

Dear Dr. Guillaume Chambon, Editor,

Dear Referees,

We would like to present here a revised version of our manuscript entitled “Observations of capillary barriers and preferential flow in layered snow during cold laboratory experiments” for possible publication in The Cryosphere. The manuscript underwent major modifications. We paid specific attention to the structure of the manuscript (e.g., we removed the section dealing with theoretical backgrounds and merged Results and Discussion in a single section), to the Introduction and the state of the art, and to the comparison between observed profiles of liquid water content and simulations by a version of SNOWPACK that includes the implementation of Richards equation by Wever et al. (2014, reference in the manuscript). We thank again both Referees for providing insightful and constructive comments on the previous version of this manuscript.

In the following Table, we detail all the changes made to the manuscript. We also discuss any amendment to the intended changes to the manuscript that we discussed in the public responses to referees. These amendments regard the comparison with SNOWPACK, as we chose to include only results by SNOWPACK v. 3.3 (i.e., the version including the full Richards equation), thus removing results by the water scheme presented in Hirashima et al. (2010, reference in the text). Motivations may be found below.

Apart from this, we do not have any additional integration to our public responses to referees. Thus, after this detailed inventory, we attach the responses to referees uploaded on the web during the public discussion and a .pdf file with major changes highlighted (yellow).

Title / Abstract	Title and abstract have been slightly changed to improve text clarity and to include some additional comments about our results (see text for details).
Introduction	The Introduction underwent major revisions. Following the suggestion by Dr. Mitterer (henceforth, R2), we now contextualize our work in the existing literature about preferential flow and capillarity in snow. We are now more explicit on the challenges posed by these two processes to snow modeling and on the added value provided by these observations. We agree with R2 that such a focus clearly improves both, the presentation of this work and its impact in the ongoing debate about liquid water in snow. From this perspective, we have also stressed that these experiments were performed choosing a relatively high vertical resolution of all the measurements (2 cm), which is a notable point for interpreting these results. As suggested by Referee #1 (henceforth, R1), we have also included some passages about the implications of preferential flow in subfreezing snow (see lines 104 – 109). Furthermore, we provide now an explicit definition of <i>ponding</i> (as suggested by both referees, line 65). All these changes slightly extended this Section compared with the previous manuscript. Nevertheless, this is balanced by the removal of previous Section 2, as suggested by both referees. We have also included here a paragraph explaining the physics of capillary barriers in snow (see lines 62-79) Some sentences in this paragraph were originally in previous Section 2 (Theoretical Backgrounds). Although this content might be basic knowledge for wet snow scientists, it introduces some important nomenclature and it may be needed by a broader public to grasp the main implications of this manuscript.
Section 2.1 Preparation of samples	In this Section, we have added a specification about the main prerequisite of our experiments, i.e., a finer-over-coarser profile in layering (see lines 112-118). We have also specified that we did not verify any stability criterion of water flow in snow thanks to previous results by Katsushima et al. (2013, reference in the text) (see lines 125-129). The choice of the three water input

	rates is now explicitly discussed (see lines 119-125), as well as the use of 1, 2 and 3 to denote samples composed by the same type of snow, but subjected to different water input rates (see lines 132-133). We have specified that we did not apply any tamping during sieving operations so we had no direct control on density (see lines 144-147). Finally, we have specified that our results are not affected by the fact that some samples are shorter than the others (see lines 148-150). All these additions comply with suggestions by R1. As already discussed in our reply to R2, we chose to keep Tables 1 and 2 separated, as one (Table 1) deals with experiments design and/or initial conditions, whereas the other one (Table 2) reports experimental results. Therefore, they will appear in different parts of the text.
Section 2.2 Data collection	This Section underwent minor changes. We specified that the specific travel time τ is defined as a reciprocal of velocity (following our discussion with both referees, see line 163). We now comment on observed differences between reference and experimental water input rates, as suggested by R1 (see lines 156-158). We are also more specific about the method used to estimate wet areas, as asked by R1 (see lines 169-172).
Section 2.3 The comparison with SNOWPACK	Here, we revised our comparison with SNOWPACK simulations. Following the suggestions by R2, we now compare our observations with predictions by SNOWPACK 3.3, i.e., the recent implementation of Richards Equation by Wever et al. (2014, reference in the text). We specify that the focus is on the simulation of capillary barriers, as the model is 1D. The model is therefore not used to compare preferential flow patterns. Note that the model simulations are here used to assist and enrich experimental interpretation. The use of only SNOWPACK 3.3 represents the main amendment to our public responses, where we expected to compare observations with both, SNOWPACK 3.3 and the numerical scheme by Hirashima et al. (2010). This is because the inclusion of a discussion about differences between two numerical schemes might overshoot the focus of this manuscript, which is the detailed discussion of a set of observations in the cold laboratory. Accordingly, we chose the most recent scheme existing in the literature (i.e., SNOWPACK 3.3). We also revised our presentation of model settings (see lines 192-209, suggested by R1). As this version of SNOWPACK is open software and is presented in details in other publications (Wever et al. 2014, 2015, references in the manuscript), we refer to these references when possible for the sake of brevity. Thus, we avoided including a specific Table about SNOWPACK setup, contrary to our response to referees in the public discussion. As discussed with both referees, we changed the threshold temperature for separating liquid and solid precipitation. All simulations were run setting this threshold at -0.01°C and laboratory temperature at 0°C (as in reality). We also slightly changed the values of emissivity when calculating longwave radiation (i.e., 1 instead of 0.97) as this provides more consistent results. A typo about mean grain sizes was fixed (i.e., 0.406 mm, 1.463 mm, and 2.926 mm). Also, we improved the way we discuss model results. In the previous version of the manuscript, laboratory measurements were compared with a single snapshot of LWC taken at the “physical” arrival time of liquid water at sample base. This is advantageous as supplied mass in experiments and in simulations matches. However, the significance of this comparison is restricted as liquid

	water in samples mainly moved in fingers, which is a process that SNOWPACK does not reconstruct explicitly, although the implementation of Richards Equation might partially mimic some effects related with it (Wever et al. 2015). Therefore, comparing with a single snapshot may miss some important elements of the evaluation, e.g., the profile below the barrier once the simulation reaches the base. Accordingly, we chose to compare observations with two different profiles. The first one is the profile at the observed arrival time of water at sample base (WE1). The second one is the simulated profile at the arrival time of water in the model (WE2, see text for details, lines 210-236).
3 Results and Discussion 3.1 Overview	As suggested by both referees, we merged previous Sections 4 and 5. On the one hand, we think that an exhaustive interpretation of these results need that all figures are introduced together; this is why we do not introduce and comment each Figure sequentially. On the other hand, we agree with referees that splitting these two sections might be arbitrary. This is why figures are now introduced in a preliminary section (3.1, Overview).
3.2 Development of capillary barriers	Here, we improved our general discussion of ponding behavior in samples MC, as suggested by both referees (see lines 261-263). We have also introduced a paragraph providing a quantitative comparison between water entry suction in medium and coarse snow and expected suction for “low” liquid water contents (e.g., 5 and 10 vol%, comment by R2). Note that these values are generally high compared with field observations, but turned out to be low if compared with peak LWC at the interface (see lines 264-277). We have also improved our discussion of peak LWC at the interface (see lines 278-290, comment raised by R2). Moreover, we have also included a new paragraph dealing with observed spatial variability in liquid water patterns at cm scale (lines 296-308). This was not asked by referees, but represents a new element for the discussion that was not reported in the previous manuscript.
3.3 Preferential flow patterns ...	We improved the general discussion here. Important changes include 1) an improved discussion about the expected relation between input rate and the total area of preferential flow (as suggested by R2, see lines 332-339), 2) a clarification about the comparison between our observations and those by Katsushima et al. (2013) (see lines 317-331, comment by R2), 3) the inclusion of a preliminary paragraph describing some observed features of fingering in samples (see lines 310-316). This is important as direct observation is a key component of experimental work that cannot be easily translated into figures or tables.
3.4 The comparison with SNOWPACK	The discussion here has been completely revised to examine in depth this comparison. We therefore refer to the revised text for details.
Section 3.5 The role of instrumental precision...	Following suggestions by both referees, we rewrote this Section. We removed any discussion about the possible effect of melting, which was very misleading, and we re-focused this section on the expected precision of LWC measurement by the Endo type calorimeter. Moreover, we also discuss in details the reasons why we chose this instrument.
Conclusions and Figures	The conclusion underwent minor modifications (see text). Figures were modified according to our fruitful discussion with referees.

Dear Referee #1,

Thank you very much for your insightful comments and extensive suggestions: we will consider all of them while revising our manuscript. Here, we provide some feedbacks about your points. Your comments are in *italic* for readability. For all the points, we provide answers and we outline our planned changes in the manuscript.

The authors studied the formation of ponding conditions inside the snowpack on microstructural transitions and subsequent preferential flow path formation in laboratory conditions. The laboratory experiments were simulated using the detailed SNOWPACK model, which yielded good correspondence with measurements regarding the ponding conditions, although the overall melt front velocity was underestimated by the model. This is understandable, as the model is 1D only, and it has already been demonstrated that multi-dimensional, or dual domain models will be necessary to adequately describe liquid water flow. The work is interesting in a broad context: from wet snow avalanche formation, to hydrological processes and snow microstructure investigations. In some aspects, the manuscript provides confirmation of previously published results, in other aspects it provides quantitative results for previously published qualitative descriptions, which makes the results useful for other researchers.

My overall judgement: In recent years, advances have been made in modelling of liquid water flow in snow and the understanding of formation of ponding conditions and preferential flow paths. This manuscript fits very well in the ongoing developments. Although the results present a relative small step and entails a relatively small study, the study is nevertheless a very nice, well contained piece of work. It provides significant results, and I can recommend publication in The Cryosphere after a revision, that takes into account, or rebuts, the major and minor issues I'll point out below. A language and grammar correction is also recommended.

Answer
We thank you for this comment. Advancing our knowledge about liquid water flow in layered snow has been one of the reasons why we started designing our experiments. We also aimed at collecting/reporting quantitative observations of capillary barrier effects for evaluating numerical models of liquid water flow in snow. In this perspective, we agree with your general view on the implications of our results.

Major issues:

My main concern for the manuscript is in the presentation of the work. To summarize: the introduction and theoretical background section is too long, contains a lot of irrelevant details and reads more as an introduction to a thesis or a review paper. In my opinion, those sections fail (in the current form) to introduce the context of the laboratory experiments and modelling study. The length of these sections seems to overshoot the size of the actual study performed. This may prevent the diagonal readers from grasping the important aspects, and harms the impact from the manuscript, in my opinion. I think the manuscript would greatly benefit from a thorough overhaul of these two sections, reducing the size of these sections by roughly one third. Some examples where I think a more concise text can be achieved:

P6632, L3-12 doesn't seem to be directly related to the experiments performed, and could be easily summarized by providing the appropriate references.

P6633, L13-16 doesn't seems to be directly related to the work presented here, because as far as I understood, only the classical grain size definition is considered.

P6633, L4-6: *Instead of explaining the background of Richards equation, one can just write that "Water flow in porous media is commonly described using Richards equation". The reader can find details in the references provided in the manuscript.*

It's not necessary to again write once more that Richards equation is a combination of mass conservation and darcy's law.

P6632, L13-P6633, L12: *This section repeats too much information previously published in my opinion. For example, the concept of a pressure head is introduced, although it is not used anywhere else in the manuscript.*

These are only a few of many examples how these sections can be made more concise and to-the-point.

Furthermore, the choice of what is discussed in "Results" and what in "Discussions" seems to be rather arbitrary. I think the results section is too short, and the discussions too long. The model simulations are not well presented in the Results section, as well as the measurements of volumetric water content. I suggest either combining both sections in a "Results and Discussion" section, or make sure that both sections get more balanced: "Results" discussing all results from the experiments, "Discussion" the connection to previous research and implications for future studies.

Answer
We agree with you that the structure of our manuscript must be improved. In the revised manuscript, we will shorten and re-focus Sections 1, 2, 4 and 5 starting from your kind suggestions.
Changes in manuscript
We will eliminate Section 2. In fact, we agree with you that materials in Section 2.1 can be found elsewhere in the literature and this is the reason why we will remove this Section completely. On the contrary, we will include some relevant passages of Section 2.2 in the Introduction in order to make our manuscript more focused on capillary barriers and preferential flow in layered snow. We will also merge Sections 4 and 5 in a unique "Results and Discussion" Section.

Minor issues:

-> I missed the mentioning and demonstration of the prerequisite for the experiment: ensure that the water inflow flux is smaller than the saturated hydraulic conductivity of snow Only then, it is considered that the wetting front is unstable. In natural snow covers, this condition would be generally fulfilled, but for laboratory experiments, it depends on snow type and infiltration rate chosen. See for example Eq. 4 in: [Z Wang, Q.JWu, LWu, C.J Ritsema, L.W Dekker, J Feyen, Effects of soil water repellency on infiltration rate and flow instability, Journal of Hydrology, Volumes 231–232, 29 May 2000, Pages 265-276, ISSN 0022-1694, [http://dx.doi.org/10.1016/S0022-1694\(00\)00200-6](http://dx.doi.org/10.1016/S0022-1694(00)00200-6).] Actually this reference is probably not the most appropriate here, as it probably has been noted long before this one that this prerequisite is required. Maybe the authors can trace back the original study.

Answer
We thank you for this comment. Actually, our main purpose here was to observe capillary barriers development and subsequent preferential flow, so the main prerequisite was an initially dry finer-over-coarser texture, since this is the typical condition where capillary barrier effects develop in porous media. Preferential flow is then observed as a result.
This is the reason why we did not mention any instability criterion when introducing and designing our experiments. Another reason is that the evaluation of stability criteria of wetting fronts in snow is still an open issue. As an example, Katsushima et al. (2013, reference in the manuscript) note that using saturated conductivity as a velocity criterion (according to the original stability analysis of Saffman and Taylor 1958, see DiCarlo 2013 for reference) performs ambiguously in snow (see their Section 4.2, page 213). In

fact, they report that the saturated water conductivity of snow is usually between 10^4 - 10^6 mm/h and therefore the wetting front should be systematically unstable in snow for any (natural) water flow velocity and texture (included those tested here). However, they have observed systematic stable infiltration in very fine snow (mean grain size of 0.231 mm). A more refined velocity criterion may consider unsaturated hydraulic conductivity for water entry suction rather than saturated conductivity (e.g., see Baker and Hillel 1990 or de Rooij 2000, references in the text). However, a few data exist of water entry suction in snow (see Katsushima et al. 2013 and Hirashima et al. 2014, references in the text). An additional complication is that our experiments were in unsteady conditions and the water flux at the interface between the two layers is therefore not known precisely.
Changes in manuscript
Starting from our reply, we will clarify the requisites of our experiments in the manuscript (Section 3.1).

-> One aspect that I didn't found well discussed: there are also a few studies that seem to indicate that the error made by neglecting preferential flow paths is relatively small, particularly in snow below freezing. See for example Fig. 9 in [Philip Marsh, M.-K. Woo (1984) Wetting front advance and freezing of meltwater within a snow cover: 2. A simulation model, Water Resources Research, December, 1984.10.1029/WR020i012p01865], or the discussion on P1862 in [Philip Marsh, M.-K. Woo (1984) Wetting front advance and freezing of meltwater within a snow cover: 1. Observations in the Canadian Arctic, Water Resources Research, December, 1984. 10.1029/WR020i012p01853]. Similarly, from a hydrological point of view, [Wever, N., Fierz, C., Mitterer, C., Hirashima, H., and Lehning, M.: Solving Richards Equation for snow improves snowpack meltwater runoff estimations in detailed multi-layer snowpack model, The Cryosphere, 8, 257-274, doi:10.5194/tc-8-257-2014, 2014] also report that neglecting preferential flow for seasonal time scales seems acceptable. This seems a particular issue for natural snow covers that are well below freezing during extended periods of time. Probably it also plays a role that natural water influx rates are much smaller than used in experiments, as for example the experiments in this manuscript. It would be good to mention this.

Answer
We have appreciated this suggestion. Here, we focus on isothermal conditions at 0°C, thus avoiding any investigation about wetting front advancement in subfreezing snow. However, we agree with you that evaluating the added value of including explicitly preferential flow modelling in snow hydrology is an interesting open issue. As an example, Marsh and Woo (1985, reference in the text) tested a multiple-flow path model against a uniform flow model using data from Arctic and Sierra Nevada and reported that this improves model performance as it predicts earlier runoff and reduced peak flow, in agreement with data (see their Figure 7). This outcome could show that considering preferential flow may make a difference for short time scales.
Changes in manuscript
We will mention this issue in the revised Introduction of our manuscript.

-> Abstract, L21: "shows high performances" -> "shows high agreement"

-> Abstract, L23: It may be good to include the reason for the underestimation. My suggestion: "while water speed in snow is underestimated by the chosen water transport scheme, which is attributed to the 1D nature of the model."

-> P6629, L1: "Liquid water in snow originates from". As snow melt is generally more important than rain, I would mention melt first. Also I don't think the references are appropriate, as this is already known for much longer than 2011!

-> P6631, L4: "together" -> maybe "concurrently" suits better here?

-> P6631, L12: "a wide dataset" -> "a broad dataset"?

-> P6631, L18: "reproduced" -> "simulated"

-> P6632, L16: "This calls" -> "This is called a", and it I think it is too strongly based on a theoretical basis as to call it an "intuitive relation".

-> P6632, L16/17: This statement is mainly true for snow, but for soil, the Brooks-Corey model is also often used.

-> P6632, L19: "As a rule of thumb" -> "Generally"

-> P6632, L20 and elsewhere: "pores shape" -> "pore shape"

-> P6633, L9: "In unsaturated conditions, K_w depends on S_r ". The references provided are inappropriate in my opinion. This should rather refer to the Mualem model? Actually, in the Richards (1931) paper, it is already mentioned that the conductivity depends on the moisture content. See P323, near the bottom of the page.

Changes in manuscript

We agree with all these observations: we will incorporate them in our revised manuscript, apart from those referring to Section 2.1 as we will remove this Section from the manuscript.

-> P6633, Section 2.2: Maybe it is a good idea to provide a definition of "ponding". Sometimes, in literature (e.g., in soil science) it refers to conditions where the suction pressure gets positive. I guess this is not the case in your experiments. To give a suggestion: can it be said that ponding in this manuscript rather can be defined as a situation where the capillary forces dominate the gravity term? And the absence of ponding is a gravity flow dominated regime?

Answer

We agree with this suggestion, as a thorough definition of ponding will make our manuscript clearer. We think that a proper definition of ponding in our conditions may be a pause in the undisturbed advancement of a wetting front due to capillarity effects and consequent accumulation of liquid water over the boundary. This definition is inspired by the description of fingering in layered soils by Baker and Hillel (1990, see page 20 in the paper). On the other hand, capillary forces could dominate gravity in other specific situations (e.g., capillary rise) and this could cause ambiguity in a definition based on the expected relevance of capillarity or gravity.
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Changes in manuscript

We will include this definition in the revised manuscript (Introduction).

-> P6633, L26: "one (historical) case". Not clear what is meant by that. Is there only one documented case where fingering arose in an initially dry fine-over-coarse profile?

Answer

We chose "historical" because fingering in an initially dry fine-over-coarse profile in layering has been a frequent condition used to study the general problem of wetting front instability in soils (see de Rooij 2000, Section 2, page 278: "Hillel and Baker (1988) and Baker and Hillel (1990, 1991) analyzed ponded infiltration into an initially dry profile with a fine-textured top layer over a coarse-textured sub-layer). This configuration (introduced by Hill and Parlange, 1972) has often been used in the laboratory to produce fingering". However, we note that this term plays a very marginal role and we will remove it from the manuscript.

Changes in manuscript

We will remove this term from the manuscript.

-> P6633, L3: "starts ponding. This causes an increase in LWC". For me, ponding **is** an increase in LWC

Answer
Please see our previous reply about how to define ponding in these experimental conditions.
Changes in manuscript
We will modify this phrasing in the manuscript.

-> P6633, L22: *Rather than mentioning that there is a debate (which is quite useless info), what is the debate about (would be more useful to know)?*

Answer
We thank you for this suggestion. We do not see any reference to a possible debate at P6633, but we suspect that this comment is related to L22 P 6634, where we quote a reference by DiCarlo 2013. In our intentions, this quotation should explain in a few words that describing how and why overshoots occur is still an open issue even in soil science. However, we will modify this sentence as kindly suggested.
Changes in manuscript
We will remove this statement from the manuscript. Our intention is to summarize Section 2.2 in the Introduction. We will therefore be more specific on this point.

-> P6633, L26: *"similar process" ... "have parallels". Very vague. Please make the sentence more clear.*

-> P6635, L11: *As it apparently was not possible to achieve these rates exactly, I suggest writing: "considered are approximately 10, 30 and 100 mm/h"*

Changes in manuscript
We agree with these observations: we will incorporate them in our revised manuscript.

-> P6635, L11: *What is the reason for this extremely high water input rates? They can hardly be considered relevant for most natural applications. Melt rates and rainfall rates are generally much lower. What is the reason? I can imagine that it has to do with the laboratory setting, as I realize that it may be hard to find a control system that is able to apply low water input rates, like 5 mm/h. Please provide some explanation here.*

Answer
We selected 10 mm / h, 30 mm / h and 100 mm / h as reference water input rates in order to explore capillary barrier effects within a broad range of natural input rates. This is because it has been sometimes reported in the literature that water entry suction may be affected by water input rate (see DiCarlo 2007, reference in the text). Moreover, Katsushima et al. (2013, reference in the text) report that preferential flow patterns (namely, the variable f that we used in the manuscript) may be also affected by W . Exploring the dynamics of capillary barriers for a wide range of W may therefore ensure that conclusions are less sensitive to velocity effects. These fluxes were also the result of a trade-off between the range of possible W and logistical constraints (such as the duration of experiments).
Changes in manuscript
We will add some comments on this point in the manuscript: first, we will elaborate on Section 3.1 to detail our choice of W ; second: we will add some comments about velocity effects in the Discussion.

-> P6635, L12: *Instead of 3g_s, I suggest writing: "As a result, nine samples were prepared (one for each of the three grain sizes and three water input rates)".*

-> P6635, L23-24: *Apparently, the statement is too strong, as it is not clear whether the initial condition of the snowpack was dry. (see P6644, L14).*

Changes in manuscript
We agree with all these observations: we will incorporate them in our revised manuscript.

-> P6635, L25-28: *Maybe just choose one unit and report all results consistently.*

Answer
We would like to keep both units as one is experimental and refers explicitly to a mass flux (g/min), whereas the second one (mm/h) is derived and represents a more familiar variable in hydrologic applications. In the text, we systematically use the second one.

-> P6636, L2: *"Consequently". It is not clear if the low variation in snow density is by design or by accident. I think "consequently" is not the right conjunction here.*

Answer
We did not apply any tamping during sieving operations so we had no direct control on the values of dry density. Given the low coefficient of variation observed, we point out that this work investigates how the properties of capillary barriers and associates preferential flow vary with grain size. Future investigations should focus on the generalization of this work to layers of different density (as e.g. done by Yamaguchi et al. 2010 and 2012, references in the text).
Changes in manuscript
We will modify this passage of the manuscript to clarify this point.

-> P6636, L5: *Unless it is irrelevant for replication of the experiments, maybe provide some detail of the "operational reasons".*

Answer
We decided to increase the thickness of the lower layer after performing a first set of experiments. The main idea was increasing the distance between the interface between layers and the lower base of the sample in order to increase the amount of observations of our experiments. However, our conclusions are not affected by this difference, as ponding of water occurs in the upper layer.
Changes in manuscript
We will remove this statement from the text. This is because our operational reasons are useless for interested readers. On the other hand, it is important to point out that conclusions are not affected by differences in the thickness of the lower layer: we will add this in the text.

-> P6636, L5-6: *It seems that the number 1, 2 and 3 refer to the water influx rate. Please introduce this nomenclature near P6635, L11-12.*

Changes in manuscript
We agree. We will add this nomenclature as suggested.

-> P6636, L15: *See my earlier comment. I guess the reason is that it is really difficult to exactly apply a specified infiltration rate? Maybe say this then explicitly.*

Changes in manuscript
Exactly. We will improve the text here.

-> P6636, L20: *"specific travel time". By dividing by a length scale, it rather is a velocity than a travel time. I suggest the term "bulk velocity" here. Or something similar that makes clear it is a kind of velocity.*

Answer
The unit of measurement of τ is min / cm, as it is the ratio between time and a length scale. Its reciprocal is a velocity. In this framework, calling it "bulk velocity" may be ambiguous as it may suggest a wrong relation between τ and travel time, as a higher τ means a slower flow, contrary to the relation between velocity and time.

Changes in manuscript
We will specify the unit of τ in the main text.

-> P6636, L27: "starting from these information" -> "These measurements are translated into ..."

Changes in manuscript
We will incorporate this.

-> P6637, L1: "ImageJ" is a rather unspecific software package. Maybe provide more information here how the wet part was determined. Probably this involves some manipulations with contrast/brightness and/or specifying some thresholds how "blue" the image should be in order to consider it to be wet? This information may be helpful for other researchers and for replicating these type of experiments.

Answer
ImageJ (http://imagej.nih.gov/ij/) is a software of image processing that is publicly available on the Internet. Calculating wet areas may be performed by using automatic image processing tools and defining, for instance, a threshold in colour. However, we have performed here a manual detection of wet areas for all the sections considered, as a high degree of human judgement may be more reliable than automatic detection when dealing with complex patterns of liquid water flow in snow. This meant manually delimiting fingers area for all the sections. Then, ImageJ performs an automatic calculation of the extension of these blue areas. This value is then used by the software to calculate the ratio between blue and total areas. Clearly, similar calculations may be performed using alternative software.
Changes in manuscript
We will provide a link to the software and its version as additional information. We will also specify in the revised manuscript that we delimited blue areas manually and that similar calculations might be performed using alternative software.

-> P6637, L11: "FEM": abbreviation is not introduced.

Changes in manuscript
We will include "Finite Element Model" in the manuscript.
-> P6637, L14: "or liquid water content" -> "and liquid water content"

Changes in manuscript
We agree.

-> P6637: I think this is not a complete description of model setup. For example, in Wever et al. 2014 and 2015, also a parameterization for saturated hydraulic conductivity is specified, as well as a model for unsaturated hydraulic conductivity. In Wever et al. 2015, additionally an averaging method is specified for hydraulic conductivity at the interface nodes. Is there a version number for the SNOWPACK version used in the paper? Maybe also include a link to a source code repository or something similar where the source code can be retrieved?

Answer
We agree with you that additional information about model setup will be very useful: we will provide the details of SNOWPACK settings in our revised manuscript. The version of SNOWPACK we are using originates from an older version of the model than the one currently presented in, e.g., Wever et al. 2014 or 2015, and it is not included in open source SNOWPACK, so we cannot link it to a precise version number or code repository. Note that, following some comments by Referee #2, we will add in the text comparative simulations using the water scheme by Wever et al. 2014.
Changes in manuscript
We will provide a table with detailed simulation conditions, such as equations of hydraulic conductivity, suction, residual water content etc. We will provide these data for both schemes used.

-> P6638, L4: How was this achieved? By just taking the incoming longwave radiation equal to $\epsilon \sigma T^4$, using Stephan Boltzmann's law?

Answer
The value of long wave radiation was determined from Stefan Boltzmann's equation with $L=\epsilon\sigma T^4$, $\epsilon=0.97$, $\sigma=5.67 \cdot 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$, $T=273.15 \text{ K}$.
Changes in manuscript
We will add this specification in the text.

-> P6638, L1: Not clear what the relation is between the air temperature and the incoming water flux?

Answer
In our simulations, we have set the rain-snow threshold value to + 1.5 °C. By then setting air temperature to +1.51°C, all incoming water is classified as liquid. This value did not affect sensible and latent heat because wind speed was set to zero in simulations. However, we agree with Referee #2 that the temperature threshold in SNOWPACK can be adjusted: setting the threshold to -0.01 °C and air temperature to 0°C will allow us to reproduce the same controlled conditions used during cold laboratory experiments.
Changes in manuscript
We will clarify this point in the text. Moreover, we will re-run our simulations by considering a rain-snow threshold value of -0.01 °C.

-> P6638, L21: "We report" -> "We show"

Changes in manuscript
We agree.

-> P6639, L19: "no definitive results" Please expand on this.

Answer
We will clarify our conclusions on this point. When considering FC and FM samples, horizontal redistribution of water and ponding over the capillary barrier was systematic: we observed a highly saturated section even 2 cm above layers' interface. Results for different water input rates are also very coherent. On the other hand, MC samples returned more varied results. For instance, water spreading is restricted for MC1, while a marked ponding effect is visible in MC3.
Changes in manuscript
We will improve our presentation here. Starting from Referee #2's suggestions, we will also provide some quantitative analyses about the differences in suction for layers of different grain sizes in order to discuss this outcome in details.

-> P6639, L21 and elsewhere: "4/6" -> I prefer "4 out of 6"

Changes in manuscript
We agree.

-> P6640, L8: For interpreting the value of 33% (and the values mentioned later), it may be really useful to have a kind of error estimation for this measurement. If it is not possible to get a quantitative error measure, maybe the authors can use their expert judgement to provide the reader with a kind of "poor-man"'s error estimation?

Answer
We agree with you that a quantitative error estimation may be helpful. We will therefore add some comments on this point (see below).
Changes in manuscript
In the revised manuscript, we will completely rewrite Section 5.4 by adding more details about 1) previous uncertainty assessments of the melting calorimetry that we used (the so-called Endo-type snow-water content meter proposed by Kawashima et al. 1998); 2) the assessment of instrumental error in our experiments, basing on a similar approach to the one kindly reported by Referee #2 in his xls-file; 3) reasons why we chose melting calorimetry instead of dielectric methods, among others. This new focus of Section 5.4 should provide enough details for interpreting LWC measurements in our paper. Thank you.

-> P6640, L8: "interlayer plane" -> "interface"

-> P6641, L7: "We measure this" -> "We describe heterogeneity using the variable f "

-> P6641, L15: I don't think that "e.g." can be used in the middle of a sentence, only as "e.g., <text>"

Changes in manuscript
We agree. We will improve the manuscript.

-> P6641, L28: Does it mean that the debate is between Schneebeli (1995) and Waldner et al. (2004)? Actually, I don't agree that there is a debate, I just think both observations have been done, and apparently both cases can occur (i.e., preferential flow paths following the same path, or creating new paths).

Answer
We agree with this comment and with your idea. Clearly, this sentence does not mean that the debate is between Schneebeli (1995) and Waldner et al. (2001).
Changes in manuscript
We will welcome Referee #2's suggestion: we will remove this discussion from the manuscript.

-> P6642, L3: I couldn't find the value of 13% in Waldner et al. (2004). I could only find a value of 1.3% in Fig 13 in that paper, or on P7 in the text (my understanding is that $0.013 \text{ m}^3/\text{m}^3 = 1.3\%$). Note that additionally, i.e. should be e.g.

Changes in manuscript
We accidentally misinterpreted the value of $0.013 \text{ m}^3/\text{m}^3$ in Waldner et al. (2004). We will modify the discussion accordingly.

-> P6642, L12: "It follows" is maybe too strong, as direct comparison of infiltration rate is rather difficult. "It suggests" suits better.

-> P6642, L12-L16: I had some difficulties understanding the sentence, I would recommend to break it into smaller sentences, because it is a rather important point.

Changes in manuscript
We agree with these comments. We will modify these passages.

-> P6642, L27: I'm not sure if Wever et al. (2014) is the suitable reference here. Doesn't this refer to their analysis of the melt water front progress measured via the ground penetrating radar, which was published in Wever et al. (2015)? In any case, please specify what "field observations" you are pointing to.

Answer
In this section of text, we refer to the comprehensive evaluation of different water schemes proposed by Wever et al. (2014). They evaluate a bucket type approach, an approximation of Richards Equation (NIED scheme, the scheme we consider here) and the full Richards Equation by using lysimeter data from Weissfluhjoch (WFJ) and Col de Porte (CDP). In that paper, Wever et al. (2014) note that “An analysis of the runoff dynamics over the season showed that the bucket-type and approximated RE scheme release meltwater slower than in the measurements, whereas RE provides a better agreement (Abstract)”, or that “The simulations with RE produce runoff soon after the first measured runoff, whereas the bucket and NIED simulations show some delay. For the rest of the melt season, there are no important differences. Because the bucket and NIED simulations withhold the water too much in the snowpack compared to the lysimeter and the simulations with RE, the daily outflow near the end of the season becomes higher than in simulations with RE”. (Section 4.1, Daily time scale). We relate this to our observations as an overestimation of runoff timing may be related to an underestimation of liquid water speed in snow due to the absence of a specific treatment of preferential flow. However, we see that this link is not clearly expressed in the text and that the current version of the manuscript may suggest a discussion of water speed in snow rather than runoff timing at snow base. We will therefore elaborate on this discussion.
Changes in manuscript
We will clarify this passage in the text as outlined in our answer.

-> P6643, L5: "decrease in LWC". At first sight, this sounds as a temporal decrease, but I guess it is about the vertical shape of the profile? Maybe write then: "The model predicts correctly the low values in LWC below the boundary."

Changes in manuscript
We agree. We will improve the manuscript on this point.

-> P6644, L5: "a heavy parametrization can play an important role". This sentence is a bit vague. It sounds like that a heavy parametrization is having so many degrees of freedom, it can fit everything and thereby plays an important role, but I don't think that this is the message to be conveyed.

Answer
We apologize for this misunderstanding. The main idea here is that the water scheme by Hirashima et al. (2010) includes the prediction of several parameters/variables, such as suction, unsaturated conductivity or permeability. Clearly, other water schemes need similar information. The predictions of all these parameters/variables rely mostly on experimental parameterizations that are clearly affected by statistical and experimental noise. This problem is paramount in the case of snow as performing experiments with a material undergoing phase change is very challenging. This noise may cause uncertainty in the prediction of parameters and this may affect the performance of any model used to predict liquid water flow in snow. We will improve our discussion on this point.
Changes in manuscript
We will clarify this passage in the text as outlined in our answer.

-> Experimental limitations: nice section to have here.

-> Conclusions: The first paragraph is a too long summary of the introduction, which is not necessary at this point. Basically, in my view, P6645, L4-12 can be removed.

-> Where Table 2 is explaining the symbols in the caption, Table 1 is not. I prefer that the symbols used in the table are explained in the table caption, so the Tables are self-explanatory.

-> Figure 1: it would be helpful if the caption mentions the diameter of the rings, in order to interpret the figure.

-> Figure 2: it would be helpful if a scale is added to the figure, for example: a vertical bar denoting the 2cm extent of each ring.

-> Figure 3, 4 and 5: in print, some lines didn't show up properly. Particularly the axes were bad in print. Please increase the thickness of the lines.

-> Figure 3: It would be helpful to explain symbol f in the caption. Maybe also mention that f is observed.

-> Figure 4: Maybe write: "in terms of measured volumetric liquid water content"

-> Figure 5: It would be more logical if the dots are plotted in the middle of the ring, as it concerned the LWC in the ring, rather than at the top of the ring.

Changes in manuscript
We agree with all these observations. Figures will be improved as suggested. The only exception is Fig. 5, where we would like to plot dots as a function of the elevation of rings top surface (i.e., to keep this Figure as it is). The main reason is that this enables a direct comparison between Fig. 5 and all the other figures, as the vertical coordinate is the same in all the plots. This is nonetheless clearly explained in the caption.

Dear Dr. Christoph Mitterer, Referee #2,

We would like to thank you very much for your meaningful comments on our manuscript and your suggestions. We will address all of them in our revised manuscript. Please find here a point-by-point reply to your comments. Your comments are in *italic*. For all the points, we provide answers and we outline our planned changes in manuscript.

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 inappropriate or need a more in depth reanalysis 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.

Answer
We agree with you that advancing our understanding of liquid water flow in layered snow is aimed at providing innovative elements to assess wet snow avalanche risk and/or at improving current description of liquid water flow in snow. We will elaborate on all the points suggested to improve the current analysis of experimental results. We will also check references and grammar, as well as the definition of all symbols used.

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.

Answer
We agree with you that our modelling analysis may be improved by considering other water schemes. As for SNOWPACK: we will include in the revised version of this manuscript comparative results obtained using the scheme presented by Wever et al. (2014, reference in the text). When preparing the first version of this manuscript, we chose the numerical scheme by Hirashima et al. (2010, reference in the text), which solves a water transport model based on van Genuchten formulation and that includes a parametrization of retention properties of snow and unsaturated conductivity, which are necessary variables for modeling liquid water flow over a capillary barrier. Moreover, we are also more familiar with this scheme and this is an important aspect when comparing laboratory experiments with complex numerical models. However, we agree with you that comparing our observations with new numerical schemes is important and this is why this comparison will be included in the text. We have already considered to include a comparison between these observations and the water scheme by Hirashima et al. (2014, reference in the text). Actually, evaluating that scheme by collecting a broad dataset of liquid water patterns around a capillary barrier was one of the reasons why we performed these experiments. In fact, we agree with you that these observations will provide valuable new data to extend the evaluation presented in Hirashima et al. (2014), which is based on experimental observations by Katsushima et al. (2013) in homogeneous snow. However, the main focus of this manuscript is on experimental results, as it should provide systematic, quantitative and repeated experimental evidences that layered snow is subjected to a pause in wetting front advancement over a capillary barrier (this is what we mean with ponding) and to associated preferential flow. These observations are motivated by scarce

quantitative characterizations of capillary barrier effects in existing literature and may be useful to snow scientists in general. In this context, an evaluation of the performance by a well-known operational snow model (SNOWPACK) may be useful to evaluate the relevance of these processes in ordinary modelling practice. On the other hand, an exhaustive analysis of the settings and performance of the scheme by Hirashima et al. (2014) needs an ad-hoc analysis. This is the reason why we are currently working on a separate manuscript on this topic, following seminal analyses in Hirashima et al. (2014a, 2014b, references at the end of this reply).

We will also enlarge our discussion in current Sections 5.1 and 5.2. For instance, we will mention that existing literature suggests a relation between water entry suction and velocity (see DiCarlo 2007, reference in the text) and this supports the idea that water input rate and liquid water patterns in snow are related. On the other hand, we will also mention that our experiments were performed in unsteady conditions and therefore the inflow rate in the sublayer is not precisely known as the capillary barrier stopped water flow. This condition might have affected our results, in that the unsteady flow below the interface is comparable for all water input rates. Moreover, considering outcomes of different experiments in sand (saturated permeability equal to 87 cm/min), DiCarlo (2013, reference in the text) reports that finger width increases with both very high and very low fluxes, whereas it keeps constant for a wide range of fluxes between ~ 0.1 and 10 cm/min (see Fig. 2 in DiCarlo (2013)). Water input rates in our experiments span 10 and 100 mm/h, which represents a narrow range if compared with expected values of saturated conductivity in snow (see Katsushima et al. (2013) for data). We therefore suggest that future developments of this work should investigate the relation between flux and wet fractions more extensively.

Changes in manuscript

We will include in the manuscript an extensive discussion about the performance by the water scheme presented in Wever et al. (2014). Moreover, we will also enlarge the discussion in Sections 5.1 and 5.2 about the relation between preferential water flow in snow and water input rate as outlined in our answer.

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.

Answer

We agree with these comments. In the revised manuscript, all the text will undergo major structural modifications (see below).

Changes in manuscript

We will eliminate Section 2. In fact, materials in Section 2.1 can be found elsewhere in the literature and this is the reason why we will remove this Section completely. On the contrary, we will include some passages of Section 2.2 in the Introduction in order to make our manuscript more focused on capillary barriers and preferential flow in layered snow. The revised Introduction will explicitly deal with existing limitations in measuring and modelling liquid water flow in snow, with a focus for capillary barriers effects and preferential flow. We will also merge Sections 4 and 5 in a unique "Results and Discussion" Section.

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 0.040.03 (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.

Answer
We apologize if our Discussion in Section 5.4 could be misleading. Actually, instrumental error is also our explanation for the mismatch between supplied and measured liquid water mass. This explanation is discussed between line 20 page 6644 and line 2 page 6645, but we see that the way we presented this discussion could be confusing. Clearly, we exclude accidental melt of our samples as they were stored at -20°C during preparation and at 0°C (in controlled conditions) during experiments.
Changes in manuscript
We will modify Section 5.4. by adding more details about 1) previous uncertainty assessments of the melting calorimetry that we used; 2) the assessment of instrumental error in our experiments, basing on a similar approach to the one kindly reported by you in the xls-file; 3) reasons why we chose melting calorimetry instead of dielectric methods, among others. We clearly agree with you that the dilution method represents a very valid alternative. We will suggest this method explicitly for future experiments.

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

Changes in manuscript
We will change our wording here.

- P. 6628, L. 18: There is no thickness = 0cm

Changes in manuscript
We will eliminate this specification in the Abstract as it is not key. In the manuscript, we will specify that the thickness is ≤ 3 cm.

- P. 6628, L. 18: Delete “extensive”

Changes in manuscript
We agree.

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.

Answer
We agree with all these comments. We will therefore modify our Introduction as kindly suggested.
Changes in manuscript
As already mentioned, we will summarize some relevant passages of Section 2.2 in the Introduction, which will be focused on existing limitations in measuring and modelling liquid water flow in layered snow. We will also include a more in depth discussion about the results of our team. Moreover, we will detail reasons why capillary barrier effects and preferential flow pose important challenges for modellers.

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 α 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.

Changes in manuscript
As already mentioned, this Section will be eliminated in a general attempt to reorganize the presentation and motivation of our work. Clearly, our Introduction will specifically focus on capillarity and preferential flow in snow, as suggested.

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.

Answer
We agree with this comment.
Changes in manuscript
In the revised manuscript, we will provide a clear definition of ponding as a pause in the undisturbed

advancement of a wetting front due to capillarity effects and consequent accumulation of liquid water over the boundary. This definition is inspired by the description of fingering in layered soils by Baker and Hillel (1990, see page 20). Moreover, we will also pay specific attention to avoid any confusion between ponding and capillary barriers.

- *Please state more clearly why the saturation overshoot found by Katsushima et al. (2013) is so important.*

Answer
Nowadays, the exact physics of preferential flow is still not known (see DiCarlo 2013, reference in the text). Observations show that, in soils, an unstable infiltration profile is marked by an overshoot profile in terms of LWC (saturation overshoot) or suction (capillary pressure overshoot, see DiCarlo (2004, 2007, 2013); Baver et al. (2014), references in the text). This represents an important point as saturation and pressure overshoots in soils are considered the cause of gravitational flow instability, rather than an effect. This suggests also the need to take into account pore-scale processes in the modelling (see again DiCarlo 2013 or Baver et al. 2014). Examples of pressure overshoots have been observed in homogeneous snow samples during preferential infiltration by Katsushima et al. (2013). In addition, Hirashima et al. (2014) report promising attempts to reproduce similar overshoot dynamics using a model. These results provide evidences that preferential flow in snow at 0°C may be explained (Katsushima et al. 2013) and modelled (Hirashima et al. 2014) starting from the theory of gravity-driven instability of fingers in soils.
Changes in manuscript
We will include a specific passage in the Introduction basing on our answer to this comment.

Laboratory experiments: Preparation of samples and experiments

- *General remarks: Combine Table 1+2 to assure better readability.*

Answer
We appreciated this suggestion. However, we would like to keep Table 1 and 2 separated as one (Table 1) deals with experiments design, whereas the other one (Table 2) reports experiments results. Therefore, they will appear in different parts of the text.

- *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*

Changes in manuscript
We will elaborate on these points.

Laboratory experiments: Data collection

- *General remarks: Why do you express τ as the inverse of velocity?*

Answer
We use min/cm as the unit of dimension of τ as it is a ratio between a time interval and a length scale, thus it is defined as the reciprocal of velocity.
Changes in manuscript
We will include a clearer definition of τ by isolating this Equation from surrounding text and specifying which is its unit of measurement.

- P. 6636, L. 20-21: Rephrase.

Changes in manuscript
We will elaborate on this point.

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.

Changes in manuscript
We will elaborate on these points.

- 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.

Answer
In our simulations, we have set the rain-snow threshold value to + 1.5 °C. By then setting air temperature to +1.51°C, all incoming water is classified as liquid. This value did not affect sensible and latent heat because wind speed was set to zero in simulations. However, we agree with you that the temperature threshold in SNOWPACK can be adjusted: setting this threshold to -0.01 °C and air temperature to 0°C will allow us to reproduce the same controlled conditions used during cold laboratory experiments.
Changes in manuscript
We will elaborate on this point in the text. Moreover, we will re-run our simulations by considering a rain-snow threshold value of -0.01 °C.

- P. 6638, L. 19-20: Delete this sentence or move it to the Intro.

Changes in manuscript
We will delete this sentence.

Results

- General remarks: see major issues above

Discussion: the ponding process

- General remarks: see major issues above

Changes in manuscript
We will modify the text accordingly, see our answers 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.

Answer
In our first version of the manuscript, we report that MC tests reveal no definitive result. This means that ponding behaviour in our MC samples was very varied, although evidences of ponding are visible in all the samples. We apologize if our wording here was misleading. We agree with you that samples MC2 and MC3 show clear ponding and water diversion over the boundary. On the contrary, only localized redistribution of water over the boundary is evident in MC1 (see Fig. 2 in the paper). In the same sample, LWC over the boundary is around 4.5 vol%, which represents a peak if compared with LWC values immediately above (2.7 vol%) and below (1.7 vol%). However, this difference is very reduced with respect to MC2 and MC3.
Changes in manuscript
We will clarify our analysis on this point.

- *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?*

Answer
Values of LWC in MC1 and MC2 are quite comparable at all depths apart from 8 cm. Here, LWC in MC2 is higher than LWC in MC1, and this is supported by a wider blue area in MC2 in Fig. 1. However, note that blue areas in Fig. 1 are poorly correlated with values of LWC in Figs 4 and 5 for some sections as areas in Fig. 1 represent just a small fraction of the volume of each acrylic ring, whereas values of LWC represent bulk LWC within each acrylic ring.

- *P. 6639, L. 26 – P. 6640, L. 4: Can you please report more quantitatively on the differences of 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).*

Answer
We agree with you that a quantitative analysis may help.
Changes in manuscript
We will include some values of suction for reference LWCs in all the three types of snow considered to evaluate the magnitude of the differences, as kindly suggested. We will also compare these differences with expected water entry suctions in medium and coarse snow.

- *P. 6640, L. 8: I think that “In particular : : :” is the wrong wording here.*

Changes in manuscript
We will elaborate on this.

- *P. 6640, L. 10: What is an interlayer plane? Do you mean layer boundary?*

Answer
We mean the interface between the two layers. The word “interlayer plane” was originally used by Baker and Hillel (1990, reference in the text) for describing fingering during infiltration into layered soils. However, we see that “interface” or “layer boundary” may be clear as well.
Changes in manuscript
We will replace “interlayer plane” with “interface” or “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.*

Answer
We agree with you that this point could be clarified. Actually, we do not aim at linking our findings to those by DiCarlo (2007). We just aim at pointing out that the imbibition curve may represent the generalized relation between capillary entry pressure and liquid water content, as suggested by DiCarlo (2007): “instead of a single valued capillary entry pressure [...], the capillary pressure is simply given by the imbibition curve.”
Changes in manuscript
We will modify this sentence to make it clearer.

- P. 6640, L. 13-16: *I think it is quite keen to assume that 33-36*

Answer
We think this comment is probably incomplete. However, in the revised version of the manuscript we will clarify this sentence.

- 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.*

Answer
We apologize if our wording was misleading. Actually, we agree with you that our MC samples reveal a peak in LWC. However, as we note in the text, this peak is smaller than the peak in FC and FM samples (this is understandable, as suction differences between fine snow and medium or coarse snow are high), thus revealing that ponding (i.e., accumulation of liquid water over the boundary) is limited in this type of layering if compared with FC and FM samples.
Changes in manuscript
We will clarify this sentence.

- P. 6640, L. 19 – P. 6641, L. 4: *This sounds like a mix of Introduction and Conclusions. Please rewrite this paragraph.*

Answer
We agree with you.
Changes in manuscript
We will move passages of this Section in the Introduction

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.*

Changes in manuscript
We will elaborate on these points.

- 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.*

Answer
We agree with you.
Changes in manuscript
We will remove 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?*

Answer
The main idea behind this paragraph is comparing specific travel times measured in fine over medium snow with those measured in either fine or medium (homogeneous) snow. The first outcome is that the specific travel time in FM snow is higher than the specific travel time in medium snow. This is clearly expected since permeability in medium snow is higher than in fine snow. Also, τ in FM snow is higher than the τ observed in a homogeneous sample made by fine snow. This is less expected as permeability in fine snow is very low. This comparison helps to quantify the relevance of capillary effects in ruling water speed in snow and the arrival time of meltwater at snow base and highlights the reason why including capillary effects in modelling liquid water flow in snow is important.
Changes in manuscript
We will clarify our discussion.

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*

Changes in manuscript
We will elaborate on these points.

References
H. Hirashima, S. Yamaguchi and Y. Ishii (2014a). Application of a multi-dimensional water transport model to reproduce the temporal change of runoff amount. Proceedings to International Snow Science Workshop, Banff, 2014.
H. Hirashima, S. Yamaguchi and Y. Ishii (2014b). Simulation of liquid water infiltration into layered snowpacks using multidimensional water transport model. Proceedings to International Snow Science Workshop, Banff, 2014.

Observations of capillary barriers and preferential flow in layered snow during cold laboratory experiments

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Abstract.

We carried out observations of dyed water infiltration in layered snow during cold laboratory experiments. We considered three different finer-over-coarser textures and three different water input rates. Nine samples of layered snow were sieved and subjected to constant supply of tracer at 0°C. By means of visual inspection, horizontal sectioning, and measurements of liquid water content, capillary barriers and associated preferential flow were characterized. The dynamics of each sample were also simulated solving Richards equation within the 1D multi-layer physically-based SNOWPACK model. Results reveal that capillary barriers and preferential flow are relevant processes ruling the speed of liquid water in stratified snow. Both are marked by a high degree of spatial variability at cm scale and complex 3D patterns. During unsteady percolation of liquid water, observed peaks in bulk volumetric liquid water content (LWC) at the interface reach $\sim 33 - 36$ vol% when the upper layer is composed by fine snow (grain size smaller than 0.5 mm). A comparison with expected wetness at water entry suction suggests that LWC might locally reach saturated conditions. Spatial variability in water transmission increases with grain size, whereas we did not observe a systematic dependency on water input rate for samples containing fine snow. The comparison between observed and simulated LWC profiles reveals that the implementation of Richards equation reproduces the existence of a capillary barrier for all observed cases and yields a good agreement with observed peaks in LWC at the interface between layers.

1 Introduction

Liquid water movement in snow rules streamflow timing and amount (Lundquist and Dettinger, 2005; Lehning et al., 2006; Wever et al., 2014), snowpack mechanical properties and stability in wet

conditions (Marshall et al., 1999; Baggi and Schweizer, 2008; Mitterer et al., 2011; Techel et al., 2011; Mitterer and Schweizer, 2013; Mitterer et al., 2013; Schmid et al., 2015), and snow albedo (Dietz et al., 2012). Furthermore, Harper et al. (2012); Forster et al. (2014); Machguth et al. (2016)

25 report that meltwater percolation - storage dynamics in snow and firn might play an important role in determining the timing of sea - level rise by Climate Change. Liquid water in snow can be measured as a volumetric fraction (LWC, or θ), i.e., the ratio between liquid water volume and total snow volume (Fierz et al., 2009). LWC is usually expressed in vol %, or %.

Water flow in snow emerges as a complex, 3D process when observed in the field or in the laboratory. The co-existence of water and ice grains causes fast metamorphism (Brun, 1989) and phase change, which leads to melt-freeze and to the possible development of ice lenses when water infiltrates in subfreezing snow (Pfeffer and Humphrey, 1996). The interaction with topography can redistribute water at slope scale (Eiriksson et al., 2013). Moreover, water movement is usually marked by high spatial variability due to the occurrence of preferential flow, or fingering (Marsh and Woo, 1984a, 1985; McGurk and Marsh, 1995; Schneebeli, 1995; Waldner et al., 2004; Williams et al., 2010; Katsushima et al., 2013). These processes deeply complicate the modeling of liquid water in snow, which has been often simplified in the past by using a simple Darcian theory that neglects effects of capillary gradients on the flow (Colbeck, 1972; Wankiewicz, 1978). In particular, fingering is deemed to play a key role in ruling water arrival time at snow base, hence runoff (Wever et al., 2014, 2015).

The exact physics of preferential flow in snow is still not known (Katsushima et al., 2013) and modeling strategies are therefore still preliminary. For instance, Marsh and Woo (1985) propose an explicit definition of multiple-path routes, whereas Katsushima et al. (2009a) introduce a threshold θ triggering preferential runoff. Wever et al. (2014) report that solving Richards equation accounting for suction gradients improves run-off estimations at different temporal resolutions, but it also accelerates meltwater front progress if compared with data from an upGPR and simulations by a bucket scheme (Wever et al., 2015). This result has been attributed to an unexpected simulation of some effects of preferential flow by the water scheme used.

The use of Richards equation for modeling wetting front instability in porous media is still a matter of debate (Egorov et al., 2003; Waldner et al., 2004; DiCarlo, 2013) due to the occurrence of peculiar pore-scale processes when water infiltrates as fingers (Egorov et al., 2003; DiCarlo, 2013; Katsushima et al., 2013; Baver et al., 2014). Observations reveal that, in soils, an unstable infiltration profile may be marked by an overshoot profile in terms of θ (saturation overshoot) or ψ (capillary pressure overshoot, see DiCarlo (2004, 2007, 2013); Baver et al. (2014)). Examples of pressure overshoots have been observed in homogeneous snow samples during preferential infiltration by Katsushima et al. (2013). In addition, Hirashima et al. (2014) report promising attempts to reproduce similar dynamics using a model; they show that including spatial heterogeneity of snow properties and water entry suction (ψ_{WE}) in a 3D resolution of Richards equation enables to re-

construct preferential flow effects. These results suggest that preferential flow in isothermal snow at
60 0°C might be explained (and modeled) basing on the theory of gravity-driven instability of fingers
in soils (Katsushima et al., 2009b, 2013).

According to Hirashima et al. (2014), water entry suction is thus a key variable ruling prefer-
ential flow development, as it impedes the movement of water between dry and wet snow during
wetting until suction reaches ψ_{WE} . This process causes local accumulation of liquid water at mi-
65 crostructural discontinuities (henceforth, simply ponding). A decrease in ψ during ponding is caused
by the fact that θ and ψ are related by a hysteretic relation called Water Retention Curve, WRC
(Daanen and Nieber, 2009; Yamaguchi et al., 2010; Adachi et al., 2012; Yamaguchi et al., 2012).
Then, water infiltrates in locations marked by local heterogeneity, thus triggering preferential flow.

In layered snow, water entry suction is also the driving parameter ruling capillary barrier develop-
70 ment (Baker and Hillel, 1990). This is a finer-over-coarser transition in layering that causes a pause
in the undisturbed advancement of the wetting front, ponding, horizontal diversion of liquid water
and a delay in the expected travel time of water. Hill and Parlange (1972); Baker and Hillel (1990);
Hillel and Baker (1988) discuss this process in soils, whereas Wakahama (1963); Jordan (1995);
Waldner et al. (2004); Peitzsch et al. (2008); Mitterer et al. (2011) report some examples in snow.
75 In soils, Hillel and Baker (1988); Baker and Hillel (1990) note that, after reaching ψ_{WE} , subsequent
flow in the coarser layer will be marked by fingers if, in steady conditions, the hydraulic conductivity
of the lower layer at ψ_{WE} is greater than the flux through the top layer q (due to mass conservation).
Thus, ponding of water above a capillary barrier is prone to subsequent flow instability, namely, to
the development of preferential channels.

80 Capillary barriers can play an important role for triggering wet snow avalanches (Mitterer et al.,
2011; Wever et al., 2016). For example, Wever et al. (2016) report that predicted local accumulations
of liquid water like those expected during ponding at capillary barriers can be used to separate
avalanche and non-avalanche days. The position of peak LWC within the snow cover correlates
with avalanche size. These processes also affect the timing of snowmelt runoff (Wever et al., 2014).
85 Furthermore, a thorough investigation of the properties of capillary barriers may help to gain a better
understanding of the physics of water instability in snow in general, as water flow around these
textural discontinuities is driven by ψ_{WE} . However, their characterization in the literature is still very
limited (Eiriksson et al., 2013). Indeed, existing ad hoc observations in the laboratory or in the field
consider a restricted variety of grain size (g_S) combinations (Jordan, 1995; Waldner et al., 2004). In
90 field conditions, LWC profiles are usually measured using destructive, manual methods that strongly
limit the temporal and spatial resolution of profiles. Thus, the evaluation of promising results from
physically-based models (Hirashima et al., 2010; Mitterer et al., 2011; Wever et al., 2014, 2015) are
often hampered by a lack of a proper high-resolution experimental database.

Here, we focus on observing capillary barriers and associated preferential flow in snow using
95 laboratory experiments. We collected systematic observations of dyed water infiltration in layered

snow samples with different grain size combinations and different water input rates. We measured, for each sample, the thickness of the volume of the upper layer affected by ponding of water at the textural boundary, LWC profiles, wet snow fraction at different depths, and the arrival time of liquid water at sample base. These experiments were performed choosing a quite high vertical resolution of all the measurements (2 cm) and a broad set of input rates and textures, thus enabling a quantitative characterization of capillary barriers properties that is more exhaustive than before. All the laboratory experiments are compared with numerical simulations of Richards equation in snow by the 1D multi-layer physically-based SNOWPACK model.

We consider isothermal conditions at 0°C, thus avoiding any investigation about wetting front advancement in subfreezing snow, which presents additional challenges. As an example, Marsh and Woo (1984a, b) report that zones with mixed wet and dry snow develop in such conditions (see also Pfeffer et al. (1990); Pfeffer and Humphrey (1996)). The impact of these processes on runoff response time of snow in sub-freezing conditions is still a matter of debate (Marsh and Woo, 1984b), especially on seasonal time scales (Wever et al., 2014).

2 Methods

2.1 Preparation of samples

The main prerequisite to observe capillary barriers in initially dry snow is a finer-over-coarser profile in layering. For this purpose, three combinations of grain size were considered here: 1) FC, i.e., fine-over-coarse snow; 2) FM, i.e., fine-over-medium snow; 3) MC, i.e., medium-over-coarse snow. We classify snow with $0.25 \text{ mm} \leq g_S \leq 0.5 \text{ mm}$ as fine, snow with $1 \text{ mm} \leq g_S \leq 1.4 \text{ mm}$ as medium, and snow with $2 \text{ mm} \leq g_S \leq 2.8 \text{ mm}$ as coarse. Note that this nomenclature is convenient for the scopes of this paper, but it is not consistent with the International Classification proposed by Fierz et al. (2009), which for instance defines medium snow grain size as $0.5 \text{ mm} \leq g_S \leq 1 \text{ mm}$.

Experimental evidences reveal that the area occupied by fingers in snow (Katsushima et al., 2013) and the value of ψ_{WE} (DiCarlo, 2007; Katsushima et al., 2013) may be both functions of water input rate. In order for our conclusions to be more general, we carried out experiments with three different water inputs W : these are $\sim 10, 30$ and 100 mm/h . These water input rates are a compromise between the need for exploring the properties of capillary barriers over a broad range of W , expected melt rates in natural conditions (DeWalle and Rango, 2011), and operational constraints (specifically, expected duration of the tests). Note that Katsushima et al. (2013) has already observed preferential infiltration in snow with average g_S between $0.421 - 1.439 \text{ mm}$ for different water input rates ($21.7 \text{ mm/h} \leq W \leq 205.5 \text{ mm/h}$). Thus, we did not consider any instability criterion (Saffman and Taylor, 1958; Baker and Hillel, 1990; de Rooij, 2000; DiCarlo, 2013) while designing our experiments.

130 Nine samples were prepared in a cold room at -20°C using refrozen melt forms (one sample for each of the three grain size combinations and three water input rates). Henceforth, numbers 1, 2 and 3 differentiate samples with same grain size combination, but subjected to different water input rate (10, 30 and 100 mm/h, respectively). Fragmented snow particles were firstly partitioned in several classes of grain size. Afterwards, the three g_S chosen were sieved a second time to prepare the samples. Snow was packed in a cylindrical container. The container was composed by a number of acrylic rings (height equal to 20 mm, diameter equal to 50 mm) that were previously taped on the external side. After sieving the lower layer, its dry density ($\rho_{D,L}$) was measured by gravimetry. The dry density of the upper layer ($\rho_{D,U}$) was measured by gravimetry at the end of sieving operations (by considering the difference between sample total weight and sample weight before sieving the upper layer). After preparation, each sample was moved to a second cold room at 0°C , where it was stored for at least 12 hours to reach initial conditions of dry snow at 0°C .

We report in Table 1 the details of each experiment. Water input rates are reported both in mm/h and in g/min (samples diameter equal to 5 cm). The coefficients of variation of $\rho_{D,U}$ and $\rho_{D,L}$ read 0.06 and 0.03. We did not apply any tamping during sieving operations so we had no direct control on the values of $\rho_{D,U}$ and $\rho_{D,L}$. Given the low variability of these two variables, we point out that this work investigates how capillary barrier effects and associated preferential flow vary with grain size only. Future investigations should focus on the generalization of this work to layers of different density. Some samples (namely, FC2, FM2 and MC2) are shorter than the others. However, the thickness of the upper layer is the same for all the samples. This is important as ponding occurs in the upper layer.

2.2 Data collection

Before starting each experiment, we placed a thin cotton ring on the top of the sample to enable the point source of the tracer to spread over the surface of the upper layer. Then, each experiment was started by supplying dyed water into samples using a micro-tube pump. The dye used was blue ink, diluted by a factor of 10 times in water at 0°C . We monitored W during each experiment by automatically measuring the weight of the tracer reservoir (1 minute resolution). Absolute relative differences between experimental (Table 1) and reference (10, 30 and 100 mm/h) values of W range between 6% - 19% as it is difficult to apply a constant, low input rate.

When the tracer reached the base of each sample, tracer supply was stopped. The arrival time of the tracer at sample base (t_t) was registered with a manual chronometer watch by visually inspecting samples during the experiments. Since samples had different heights, we define a specific travel time,

$$\tau = t_t/h, \quad (1)$$

with h equal to sample height. Note that τ is in min/cm as it is the reciprocal of velocity. After each experiment, pictures of the external sides of the sample were taken to estimate the approximate thickness of the upper layer marked by liquid water accumulation (p , in cm). Soon afterwards, we took pictures of the top section of each acrylic ring (by gradually removing them from the column, snow included). At the same time, the liquid water mass w , in grams, in each of the rings was measured using a portable calorimeter (Kawashima et al., 1998). These measurements were translated into profiles of volumetric liquid water content by converting w to θ . Fractions of wet areas over total area (f) were also estimated for each section by manually delimiting fingers in all the pictures taken and calculating their extension using the ImageJ software (<http://imagej.nih.gov/ij/>, 1.48 v, see Abramoff et al. (2004)). Clearly, similar calculations may be performed using alternative software.

2.3 The comparison with SNOWPACK

We simulated the dynamics of each sample using the 1D multi-layer model SNOWPACK (Bartelt and Lehning, 2002). These simulations aim at comparing observations of capillary barrier development with predictions by a physically-based model, as previously done by, e.g., Hirashima et al. (2010); Mitterer et al. (2011); Wever et al. (2015) mainly using field observations. The relatively high-resolution of LWC measurements (2 cm) enables a detailed discussion of both, the physical process and its simulation by a operation model. This comparison will not include preferential flow patterns, as the model is 1D.

The model discretizes snow using a finite element grid. It simulates the evolution in time of a broad set of variables along a vertical profile of snow starting from external forcings. The original version of SNOWPACK considers a bucket-type approach to simulate liquid water percolation in snow. Accordingly, liquid water is retained at a given position in the profile until it exceeds a threshold (see Bartelt and Lehning (2002)). After exceeding, excess water is transmitted downwards. Hirashima et al. (2010) have introduced in SNOWPACK a water transport model based on the model by van Genuchten (1980) and on an equilibrium approximation of water flow to tackle numerical instability (see Hirashima et al. (2010) for details). Recently, Wever et al. (2014) have also introduced a discretization of Richards equation that significantly improves several aspects of liquid water simulation in snow. We used the numerical scheme by Wever et al. (2014) in this paper (WE, SNOWPACK version 3.3).

The initial spatial resolution of simulations was set to 2 cm. The time step was set to 1 minute, but the numerical scheme by Wever et al. (2014) reduces this initial time step basing on an iteration rule (see Wever et al. (2014) for details). Snow initial conditions were chosen to replicate the granulometry, density (Table 1), θ (initially dry), and temperature (0°C) of the physical samples. Using the same sieves that we used here, Katsushima et al. (2013) obtained a mean grain size (hereinafter, $\bar{g}_S$) for the class 0.25 - 0.5 mm and the class 1 - 1.4 mm equal to 0.406 mm and 1.463 mm, respectively. $\bar{g}_S$ for medium snow is greater than the upper boundary of the sieve probably because snow grains

used were not perfectly spherical. In the simulation, we therefore set $\bar{g}_S = 0.406$ mm for fine snow, $\bar{g}_S = 1.463$ mm for medium snow and $\bar{g}_S = 2.926$ mm for coarse snow (by assuming this last value as two times the average medium grain size). Bond size was assumed equal to one third of grain radius. Input data were chosen to replicate experimental conditions in the cold chamber, i.e., a constant precipitation flux (equal to the measured water input flux W , see Table 1) and a fixed air temperature of $\pm 0^\circ\text{C}$. The threshold temperature for classifying solid and liquid events was set to -0.01°C , in order for W to be classified as liquid. Wind speed and solar radiation were set to zero, while incoming longwave radiation was calculated as σT^4 , where $\sigma = 5.67 \cdot 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$, and $T = 273.15 \text{ K}$. Parametrizations for snow permeability, unsaturated hydraulic conductivity, water retention curve, residual water content and averaging method for hydraulic conductivity at the interface were all kept at the default settings discussed for SNOWPACK in Wever et al. (2014, 2015).

Particular attention is paid to the comparison between observed and simulated LWC peak over the interface between layers, as this is an important variable involved in capillary barrier formation and in wet snow avalanche forecasting (Wever et al., 2016). Another key feature of capillary barriers is the vertical profile in LWC, which usually shows sharp variations with depth (Hirashima et al., 2010). However, choosing a precise snapshot of simulated LWC for the comparison with our observations is difficult, as the model is 1D and, at this stage, does not include an explicit treatment of preferential flow patterns. These are expected to play a key role in water flow around capillary barriers as water concentrates in fingers that are characterized by a higher-than-average unsaturated hydraulic conductivity (due to a higher-than-average LWC). It follows that restricting this comparison to a single profile may be misleading as possible differences between observations and simulations might be due to a process that is currently not treated by the model; this would severely limit the comparison. Thus, we will compare observed profiles of LWC with both, i) the simulated profile at the observed arrival time of water at sample base (WE1), and ii) the simulated profile at the arrival time of water in the model (WE2), which is chosen by identifying the instant when θ at sample base reaches ~ 3 vol% in the simulation (Mitterer et al., 2011).

On the one hand, WE1 is advantageous as supplied mass in experiments and in simulations matches, because both profiles refer to the same time step. On the other hand, flow in the lower layer will be at the beginning spatially variable, strongly accelerated and highly fingered (Katsushima et al., 2013), which are all features that are not explicitly included in a 1D model and that might hamper the application of Richards equation. Thus, when considering WE1, we will focus on the profile over the interface, where the peak of LWC develops. Conversely, WE2 enables a comparison of a full profile of LWC, but the simulated mass of liquid water will be greater than observed due to the possible mismatch between observed and expected arrival time of water in simulations (Wever et al., 2014). This is particularly evident in the upper layer of FC and FM samples, as water speed in fine snow during matrix flow is slow. Thus, when considering WE2, we will focus on the profile in the lower

235 layer. We suggest that additional investigations should be carried out to establish proper frameworks
for the high-resolution comparison of complex models and laboratory (or field) observations.

3 Results and Discussion

3.1 Overview

Figure 1 reports the horizontal sections of all the samples (2 cm vertical resolution) at the end of
240 the experiments (i.e., when dyed water arrived at sample base). Dyed water is visible as blue stains.
Generally, the darker the color is, the higher is local LWC (Waldner et al., 2004). We report in Figure
2 three examples of samples at the end of the experiment. These are FC2 (as an example of FC tests),
FM2 (as an example of FM experiments) and MC1 (as an example of MC experiments).

Table 2 reports observations in terms of thickness of the upper layer marked by liquid water
245 accumulation (p), arrival time of water at the base of each sample (t_t), and specific travel time of
liquid water in snow (τ). In Figures 3 and 4, profiles of wet snow fractions f and LWC are given. In
Fig. 4, each point represents bulk LWC in the underlying 2 cm. As an example, any value reported
at a depth equal to 8 cm is bulk LWC between 8 cm and 10 cm. This represents the LWC measured
immediately over the interface between layers.

250 Figure 5 compares observed and SNOWPACK-based profiles of volumetric LWC for each sample.
Each point represents bulk LWC in the underlying 2 cm. As described in Section 2, two simulated
profiles are reported (WE1 and WE2). When considering MC samples, we note that the total duration
of experiments is very short (see Table 2) compared with FC and FM samples. Thus, we plotted only
WE2 as the expected mismatch between supplied and simulated liquid water mass is limited.

255 3.2 Development of capillary barriers

Fig. 1 confirms that liquid water movement through a finer-over-coarser snow texture is subjected
to ponding and horizontal diversion of water when the wetting front comes to the textural interface.
In FC and FM samples, horizontal spreading of water at the interface introduces a clear textural
transition in wetness between finer and coarser layers (see Fig. 2). In 4 out of 6 samples of these two
260 classes, a homogeneously blue area is observed even at a depth equal to 8 cm (i.e., 2 cm above the
interface). MC samples show a more variable behavior. In fact, water spreading is spatially restricted
for MC1 (see also Fig. 2), whereas marked horizontal redistribution of water is visible in MC2 and
MC3. MC samples show a smaller p than FC and FM samples.

The difference between FC-FM and MC samples in terms of ponding behavior can be explained
265 considering the retention properties of snow with different grain size. ψ_{WE} for medium and coarse
snow can be estimated from grain size using the relation reported in Katsushima et al. (2013) and
Hirashima et al. (2014): $\psi_{WE} \sim 0.025$ m in coarse snow and ~ 0.04 m in medium snow. Conversely,
 ψ in fine snow is ~ 0.22 m ($\theta = 5$ vol%) and 0.21 m ($\theta = 10$ vol%), whereas ψ in medium snow

is ~ 0.09 m ($\theta = 5$ vol%) and 0.08 m ($\theta = 10$ vol%). These approximate values of suction in snow
 270 were estimated using the WRC parametrization in snow by Yamaguchi et al. (2012), assuming an
 irreducible LWC equal to 2.4 vol % (Yamaguchi et al., 2010; Hirashima et al., 2014), and consider-
 ing 5 vol% and 10 vol% as reference values for relatively low saturation. Thus, in FC-FM samples
 the difference between ψ at relatively low saturation and ψ_{WE} is much greater than in MC sam-
 ples. Generally, the higher the difference between ψ in the upper layer and ψ_{WE} is, the larger is
 275 the mass of water accumulated and horizontally diverted. Note that the WRC by Yamaguchi et al.
 (2012) refers to a drying process and this may trigger some additional uncertainty when estimating
 ψ for a wetting process (see Section 3.4).

FC and FM samples are characterized by similar LWC profiles (Fig. 4). LWC increases with depth
 in the upper layer, it presents a marked peak at the textural boundary, and it decreases again below the
 280 capillary barrier. Peaks in LWC at the interface are a characteristic feature of capillary barriers as wa-
 ter ponds until $\psi \rightarrow \psi_{WE}$: similar examples are reported or discussed in, e.g., Waldner et al. (2004);
 Hirashima et al. (2010); Mitterer et al. (2011); Avanzi et al. (2015); Wever et al. (2015, 2016). All
 FC-FM samples yield a similar LWC in the upper layer at the interface: ~ 33 vol% in FC samples
 and ~ 34 vol% - 36 vol% in FM samples. This value is coupled with suction through a wetting curve
 285 (DiCarlo, 2007). This may be the reason why LWCs at the interface are similar, as ψ_{WE} is the same
 in all these six samples. Note that such values of LWC are much greater than those usually reported
 in field profiles (Fierz et al., 2009). LWC drives, among others, snow settling (Marshall et al., 1999)
 and wet snow metamorphism (Brun, 1989). Both processes experience a dramatic acceleration with
 increasing LWC. This supports the idea that capillary barriers may play an essential role for snow
 290 stability in wet conditions (Wever et al., 2016).

In MC samples, a smaller, but distinct, peak in LWC was measured at the interface: in MC1, LWC
 over the boundary is ~ 4.5 vol%, whereas LWC values immediately above and below are 2.7 vol%
 and 1.7 vol%, respectively. In MC2 and MC3, the peak in LWC over the interface is ~ 9 vol%. A
 smaller peak of LWC in MC layering is attributed to the small difference between ψ in medium snow
 295 and ψ_{WE} in coarse snow.

The occurrence of capillary barrier causes horizontal redistribution of water. Thus, spatial ho-
 mogenization of liquid water patterns at the interface is promoted. Indeed, f increases with depth
 over the boundary (where $f = 1$ for all FC and FM samples, see Fig. 3). However, sections in Fig.
 1 reveal a remarkable spatial variability of this process at cm scale. For example, some pockets of
 300 dry snow persist at depths equal to 8 cm in samples FC2 and FC3 (i.e., 2 cm above the interface).
 Other hints are the observed spatial variability of p in each sample (Table 2) and the differences
 of coloring in some sections at depths equal to 8 or 10 cm (e.g., FC2, FC3 and FM3), as this is a
 signature of LWC (Waldner et al., 2004). Isolated clusters of liquid water surrounded by dry snow
 are also visible in MC1 and MC2. All these observations show that the distribution of liquid water
 305 above a capillary barrier has a marked 2/3D structure at local scale, probably due to heterogeneity in

snow microstructure. The difference in wet areas in MC samples for different water input rates might be on the contrary an effect of water input rate on ψ_{WE} , as observed in snow by Katsushima et al. (2013).

3.3 Preferential flow patterns and travel time of water in snow

Observed profiles of f suggest that liquid water movement in samples was marked by high spatial variability and that this variability is lower in fine snow layers than in medium or coarse snow. Overall, preferential flow turns out as the predominant pattern of liquid water infiltration in snow (Schneebeli, 1995). We observed that new fingers created during the percolation, and that sometimes fingers stopped their vertical percolation at some locations but continued to develop at others. The movement of fingers in the lower layer was very rapid and represented a small fraction of the total duration of each experiment (say, up to a few minutes even for slower input rates).

Katsushima et al. (2013) report that the total area of preferential flow (hence f) in snow samples made by vertically homogeneous snow decreases with increasing grain size, but increases with increasing input flux. We also observed a decrease in f with increasing g_S , whereas a clear increase of f with increasing W was detected only for MC samples. On the one hand, the expected dependency of f on sublayer unsaturated conductivity at ψ_{WE} (Hillel and Baker, 1988; Baker and Hillel, 1990) and the relation between ψ_{WE} and velocity (Weitz et al., 1987; DiCarlo, 2007; Katsushima et al., 2013) support the existence of a relation between f and W (albeit both effects have been mainly observed only in soils). On the other hand, these experiments included a capillary barrier, contrary to experiments by Katsushima et al. (2013), and this represents a major driver of liquid water patterns at local scale (see the previous Section). Accordingly, liquid water speed in the upper layer was locally affected by ponding, whereas inflow rate in the sublayer was driven by breakthrough of water at ψ_{WE} . Both processes limit the impact of external water input rate on f , at least until steady conditions are reached. In MC samples, the difference in retention properties between layers is lower; thus, the effect of a capillary barrier is spatially very localized. This may explain why observations in MC samples agree with previous observations in homogeneous snow.

Considering outcomes of different experiments in sand, DiCarlo (2013) reports that finger width might increase with both, very high (i.e., close to saturated conductivity) and very low supplied fluxes, while finger width keeps constant for a broad range of supplied flux in between. Water input rates in our experiments span 11 and 113 mm/h; these values are very small if compared with expected values of saturated conductivity in snow ($\sim 10^4 - 10^6$ mm/h, see Katsushima et al. (2013)). We therefore suggest that future developments of this work should investigate the relation between flux and f extensively, i.e., enlarging the range of W considered during the experiments and/or reaching steady conditions.

τ increases with decreasing W , as clearly expected (Table 2). In the case of FM2 (fine over medium snow, $W = 27.7$ mm/h), we can compare the τ measured during the experiment (2.2

min/cm) with the τ observed during the experiment by Katsushima et al. (2013), since this is the only $g_S - W$ combination that these two works share. The τ measured by Katsushima et al. (2013) for fine snow and $W = 22.3$ mm/h is equal to 1.7 min/cm, while the τ for medium snow and $W = 21.7$ mm/h is equal to 0.7 min/cm. These results suggest that τ in a FM sample is higher than the τ observed in a homogeneous sample composed by medium snow. This is clearly expected since permeability in medium snow is higher than in fine snow. However, this τ is even higher than the specific travel time observed in a homogeneous sample made by fine snow, which is less expected. This comparison helps to quantify the relevance of capillary effects in ruling water speed in snow and the arrival time of meltwater at snow base.

3.4 The comparison with SNOWPACK

Figure 5 shows promising results for the simulation of a capillary barrier. Indeed, the model clearly reproduces an increasing LWC with depth in the upper layer and a peak of LWC at the interface. Furthermore, LWC profiles below the barrier are generally in good agreement, once water has reached the base in the simulation. Point differences between observed and simulated LWC at the interface at WE1 read $\sim 2 - 5$ vol% in FC1-FC2, $\sim 3 - 8$ vol% in FM1-FM2, and $\sim 0.1 - 5$ vol% in MC samples. As already mentioned, a good simulation of peak LWC is very important to correctly predict the occurrence of wet snow avalanches (Wever et al., 2016). A larger difference ($\sim 9 - 13$ vol%) is found for higher input rates. However, note that FC3 and FM3 were subjected to an extremely high water input rate compared with natural conditions.

Previous evaluations of SNOWPACK already show that the inclusion of Darcy-Buckingham equation in snow enables a correct prediction of the onset of capillary barriers at textural discontinuities (Hirashima et al., 2010; Mitterer et al., 2011; Wever et al., 2015). Here, we enlarged previous findings by considering a broad set of snow textures and input rates, and a relatively high resolution of measurements.

Overall, observations show that both, breakthrough of liquid water below a capillary barrier and wet conditions in the upper layer or in fingers (Waldner et al., 2004) may present a proper process scale (Blöschl, 1999) of a few cm. This is because natural snow is spatially heterogeneous (Hirashima et al., 2014) and this may affect 3D patterns of capillary barriers (e.g., see the already discussed pockets of dry snow in FM3). Alternation of dry and wet snow can sensibly decrease the bulk LWC in a ring, although local LWC can still be very high. This may partially explain some differences between observations and 1D simulations. For example, predicted peak LWC in FC3 and FM3 is $\sim 43 - 46$ vol%, which is close to saturated conditions (the porosity of fine snow in both samples is ~ 0.5), but greater than observations. An approximate estimation of LWC at ψ_{WE} in fine snow (obtained assuming continuity of suction at the interface) reads 50 vol%, which is closer to SNOWPACK simulations than data. Thus, saturated conditions might be reached at local scale,

while bulk LWC (which is the effect of both, capillary barrier effects and snow heterogeneity in wetness at ring scale) can be lower.

Another example is water flow below the interface, which showed a high degree of spatial variability. The good agreement between the model and the data (at WE2) might suggest that, at this measurement scale, differences in LWC between a highly channeled flow and a matrix-only simulation balance, that is, fingers are usually highly saturated (Waldner et al., 2004), but occupy only a small fraction of total volume. Thus, the average LWC at ring scale is much lower than saturation and close to matrix conditions.

This result suggests that an exhaustive process understanding of the physics of capillary barriers in snow and water flow instability may need that a proper measurement and/or modeling scale are defined to clearly separate model-data significant discrepancies and effects due to the sampling strategy (see again Blöschl (1999) for a definition). Importantly, the measurement scale needed to capture 3D patterns of capillary barriers might be smaller than that usually used to sample LWC in the field (see again Fig. 1). Increasing the spatial resolution of LWC measurements is challenging as measuring LWC in snow is still marked by high uncertainties (Colbeck, 1978; Fierz and Föhn, 1995; Techel and Pielmeier, 2011; Avanzi et al., 2014). It is only recently that undisturbed, non-destructive and repetitive measurements of LWC have been obtained (Heilig et al., 2010; Schmid et al., 2015; Heilig et al., 2015; Kinar and Pomeroy, 2015). A promising alternative might be given by pore-scale measurements of liquid water flow (Adachi et al., 2012; Walter et al., 2013). This discussion also reveals the role played by heterogeneity (Hirashima et al., 2014) in introducing possible differences in LWC between 3D (bulk) and point (1D) conditions. Additional uncertainty may be caused by instrumental precision (see next Section), ambiguity in the identification of the correct snapshot of LWC for this comparison, and possible air trapped in voids at saturation (Yamaguchi et al., 2010).

Another important limitation for this discussion may be the present lack of an exhaustive investigation of WRC hysteresis in snow. Indeed, differences of LWC for a given suction are expected if hysteresis is explicitly taken into account. Furthermore, the absence of a proper parametrization of hysteresis may hamper the estimation of expected LWC at ψ_{WE} during ponding (i.e., wetting), if different WRCs for a wetting and a drying process are not known. Also, the hysteretic behavior of the WRC is considered an important factor in driving preferential flow in general, since for example it promotes the persistence of fingers in soils (Liu et al., 1994; DiCarlo, 2013). The magnitude of hysteresis is also related with the magnitude of capillary overshoot (Katsushima et al., 2013), although it is not the prime cause of instability (DiCarlo, 2013). At present, existing observations of hysteresis in snow are still very sparse (Adachi et al., 2012) and this represents an important limitation for interpreting existing results, although the WRC hysteresis of snow is expected to be smaller than the hysteresis of, e.g., sand (Katsushima et al., 2013).

3.5 The role of instrumental precision

A mass balance between supplied and measured liquid water mass reveals that the measured mass ranges between 93% and 176% of supplied mass in 8 out of 9 samples, while in MC1 measured mass is 434% of supplied mass. Note that in this last sample the total mass supplied is nonetheless very low due to the short duration of this experiment (~ 2.88 g).

This discrepancy can be explained by instrumental noise. Melting calorimetry has been widely used to measure LWC for decades (Yosida, 1960), but Colbeck (1978) points out that this method may be inaccurate as it implies the calculation of a difference between large numbers (Stein et al., 1997). According to Kinar and Pomeroy (2015), absolute errors in measuring LWC using calorimetry span 1% and 5%. The instrument we used here (the so-called Endo-type snow-water content meter) was proposed by Kawashima et al. (1998). They note that measured LWC span $\pm 2\%$ of known LWC (by weight) in 87% of the cases. By comparing measurements by the Endo-type calorimeter with those by a dielectric device in snow pits (see Kawashima et al. (1998) for details), they note that this device returns alternatively higher or lower LWC if compared with high and low readings by the dielectric device.

We estimated an absolute error for these experiments by comparing the height-integrated LWC measured using calorimetry within each sample with the ratio between supplied liquid water volume and total volume of samples. The absolute difference spans 0.8 vol% and 2.97 vol%, thus it is consistent with the literature (Kinar and Pomeroy, 2015). Measured and simulated LWC by SNOWPACK are also in fairly agreement (see previous Section) and this is another good point since SNOWPACK bases on mass and energy conservation.

Capillary barriers and associated preferential flow represents a big challenge for LWC measurements. On the one hand, peaks in LWC at the interface are rather high and this is a problem for those instruments that may lose accuracy for high LWC, such as a Snow Fork (Techel and Pielmeier, 2011). On the other hand, bulk LWC in fingered snow may be very low, as water accelerates and occupies a small fraction of total volume. This means that such experiments need an instrument that guarantees a comparable performance for both, high and low LWC. This may represent a benefit of the Endo calorimeter (see Fig. 4 in Kawashima et al. (1998)), which seems also appropriate given the small dimension of each ring. Furthermore, Fierz and Föhn (1995) report that the absolute error in measuring water content using dielectric methods spans 0.2 and 0.9 vol%, while Techel and Pielmeier (2011) note that the expected difference between measurements taken using a Denoth meter and a Snow Fork is ~ 1 vol%. Thus, measuring low LWCs is generally very challenging for several existing techniques. Finally, a highly fingered flow may be missed and/or disturbed by using bigger instruments, like TDRs (Stein et al., 1997). For future experiments, we will also consider alternative portable techniques, such as a dilution method (Davis et al., 1985; Kinar and Pomeroy, 2015; Mitterer, 2016).

4 Conclusions

We focused on the systematic observation of capillary barriers and associated preferential flow during laboratory experiments in a cold chamber. We sieved nine samples of finer-over-coarser snow. These samples were subjected to controlled supply of dyed water until water arrived at sample base. Liquid water patterns in stratified snow were characterized using visual inspection, LWC measurements and horizontal sectioning. Results were also compared with SNOWPACK simulations.

Overall, results confirmed that a finer-over-coarser transition in snow layering causes ponding of water when this comes at the textural boundary. Measured peaks in LWC over the boundary are large with respect to usual measurements in the field (up to ~ 33 vol% in FC samples and $\sim 34 - 36$ vol% in FM samples), while peaks in MC samples are usually ≤ 10 vol%. Differences in peak LWC between samples were explained basing on retention properties of snow with different grain size. A more detailed analysis of horizontal sections revealed marked variability of wetness conditions at cm scale, thus suggesting that local LWC might even reach saturated conditions, as expected by a simple estimation of LWC at water entry suction.

Horizontal sectioning of samples confirmed that preferential flow seems the dominant process in water transmission in snow. The area occupied by fingers (f) increases with grain size, while no definitive result was obtained to establish a relation between f and water input rate. This is explained by the strong perturbation introduced by the capillary barrier in liquid water patterns if compared with previous observations in homogeneous snow.

The comparison with SNOWPACK showed that, in general terms, the implementation of Richards equation clearly reproduces the existence of a capillary barrier and yields a good agreement with observed peaks in LWC at the interface. A discussion of observed and simulated LWC revealed possible discrepancies between point conditions and 3D patterns even at cm scale.

5 Author contribution

Francesco Avanzi, Hiroyuki Hirashima and Satoru Yamaguchi designed the experiments, Francesco Avanzi and Satoru Yamaguchi performed the experiments, Hiroyuki Hirashima performed SNOWPACK simulations, Francesco Avanzi prepared the manuscript with the contribution of all coauthors.

Acknowledgements. Fruitful discussions about this work with Dr. Atsushi Sato and Dr. Yoshiyuki Ishii are acknowledged. We would like to thank the staff of the Snow and Ice Research Center, National Research Institute for Earth Science and Disaster Prevention, for helpful discussions. FA is grateful for the support received during his research period at the Snow and Ice Research Center in Nagaoka. We would like to thank Mr. Sugai Yusuke for his assistance during experimental activities. We acknowledge the Editor Dr. Guillaume Chambon, Dr. Christoph Mitterer, and an anonymous referee for their constructive comments on the manuscript.

References

- Abramoff, M. D., Magalhães, P. J., and Ram, S. J.: Image Processing using ImageJ, *Biophotonics international*, 11, 36–43, 2004.
- Adachi, S., Yamaguchi, S., Ozeki, T., and Kose, K.: Hysteresis in the water retention curve of snow measured
485 using an MRI system, in: *Proceedings to the 2012 International Snow Science Workshop*, Anchorage, Alaska, 2012.
- Avanzi, F., Caruso, M., Jommi, C., De Michele, C., and Ghezzi, A.: Continuous-time monitoring of liquid water content in snowpacks using capacitance probes: A preliminary feasibility study, *Advances in Water Resources*, 68, 32–41, doi:10.1016/j.advwatres.2014.02.012, 2014.
- 490 Avanzi, F., Yamaguchi, S., Hirashima, H., and De Michele, C.: Bulk volumetric liquid water content in a seasonal snowpack: modeling its dynamics in different climatic conditions, *Advances in Water Resources*, 2015.
- Baggi, S. and Schweizer, J.: Characteristics of wet-snow avalanche activity: 20 years of observations from a high alpine valley (Dischma, Switzerland), *Natural Hazards*, 50, 97–108, 2008.
- Baker, R. S. and Hillel, D.: Laboratory tests of a theory of fingering during infiltration into layered soils, *Soil*
495 *Sci. Soc. Am. J.*, 54, 20–30, 1990.
- Bartelt, P. and Lehning, M.: A physical SNOWPACK model for the Swiss avalanche warning Part I: numerical model, *Cold Regions Science and Technology*, 35, 123–145, doi:10.1016/S0165-232X(02)00074-5, 2002.
- Baver, C. E., Parlange, J. Y., Stoof, C. R., DiCarlo, D. A., Wallach, R., Durnford, D. S., and Steenhuis, T. S.: Capillary pressure overshoot for unstable wetting fronts is explained by Hoffman’s velocity-dependent
500 contact-angle relationship, *Water Resources Research*, 50, 5290–5297, 2014.
- Blöschl, G.: *Scaling issues in snow hydrology*, *Hydrological Processes*, 1999.
- Brun, E.: Investigation on wet-snow metamorphism in respect of liquid-water content, *Annals of Glaciology*, 13, 22–26, 1989.
- Colbeck, S. C.: A theory of water percolation in snow, *Journal of Glaciology*, 11, 369–385, 1972.
- 505 Colbeck, S. C.: The difficulties of measuring the water saturation and porosity of snow, *Journal of Glaciology*, 20, 189 – 201, 1978.
- Daanen, R. P. and Nieber, J. L.: Model for Coupled Liquid Water Flow and Heat Transport with Phase Change in a Snowpack, *J. Cold Reg. Engrg.*, 23, 43–68, 2009.
- Davis, R. E., Dozier, J., LaChapelle, E. R., and Perla, R.: Field and Laboratory Measurements of Snow Liquid
510 Water by Dilution, *Water Resources Research*, 21, 1415–1420, 1985.
- de Rooij, G. H.: Modeling fingered flow of water in soils owing to wetting front instability: a review, *Journal of Hydrology*, 231-232, 277–294, 2000.
- DeWalle, D. R. and Rango, A.: *Principles of Snow Hydrology*, Cambridge University Press, 2011.
- DiCarlo, D. A.: Experimental measurements of saturation overshoot on infiltration, *Water Resources Research*,
515 40, W04 215, 2004.
- DiCarlo, D. A.: Capillary pressure overshoot as a function of imbibition flux and initial water content, *Water Resources Research*, 43, W08 402, 2007.
- DiCarlo, D. A.: Stability of gravity-driven multiphase flow in porous media: 40 years of advancements, *Water Resources Research*, 49, 4531–4544, 2013.

- 520 Dietz, A. J., Kuenzer, C., Gessner, U., and Dech, S.: Remote sensing of snow - a review of available methods, *International Journal of Remote Sensing*, 33, 4094 – 4134, doi:10.1080/01431161.2011.640964, 2012.
- Egorov, A. G., Dautov, R. Z., Nieber, J. L., and Sheshukov, A. Y.: Stability analysis of gravity-driven infiltrating flow, *Water Resources Research*, 39, 1266, 2003.
- Eiriksson, D., Whitson, M., Luce, C. H., Marshall, H. P., Bradford, J., Benner, S. G., Black, T., Hetrick, H., and
525 McNamara, P.: An evaluation of the hydrologic relevance of lateral flow in snow at hillslope and catchment scales, *Hydrological Processes*, 27, 640–654, doi:10.1002/hyp.9666, 2013.
- Fierz, C. and Föhn, P. M. B.: Long - term observation of the water content of an alpine snowpack, in: *Proceedings of the International Snow Science Workshop*, 30 October - 3 November 1994, Snowbird, Utah, 1995.
- 530 Fierz, C., Armstrong, R., Durand, Y., Etchevers, P., Greene, E., McClung, D., Nishimura, K., Satyawali, P., and Sokratov, S.: The International Classification for Seasonal Snow on the Ground, Tech. rep., IHP-VII Technical Documents in Hydrology N 83, IACS Contribution N 1, UNESCO - IHP, Paris, 2009.
- Forster, R. R., Box, J. E., van den Broeke, M. R., Miegge, C., Burgess, E. W., van Angelen, J. H., Lenaerts, J. T. M., Koenig, L. S., Paden, J., Lewis, C., Prasad Gogineni, S., Leuschen, C., and McConnell, J. R.: Extensive
535 liquid meltwater storage in firn within the Greenland ice sheet, *Nature Geoscience*, 7, 95–98, 2014.
- Harper, J., Humphrey, N., Pfeffer, W. T., Brown, J., and Fettweis, X.: Greenland ice - sheet contribution to sea - level rise buffered by meltwater storage in firn, *Nature*, 491, 240 – 243, 2012.
- Heilig, A., Eisen, O., and Schneebeli, M.: Temporal observations of a seasonal snowpack using upward-looking GPR, *Hydrological Processes*, 24, 3133–3145, 2010.
- 540 Heilig, A., Mitterer, C., Schmid, L., Wever, N., Schweizer, J., Marshall, H.-P., and Eisen, O.: Seasonal and diurnal cycles of liquid water in snow - measurements and modeling, *Journal of Geophysical Research - Earth Surface*, 2015.
- Hill, D. E. and Parlange, J.-Y.: Wetting front instability in layered soils, *Soil Science Society of America Proceedings*, 36, 697–02, 1972.
- 545 Hillel, D. and Baker, R. S.: A descriptive theory of fingering during infiltration into layered soils, *Soil Science*, 146, 51–55, 1988.
- Hirashima, H., Yamaguchi, S., Sato, A., and Lehning, M.: Numerical modeling of liquid water movement through layered snow based on new measurements of the water retention curve, *Cold Regions Science and Technology*, 64, 94–103, doi:10.1016/j.coldregions.2010.09.003, 2010.
- 550 Hirashima, H., Yamaguchi, S., and Katsushima, T.: A multi-dimensional water transport model to reproduce preferential flow in the snowpack, *Cold Regions Science and Technology*, 108, 80–90, 2014.
- Jordan, R.: Effects of capillary discontinuities on water flow and water retention in layered snowcovers, *Defence Science Journal*, 45, 79–91, 1995.
- Katsushima, T., Kumakura, T., and Takeuchi, Y.: A multiple snow layer model including a parameteriza-
555 tion of vertical water channel process in snowpack, *Cold Regions Science and Technology*, 59, 143–151, doi:10.1016/j.coldregions.2009.09.002, 2009a.
- Katsushima, T., Yamaguchi, S., Kumakura, T., and Sato, A.: Measurement of dynamic water entry value for dry snow, in: *Proceedings to the International Snow Science Workshop 2009*, Davos, Switzerland, 2009b.

- Katsushima, T., Yamaguchi, S., Kumakura, T., and Sato, A.: Experimental analysis of preferential flow in dry snowpack, *Cold Regions Science and Technology*, 85, 206–216, doi:10.1016/j.coldregions.2012.09.012, 2013.
- Kawashima, K., Endo, T., and Takeuchi, Y.: A portable calorimeter for measuring liquid-water content of wet snow, *Annals of Glaciology*, 26, 103–106, 1998.
- Kinar, N. J. and Pomeroy, J. W.: SAS2: the system for acoustic sensing of snow, *Hydrological Processes*, 29, 4032–4050, 2015.
- Lehning, M., Völksch, I., Gustafsson, D., Nguyen, T. A., Stähli, M., and Zappa, M.: ALPINE3D: a detailed model of mountain surface processes and its application to snow hydrology, *Hydrological Processes*, 20, 2111–2128, doi:10.1002/hyp.6204, 2006.
- Liu, Y., Steenhuis, T. S., and Parlange, J.-Y.: Formation and persistence of fingered flow fields in coarse grained soils under different moisture contents, *Journal of Hydrology*, 159, 187 – 195, 1994.
- Lundquist, J. D. and Dettinger, M. D.: How snowpack heterogeneity affects diurnal streamflow timing, *Water Resources Research*, 41, W05 007, doi:10.1029/2004WR003649, 2005.
- Machguth, H., MacFerrin, M., van As, D., Box, J. E., Charalampidis, C., Colgan, W., Fausto, R. S., Meijer, H. A. J., Mosley-Thompson, E., and van de Wal, R. S. W.: Greenland meltwater storage in firn limited by near-surface ice formation, *Nature Climate Change*, doi:10.1038/nclimate2899, 2016.
- Marsh, P. and Woo, M.: Meltwater movement in natural heterogeneous snow covers, *Water Resources Research*, 21, 1710–1716, doi:10.1029/WR021i011p01710, 1985.
- Marsh, P. and Woo, M.-K.: Wetting front advance and freezing of meltwater within a snow cover 1. Observations in the Canadian Arctic, *Water Resources Research*, 20, 1853–1864, doi:10.1029/WR020i012p01853, 1984a.
- Marsh, P. and Woo, M.-K.: Wetting front advance and freezing of meltwater within a snow cover 2. A simulation model, *Water Resources Research*, 20, 1865–1874, doi:10.1029/WR020i012p01865, 1984b.
- Marshall, H. P., Conway, H., and Rasmussen, L. A.: Snow densification during rain, *Cold Regions Science and Technology*, 30, 35–41, 1999.
- McGurk, B. J. and Marsh, P.: Flow-finger continuity in serial thick-sections in a melting Sierran snowpack, in: *Biogeochemistry of Seasonally Snow-Covered Catchments (Proceedings of a Boulder Symposium)*, 1995.
- Mitterer, C.: Interactive comment on Laboratory-based observations of capillary barriers and preferential flow in layered snow by F. Avanzi et al., *The Cryosphere Discuss.*, 9, C2938–C2949, 2016.
- Mitterer, C. and Schweizer, J.: Analysis of the snow-atmosphere energy balance during wet-snow instabilities and implications for avalanche prediction, *The Cryosphere*, 7, 205 – 216, <http://www.the-cryosphere.net/7/205/2013/>, 2013.
- Mitterer, C., Hirashima, H., and Schweizer, J.: Wet-snow instabilities: comparison of measured and modelled liquid water content and snow stratigraphy, *Annals of Glaciology*, 52, 201 – 208, 2011.
- Mitterer, C., Techel, F., Fierz, C., and Schweizer, J.: An operational supporting tool for assessing wet-snow avalanche danger, in: *International Snow Science Workshop Grenoble - Chamonix Mont-Blanc - 2013*, 2013.
- Peitzsch, E., Birkeland, K. W., and Hansen, K. J.: Water movement and capillary barriers in a stratified and inclined snowpack, in: *Proceedings of the 2008 International Snow Science Workshop*, Whistler, British Columbia, 2008.

- Pfeffer, W. T. and Humphrey, N. F.: Determination of timing and location of water movement and ice-layer formation by temperature measurements in sub-freezing snow, *Journal of Glaciology*, 42, 292–304, 1996.
- 600 Pfeffer, W. T., Illangasekare, T. H., and Meier, M. F.: Analysis and modeling of melt-water refreezing in dry snow, *Journal of Glaciology*, 36, 238–246, 1990.
- Saffman, P. and Taylor, G.: The penetration of a fluid into a porous medium or Hele-Shaw cell containing a more viscous fluid, *Proc. R. Soc. London*, 245, 312–329, 1958.
- Schmid, L., Koch, F., Heilig, A., Prasch, M., Eisen, O., Mauser, W., and Schweizer, J.: A novel sensor combination (upGPR - GPS) to continuously and nondestructively derive snow cover properties, *Geophysical Research Letters*, 42, 1 – 9, 2015.
- 605 Schneebeli, M.: Development and stability of preferential flow paths in a layered snowpack, in: *Biogeochemistry of Seasonally Snow-Covered Catchments (Proceedings of a Boulder Symposium)*, IAHS Publ. no. 228, 1995.
- 610 Stein, J., Laberge, G., and Lévesque, D.: "Monitoring the dry density and the liquid water content of snow using time domain reflectometry (TDR)", *Cold Regions Science and Technology*, 25, 123 – 136, 1997.
- Techel, F. and Pielmeier, C.: Point observations of liquid water content in wet snow - investigating methodical, spatial and temporal aspects, *The Cryosphere*, 5, 405–418, doi:10.5194/tc-5-405-2011, <http://www.the-cryosphere.net/5/405/2011/>, 2011.
- 615 Techel, F., Pielmeier, C., and Schneebeli, M.: Microstructural resistance of snow following first wetting, *Cold Regions Science and Technology*, 65, 382–391, doi:10.1016/j.coldregions.2010.12.006, 2011.
- van Genuchten, M. T.: A Closed-form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils, *Soil Sci. Soc. Am. J.*, 44, 892–898, 1980.
- Wakahama, G.: The infiltration of melt water into snow cover 1 (in Japanese, with English Abstr.), Tech. rep.,
- 620 Low Temperature Science, Series A 21, 45-74, 1963.
- Waldner, P. A., Schneebeli, M., Schultze-Zimmermann, U., and Flühler, H.: Effect of snow structure on water flow and solute transport, *Hydrological Processes*, 18, 1271–1290, doi:10.1002/hyp.1401, 2004.
- Walter, B., Horender, S., Gromke, C., and Lehning, M.: Measurements of the pore-scale water flow through snow using Fluorescent Particle Tracking Velocimetry, *Water Resources Research*, 49, 2013.
- 625 Wankiewicz, A.: A review of water movement in snow, in: *Modeling of snow cover runoff*, edited by Colbeck, S. C. and Ray, M., U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, 1978.
- Weitz, D. A., Stokes, J. P., Ball, R. C., and Kushnick, A. P.: Dynamic Capillary Pressure in Porous Media: Origin of the Viscous-Fingering Length Scale, *Phys. Rev. Lett.*, 59, 2967, 1987.
- 630 Wever, N., Fierz, C., Mitterer, C., Hirashima, H., and Lehning, M.: Solving Richards Equation for snow improves snowpack meltwater runoff estimations in detailed multi-layer snowpack model, *The Cryosphere*, 8, 257–274, doi:10.5194/tc-8-257-2014, <http://www.the-cryosphere.net/8/257/2014/>, 2014.
- Wever, N., Schmid, L., Heilig, A., Eisen, O., Fierz, C., and Lehning, M.: Verification of the multi-layer SNOWPACK model with different water transport schemes, *The Cryosphere Discussions*, 9, 2655–2707,
- 635 doi:10.5194/tcd-9-2655-2015, 2015.
- Wever, N., Vera Valero, C., and Fierz, C.: Assessing wet snow avalanche activity using detailed physics based snowpack simulations, *Geophysical Research Letters*, 2016.

- Williams, M. W., Erickson, T. A., and Petzelka, J. L.: Visualizing meltwater flow through snow at the centimetre-to-metre scale using a snow guillotine, *Hydrological Processes*, 24, 2098 – 2110, 2010.
- 640 Yamaguchi, S., Katsushima, T., Sato, A., and Kumakura, T.: Water retention curve of snow with different grain sizes, *Cold Regions Science and Technology*, 64, 87–93, doi:10.1016/j.coldregions.2010.05.008, 2010.
- Yamaguchi, S., Watanabe, K., Katsushima, T., Sato, A., and Kumakura, T.: Dependence of the water retention curve of snow on snow characteristics, *Annals of Glaciology*, 53, 6–12, doi:http://dx.doi.org/10.3189/2012AoG61A001, 2012.
- 645 Yosida, Z.: A calorimeter for measuring the free water content of wet snow, *Journal of Glaciology*, 3, 574–576, 1960.

Table 1. Experimental details. W is the applied water input rate, $\rho_{D,U}$ is the dry density of the upper layer, $\rho_{D,L}$ is the dry density of the lower layer.

Sample ID	W (mm/h)	W (g/min)	$\rho_{D,U}$ (kg/m ³)	$\rho_{D,L}$ (kg/m ³)	Upper layer thickness (cm)	Lower layer thickness (cm)
FC1	11.9	0.39	417	465	10	10
FC2	28	0.92	449	483	10	8
FC3	113	3.7	433	470	10	10
FM1	11.9	0.39	444	484	10	10
FM2	27.7	0.91	442	487	10	8
FM3	110	3.6	455	510	10	10
MC1	11	0.36	472	487	10	10
MC2	27.3	0.89	498	480	10	8
MC3	111	3.6	494	478	10	10

Table 2. Experimental results: observed ponding layer thickness p , experiment duration t_t , specific travel time τ . As for p , approximated lower and upper values are reported due to spatial heterogeneity in this variable.

Sample ID	p (min - max)	t_t	τ
	(cm)	(min)	(min/cm)
FC1	2 - 3	92	4.6
FC2	3 - 4	50	2.8
FC3	2 - 3	14.5	0.725
FM1	2 - 3	90	4.5
FM2	2 - 3	40	2.2
FM3	1 - 2	13.5	0.675
MC1	0 - 1	8	0.4
MC2	1 - 1	8.45	0.47
MC3	0.5 - 1	5.3	0.265

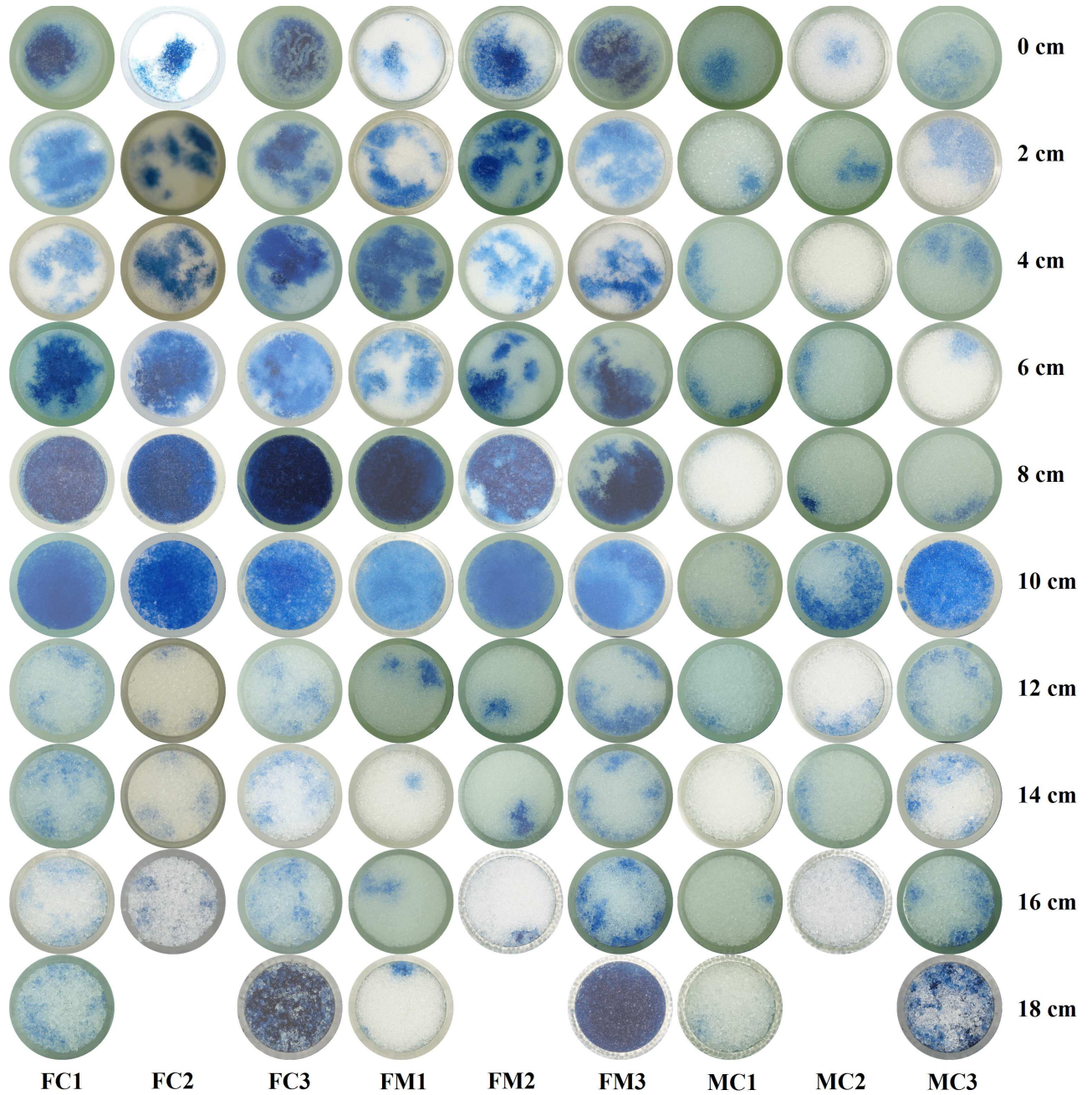


Figure 1. Sections of all the samples (rings diameter equal to 5 cm, 2 cm vertical resolution) at the end of each experiment. Each column refers to a different sample (as indicated in the last row), while each row refers to the same depth from sample top surface (depth indicated by the number on the right side of each row). For all the samples, the texture boundary between different grain sizes is located at a depth equal to 10 cm.

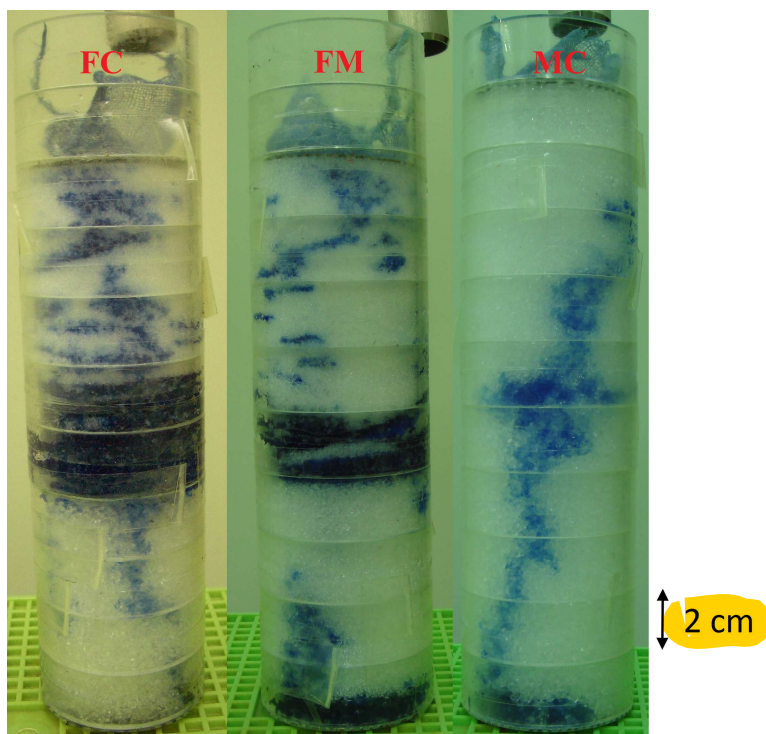


Figure 2. Three samples at the end of the experiments: FC2 (on the left, as an example of FC samples), FM2 (at the center, as an example of FM samples) and MC1 (on the right, as an example of MC samples).

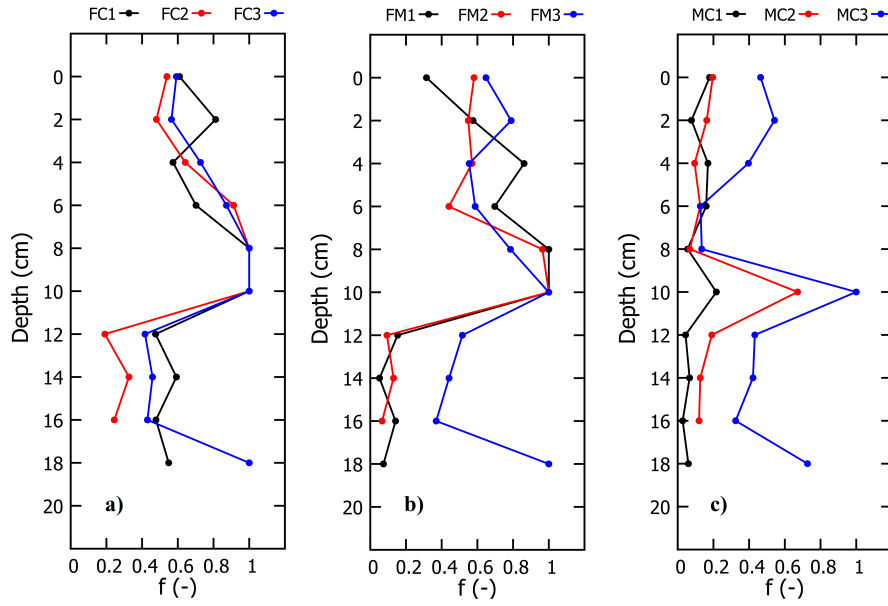


Figure 3. Measured f profiles. f is the ratio between wet and total area for all the sections in Fig. 1. Panel (a): FC samples; panel (b): FM samples; panel (c): MC samples. The vertical coordinate refers to the depth of the section from sample top surface.

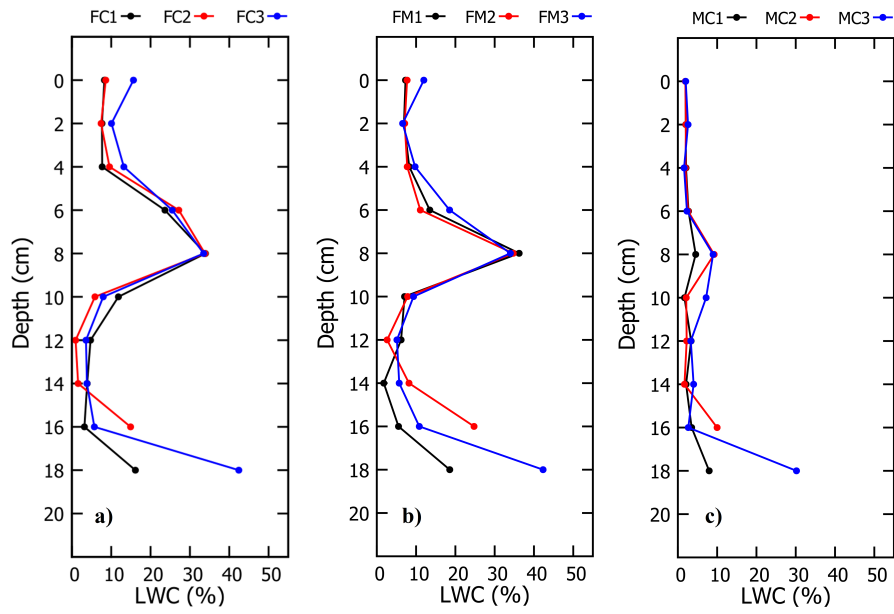


Figure 4. Measured LWC (vol %). Panel (a): FC samples; panel (b): FM samples; panel (c): MC samples. Each point represents bulk LWC in the underlying 2 cm. This convention is consistent with Fig. 1 and 3.

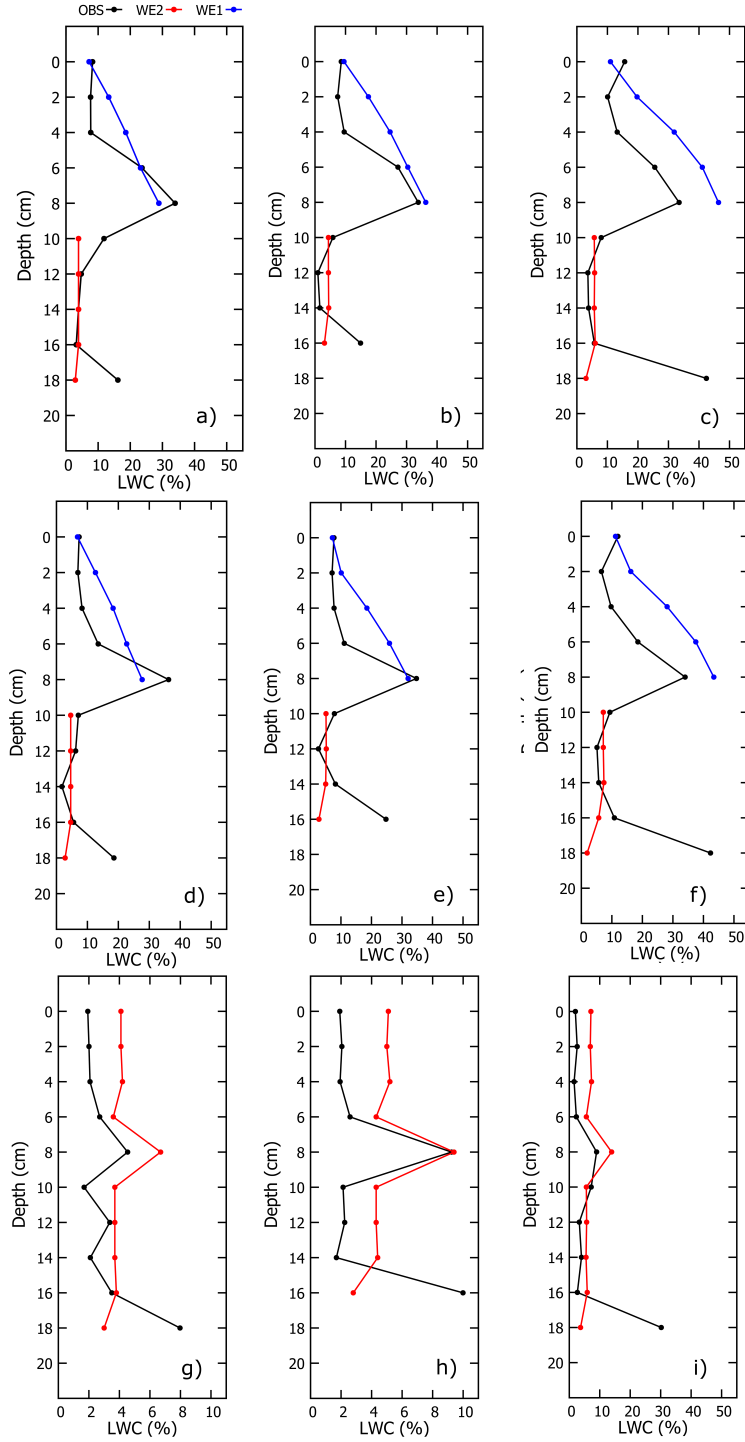


Figure 5. Comparison between observed and simulated profiles of volumetric LWC. Panels (a), (b) and (c) refer to samples FC1, FC2 and FC3. Panels (d), (e) and (f) refer to samples FM1, FM2 and FM3. Panels (g), (h) and (i) refer to samples MC1, MC2 and MC3. Note that panels (g) and (h) have a different horizontal range from the others. Each point represents bulk LWC in the underlying 2 cm.