

Dear Dr. Guillaume Chambon, Editor,

Dear Referees,

We would like to thank you for providing new suggestions and comments on our manuscript. We present here a revised version for possible publication in *The Cryosphere*.

During this second revision, we tried to address all remaining points at our best. In particular, we included all suggestions about writing style and grammar. Furthermore, we also modified the discussion as kindly suggested. We would like to again thank referees since we feel that these changes in the manuscript greatly improved the quality and the impact of this work for future use.

Please find additional details about our revision in the point-by-point reply to referees (next pages) and in the attached marked-up version of the manuscript. As revisions are now limited, we do not provide an additional table summarizing all changes made. These are nonetheless detailed in our replies to referees.

Thank you and kind regards,

*Francesco Avanzi and coauthors*

Dear Referee #1,

We thank you for your additional comments on the manuscript. Please find here a point-by-point reply to your kind suggestions. Your comments are in *italic*. For all the points, we provide answers and we outline our changes to the manuscript.

*1) The results are probably too much interpreted in terms of water entry suction only. In the implementation of Richards equation in the SNOWPACK model, the water entry suction is not considered, yet SNOWPACK is able to reproduce water ponding on microstructural transitions. So other factors that play a role are (i) that even in an equilibrium situation (no flow), the pressure head decreases with height above the ground only. Then, in fine grained snow, a particular pressure head will be associated with a higher LWC than in the coarse grained snow below, which one could interpret as ponding. This effect is also present during non-equilibrium flow. Note that it implies that interpreting a higher LWC in one layer as ponding due to the pressure head being below the water entry suction of the layer below is therefore also not justified. This should be interpreted in terms of pressure head. (ii) the capillary barrier will also introduce a jump in hydraulic conductivity, particularly if the snow below the barrier is dry. That means that a water accumulation can also arise when water is transported to the capillary barrier from above faster than can be transported away below the barrier. So I'm not so sure that all the ponding observed in the experiments can be uniquely explained in terms of water entry suction. Or can the authors argue that the water entry pressure is a kind of net description of the other processes I mentioned (i.e., difference in LWC for same pressure head and gradients in hydraulic conductivity)?*

*As the authors are very knowledgeable on this topic, they can maybe provide clarity to the snow science community at this point. I hope they can either rebut this point, or that they go once more through the manuscript to make sure that explanations provided are interpreted as representing the correct process and an appropriate discussion of causes for ponding on capillary barriers is provided.*

**Answer**

We agree with Referee #1 that our discussion on this point could be improved. We also agree with the referee that focusing only on water entry suction could be misleading as SNOWPACK does not include a parametrization for this parameter, as done by, e.g., the 3-D model by Hirashima et al. (2014, reference in the text), but it is nonetheless able to simulate capillary barriers. From this perspective, the manuscript could be clarified by introducing a more exhaustive description of all the processes involved in capillary barriers and a clearer discussion of the role of water entry suction.

In several papers on this topic from soil science, water entry suction is indicated as the suction head that allows breakthrough of liquid water at the interface (Baker and Hillel 1990, DiCarlo 2007, Stormont and Morris 1998, Stormont and Anderson 1999, and Khire et al. 2000 – all references are listed in the manuscript). Also, Stormont and Anderson (1999) point out that “initial percolation or breakthrough into the coarser soil occurs when the suction head is reduced to a value that permits water to enter and form a continuous network in an initially dry soil. This suction head value is termed the breakthrough head and is coincident with the soil becoming conductive.” Thus, we agree with the referee that unsaturated conductivity at low LWC plays also a role and that the processes occurring at capillary barriers cannot be interpreted basing on suction alone, as kindly suggested. Stormont and Anderson (1999) also report that “the observed breakthrough heads from the infiltration tests correspond to the first bend in the moisture characteristic curve encountered during wetting, coincident with the soil first taking up substantial water”. Thus, water entry suction may be related to the more general relation between suction, LWC and unsaturated conductivity. Compatible results are also reported in DiCarlo 2007. This relation is usually modelled using a water retention curve and a suitable parametrization of unsaturated conductivity. Note that SNOWPACK already implements both relations (see Wever et al. 2014 and 2015) and solves unsaturated flow in snow using Richards Equation. It may be that implementing Richards Equation in 1-D is sufficient to mimic some essential features of capillary barriers in snow (i.e., ponding and peak LWC) even without a separate calculation of water entry suction.

An important limitation emerges when discussing our experiments. Indeed, only a few data are currently available about the hysteresis of suction in snow, and this is key because available data in soils suggest that water entry suction may be related to a primary imbibition curve. Thus, we now suggest in the manuscript that a more detailed analysis of capillary barrier dynamics in snow necessarily needs observations of suction profiles during infiltration; this represents an important step of future research. Clearly, we agree with the referee that abrupt transitions of LWC cannot be easily attributed to accumulation of water due to a mismatch in conductivity or to water entry suction, as LWC at equilibrium can increase even with decreasing suction when changing layer properties. We now specify this in the manuscript. Nevertheless, we would like to point out that, during our experiments, we started with initially dry snow and observed a pause in wetting front propagation at the interface and consequent accumulation of water. This represents a key feature of capillary barriers that cannot be easily explained using only an equilibrium assumption (see again Stormont and Morris 1998 and Stormont and Anderson 1999 on this).

#### **Changes in manuscript**

First, we edited our initial description of capillary barriers in snow (Introduction). Second, we now refer to “unsaturated hydraulic properties of snow” instead of simply water entry suction when discussing our results. Third, we included a focus on the reasons why SNOWPACK succeeds in reproducing capillary barriers even if it does not include an explicit parametrization of water entry suction (Section 3.4).

*2) It is somewhat inconvenient that the model simulations are presented differently from the previous version of the manuscript and that the discussion paper will remain public. I'm aware that the other reviewer was asking to repeat the simulations using the latest version of SNOWPACK and I'm glad to see that the latest SNOWPACK version is giving results where the authors are happy with. Actually, it looks like the new SNOWPACK version is doing a better job for the MC samples (Figures 5g, h and i). Do the authors agree that the results seem better than with the old version of SNOWPACK? It is only a bit strange that the authors now found it necessary to plot 2 profiles, and only show a part of them, whereas in the discussion paper, full profiles are shown at one point in time. I think it is important to show full LWC profiles, even though it is well argued why they choose the 2 profiles from different moments of time in the simulations. At least I feel it is as necessary that the authors include a sentence or two of how the new and old SNOWPACK simulations compare, as the old SNOWPACK simulations are now public in the discussion paper.*

#### **Answer**

We see that reporting (and discussing) results with different water schemes is somehow inconvenient. However, this was an explicit request by the other referee. Furthermore, the main focus of this manuscript is on experimental data. Thus, the room for a detailed intercomparison between different models is very limited. Coherently, we selected the most recent scheme existing in the literature as it should represent the state of the art. The management of discussion papers by TC is now very explicit, as the discussion paper will be clearly linked to the final paper (the link to the discussion paper appears along with final papers). Thus, we are confident that the inconvenience given by the different analysis will be limited. Nonetheless, we now specify in the manuscript that the model version used is different from the one used in the discussion paper.

As we specify in the text, we decided to use two simulated profiles instead of one in order to improve our evaluation of model results vs. observations. This approach was included only in the revised manuscript as we took the revision as an opportunity to improve our methodology. This new validation is interesting because it shows important aspects of modelling at WE2 that would be missed if one focused only on WE1. The reason has clearly to do with the need for correctly comparing highly fingered simulations with a 1-D model when discussing the development of capillary barriers: in this perspective, using only the physical arrival time provides limited insight into process understanding. This issue is very important when dealing with a highly fingered infiltration like in MC samples. Accordingly, the LWC profiles reported in the discussion and in the final paper for MC samples refer to different times. Thus, a direct comparison between the two models is not possible in MC samples. This is now specified in the paper. In general, we also specified that the comparison with SNOWPACK does not focus on arrival time; this is because it highly depends on preferential flow. For all these reasons, we prefer not to discuss differences between the two models in this paper and we would like to show only two parts of profiles, if possible.

<b>Changes in manuscript</b>
We specified in the manuscript that “both, model version and the evaluation methodology are different from the preliminary results reported in the discussion paper, thus a direct comparison between them is not possible.” We also specified that the comparison with SNOWPACK does not focus on arrival time.

*Some minor and technical issues:*

*P1L4: "to a constant supply"*

<b>Changes in manuscript</b>
This sentence was removed following a comment by Referee 2.

*P3/4L94: Maybe it is a good idea to state the research goals a bit more clear in the introduction. As the text is now, it all doesn't sound that ambitious. I therefore suggest that the authors amend that they want to obtain quantitative information about the liquid water flow over a capillary barrier. And instead of just writing that you compare the results with SNOWPACK models, I suggest to word this as something like (P4L102): "All laboratory experiments ... SNOWPACK model, in order to investigate how well 1D snowpack models representing liquid water flow are able to capture the behaviour of liquid water flow over capillary barriers."*

<b>Changes in manuscript</b>
We amended the text as suggested.

*P4L106: This is not so well argued. On P 5L141, you write that you used dry snow. That means that in your experiments you also will have to deal with a mixture of dry and wet snow. Best is to reformulate P4L106.*

<b>Answer</b>
We agree with the referee that this passage could be improved. We now specify that Marsh and Woo (1984a, b) report that water infiltration in initially subfreezing snow is marked by an alternation of wet snow at 0°C and dry snow in subfreezing conditions.

<b>Changes in manuscript</b>
This passage was corrected, see text.

*P4L127-129: In my original review, I was thinking that it is relatively easy to address this issue, as the saturated hydraulic conductivity of snow is generally very high, well above natural water fluxes in snow, and well above the water influx rates you use in your experiments. It sounds a bit weak that you did not consider any instability criterion. For me, you can just write that due to the high saturated hydraulic conductivity of snow compared to the water influx rate in your experiments, most instability criterions will predict unstable flow, which is confirmed by Katsushima et al. 2013. But this is up to the authors.*

<b>Changes in manuscript</b>
We agree with this revision. The text was amended as kindly suggested.

*P6L179: "by a operation model". What do you mean? "by an operational model"? Also not clear what defines an operational model. Do you intend to say that it is a model that incorporates most processes related to snow and can be applied to natural snow covers?*

<b>Changes in manuscript</b>
Yes, exactly. We tried to summarize this by replacing “operational” with “physically-based”.

P6L185: Probably better to cite Coleou and Lesaffre here, which defines the bucket scheme used in SNOWPACK. [Coléou, C. and Lesaffre, B.: Irreducible water saturation in snow: experimental results in a cold laboratory, *Ann. Glaciol.*, 26, 64–68, 1998.]

<b>Changes in manuscript</b>
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We agree. The text was modified as suggested.
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P6L172: "Clearly...software.". I'm not sure if the authors included this based on my first review, but the sentence feels a bit too obvious, out of place and may be removed.

P8L261: "spatially restricted" well, actually it is almost no water spreading...

P8L267-269: This part is really hard to follow now. I think "Conversely" should be "In contrast". Then you can write: "In contrast,  $\psi$  in fine snow for 5% and 10% LWC is 0.22 and 0.21, respectively and  $\psi$  in medium snow for 5% and 10% LWC is 0.09 and 0.08, respectively. This implies that for typical low saturation values in snow, the difference in suction pressure in the finer snow with the water entry pressure of the courser snow is larger for fine snow." Or something similar.

P9301L: "other hints" -> I suggest "Other indications for the spatial variability are the observed spatial variability ..."

P9L303: "as this is a signature of LWC" -> "which can be linked to/attributed to/interpreted as differences in LWC"

P10L316: "say" -> "maximally"

<b>Changes in manuscript</b>
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We modified the text as suggested.
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P10L338-339: Actually, I think for a good investigation of the relationship of  $f$  with  $W$ , also larger containers need to be used, as now, with the 5cm rings, preferential flow tend to form at the boundaries of the sample, so there seems to be a boundary effect here (see Figure 1). When the authors agree, they can mention this here. This point may also be mentioned in the comparison section with SNOWPACK, where discrepancies are discussed. Boundary effects may also explain discrepancies between model and laboratory experiments.

<b>Changes in manuscript</b>
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We agree with this comment and are happy to include this implication in the revised text.
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P11L348: "less expected" -> I had the impression that the authors were arguing at some point that capillary barriers may influence the travel time, as the progress of the melt water front is temporarily blocked at the capillary barrier. Why is it then "less expected"?

<b>Answer</b>
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Because 50% of each sample was made by medium or coarse snow (high saturated conductivity), it may be expected that the travel time of water in layered snow may be shorter than the travel time in purely fine snow.
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<b>Changes in manuscript</b>
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We modified the text here by removing "less expected" and including "which is marked by a very low saturated conductivity" (see text).
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P14L457: "basing" -> "based"

*Conclusions: Some people only read conclusions, so maybe replace FC with fine-over-coarse, etc here.*

<b>Changes in manuscript</b>
We modified the text as suggested.

*P14L470: "point conditions" is a bit confusing. It may also refer to a point in 3D, but I guess the authors mean here the 1D representation in the SNOWPACK model?*

*P14L469-470: I generally don't like a sentence like this in the conclusions. It is the conclusion section after all. So please state the outcome (so, the conclusion!) of the discussion; a sentence like: "The comparison of observed and simulated LWC revealed this, this and this."*

<b>Answer</b>
We agree with the referee that 1) "point conditions" should be replaced by a more specific reference to the 1-D nature of SNOWPACK. Furthermore, we also agree with the referee that the conclusion section should be more explicit about our results.
<b>Changes in manuscript</b>
The text was amended on this point as follows: "The marked spatial variability of liquid water content in snow represents a source of uncertainty when comparing measurements at a relatively high resolution with a 1-D model."

*In response to the reply to reviewers:*

*The value of 1.3% found by Waldner et al. (2004) was originally used as a comparison with the laboratory experiments. The authors originally interpreted the value as 13% and made a comparison with their experiments. Now that it is clear that the value is 1.3%, the discussion is dropped by the authors. It is not clear now how this measurement relate to the work of the authors. I think it can be attributed to differences in the characteristics of the snow used in the experiments as well as the applied water flux, and the experiment duration? This measurement by Waldner et al. (2004) may still be important to be discussed in the manuscript, given the limited experimental data on capillary barriers.*

<b>Answer</b>
We agree with the referee that this comparison is helpful. In our interpretation, this difference may be due to (microstructural) heterogeneity in snow, infiltration rate, experiment durations and the larger measurement area of the TDR system used by Waldner et al. (2004) compared to a calorimeter.
<b>Changes in manuscript</b>
We included this discussion in the text.

Dear Dr. Christoph Mitterer, Referee #2,

We thank you for your additional comments on the manuscript. Generally, we have included your suggestions about text and grammar in the final draft. Here, we comment on some specific suggestions that needed a more extensive elaboration from our side. Your comments are in *italic*. For all the points, we provide answers and we outline our planned changes in manuscript.

As comments were originally placed in the .pdf draft of the manuscript, we will here specify the line number to which the comment refers (according to the previous version of the manuscript).

*Line 1: Maybe you want to write an intro sentence explaining why you do the experiments.*

<b>Changes in manuscript</b>
An intro sentence was included.

*Line 221: add "content"*

<b>Answer</b>
We did not add "content" here as, in our opinion, LWC is a numerical variable, whereas here we refer to the physical arrival of water as sample base.

*Line 221: Please improve this explanation as it is hard to understand what you did; Is Mitterer et al. 2011 the correct reference? Not better to use Mitterer et al. 2013?*

<b>Changes in manuscript</b>
We improved our explanation here. We thank the referee as this point is key to understand our manuscript.

*Line 235: I suggest moving this sentence to the conclusion or discussion.*

<b>Changes in manuscript</b>
We moved this sentence to the discussion.

*Line 253: Please note that also within the results and discussion section on SNOWPACK*

<b>Changes in manuscript</b>
We moved this explanation about how to compare data in MC samples and SNOWPACK simulations to the section about SNOWPACK (Section 2.3). Here, the explanation was removed and substituted with a more concise reference to that section.

*Line 276: You must stress this a little more. In fact, the numbers for the relation of theta-psi you present in lines 268-270 seem quite high. If you compare it to measurements by Denoth, Colbeck or Wankewicz (see Book Snow and Climate, Page 47) you would rather expect values of max 0.15 m to 0.1 m of pressure head for psi at water contents of 0.05 and 0.1 respectively. Basically this represents your hysteresis mentioned earlier and similar to sand also in snow the drying curve will be less steep at both kinks than the wetting curve. Still your difference for in psi to psi\_we has the factor 5 and not 10. Please include that within your discussion on that topic.*

<b>Answer</b>
We agree with the referee that hysteresis is key to understand our results.
<b>Changes in manuscript</b>
We added some details about this issue here. In particular, we note that the WRC by Yamaguchi et al.

(2012) refers to a drying process and this may trigger some additional uncertainty when estimating suction for a wetting process, due to hysteresis. Available data of hysteresis in snow are, however, very preliminary (Adachi et al., 2012). We also refer to a more exhaustive discussion in Section 3.4.

*Line 411: Not so sure, since we change the structure of our porous medium a lot while infiltrating. So wetting will be for sure different from drying.*

**Changes in manuscript**

We removed this sentence from the manuscript.

*Line 469: Please give a more concise outlook, e.g. on comparison with Hirashima et al 2014.*

**Changes in manuscript**

We included a short outlook about the expected comparison with a 3-D model in the conclusion.

*Figure 5: Please mention WE1 before WE2 within the legend. Add information on why g-i have only WE1.*

**Changes in manuscript**

We modified the legend as suggested. We did not include an extensive explanation about why g-i have only WE2 as this is already in the main text. Nonetheless, we specify that, “as described in Section 2, two simulated profiles are reported for FC and FM samples (WE1 and WE2), whereas only WE2 is reported for MC samples”.

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

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## Abstract.

~~We~~ Data of liquid water flow around a capillary barrier in snow are still limited. To gain insight into this process, we carried out observations of dyed water infiltration in layered snow at 0°C 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 flow dynamics of each sample were also simulated solving Richards equation within the ~~4D-1-D~~ multi-layer physically-based SNOWPACK model. Results reveal snow cover model SNOWPACK. Results revealed that capillary barriers and preferential flow are relevant processes ruling the speed of liquid water-water infiltration in stratified snow. Both are marked by a high degree of spatial variability at cm scale and complex ~~3D-3-D~~ patterns. During unsteady percolation of liquid water, observed peaks in bulk volumetric liquid water content (LWC) at the interface ~~reach-reached~~ ~ 33 - 36 vol% when the upper layer ~~is was~~ composed by fine snow (grain size smaller than 0.5 mm). ~~A comparison with expected wetness at water entry suction suggests that~~ However, LWC might locally ~~reach saturated conditions~~ be greater due to the observed heterogeneity in the process. 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 runoff~~ timing and amount (~~Lundquist and Dettinger, 2005; Lehning et al., 2006; W~~  
snowpack mechanical properties and stability in wet conditions (Marshall et al., 1999; Baggi and  
25 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) report that meltwater percolation - storage dy-  
namics 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  $\theta$ ), i.e.,  
30 the ratio between liquid water volume and total snow volume (Fierz et al., 2009). LWC is usually  
expressed in ~~vol %, or %~~ percent of volume (vol % or just %).

Water flow in snow emerges as a complex, ~~3D-3-D~~ 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 hence~~ melt-freeze and ~~to~~ the possible development of ice lenses when  
35 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 wa-  
40 ter 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) and snowpack stability (Techel et al., 2011; Mitterer et al., 2011; Mitterer and Schweizer, 2013).

The exact physics of preferential flow in snow is still not known (Katsushima et al., 2013) and  
45 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  
value for  $\theta$  triggering preferential runoff. Wever et al. (2014) report that solving Richards equation  
accounting for suction ( $\psi$ ) gradients improves run-off estimations at different temporal resolutions,  
but it also accelerates meltwater front progress if compared with data from an upGPR and simu-  
50 lations 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 mat-  
ter 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;  
55 Katsushima et al., 2013; Baver et al., 2014). Observations reveal that ~~, in soils, in soils~~ an unstable infil-  
tration profile may be marked by an overshoot profile in terms of  $\theta$  (saturation ~~osverhootovershoot~~)  
or  $\psi$  (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 infil-

tration by Katsushima et al. (2013). In addition, Hirashima et al. (2014) report promising attempts to  
60 reproduce similar dynamics using a 3-D model; they show that solving Richards equation by includ-  
ing spatial heterogeneity of snow properties and water entry suction ( $\psi_{WE}$ ) ~~in a 3D resolution of~~  
~~Richards equation enables to reconstruct~~ enables to simulate preferential flow effects. These results  
suggest that preferential flow in isothermal snow at 0°C might be explained (and modeled) ~~basing~~  
~~on with a similar approach to~~ the theory of gravity-driven instability of fingers in soils (Katsushima  
65 et al., 2009b, 2013).

~~According to Hirashima et al. (2014), water entry suction is thus a key variable ruling preferential~~  
~~flow development, as it impedes the movement of water between dry and wet snow during wetting~~  
~~until suction reaches  $\psi_{WE}$ . This process causes~~ Unsaturated hydraulic properties of snow may  
impede water infiltration in a finer-over-coarser profile. This impedance is usually referred to as  
70 a capillary barrier (Khire et al., 2000; Waldner et al., 2004) and is due to the infiltrating water being  
generally marked by a very high suction when it initially moves in the finer layer. This prevents water  
from entering the lower layer, thus causing local accumulation of ~~liquid water at microstructural~~  
~~discontinuities~~ water at the interface (henceforth, simply ponding). ~~A decrease in  $\psi$  during ponding~~  
~~is caused by the fact that  $\theta$  and  $\psi$  are related by a hysteretic relation called Water Retention Curve;~~  
75 ~~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 development~~  
~~(Baker and Hillel, 1990). This is a finer-over-coarser transition in layering that causes a pause in, a~~  
~~deceleration in~~ the undisturbed advancement of the wetting front, ~~ponding,~~ horizontal diversion of  
80 ~~liquid~~ water and a delay in the expected travel time of water. ~~Hill and Parlange (1972); Baker and Hillel (1990); Hillel and Baker (1990)~~  
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.~~ for layered snowpack. According to the  
results by Stormont and Anderson (1999) in soils, water will enter the underlying coarser layer when  
 $\psi$  at the interface decreases to  $\psi_{WE}$ ; at this suction, the coarser soil layer firstly becomes conductive  
85 (Stormont and Morris, 1998; Khire et al., 2000). A decrease in  $\psi$  during ponding is caused by the  
fact that  $\theta$  and  $\psi$  are related by a hysteretic relation called Water Retention Curve, WRC (Daanen and Nieber, 2009; Yamaguchi et al.,  
In soils, Hillel and Baker (1988); Baker and Hillel (1990) note also that, after reaching  $\psi_{WE}$ , sub-  
sequent flow in the coarser layer will be marked by fingers if, in steady conditions, the hydraulic  
conductivity of the lower layer at  $\psi_{WE}$  is greater than the flux through the top layer  $q$  (due to mass  
90 conservation). Thus, ponding of water above a capillary barrier is prone to subsequent flow instabil-  
ity, namely, to the development of preferential channels.

~~Capillary barriers~~ Understanding water flow around capillary barriers may be an important step  
toward efficiently modeling liquid water flow in snow. Furthermore, capillary barriers can play an im-  
portant role for triggering wet snow avalanches (Mitterer et al., 2011; Wever et al., 2016). For exam-  
95 ple, 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 from~~ 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). ~~Furthermore, a thorough investigation of the properties of capillary barriers may help to gain a better understanding of the physics of~~  
100 ~~water instability in snow in general, as water flow around these textural discontinuities is driven by~~  
 ~~$\psi_{WE}$ , especially during initial infiltration in dry snow.~~ However, their characterization in the literature is still very limited (Eiriksson et al., 2013). Indeed, existing ~~ad-hoc-real-time~~ 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-Under~~ field conditions, LWC profiles are usually measured using  
105 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~~ collected quantitative  
110 information about the liquid water flow around a capillary barrier in snow using laboratory experiments. We ~~collected systematic observations of dyed water infiltration in~~ considered nine 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~~  
115 ~~water at~~ water at the 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-1-D~~ multi-layer physically-based ~~SNOWPACK model~~ snow cover model SNOWPACK,  
120 in order to investigate how well 1-D snowpack models are able to capture the behavior of water flow over capillary barriers.

We consider isothermal conditions at  $0^\circ\text{C}$ , thus avoiding any investigation about wetting front advancement in subfreezing snow, which presents additional challenges. ~~As an example~~ Indeed, Marsh and Woo (1984a, b) report that ~~zones with mixed wet~~ water infiltration in initially subfreezing snow  
125 is marked by an alternation of wet snow at  $0^\circ\text{C}$  and dry snow ~~develop in such in~~ subfreezing 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

### 130 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~~presented work, 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~~revealed that the area occupied by fingers in snow (~~Katsushima et al., 2013~~) and the value of  $\psi_{WE}$  (~~DiCarlo, 2007; Katsushima et al., 2013~~) may be both functions of water input rate (~~Katsushima et al., 2013~~). 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  $100 \text{ mm/h}$ . 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~~ Because the saturated conductivity of snow is rather high compared with the chosen input rates, most existing instability criteria (Saffman and Taylor, 1958; Baker and Hillel, 1990; de Rooij, 2000; DiCarlo, 2013) will predict unstable flow in these conditions. Accordingly, Katsushima et al. (2013) have 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.~~

Nine samples were prepared in a cold room at  $-20^\circ\text{C}$  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  $100 \text{ mm/h}$ , 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  $20 \text{ mm}$ , diameter equal to  $50 \text{ mm}$ ) 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  $0^\circ\text{C}$ , where it was stored for at least 12 hours to reach initial conditions of dry snow at  $0^\circ\text{C}$ .

165 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  
170 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

175 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  
180 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,

185 
$$\tau = t_t/h, \tag{1}$$

with  $h$  equal to sample height. Note that  $\tau$  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,  
190 snow included). At the same time, the liquid water mass  $w$ , in grams, in each of the rings was mea-  
sured using a portable calorimeter (Kawashima et al., 1998). These measurements were translated  
into profiles of volumetric liquid water content by converting  $w$  to  $\theta$ . 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  
195 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~~-physically-based 1-D multi-layer snow cover 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  
200 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 rather detailed discussion of both, the physical process and its simulation by a ~~operation~~-physically-based model. This comparison will not include preferential flow patterns and arrival times, as the model ~~is 1D~~does not include an explicit treatment of preferential flow regimes.

205 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)~~Coleou and Lesaffre (1998)). After exceeding, excess water is  
210 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 content simulation in snow. We used the numerical scheme by Wever et al.  
215 (2014) in this paper (WE, SNOWPACK version 3.3, <https://models.slf.ch/>).

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, grain type, size and~~ density (Table 1),  $\theta$  (initially dry), and temperature ( $0^\circ\text{C}$ ) of the  
220 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  
225 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  $+0^\circ\text{C}$ . The threshold temperature for classifying solid and liquid events was set to  $-0.01^\circ\text{C}$ , in order for  $W$  to be classified as liquid. Wind speed and  
230 solar radiation were set to zero, while incoming longwave radiation was calculated as  $\sigma T^4$ , 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 hy-

draulic conductivity at the interface were all kept at the default settings discussed for SNOWPACK in Wever et al. (2014, 2015).

235 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 single~~ snapshot of simulated LWC for the comparison with  
240 our observations is ~~difficult~~ problematic, as the model is ~~1D-1-D~~ 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 (i.e., only one time step) may be misleading as possible  
245 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~~. This may limit a comparison aiming at assessing the capability of a model to reproduce capillary barriers. Thus, we will compare observed profiles of LWC with ~~both, i) the simulated profile at the model results at two different times. The first one (WE1) is the~~ observed arrival time of water at sample base (WE1), and ~~ii) the simulated profile at the~~; the second one (WE2) is the simulated arrival time of water ~~in the model (WE2) at sample base~~, which is chosen by identifying the instant when  $\theta$  at sample base reaches  $\sim 3$  vol% in the simulation (~~Mitterer et al., 2011~~). (Mitterer et al., 2013). Note that WE1 and WE2 for each sample were obtained from the same simulation.

On the one hand, WE1 is advantageous as supplied mass in experiments and in simulations  
255 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-1-D~~ 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  
260 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 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~~ Because liquid water flow in MC samples turned out to be highly fingered (see next Section), observations in these samples are compared only with WE2 (full profile), which is probably less affected by effects due to preferential flow, including the time arrival of water at a certain point of the profile.

## 270 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 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~~ greater is local LWC (Waldner et al., 2004). We report  
275 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 accumulation ( $p$ ), arrival time of water at the base of each sample ( $t_t$ ), and specific travel time of ~~liquid~~ water in snow ( $\tau$ ). In Figures 3 and 4, profiles of wet snow fractions  $f$  and LWC are given. In  
280 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.

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  
285 profiles are reported for FC and FM samples (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, whereas only WE2 is reported for MC samples. Note that both, model version and the evaluation methodology are different from the preliminary results reported in the~~  
290 discussion paper, thus a direct comparison between them is not possible.

### 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  
295 transition in wetness between finer and coarser layers (see Fig. 2). In 4 out of 6 samples of these two 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~~ Indeed, almost no water spreading was observed 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  
300 FC and FM samples.

The difference between FC-FM and MC samples in terms of ponding behavior ~~can~~ may be explained considering the retention properties of snow with different grain size.  $\psi_{WE}$  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  $\sim 0.04$  m in medium snow.

305 ~~Conversely~~In contrast,  $\psi$  in fine snow for 5% and 10% LWC is  $\sim 0.22$  m ( $\theta = 5$  vol%) and  $0.21$  m ( $\theta = 10$  vol%), whereas, respectively and  $\psi$  in medium snow for 5% and 10% LWC is  $\sim 0.09$  m ( $\theta = 5$  vol%) and  $0.08$  m ( $\theta = 10$  vol%), respectively. This implies that for typical low saturation values in snow, the difference between the suction pressure in the finer snow and the water entry pressure of the coarser snow is larger for fine snow. Furthermore, unsaturated conductivity of coarser snow is likely to quickly decrease with increasing  $\psi$ , as already observed in soils (Stormont and Anderson, 1999). It follows that, at the same  $W$ , the greater the mismatch between unsaturated properties of finer and coarser snow is, the larger is the mass of water accumulated and horizontally diverted until the underlying layer is able to convey the supplied flux. These approximate values of suction in snow were estimated using the WRC parametrization in snow by Yamaguchi et al. (2012), assuming an

315 ~~irreducible a residual~~ LWC equal to 2.4 vol % (Yamaguchi et al., 2010; Hirashima et al., 2014), and considering 5 vol% and 10 vol% as reference values for relatively low saturation. Thus, in FC-FM samples the difference between  $\psi$  at relatively low saturation and  $\psi_{WE}$  is much greater than in MC samples. Generally, the higher the difference between  $\psi$  in the upper layer and  $\psi_{WE}$  is, the larger is the mass of water accumulated and horizontally diverted. Note that the WRC by Yamaguchi et al.

320 (2012) refers to a drying process and this may trigger cause some additional uncertainty when estimating  $\psi$  for a wetting process (see Section 3.4), due to hysteresis. Indeed,  $\psi$  for a primary wetting process is expected to be smaller than  $\psi$  for a primary drying process. Available data of hysteresis in snow are, however, very preliminary (Adachi et al., 2012). A specific discussion about the role of hysteresis for interpreting these results is given in Section 3.4.

325 ~~FC and FM samples~~ All layering types are characterized by similar LWC profiles with the only difference in absolute values for LWC (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 capillary barrier. Peaks in LWC at the interface are a characteristic feature of may be associated with capillary barriers as water ponds until  $\psi \rightarrow \psi_{WE}$   $\psi$  reaches  $\psi_{WE}$  and the underlying layer becomes conductive

330 (Stormont and Anderson, 1999): 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:  $\sim 33$  vol% in FC samples and  $\sim 34$  vol% - 36 vol% in FM samples. This value is coupled with suction through a wetting curve (DiCarlo, 2007). This may be the reason why LWCs at the interface are similar, as

335  $\psi_{WE}$  is the same in all these six samples. Again, this may be explained by considering that the peak of LWC at the boundary is ruled by the retention properties of snow with different grain size and by their contrast (see Khire et al. (2000) for a similar discussion in soils). 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 stability in wet conditions (Wever et al., 2016).

340

In MC samples, a smaller, but distinct, peak in LWC was measured at the interface: in MC1, LWC over the boundary is  $\sim 4.5$  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  $\sim 9$  vol%.

345 A smaller peak of LWC in MC layering is attributed to the small difference between unsaturated hydraulic properties in medium and coarse snow (for example, a smaller difference between  $\psi$  in medium snow and  $\psi_{WE}$  in coarse snow). Note again that this difference could be even smaller than expected if hysteresis was explicitly taken into account (Adachi et al., 2012). The observed peaks in MC samples are generally greater than the peak value observed by Waldner et al. (2004) during

350 snowmelt infiltration through a 1.5 mm over 2.5 mm transition in an artificially sieved snowpack. This difference may be due to (microstructural) heterogeneity in snow, infiltration rate, experiment durations and the larger measurement area of the TDR system used by Waldner et al. (2004) compared to a calorimeter (see Sections 3.4 and 3.5).

The occurrence of capillary barrier causes horizontal redistribution of water. Thus, spatial homogenization 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 dry snow persist at depths equal to 8 cm in samples FC2 and FC3 (i.e., 2 cm above the interface). Other

355 hints-indications 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 which can be linked to differences in 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 above a capillary barrier has a marked 2D-2-D (or even 3-D) structure at local scale, probably due to heterogeneity in snow microstructure. The difference in wet

360 areas in MC samples for different water input rates might be on the contrary an effect of water input rate on  $\psi_{WE}$ , 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.

370 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 typically in the range

375 of minutes).

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 in-

creasing 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  $\psi_{WE}$~~  (Hillel and Baker, 1988; Baker and Hillel, 1990) and the possible relation between  $\psi_{WE}$  and velocity (~~Weitz et al., 1987; DiCarlo, 2007; Katsushima et al., 2013~~) (DiCarlo, 2007, 20 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 content patterns~~ at a more 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 when reaching~~  $\psi_{WE}$ . 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. Furthermore, additional experiments should be carried out using containers of different size, in order to assess whether the experimental geometry used may induce possible boundary effects (see also Katsushima et al. (2013) on this).

$\tau$  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  $\tau$  measured during the experiment (2.2 min/cm) with the  $\tau$  observed during the experiment by Katsushima et al. (2013), since this is the only  $g_S - W$  combination that these two works share. The  $\tau$  measured by Katsushima et al. (2013) for fine snow and  $W = 22.3$  mm/h is equal to 1.7 min/cm, while the  $\tau$  for medium snow and  $W = 21.7$  mm/h is equal to 0.7 min/cm. These results suggest that  $\tau$  in a FM sample is higher than the  $\tau$  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  $\tau$  is even higher than the specific travel time observed in a homogeneous sample made by fine snow, which is ~~less-expected~~ marked by a very low saturated conductivity. 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 According to Figure 5, SNOWPACK clearly reproduces an increasing LWC with depth in the upper layer and a peak of LWC at the interface at WE1. Furthermore, LWC profiles below the barrier are generally in good agreement, once water has reached the base in the simulation (WE2). 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. Note that the version of SNOWPACK used does not implement a parametrization of water entry suction (Wever et al., 2014), but the model is anyway able to provide a sufficiently good performance in reproducing the profile around a capillary barrier. Results by Stormont and Morris (1998); Stormont and Anderson (1999); Khire et al. (2000); DiCarlo (2007) show that  $\psi$  and  $\theta$  at an infiltrating front (hence,  $\psi_{WE}$ ) may follow a wetting WRC. Both variables are also strictly coupled with unsaturated conductivity (Mualem, 1976; Stormont and Anderson, 1999) and the impedance mismatch given by the low unsaturated conductivity of the coarser layer compared to the applied flux plays a key role in delaying water on the barrier. SNOWPACK currently includes a parametrization of both, a WRC and unsaturated conductivity and solves Richards equation. It may be that implementing Richards equation in 1-D is sufficient to mimic some essential features of capillary barriers in snow (e.g., ponding) even without an explicit calculation of  $\psi_{WE}$ . Note that an increase in LWC with depth as well as abrupt transitions in LWC at the interface may occur even in equilibrium, i.e., when suction increases with height. This is due to the different retention properties of fine, medium, and coarse snow. Furthermore, suction profiles over the barrier may depend on applied flux too (Stormont and Morris, 1998; Stormont and Anderson, 1999). Thus, a more detailed analysis of capillary barrier dynamics in snow necessarily needs observations of suction profiles during infiltration; this represents an important step of future research.

~~Overall, observations~~ Another important limitation for this discussion may be the present lack of an exhaustive investigation of WRC hysteresis in snow (Adachi et al., 2012). As already noted, the absence of a proper parametrization of hysteresis may hamper the estimation of expected LWC at  $\psi_{WE}$  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).

450 The magnitude of hysteresis is also related with the magnitude of capillary and saturation overshoot (DiCarlo, 2007; Katsushima et al., 2013), although it is not the prime cause of instability (DiCarlo, 2013). In this context, note that, according to Khire et al. (2000), hysteresis plays a less important role than the difference in unsaturated hydraulic properties between the finer and the coarser layer when studying the general properties of capillary barriers in soils and how they depend on layer parameters;  
455 this may again support the idea that the existing implementation of unsaturated flow in a complex 1-D model may be sufficient to mimic LWC distribution around a capillary barrier. A possible improvement may be represented by the set of parametric models proposed by Luckner et al. (1989) for porous media, which include hysteresis.

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~~ high spatial variability at cm scale. This is because natural snow is spatially heterogeneous (Hirashima et al., 2014) and this may affect ~~3D-3-D~~ 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  
465 may partially explain some differences between observations and ~~1D-1-D~~ 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  $\sim 0.5$ ), but greater than observations. An approximate estimation of LWC at  $\psi_{WE}$  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  
470 might be reached at a very local scale, while bulk LWC (~~which is the effect of both, capillary barrier effects and snow heterogeneity in wetness at ring scale~~) in each ring can be lower -

due to heterogeneity in wetness at a larger scale. 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,~~ resolution differences in LWC  
475 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  
480 ~~defined-established~~ 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~~ spatial resolution needed to capture ~~3D-3-D~~ 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  
485 (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).

490 This discussion also reveals the role played by heterogeneity (Hirashima et al., 2014) in introducing possible differences in LWC between ~~3D-3-D~~ (bulk) and ~~point (1D)-1-D~~ conditions. Additional uncertainty in this comparison 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), and possible boundary effects due to the experimental geometry. To summarize, 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.

~~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  $\psi_{WE}$  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).~~

### 510 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-small due to the short duration of this experiment ( $\sim 2.88$  g).

515 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) 520 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.

525 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 fair agreement (see previous Section) ~~and this is another good point~~ which  
530 underlines the above mentioned range of absolute error, since SNOWPACK bases on mass an energy conservation.

Capillary barriers and associated preferential flow represents a big-large 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,  
535 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 er-  
540 ror 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  $\sim 1$  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~~ larger instruments (Stein et al., 1997). For future experiments,  
545 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.  
550 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 it arrives~~ at the textural boundary. Measured peaks in LWC over the bound-  
555 ary are large with respect to usual measurements in the field (up to  $\sim 33$  vol% in FC fine-over-coarse samples and  $\sim 34 - 36$  vol% in FM fine-over-medium samples), while peaks in MC medium-over-coarse samples are usually  $\leq 10$  vol%. Differences in peak LWC between samples were explained ~~basing~~

~~on retention by varying unsaturated hydraulic~~ properties of snow with different grain ~~sizes~~sizes. A more detailed analysis of horizontal sections revealed marked variability of wetness conditions at  
560 cm scale, thus suggesting that local LWC might even ~~reach saturated conditions, as expected by a~~  
~~simple estimation of LWC at water entry suction~~be greater than measured.

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  
565 by the strong perturbation introduced by the capillary barrier in liquid water content 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~~  
570 ~~possible discrepancies between point conditions and 3D patterns even at cm scale.~~ The marked spatial variability of liquid water content in snow represents a source of uncertainty when comparing measurements at a relatively high resolution with a 1-D model. Future steps of this work will compare these measurements with a 3-D simulation of liquid water infiltration in snow (Hirashima et al., 2014).

## 575 **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.

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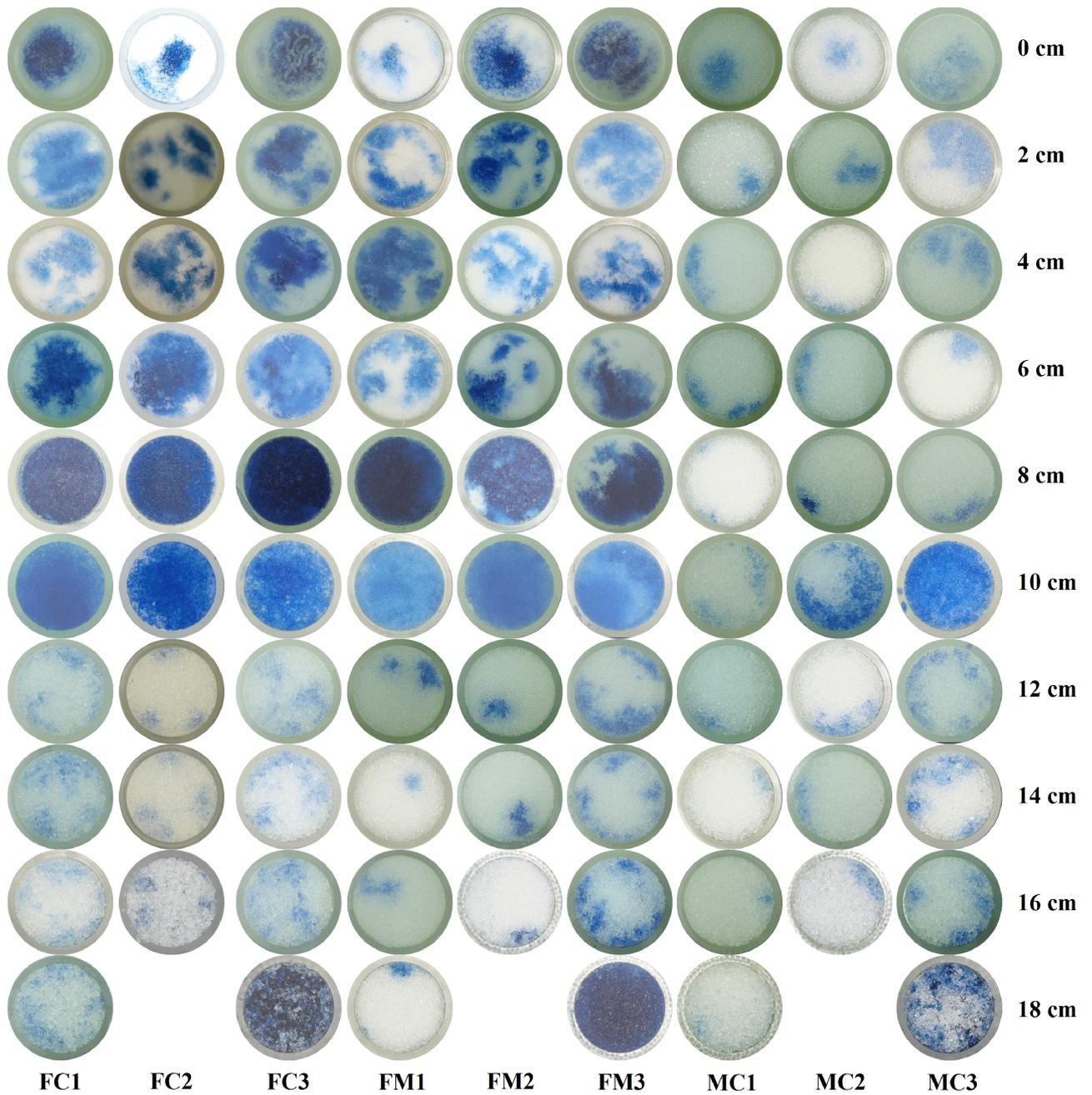
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**Table 1.** Experimental details.  $W$  is the applied water input rate,  $\rho_{D,U}$  is the dry density of the upper layer,  $\rho_{D,L}$  is the dry density of the lower layer.

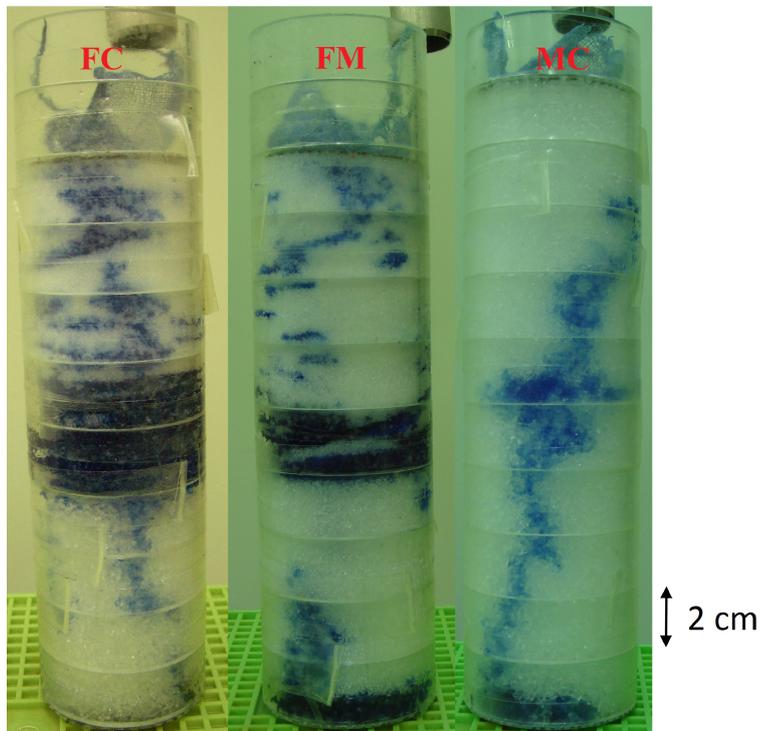
<b>Sample ID</b>	$W$ (mm/h)	$W$ (g/min)	$\rho_{D,U}$ (kg/m <sup>3</sup> )	$\rho_{D,L}$ (kg/m <sup>3</sup> )	<b>Upper layer</b> thickness (cm)	<b>Lower layer</b> thickness (cm)
FC1	11.9	0.39	417	465	10	10
FC2	28	0.92	449	483	10	8
FC3	113	3.7	433	470	10	10
FM1	11.9	0.39	444	484	10	10
FM2	27.7	0.91	442	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  $t_t$ , and specific travel time  $\tau$ . As for  $p$ , approximated lower and upper values are reported due to spatial heterogeneity in this variable.

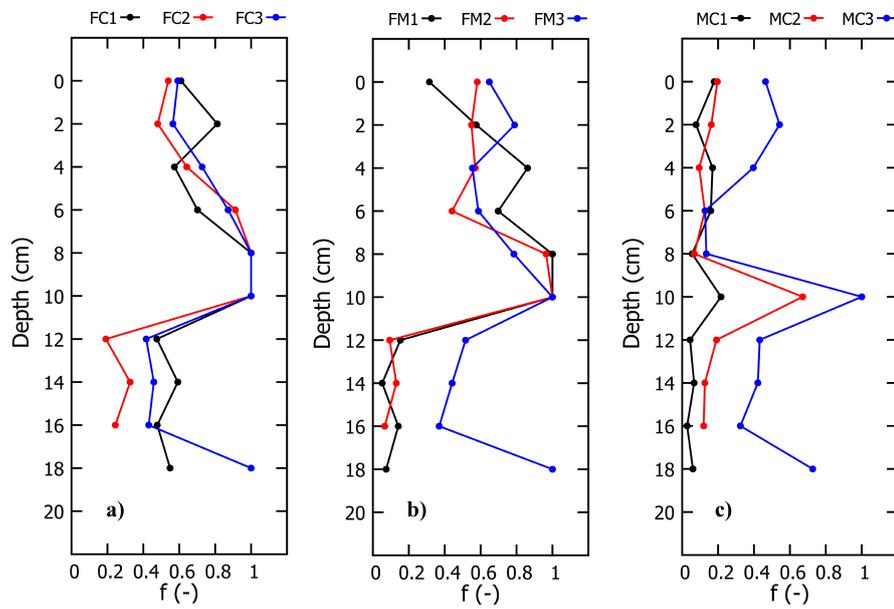
<b>Sample ID</b>	<b><math>p</math> (min - max)</b>	<b><math>t_t</math></b>	<b><math>\tau</math></b>
	<b>(cm)</b>	<b>(min)</b>	<b>(min/cm)</b>
FC1	2 - 3	92	4.6
FC2	3 - 4	50	2.8
FC3	2 - 3	14.5	0.725
FM1	2 - 3	90	4.5
FM2	2 - 3	40	2.2
FM3	1 - 2	13.5	0.675
MC1	0 - 1	8	0.4
MC2	1 - 1	8.45	0.47
MC3	0.5 - 1	5.3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



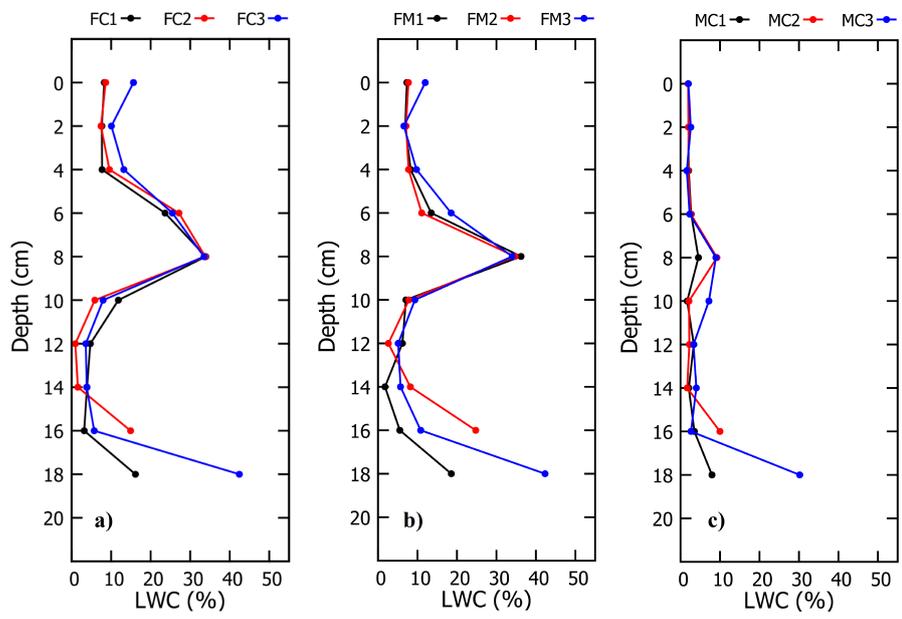
**Figure 1.** Sections of all the samples (rings diameter equal to 5 cm, 2 cm vertical resolution) at the end of each experiment. Each column refers to a different sample (as indicated in the last row), while each row refers to the same depth from sample top surface (depth indicated by the number on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



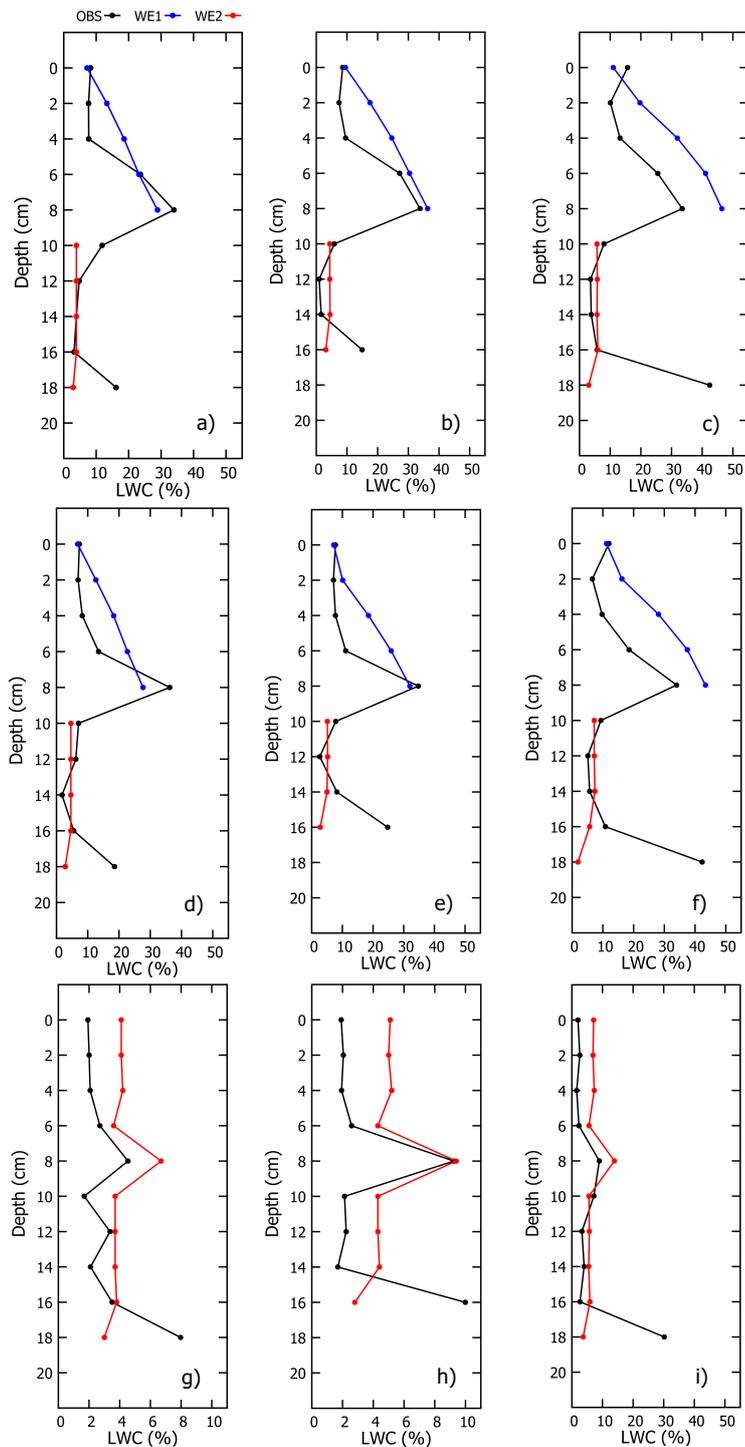
**Figure 2.** Three samples at the end of the experiments: FC2 (on the left, as an example of FC samples), FM2 (at the center, as an example of FM samples) and MC1 (on the right, as an example of MC samples).



**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. [Serial numbering 1-3 represent the three different input rates.](#)



**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. [Serial numbering 1-3 represent the three different input rates.](#)



**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. As described in Section 2, two simulated profiles are reported for FC and FM samples (WE1 and WE2), whereas only WE2 is reported for MC samples.