarks: Combine Table 1+2 to assure better readability.
- P. 6635, L. 12: Delete "As a results,. . ."
- P. 6635, L. 25 – P. 6636, L. 8: Rewrite this small paragraph
- P. 6636, L.9-10: Rephrase

Laboratory experiments: Data collection

- General remarks: Why do you express τ as the inverse of velocity?
- P. 6636, L. 20-21: Rephrase.

The comparison with the SNOWPACK model

- General remarks: Keep past tense
- P. 6637, L. 6: You do not give any predictions, but rather compare modelling and measurement approaches.
- P. 6637, L. 8: Please define what you mean with ponding.
- P. 6637, L. 11-25: Please be more specific and shorten this paragraph.
- P. 6638, L. 1: Why did you chose this value of 1.51°C? In SNOWPACK it is possible to set the threshold value of air temperature when snow should turn into rain.
- P. 6638, L. 19-20: Delete this sentence or move it to the Intro.

Results

- General remarks: see major issues above

Discussion: the ponding process

- General remarks: see major issues above

- P. 6639 L. 18-20: Are you sure that there is no ponding behaviour? In my opinion the chosen resolution hampers the detection, but as far as I can see it from Figure 5 g,h,i there is a pronounced increase in LWC at the transition of the two layers. In Fig. 5i the increase is hardly detectable due to the chosen resolution of the x-axis. If you enlarge the resolution, you will probably see a distinct increase of LWC too.
- P. 6639, L. 21-25: How can you explain the differences between the values of LWC given in Figure 5 and the fraction of blue colour in Fig. 1 for MC1 and MC2?
- P. 6639, L. 26 – P. 6640, L. 4: Can you please report more quantitatively on the differences of ψ for the various layer transitions, or at least, can you qualitatively show WRC curves and estimate the magnitude of difference for the various transitions? Since you know grain size and density, you can use the parameterisation of Yamaguchi et al. (2010) to determine all necessary variables for modelling a WRC according to van Genuchten (1980).
- P. 6640, L. 8: I think that "In particular . . ." is the wrong wording here.
- P. 6640, L. 10: What is an interlayer plane? Do you mean layer boundary?
- P. 6640, L. 11-13: You link to the findings of DiCarlo (2007), but it is not clear to which findings you interpret your link.
- P. 6640, L. 13-16: I think it is quite keen to assume that 33-36
- P. 6640, L. 17-18: I think this is not true; in 2 out of 3 experiments you show a distinct increase of LWC for your MC samples.
- P. 6640, L. 19 – P. 6641, L. 4: This sounds like a mix of Introduction and Conclusions. Please rewrite this paragraph.

Discussion: Preferential flow patterns and travel time of water in snow

- P. 6641, L. 6-26: Please rephrase both paragraphs since it is not clear what you want to explain here.
- P. 6642, L. 1-4: I think it is again keen to report on the stability of position of preferential flow paths since your experimental setup does not provide the possibility to explore this; I consider to skip this interpretation.
- P. 6642, L. 5-17: I do not get the argumentation of this paragraph: It is obvious that a capillary barrier will decrease your propagation velocity. In addition, τ is in the same order of magnitude, so maybe it is only subject to measurement errors?

Discussion: the comparison with SNOWPACK

- Please rewrite this sections after examining the results with the above suggested water transport model

Experiments limitations

- Please rewrite this sections after examining the above mentioned suggestions

References

DiCarlo, D.A., 2007. Capillary pressure overshoot as a function of imbibition flux and initial water content. Water Resources Research, 43(8): W08402.

Hirashima, H., Yamaguchi, S. and Katsushima, T., 2014. A multi-dimensional water transport model to reproduce preferential flow in the snowpack. Cold Regions Science and Technology, 108: 80-90.

Hirashima, H., Yamaguchi, S., Sato, A. and Lehning, M., 2010. Numerical modelling of liquid water movement through layered snow based on new measurments of the water retention curve. Cold Regions Science and Technology, 64(2): 94-103.

Katsushima, T., Kumakura, T. and Takeuchi, Y., 2009a. A multiple snow layer model including a parameterization of vertical water channel process in snowpack. Cold Regions Science and Technology, 59(2-3): 143-151.

Katsushima, T., Yamaguchi, S., Kumakura, T. and Sato, A., 2009b. Measurement of dynamic water-entry value for dry snow. In: J. Schweizer and A. van Herwijnen (Editors), International Snow Science Workshop ISSW, Davos, Switzerland, 27 September - 2 October 2009. Swiss Federal Institute for Forest, Snow and Landscape Research WSL, pp. 248-251.

Katsushima, T., Yamaguchi, S., Kumakura, T. and Sato, A., 2013. Experimental analysis of preferential flow in dry snowpack. Cold Regions Science and Technology, 85: 206-216. Kinar, N.J. and Pomeroy, J.W., 2015. Measurement of the physical properties of the snowpack. Reviews of Geophysics, 53.

van Genuchten, M.T.A., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated flow. Soil Science Society of America Journal, 44: 892-898. Wever, N., Fierz, C., Mitterer, C., Hirashima, H. and Lehning, M., 2014. Solving Richards Equation for snow improves snowpack meltwater runoff estimations in detailed multi-layer snowpack model. The Cryosphere, 8: 257-274.

Wever, N., Schmid, L., Heilig, A., Eisen, O., Fierz, C. and Lehning, M., 2015. Verification of the multi-layer SNOWPACK model with different water transport schemes. The Cryosphere, 9: 2271-2293.

Yamaguchi, S., Katsushima, T., Sato, A. and Kumakura, T., 2010. Water retention curve of snow with different grain sizes. Cold Regions Science and Technology, 64(2): 87-93, doi: 10.1016/j.coldregions.2010.05.008

Please also note the supplement to this comment:
http://www.the-cryosphere-discuss.net/9/C2938/2016/tcd-9-C2938-2016-supplement.zip

Interactive comment on The Cryosphere Discuss., 9, 6627, 2015.