

Capillary barriers in snow

F. Avanzi et al.

Laboratory-based observations of capillary barriers and preferential flow in layered snow

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Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Abstract

Several evidences are nowadays available that show how the effects of capillary gradients and preferential flow on water transmission in snow may play a more important role than expected. To observe these processes and to contribute in their characterization, we performed observations on the development of capillary barriers and preferential flow patterns in layered snow during cold laboratory experiments. We considered three different layering (all characterized by a finer-over-coarser texture in grain size) and three different water input rates. Nine samples of layered snow were sieved in a cold laboratory, and subjected to a constant supply of dyed tracer. By means of visual inspection, horizontal sectioning and liquid water content measurements, the processes of ponding and preferential flow were characterized as a function of texture and water input rate. The dynamics of each sample were replicated using the multi-layer physically-based SNOWPACK model. Results show that capillary barriers and preferential flow are relevant processes ruling the speed of liquid water in stratified snow. Ponding is associated with peaks in LWC at the boundary between the two layers equal to $\sim 33\text{--}36$ vol. % when the upper layer is composed by fine snow (grain size smaller than 0.5 mm). The thickness of the ponding layer at the textural boundary is between 0 and 3 cm, depending on sample stratigraphy. Heterogeneity in water transmission increases with grain size, while we do not observe any clear dependency on water input rate. The extensive comparison between observed and simulated LWC profiles by SNOWPACK (using an approximation of Richards Equation) shows high performances by the model in estimating the LWC peak over the boundary, while water speed in snow is underestimated by the chosen water transport scheme.

1 Introduction

Around one century has passed since Horton noted that “there is a marked lag between the melting of snow and the appearance of the resulting water as run-off in the

TCD

9, 6627–6659, 2015

Capillary barriers in snow

F. Avanzi et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Capillary barriers in snow

F. Avanzi et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



streams” (Horton, 1915). Liquid water in snow is originated by rain events and/or by melting (Techel and Pielmeier, 2011; De Michele et al., 2013). The modeling and/or measuring of its flow through the snow porous matrix have interested hydrologists as well as avalanche forecasters for decades. In fact, within snow-dominated catchments, the process of water transmission in snow rules streamflow timing and amount (Lundquist and Dettinger, 2005; Lehning et al., 2006; Wever et al., 2014), while wet snow instabilities due to water movement are considered a serious hazard for mountain environments (Baggi and Schweizer, 2008; Mitterer et al., 2011b, 2013; Mitterer and Schweizer, 2013; Schmid et al., 2015). Harper et al. (2012) report that meltwater storage capacity of snow and firn (and associated percolation dynamics) may play an important role even in arctic environments by buffering sea-level rise (see also Gascon et al., 2014 on this point), while Zawierucha et al. (2015) note that some water-filled holes on glaciers called cryoconite holes are a valuable ecological hotspot.

Starting from the first observations by, e.g., Horton (1915), Hughes and Seligman (1938) or Gerdel (1945), the flow of liquid water in snow has been often assimilated to the process occurring in other porous materials, like soils (Wankiewicz, 1978). In particular, a collection of papers by Colbeck and others in the 70s (Colbeck, 1972, 1974b, 1976; Colbeck and Davidson, 1972; Dunne et al., 1976; Wankiewicz, 1978) propose the use of a Darcy-based theory to describe water movement in snow. Within this framework, a frequent hypothesis is that capillary gradients in snow are negligible. Consequently, water flux at a point is assumed as driven by gravity alone (Colbeck, 1972, 1974a; DeWalle and Rango, 2011). In this perspective, Wankiewicz (1978) reports examples of suction profiles in snow, showing that expected suction gradients are usually much lower than gravitational potential gradients. This assumption has been largely used within the field of snow hydrology (Avanzi et al., 2015), and even simplified in many complex one-dimensional models, such as CROCUS (Brun et al., 1989, 1992; Vionnet et al., 2012), or the first version of SNOWPACK (Bartelt and Lehning, 2002), that consider a bucket-type approach for water percolation.

Capillary barriers in snow

F. Avanzi et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



However, increasing evidences show how liquid water percolation in snow is a very complex, and multi-dimensional, problem (Hirashima et al., 2014; Wever et al., 2014). As an example, Marsh and Woo (1985) observed spatial heterogeneity in the percolation process (also known as preferential flow). Schneebeli (1995) notes that heterogeneity seems to be the prevalent process involved in water flow in snow, and that fingers (i.e., preferential channels) seem to migrate from one position to another during a snow season. By means of laboratory experiments, Waldner et al. (2004) observe that a finer-over-coarser transition in snow layering constitutes a capillary barrier. This is a textural discontinuity that causes water ponding, hence a delay in the expected arrival time of water at the snow base. Moreover, they observe that fingers seem to be stable in their position in time. Recently, Wever et al. (2014) report that solving Richards equation accounting for suction gradients improves run-off estimations at different temporal resolutions with respect to a simple bucket-type approach, although the latter seems to return a better agreement with observed snow microstructure profiles (Wever et al., 2015). As an additional complication, percolation in snow usually starts while most of the snowpack is still at sub-freezing conditions (Pfeffer and Humphrey, 1996). This causes a strict coupling between hydraulic and energetic processes (Illan-gasekare et al., 1990). Moreover, wet snow structure evolves quickly once it has come in contact with liquid water (Wakahama, 1968; Colbeck, 1986; Brun, 1989).

As a result, it is nowadays argued that the impact of capillary effects on water flow in snow may have been generally underestimated (Wever et al., 2014). As a result, the degree of quantitative characterization of several associated processes, such as capillary barriers, is still limited (Eiriksson et al., 2013). This is also partially due to difficulties in measuring liquid water distribution (Colbeck, 1978; Techel and Pielmeier, 2011; Avanzi et al., 2014) and to the fact that running experiments with wet snow is sometimes cumbersome due to water redistribution and wet snow metamorphism (Brun, 1989). Examples of previous attempts include Jordan (1995), who observed capillary barriers in the field throughout a snow season. Similar observations are reported by Waldner et al. (2004); Peitzsch et al. (2008). In soil science, capillary barriers have been often

associated with the occurrence of instability in the wetting front at the textural boundary and onset of preferential flow, or fingering (Hill and Parlange, 1972; Hillel and Baker, 1988; Baker and Hillel, 1990; Liu et al., 1994; de Rooij, 2000; DiCarlo, 2007, 2013). On the contrary, these two processes have been rarely investigated together in snow (see e.g. Marsh and Woo, 1984).

Here, we focus on investigating capillary barriers development and associated preferential flow patterns in snow using 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 ponding layer at the textural boundary, liquid water distribution, wet snow fraction at different levels and the time of arrival of liquid water at sample base. Such a wide data-set allows a characterization of capillary barriers properties that is more exhaustive than before. The focus on preferential flow allows also to investigate how these two processes combine in snow. Similar analyses have been recently performed by Katsushima et al. (2013), who note that the fraction of snow involved in water flow seems to depend on both snow grain size and infiltration rate. Their analysis focuses on homogeneous snow, while here we focus the investigation on stratified snow. In addition, all the laboratory experiments were reproduced numerically by using the SNOW-PACK model.

2 Theoretical backgrounds

2.1 Capillarity in snow

In melting snow covers, liquid water occupies a variable amount of pores volume. We define as saturation degree S_r (–) the ratio between the volume occupied by liquid water (V_W) and the volume of pores V_P , at a given point, $S_r = V_W/V_P$. We define as volumetric liquid water content (LWC, or θ) the ratio V_W/V , where V is the total volume

Capillary barriers in snow

F. Avanzi et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



of the mixture, at a given point (Fierz et al., 2009). We measure this quantity in vol. %, or simply %.

In unsaturated snow, liquid water is usually under tension. Under equilibrium, the pressure drop across the interface between the phases, $\Delta P = P_A - P_W$, with P_A the pressure of air and P_W the pressure of water, is given by Laplace equation (see Jordan, 1995; Jordan et al., 1999 for details). ΔP depends on the surface tension T and the mean radius of curvature of the interface γ . Accordingly, ΔP increases with increasing T and with decreasing γ . ΔP can be easily related with the height reached by water in capillary tubes. In fact, capillary rise is caused by the need for balancing water weight and the pressure drop across the meniscus (Jordan et al., 1999): the narrower the tube is, the higher the elevation reached by water. Accordingly, ΔP is usually referred to as capillary pressure, or suction ψ (DiCarlo, 2007), and is usually measured in m.

Natural snow is formed by a great variety of pores with different dimensions. In this context, a capillary bundle model (i.e., a collection of capillary tubes with different diameters, see Millington and Quirk, 1959) can be employed to establish an intuitive relation between θ and ψ . This calls Water Retention Curve (WRC) and is nowadays usually modeled using the approach by van Genuchten (1980), which depends on a number of parameters, including θ_r (residual volumetric liquid water content), θ_s (saturated volumetric liquid water content), α and n (shapes parameters). As a rule of thumb, the lower is LWC, the higher is ψ , but this relation is strongly dependent on pores shape and, in general, medium structure. Although first experimental examples of WRC in snow date back to the 70s (Colbeck, 1974a), Yamaguchi et al. (2010) and Yamaguchi et al. (2012) have been the first ones, to our knowledge, to provide a systematic parametrization of α and n basing on snow density and grain size as predictors. These expand the preliminary results reported, e.g., in Colbeck (1974a); Jordan (1983); Daanen and Nieber (2009). Following additional experiments, Adachi et al. (2012) note that snow WRCs seem to be hysteretic. This means that the relation between ψ and θ is not univocal, since it depends on the process considered (wetting or drainage, see Jordan et al., 1999). Usually, at a given θ , ψ is higher during a drying process than during a wet-

Capillary barriers in snow

F. Avanzi et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



ting process, if snow structure keeps constant (Jordan et al., 1999). The relationship between ψ and the height reached by water in snow allows for a straightforward derivation of these curves in the laboratory (Yamaguchi et al., 2010, 2012).

Suction gradients and gravity rule water movement in a porous material. In particular, the combination of the Darcy–Buckingham equation and mass conservation returns the well-known Richards equation (Richards, 1931). According to this equation, water movement in snow is related to the hydraulic conductivity (K_W) and to the gradient in water head (H), which is defined as the algebraic sum of elevation z and suction ψ . In unsaturated conditions, K_W depends on S_r (DeWalle and Rango, 2011; Wever et al., 2014) and saturated hydraulic conductivity (K_S). The latter depends on dynamic viscosity ν , liquid water density ρ_W , acceleration due to gravity g and intrinsic permeability K , which has been initially related with snow density and grain size (Shimizu, 1970; Sommerfeld and Rocchio, 1993; Jordan et al., 1999). However, a number of works are now available that relate this quantity with density and equivalent sphere radius (hence, Specific Surface Area SSA, see Carmagnola et al., 2014). Examples include Calonne et al. (2012) and Zermatten et al. (2014).

2.2 Ponding and water flow instability

Typically, vertical water movement in an uniform porous medium like soils obeys to a stable infiltration profile, with no lateral heterogeneity in the front position in time. However, both laboratory and field observations have shown that sometimes infiltration is prone to instability, namely to the development of preferential channels that break the uniform infiltration front in fingers (DiCarlo, 2013). As already mentioned, this behavior has been largely observed in snow, too (DeWalle and Rango, 2011; Schneebeli, 1995; Katsushima et al., 2013).

A number of factors can trigger water flow instability in soils (de Rooij, 2000). Among these, one (historical) case is the fingering associated with an initially dry fine-over-coarse profile in layering. First attempts to explain instability under such conditions were made by Hill and Parlange (1972); Baker and Hillel (1990); Hillel and Baker



Capillary barriers in snow

F. Avanzi et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



(1988). Accordingly, when the wetting front arrives at the layer boundary, it is still marked by a high ψ . As a result, water cannot enter the lower (coarser) layer, so that it starts ponding. This causes an increase in LWC, hence a decrease in ψ at the boundary. This process continues until suction reaches a value that allows water to enter in the smallest pores of the coarser layer that are interconnected. At this stage, water starts entering at various locations. This process continues until suction at the inter-layer plane reaches a value permitting massive entering of water in the lower layer (the so-called effective water entry suction ψ_{WE}). According to the stability criterion developed by Hillel and Baker (1988); Baker and Hillel (1990), subsequent flow should 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 . In fact, in those conditions, only a fraction of the lower medium can convey water (due to mass conservation). Such a process (together with ponding time) has clear implications in determining the time of arrival of water at a given location. This is one of the reasons why soil scientists have been largely interested in the prediction and modeling of these phenomena.

During recent years, additional observations have shown that, in soils, an unstable infiltration profile is marked by an overshoot profile in terms of S_r (DiCarlo, 2004). Accordingly, “unstable fronts dry out, while stable fronts wet up behind the wetting front” (Baver et al., 2014). This process is clearly related with a capillary pressure overshoot, since these two variables are linked by the water retention curve (DiCarlo, 2007). Although “the exact physics for the creation of pressure and saturation overshoot at the wetting front remains in debate” (DiCarlo, 2007), saturation and pressure overshoots in soils are nowadays considered the cause of gravitational flow instability, rather than an effect. Examples of pressure overshoots have been also observed in homogeneous snow samples during preferential infiltration by Katsushima et al. (2013), thus suggesting that a similar process may have parallels within an ice porous matrix.

3 Laboratory experiments

3.1 Preparation of samples and experiments run

To observe capillary barriers development and associated preferential flow patterns in snow, three combinations of grain sizes g_S and three different water inputs W were considered. Grain size combinations are (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 consider snow with $0.25 \leq g_S \leq 0.5$ mm as fine, snow with $1 \leq g_S \leq 1.4$ mm as medium, and snow with $2 \leq g_S \leq 2.8$ mm as coarse. Note that we adopt such a nomenclature because it is convenient for the scopes of this paper, although it is not consistent with the International Classification proposed by Fierz et al. (2009) that, e.g., defines medium snow grain size as $0.5 \text{ mm} \leq g_S \leq 1 \text{ mm}$. The water input rates considered are 10, 30 and 100 mm h^{-1} . As a results, nine samples were prepared ($3g_S$ combinations for each W).

Samples were prepared in a cold room at -20°C using refrozen melt forms. Fragmented snow particles were firstly partitioned in several grain size classes. Afterwards, the three g_S chosen were sieved a second time to prepare the samples. Snow was packed in a cylindrical container. No tamping was applied. 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 h to guarantee that initial conditions of snow during the experiments were dry and isothermal at 0°C .

We report in Table 1 the details of each experiment. W is reported both in mm h^{-1} (that is the unit of measurements we will use in the paper) and in g min^{-1} , which is the original unit of measurements of the data. The conversion can be done by calculating

TCD

9, 6627–6659, 2015

Capillary barriers in snow

F. Avanzi et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Capillary barriers in snow

F. Avanzi et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



sample area from sample diameter (5 cm). The coefficient of variation of $\rho_{D,U}$ and $\rho_{D,L}$ is equal to 0.06 and 0.03, respectively. Consequently, this work investigates how ponding and associated preferential flow vary as a function of the grain size combination, and not density. Future investigations should focus on the generalization of this work to layers of different density. Due to operational reasons, some samples (namely, FC2, FM2 and MC2) have a different total height from the others. However, the thickness of the upper layer (the one that is affected by ponding) was kept constant throughout all the experiments.

At the beginning of each experiment, dye tracer supplying at the top of each sample was started using a micro-tube pump. The dye used was blue ink, diluted by a factor of 10 times in water, at 0 °C. We placed a thin cotton ring on the top of each sample, to let the point source of the tracer to spread over the surface of the upper layer. By automatically registering the weight of the tracer reservoir (1 min resolution), we estimated W . As visible in Table 1, experimental values of W are slightly different from those chosen at the beginning of this paragraph (mainly due to operational reasons).

3.2 Data collection

When the tracer reached the base of each sample, tracer supply was stopped. The time needed by the tracer to reach the base (t_t) was registered with a manual chronometer watch by visually inspecting samples during the experiments. Since samples have different total heights, we will consider a specific travel time $\tau = t_t/h$ in what follows, with h equal to sample height. Pictures of the external sides of the samples were taken to estimate the approximate thickness of the ponding layer (ρ , in cm), i.e. the volume of the upper layer marked by horizontal spreading of the tracer and tracer accumulation (see Sect. 2.2 for details). 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). Starting from these information, profiles of volumetric liquid water content were obtained by converting w to θ . By using

the ImageJ software (Abramoff et al., 2004), fractions of wetted areas over total area (f) were estimated for each section using the pictures taken.

3.3 The comparison with the SNOWPACK model

We replicated the dynamics of each sample during the experiment using the well-known 1-D model SNOWPACK (Bartelt and Lehning, 2002). In this way, it is possible to compare observations with predictions by a multi-layer physically-based model. Particular attention is paid to the following variables: (1) capillary barriers development, (2) ponding layer thickness, (3) LWC distribution. On the contrary, the model cannot reproduce spatial heterogeneity, hence preferential flow patterns, due to the 1-D geometry used (Hill and Parlange, 1972).

The model discretizes the snow medium using a FEM grid and simulates the evolution in time of a wide set of variables along a vertical profile of snow, subjected to known external forcings (Bavay and Egger, 2014). Examples are snow density, temperature, grain size and shape or liquid water content. A number of papers are available in the literature where it is possible to find exhaustive details about SNOWPACK formulation and examples of previous applications. Examples are Bartelt and Lehning (2002); Lehning et al. (2002); Hirashima et al. (2004); Yamaguchi et al. (2004); Mitterer et al. (2011b). The original version of SNOWPACK considers a simple bucket-type approach to describe liquid water percolation in snow. Accordingly, liquid water is retained at a given position in the profile until it exceeds a threshold. After exceeding, excess water is transmitted to the lower layer. Hirashima et al. (2010) modifies this scheme, introducing a water transport model based on the van Genuchten equation (van Genuchten, 1980) and on gravity drainage experiments by Yamaguchi et al. (2010). Recently, Wever et al. (2014) has also introduced a discretization of Richards equation.

Here, the temporal resolutions of simulations was set to 1 min, while the initial spatial resolution was set to 2 cm. We set input data to replicate experiments conditions, i.e. a constant precipitation flux (equal to the measured water input flux W , see Table 1)

Capillary barriers in snow

F. Avanzi et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



and a fixed (positive) air temperature of $+1.51^{\circ}\text{C}$, so that this incoming flux is classified as liquid and not as new snow. According to laboratory conditions, wind speed and solar radiation were set to zero, while incoming longwave radiation was determined to balance with upward long wave radiation from a 0°C snow surface. At the base of the sample, we considered as a boundary condition a clay soil, with parameters given by Carsel and Parrish (1988). As snow initial conditions, we considered a replication of samples granulometry, density (Table 1), wetness (initially dry) and temperature (0°C). Using the same sieves 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 0.421 and 1.439 mm, respectively. The fact that \bar{g}_S for medium snow is greater than the upper boundary of the sieve is probably caused by snow grains not being perfectly spherical. In the simulation, we therefore set $\bar{g}_S = 0.421$ mm for fine snow, $\bar{g}_S = 1.439$ 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. As for the water transport simulation, we chose the approach introduced by Hirashima et al. (2010) and the WRC parametrization by Yamaguchi et al. (2012). It has been reported in Hirashima et al. (2010); Mitterer et al. (2011b) that this approach is able to reproduce capillary barriers, and this is the main target of this evaluation. These measurements could allow an exhaustive evaluation of this modeling scheme, that simplifies the explicit solution of the Richards equation.

4 Results

We report in Fig. 1 the horizontal sections of the samples at the end of the experiments (i.e., when dyed water arrived at sample base). Dyed water is visible as blue areas. As a rule of thumb, the darker the blue is, the higher is local LWC. In Fig. 2, we report 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).

Capillary barriers in snow

F. Avanzi et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Capillary barriers in snow

F. Avanzi et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Table 2 reports the results in terms of observed thickness of the ponding layer (ρ), time of arrival of liquid water at the base of each sample, t_t , and specific travel time τ . In Figs. 3 and 4, profiles of wet snow fractions f and LWC for the different samples are reported. For LWC, each point represents an average θ in the underlying 2 cm.

As an example, any value reported at a depth equal to 8 cm is an average value between 8 and 10 cm. These represent the LWC registered immediately over the textural boundary.

Figure 5 compares observed and SNOWPACK-based profiles of volumetric LWC for each sample. As described in Sect. 3, observed profiles were obtained at the end of each experiment. Accordingly, SNOWPACK-based data refer to the predictions by the model at the same instant. As an example, Fig. 5a compares the LWC profile observed in sample FC1 with the SNOWPACK prediction obtained 92 min after the beginning of the simulation (see Table 2).

5 Discussion

5.1 The ponding process

Observations confirm that liquid water movement within a finer-over-coarser snow texture is subjected to ponding when water comes to a textural boundary. Such a behavior is systematic in FC and FM samples (irrespective to W), while MC samples report no definitive results. In fact, all FC and FM samples are characterized by horizontal spreading of water at 10 cm (Fig. 1). This creates a clear transition between finer and coarser layers (see Fig. 2). In 4/6 samples of these two classes, a homogeneously blue area develops at a depth equal to 8 cm as well. On the contrary, MC samples show a more variable behavior: water spreading is minimum for MC1, while a marked ponding layer is visible in MC3. In terms of ρ , MC samples show again a small or absent ponding layer, while FC and FM samples show from 2 to 4 cm of ponding. In FC-FM samples, infiltrating water is under a high suction when it initially arrives at the textural bound-

ary. The higher the initial ψ is, the longer is the duration of the ponding process at the same W . As a result, the larger is the mass of water accumulated. When considering MC samples, differences in ψ between the upper and the lower layer are smaller than in FC-FM samples. Thus, p is reduced.

FC and FM samples are characterized by similar LWC profiles. In particular, LWC increases with depth in the upper layer and presents a peak at the textural boundary. Below this boundary, LWC decreases again. All FC-FM samples report a similar LWC at the boundary. In particular, at that position LWC is ~ 33 vol. % in FC samples, while it spans between 34 and 36 vol. % for FM samples. At the boundary, water accumulates until suction at the interlayer plane becomes equal to the water entry suction ψ_{WE} (Baker and Hillel, 1990). ψ_{WE} is driven by LWC through the Water Retention Curve (specifically, by the primary imbibition curve in conditions of hysteresis, see DiCarlo, 2007). It follows that 34–36 vol. % may be seen as the threshold LWC that allows massive transportation of water across the boundary between the fine snow layer (which is the same in all these six samples) and a coarse or medium snow layer. No variability in this process as a function of W was detected. On the contrary, MC samples show a much smaller peak in LWC at the boundary, here again attesting that this type of texture seems prone to limited ponding.

The occurrence of ponding in snow has been already reported in the literature. As an example, Jordan (1995) reported that a newer over older snow transition can cause horizontal spreading and capillary barriers development. A similar conclusion is also reported by Waldner et al. (2004). During a laboratory experiment, they subjected a layered sample to artificially induced melting and measured LWC dynamics by means of TDRs (Schneebeli et al., 1998). However, a restricted variety of g_S combinations were considered by both works ($g_S < 1$ mm in the first paper, and a 1.5 mm over 2.5 mm transition in the second one). In this perspective, our analysis enlarge these conclusions by (1) including the case of a fine (i.e., 0.25–0.5 mm) over medium (i.e., 1–1.4 mm), or coarse (i.e. 2–2.8 mm) stratigraphy and (2) considering different (controlled) water input rates. A comparison between the LWC profiles measured by Waldner et al. (2004) and

Capillary barriers in snow

F. Avanzi et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



those reported in Fig. 4c (i.e., those experiments that show a comparable g_S transition) shows that the LWC peak at the inter-layer boundary measured by Waldner et al. (2004) (i.e. 13%) is not far from the one measured during our experiments for faster input rates ($\sim 9\%$).

5.2 Preferential flow patterns and travel time of water in snow

Liquid water transmission in samples is marked by a high degree of heterogeneity. We measure this using the variable f . This is higher in fine snow layers than in medium or coarse snow layers and, in general, it increases with depth over the boundary (where $f = 1$ for all FC and FM samples), while it decreases below it. This is expected since horizontal suction gradients in fine layers are higher than in coarser layers. As a result, one-dimensional gravitational movement is easier in coarser snow than in finer snow. The external source of water was punctual and this may represent a limitation to this analysis. However, we used cotton rings to limit this problem, while deeper sections (i.e., depth ≥ 2 cm) show that water is also able to spread horizontally and change the position of fingers (compare e.g. the positions of the blue area at 0 and 2 cm in Fig. 1). As a result, this problem is probably restricted to sample surface, only.

A similar analysis has been recently conducted by Katsushima et al. (2013) using samples made by vertically homogeneous snow. They observe that heterogeneity in water flux increases with grain size but decreases with increasing input flux. We also observe an increase in heterogeneity with g_S , while no clear decrease of heterogeneity with W is found. Note that an increase in heterogeneity means that f decreases, and vice versa. Fingering behavior is clearly sensitive to snow microstructure heterogeneity. Sieving snow samples that are homogeneous at the particles scale is very difficult since some variations will occur at random locations. As a result, outcomes of different samples on this point are probably difficult to be compared. Additional investigations are clearly needed on this point.

During recent years, it has been sometimes debated if preferential flow paths in snow are stable in their positions in time, or not (Schneebeli, 1995; Waldner et al., 2004). Al-

Capillary barriers in snow

F. Avanzi et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



though we observed here that new paths create during the percolation, and that sometimes fingers stop their vertical percolation at some locations but continued to develop at others (hence showing that the process of preferential flow development is dynamic in time), experiments duration did not allow to investigate this problem extensively.

τ increases with decreasing W , as widely expected (Table 2). No clear difference between FC and FM samples is visible, thus confirming the general agreement between these experiments. In the case of FM2 (fine over medium snow, $W = 27.7 \text{ mm h}^{-1}$), we can compare the τ measured during our experiment (2.2 min cm^{-1}) with the τ observed during the experiments 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 $W = 22.3 \text{ mm h}^{-1}$ is equal to 1.7 min cm^{-1} , while the τ for medium snow and $W = 21.7 \text{ mm h}^{-1}$ is equal to 0.7 min cm^{-1} . It follows that, if samples are subjected to a comparable W , τ for a FM snow sample is not only higher than the τ observed in a sample composed by snow with the same grain size as the coarser snow layer of the layered sample (as expectable), but this is even higher than the τ observed in a sample made by snow with the same grain size of the finer snow layer. This difference shows the strong effect of ponding on liquid water travel time in snow.

5.3 The comparison with SNOWPACK

Results in Fig. 5 show that the considered version of SNOWPACK is able to predict the occurrence of a capillary barrier at different grain sizes and W combinations. A similar result was already shown by Hirashima et al. (2010); Mitterer et al. (2011b), but, in this case, we considered a wide set of laboratory experiments, where different snow textures were subjected to various water input rates. This comparison shows also that, generally, this water transport scheme underestimates observed water speed. In fact, in 8/9 samples the simulated front has not reached the base of the sample at the end of the associated laboratory experiment. A similar conclusion has been reported recently by Wever et al. (2014), who compare the performances by this scheme with an explicit resolution of Richards equation in SNOWPACK and with field observations.

Capillary barriers in snow

F. Avanzi et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Clearly, these conclusions are limited to the grain sizes combinations and the water input rates used in these experiments.

In the case of FC and FM samples, the SNOWPACK-based profile usually overestimates θ in the upper layer due to the fact that the simulated velocity of water is slower than observed. The model predicts correctly the decrease in LWC below the boundary. Predictions and observations of LWC at the boundary are very close for FC1 and FM1 (i.e., when W is small), since their difference is equal to ~ 2 vol. % (as absolute value). In the case of FC2 and FM2, the absolute difference is equal to ~ 4.8 and 0.43 vol. %, respectively, while it is equal to ~ 12 and 8.3 vol. % for FC3 and FM3. In some cases, the predicted LWC at the boundary is higher than the observed one: this may be a hint that the observed LWC at that location is smaller than the actual peak reached by LWC during the ponding process.

Results are much more variegated when looking at MC samples. As an example, the simulated wetting front in MC1 has not reached the textural boundary at the end of the physical experiment. On the contrary, for MC3 (Fig. 5i) data and SNOWPACK return the same time of arrival of water at sample base and a similar LWC profile. Simulated profiles in MC1 and MC2 resemble a typical Richards-based infiltration profile where S_r increases behind the front (DiCarlo, 2004).

At this stage, SNOWPACK cannot model a horizontal heterogeneity of flow due to its 1-D nature, and this process has a dramatic impact on this problem since water concentrates in fingers that are characterized by a higher-than-average unsaturated hydraulic conductivity (due to a higher-than-average LWC). Accordingly, it should come as no surprise that (1) the modeled velocity of the wetting front is slower than observed and (2) that these phenomena are paramount in case of MC samples, where fingering is particularly evident. However, observations and simulations agree very well in MC3. This suggests that measuring and modeling liquid water flow in snow are still marked by high uncertainties. The approach used by Hirashima et al. (2010) to model water velocity in snow needs the prediction of a wide set of variables, which includes, among others, suction and unsaturated conductivity. While ψ can be predicted basing on LWC

Capillary barriers in snow

F. Avanzi et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



itself and on a parametrization of retention that bases, for instance, on grain size and density (Yamaguchi et al., 2012), unsaturated conductivity depends on a given relation with LWC (Hirashima et al., 2010) and on a suitable parametrization of intrinsic permeability (hence on grain size or equivalent sphere radius and density). Clearly, such a heavy parametrization can play an important role in the success of these predictions.

5.4 Experiments limitations

There is still room for improvements of this analysis. In particular, while comparing simulated and observed LWC profiles in Fig. 5, observed profiles suggest that the total mass of liquid water in each sample is different from the total mass supplied. A mass balance between supplied and measured liquid water mass shows that the measured mass ranges between 93 and 176 % of supplied mass in 8/9 samples, while in MC1 measured mass is 434 % of supplied mass. Note that in this last sample the total mass supplied is very low, due to a short experiment duration.

A first explanation may be that the initial LWC was not equal to zero. An initial LWC > 0 may help explaining the peculiar behavior of MC1: as an example, its τ is the same observed in MC2 (Table 2), which is unexpected given that W for MC1 and MC2 are 11 and 27.3 mmh⁻¹, respectively. However, any undesired melting was avoided, as samples were all prepared at -20°C and brought to 0°C within a cold chamber where also dyed water was stored before using it in the experiment.

Another explanation may be instrumental noise. LWC measurements by gravimetry depend on a set of temperature and density measurements and Kawashima et al. (1998) noted that this device returns alternatively higher or lower LWC if compared with high and low readings by a dielectric device. Sample dimensions make it challenging to use dielectric devices for similar experiments, while a highly fingered flow may be missed and/or disturbed. Fierz and Föhn (1995) report that the absolute error in measuring water content using dielectric methods spans between 0.2 and 0.9 vol. %, while Techel and Pielmeier (2011) note that 1 vol. % is the expected difference between mea-

Capillary barriers in snow

F. Avanzi et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



surements taken using a Denoth meter and a Snow Fork. This suggests that, generally, measuring low LWCs is very challenging for existing techniques.

6 Conclusions

In the recent past, the problem of measuring and modeling wet snow dynamics has emerged as a living topic in snow research. Examples of recent works on this topic include Mitterer et al. (2011a); Eiriksson et al. (2013); Mitterer and Schweizer (2013); Avanzi et al. (2014); Hirashima et al. (2014); Wever et al. (2014, 2015); Schmid et al. (2015). Most of these works stem from two general impressions: on the one hand, as Fierz and Föhn said in 1995, “reliable measurements on wet snow are difficult to perform and therefore our understanding relies mostly on qualitative observations”. On the other hand, “there is a strong need for a better understanding and improved models to describe the complex water flow in natural snow covers” (Wever et al., 2014).

In this paper, we focused on the systematic observation of capillary barriers development and associated preferential flow using laboratory experiments in a cold chamber. We considered three different textures and three water input rates. Nine samples were prepared and subjected to controlled infiltration of dyed water until water reached sample base. By means of visual inspection, LWC measurements and horizontal sectioning, the processes of ponding and preferential flow development were characterized. Results were also compared with SNOWPACK simulations.

We confirm that a fine-over-coarse/medium snow layering can cause ponding of water when this comes at the textural boundary. However, the process seems more variable when passing to a medium-over-coarse texture. Peaks in LWC over the boundary can reach ~ 33 vol.% in FC samples and ~ 34 – 36 vol.% in FM samples. Horizontal sectioning of samples confirmed that preferential flow seems the dominant process in water transmission in snow. Heterogeneity is observed to increase with grain size, while no explicit relation with W has been observed. The comparison with SNOWPACK showed that, in general terms, the water transport scheme that we considered here re-

TCD

9, 6627–6659, 2015

Capillary barriers in snow

F. Avanzi et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



produces LWC distribution over a capillary barrier, but underestimates the velocity of water in snow. Implications and limitations of these results in view of existing theory and technology within this field were discussed.

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References

- Abramoff, M. D., Magalhães, P. J., and Ram, S. J.: Image Processing using ImageJ, *Biophotonics International*, 11, 36–43, 2004. 6637
- Adachi, S., Yamaguchi, S., Ozeki, T., and Kose, K.: Hysteresis in the water retention curve of snow measured using an MRI system, in: Proceedings to the 2012 International Snow Science Workshop, Anchorage, Alaska, 16–21 September 2012, 918–922, 2012. 6632
- 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, *Adv. Water Resour.*, 68, 32–41, doi:10.1016/j.advwatres.2014.02.012, 2014. 6630, 6645
- 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, *Adv. Water Resour.*, 86, 1–13, doi:10.1016/j.advwatres.2015.09.021, 2015. 6629
- Baggi, S. and Schweizer, J.: Characteristics of wet-snow avalanche activity: 20 years of observations from a high alpine valley (Dischma, Switzerland), *Nat. Hazards*, 50, 97–108, 2008. 6629
- Baker, R. S. and Hillel, D.: Laboratory tests of a theory of fingering during infiltration into layered soils, *Soil Sci. Soc. Am. J.*, 54, 20–30, 1990. 6631, 6633, 6634, 6640
- Bartelt, P. and Lehning, M.: A physical SNOWPACK model for the Swiss avalanche warning Part I: Numerical model, *Cold Reg. Sci. Technol.*, 35, 123–145, doi:10.1016/S0165-232X(02)00074-5, 2002. 6629, 6637

**Capillary barriers in
snow**

F. Avanzi et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

I ◀

▶ I

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Bavay, M. and Egger, T.: Meteolo 2.4.2: a preprocessing library for meteorological data, *Geosci. Model Dev.*, 7, 3135–3151, doi:10.5194/gmd-7-3135-2014, 2014. 6637
- 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 contact-angle relationship, *Water Resour. Res.*, 50, 5290–5297, 2014. 6634
- Brun, E.: Investigation on wet-snow metamorphism in respect of liquid-water content, *Ann. Glaciol.*, 13, 22–26, 1989. 6630
- Brun, E., Martin, E., Simon, V., Gendre, C., and Coleou, C.: An energy and mass model of snow cover suitable for operational avalanche forecasting, *J. Glaciol.*, 35, 333–342, 1989. 6629
- Brun, E., David, P., Sudul, M., and Brunot, G.: A numerical model to simulate snow-cover stratigraphy for operational avalanche forecasting, *J. Glaciol.*, 38, 13–22, 1992. 6629
- Calonne, N., Geindreau, C., Flin, F., Morin, S., Lesaffre, B., Rolland du Roscoat, S., and Charrier, P.: 3-D image-based numerical computations of snow permeability: links to specific surface area, density, and microstructural anisotropy, *The Cryosphere*, 6, 939–951, doi:10.5194/tc-6-939-2012, 2012. 6633
- Carmagnola, C. M., Morin, S., Lafaysse, M., Domine, F., Lesaffre, B., Lejeune, Y., Picard, G., and Arnaud, L.: Implementation and evaluation of prognostic representations of the optical diameter of snow in the SURFEX/ISBA-Crocus detailed snowpack model, *The Cryosphere*, 8, 417–437, doi:10.5194/tc-8-417-2014, 2014. 6633
- Carsel, R. F. and Parrish, R. S.: Developing joint probability distributions of soil water retention characteristics, *Water Resour. Res.*, 24, 755–769, 1988. 6638
- Colbeck, S. C.: A theory of water percolation in snow, *J. Glaciol.*, 11, 369–385, 1972. 6629
- Colbeck, S. C.: The capillary effects on water percolation in homogeneous snow, *J. Glaciol.*, 13, 85–97, 1974a. 6629, 6632
- Colbeck, S. C.: Snow flow through snow overlying an impermeable boundary, *Water Resour. Res.*, 10, 119–123, doi:10.1029/WR010i001p00119, 1974b. 6629
- Colbeck, S. C.: An analysis of water flow in dry snow, *Water Resour. Res.*, 12, 523–527, doi:10.1029/WR012i003p00523, 1976. 6629
- Colbeck, S. C.: The difficulties of measuring the water saturation and porosity of snow, *J. Glaciol.*, 20, 189–201, 1978. 6630
- Colbeck, S. C.: Statistics of coarsening in water-saturated snow, *Acta Metall.*, 34, 347–352, 1986. 6630

Capillary barriers in snow

F. Avanzi et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Colbeck, S. C. and Davidson, G.: Snow percolation through homogeneous snow, in: *Int. Symp. on the Role of Snow and Ice in Hydrology*, Banff, AB, Canada, September 1972, 242–257, 1972. 6629
- 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. Eng.*, 23, 43–68, 2009. 6632
- De Michele, C., Avanzi, F., Ghezzi, A., and Jommi, C.: Investigating the dynamics of bulk snow density in dry and wet conditions using a one-dimensional model, *The Cryosphere*, 7, 433–444, doi:10.5194/tc-7-433-2013, 2013. 6629
- de Rooij, G. H.: Modeling fingered flow of water in soils owing to wetting front instability: a review, *J. Hydrol.*, 231–232, 277–294, 2000. 6631, 6633
- DeWalle, D. R. and Rango, A.: *Principles of Snow Hydrology*, Cambridge University Press, 428 pp., Cambridge 2011. 6629, 6633
- DiCarlo, D. A.: Experimental measurements of saturation overshoot on infiltration, *Water Resour. Res.*, 40, W04215, doi:10.1029/2003WR002670, 2004. 6634, 6643
- DiCarlo, D. A.: Capillary pressure overshoot as a function of imbibition flux and initial water content, *Water Resour. Res.*, 43, W08402, doi:10.1029/2006WR005550, 2007. 6631, 6632, 6634, 6640
- DiCarlo, D. A.: Stability of gravity-driven multiphase flow in porous media: 40 years of advancements, *Water Resour. Res.*, 49, 4531–4544, 2013. 6631, 6633
- Dunne, T., Price, A. G., and Colbeck, S. C.: The generation of runoff from subarctic snowpacks, *Water Resour. Res.*, 12, 677–685, doi:10.1029/WR012i004p00677, 1976. 6629
- Eiriksson, D., Whitson, M., Luce, C. H., Marshall, H. P., Bradford, J., Benner, S. G., Black, T., Hetrick, H., and McNamara, P.: An evaluation of the hydrologic relevance of lateral flow in snow at hillslope and catchment scales, *Hydrol. Process.*, 27, 640–654, doi:10.1002/hyp.9666, 2013. 6630, 6645
- 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, 117–131, 1995. 6644
- 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. 6632, 6635

Capillary barriers in snow

F. Avanzi et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Gascon, G., Sharp, M., Burgess, D., Bezeau, P., Bush, A. B. G., Morin, S., and Lafaysse, M.: How well is firn densification represented by a physically based multilayer model? Model evaluation for Devon Ice Cap, Nunavut, Canada, *J. Glaciol.*, 60, 694–704, 2014. 6629
- 5 Gerdel, R. W.: The dynamics of liquid water in deep snowpacks, *EOS T. Am. Geophys. Un.*, 26, 83–90, 1945. 6629
- 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. 6629
- 10 Hill, D. E. and Parlange, J.-Y.: Wetting front instability in layered soils, *Soil Sci. Soc. Am. Pro.*, 36, 697–602, 1972. 6631, 6633, 6637
- Hillel, D. and Baker, R. S.: A descriptive theory of fingering during infiltration into layered soils, *Soil Sci.*, 146, 51–55, 1988. 6631, 6633, 6634
- Hirashima, H., Nishimura, K., Baba, E., Hachikubo, A., and Lehning, M.: SNOWPACK model simulations for snow in Hokkaido, Japan, *Ann. Glaciol.*, 38, 123–129, 2004. 6637
- 15 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 Reg. Sci. Technol.*, 64, 94–103, doi:10.1016/j.coldregions.2010.09.003, 2010. 6637, 6638, 6642, 6643, 6644
- Hirashima, H., Yamaguchi, S., and Katsushima, T.: A multi-dimensional water transport model to reproduce preferential flow in the snowpack, *Cold Reg. Sci. Technol.*, 108, 80–90, 2014. 6630, 6645
- 20 Horton, R. E.: The melting of snow, *Mon. Weather Rev.*, 43, 599–605, doi:10.1175/1520-0493(1915)43<599:TMOS>2.0.CO;2 1915. 6629
- Hughes, T. P. and Seligman, G.: The temperature, melt water movement and density increase in the névé of an apline glacier, *Monthly Notice of the Royal Astronomical Society, Geophysical Supplement*, 4, 616–647, 1938. 6629
- 25 Illangasekare, T. H., Walter Jr, R. J., Meier, M. F., and Pfeffer, W. T.: Modeling of meltwater infiltration in subfreezing snow, *Water Resour. Res.*, 26, 1001–1012, doi:10.1029/WR026i005p01001, 1990. 6630
- 30 Jordan, P.: Meltwater movement in a deep snowpack 1. Field observations, *Water Resour. Res.*, 19, 971–978, 1983. 6632
- Jordan, R.: Effects of capillary discontinuities on water flow and water retention in layered snow-covers, *Defence Sci. J.*, 45, 79–91, 1995. 6630, 6632, 6640

Capillary barriers in snow

F. Avanzi et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Jordan, R. E., Hardy, J. P., Perron Jr, F. E., and Fisk, D. J.: Air permeability and capillary rise as measures of the pore structure of snow: an experimental and theoretical study, *Hydrol. Process.*, 13, 1733–1753, doi:10.1002/(SICI)1099-1085(199909)13:12/13<1733::AID-HYP863>3.0.CO;2-2, 1999. 6632, 6633
- 5 Katsushima, T., Yamaguchi, S., Kumakura, T., and Sato, A.: Experimental analysis of preferential flow in dry snowpack, *Cold Reg. Sci. Technol.*, 85, 206–216, doi:10.1016/j.coldregions.2012.09.012, 2013. 6631, 6633, 6634, 6638, 6641, 6642
- Kawashima, K., Endo, T., and Takeuchi, Y.: A portable calorimeter for measuring liquid-water content of wet snow, *Ann. Glaciol.*, 26, 103–106, 1998. 6636, 6644
- 10 Lehnig, M., Bartelt, P., Brown, B., Fierz, C., and Satyawali, P.: A physical SNOWPACK model for the Swiss avalanche warning Part II. Snow microstructure, *Cold Reg. Sci. Technol.*, 35, 147–167, 2002. 6637
- Lehnig, 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, *Hydrol. Process.*, 20, 2111–2128, doi:10.1002/hyp.6204, 2006. 6629
- 15 Liu, Y., Steenhuis, T. S., and Parlange, J.-Y.: Formation and persistence of fingered flow fields in coarse grained soils under different moisture contents, *J. Hydrol.*, 159, 187–195, 1994. 6631
- Lundquist, J. D. and Dettinger, M. D.: How snowpack heterogeneity affects diurnal streamflow timing, *Water Resour. Res.*, 41, W05007, doi:10.1029/2004WR003649, 2005. 6629
- 20 Marsh, P. and Woo, M.-K.: Wetting front advance and freezing of meltwater within a snow cover 1. Observations in the Canadian Arctic, *Water Resour. Res.*, 20, 1853–1864, doi:10.1029/WR020i012p01853, 1984. 6631
- Marsh, P. and Woo, M.: Meltwater movement in natural heterogeneous snow covers, *Water Resour. Res.*, 21, 1710–1716, doi:10.1029/WR021i011p01710, 1985. 6630
- 25 Millington, R. J. and Quirk, J. P.: Permeability of porous media, *Nature*, 183, 387–388, 1959. 6632
- 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, doi:10.5194/tc-7-205-2013, 2013. 6629, 6645
- 30 Mitterer, C., Heilig, A., Schweizer, J., and Eisen, O.: Upward-looking ground-penetrating radar for measuring wet-snow properties, *Cold Reg. Sci. Technol.*, 69, 129–138, 2011a. 6645

Capillary barriers in snow

F. Avanzi et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

- Mitterer, C., Hirashima, H., and Schweizer, J.: Wet-snow instabilities: comparison of measured and modelled liquid water content and snow stratigraphy, *Ann. Glaciol.*, 52, 201–208, 2011b. 6629, 6637, 6638, 6642
- 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*, 7–11 October 2013, 334–338, 2013. 6629
- 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*, 21–27 September, Whistler, British Columbia, Canada, 179–187, 2008. 6630
- 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, *J. Glaciol.*, 42, 292–304, 1996. 6630
- Richards, L.: Capillary conduction of liquids through porous mediums, *Physics-J. Gen. Appl. P.*, 1, 318–333, 1931. 6633
- 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, *Geophys. Res. Lett.*, 42, 1–9, 2015. 6629, 6645
- 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, 12–13 July 1995 89–95, 1995. 6630, 6633, 6641
- Schneebeli, M., Coléou, C., Touvier, F., and Lesaffre, B.: Measurement of density and wetness in snow using time-domain reflectometry, *Ann. Glaciol.*, 26, 69–72, 1998. 6640
- Shimizu, H.: Air Permeability of Deposited Snow, *Tech. Rep.*, Hokkaido University, Sapporo, Hokkaido, Japan, A22, 1–32, *Contributions from the Institute of Low Temperature Science*, 1970. 6633
- Sommerfeld, R. A. and Rocchio, J. E.: Permeability measurements on new and equitemperature snow, *Water Resour. Res.*, 29, 2485–2490, 1993. 6633
- 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, 2011. 6629, 6630, 6644
- 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. 6632, 6637

Capillary barriers in snow

F. Avanzi et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Vionnet, V., Brun, E., Morin, S., Boone, A., Faroux, S., Le Moigne, P., Martin, E., and Willemet, J.-M.: The detailed snowpack scheme Crocus and its implementation in SURFEX v7.2, *Geosci. Model Dev.*, 5, 773–791, doi:10.5194/gmd-5-773-2012, 2012. 6629
- Wakahama, G.: The metamorphism of wet snow, IAHS Publication 79 (General Assembly of Bern 1967 – Snow and ice), 370–379, 1968. 6630
- Waldner, P. A., Schneebeli, M., Schultze-Zimmermann, U., and Flüeler, H.: Effect of snow structure on water flow and solute transport, *Hydrol. Process.*, 18, 1271–1290, doi:10.1002/hyp.1401, 2004. 6630, 6640, 6641
- 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, 222–252, 1978. 6629
- 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. 6629, 6630, 6633, 6637, 6642, 6645
- 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 Discuss.*, 9, 2655–2707, doi:10.5194/tcd-9-2655-2015, 2015. 6630, 6645
- Yamaguchi, S., Sato, A., and Lehning, M.: Application of the numerical snowpack model (SNOWPACK) to the wet-snow region in Japan, *Ann. Glaciol.*, 38, 266–272, 2004. 6637
- Yamaguchi, S., Katsushima, T., Sato, A., and Kumakura, T.: Water retention curve of snow with different grain sizes, *Cold Reg. Sci. Technol.*, 64, 87–93, doi:10.1016/j.coldregions.2010.05.008, 2010. 6632, 6633, 6637
- Yamaguchi, S., Watanabe, K., Katsushima, T., Sato, A., and Kumakura, T.: Dependence of the water retention curve of snow on snow characteristics, *Ann. Glaciol.*, 53, 6–12, doi:10.3189/2012AoG61A001, 2012. 6632, 6633, 6638, 6644
- Zawierucha, K., Kolicka, M., Takeuchi, N., and Kaczmarek, L.: What animals can live in cryoconite holes? A faunal review, *J. Zool.*, 295, 159–169, 2015. 6629
- Zermatten, E., Schneebeli, M., Arakawa, H., and Steinfeld, A.: Tomography-based determination of porosity, specific area and permeability of snow and comparison with measurements, *Cold Reg. Sci. Technol.*, 97, 33–40, doi:10.1016/j.coldregions.2013.09.013, 2014. 6633

Capillary barriers in snow

F. Avanzi et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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

Sample ID	ρ (min–max) (cm)	t_t (min)	τ (min cm ⁻¹)
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

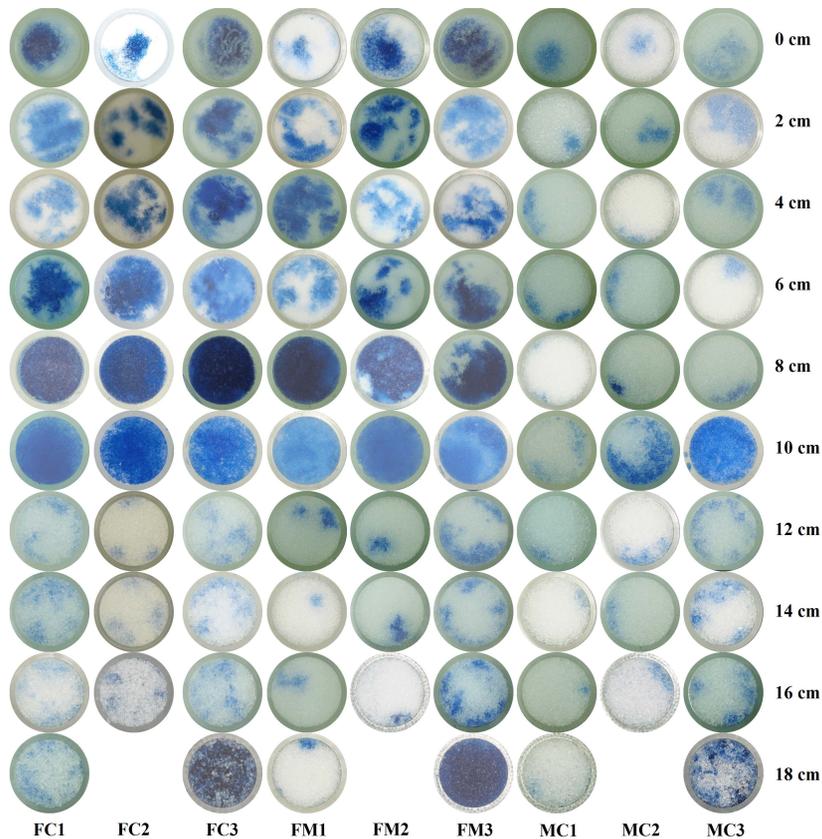


Figure 1. Sections of all the samples considered (2 cm vertical resolution) at the end of the experiment. Each column refers to a different sample (as indicated in the last row), while each row refers to the same depth from sample top surface (depth indicated by the number on the right side of each row).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

Capillary barriers in snow

F. Avanzi et al.

Title Page	
Abstract	Introduction
Conclusions	References
Tables	Figures
◀	▶
◀	▶
Back	Close
Full Screen / Esc	
Printer-friendly Version	
Interactive Discussion	



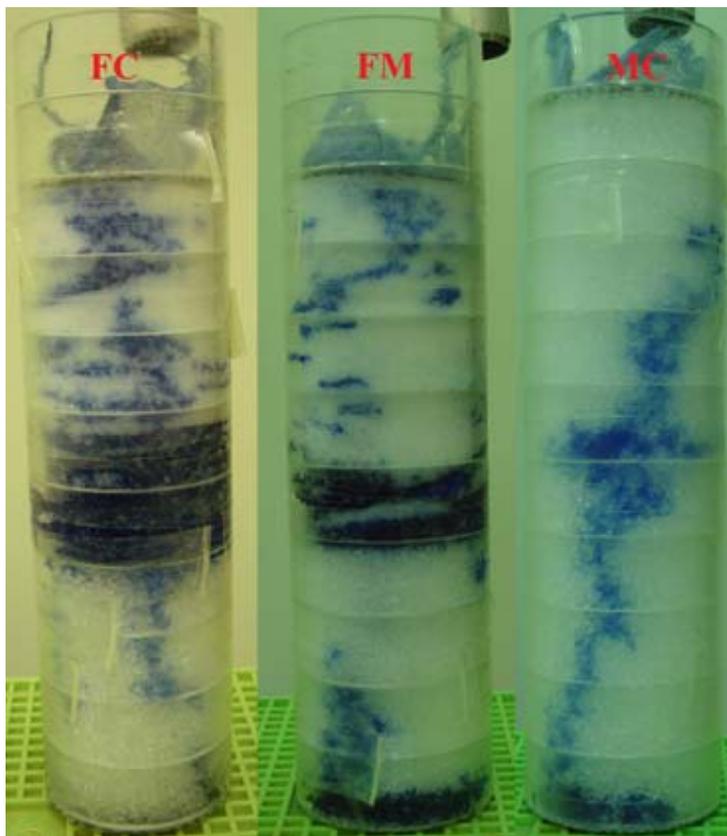


Figure 2. Three samples at the end of the experiment. These are FC2 (on the left, as an example of FC samples), FM2 (at the center, as an example of FM samples) and MC1 (on the right, as an example of MC samples).

Capillary barriers in snow

F. Avanzi et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Capillary barriers in snow

F. Avanzi et al.

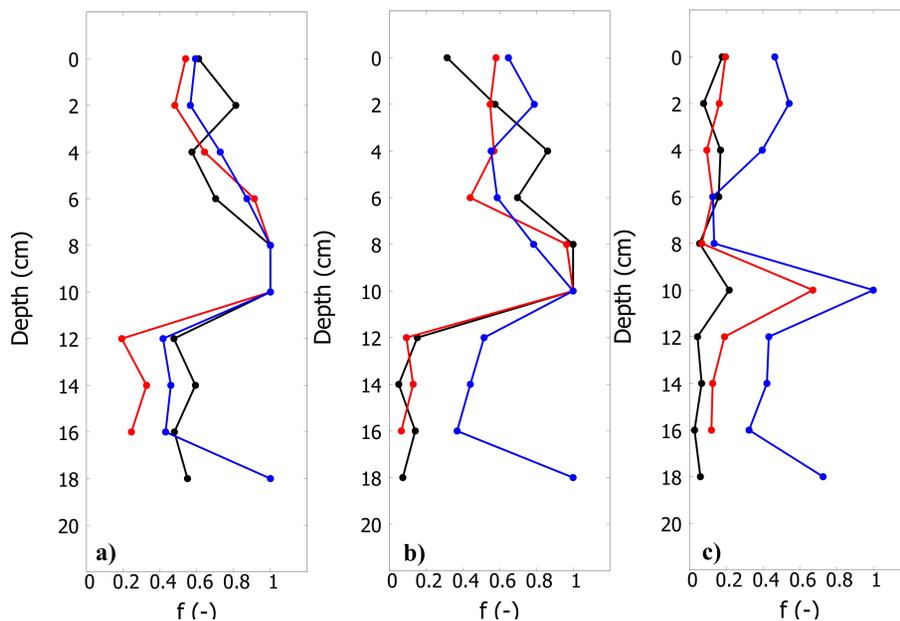


Figure 3. Experimental results in terms of f profiles. Panel (a) refers to FC samples, panel (b) to FM samples and panel (c) to MC samples, while black lines refer to $W \sim 10 \text{ mm h}^{-1}$, the red line to $W \sim 30 \text{ mm h}^{-1}$ and the blue line to $W \sim 100 \text{ mm h}^{-1}$. The vertical coordinate refers to the depth of the section from sample top surface.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Capillary barriers in snow

F. Avanzi et al.

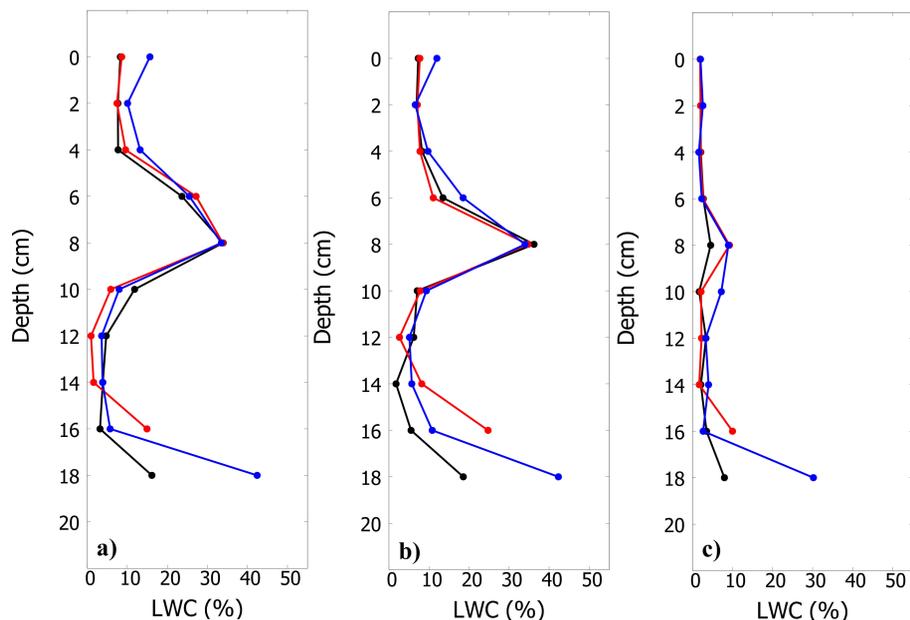


Figure 4. Experimental results in terms of volumetric liquid water content profiles. Panel **(a)** refers to FC samples, panel **(b)** to FM samples and panel **(c)** to MC samples, while black lines refer to $W \sim 10 \text{ mm h}^{-1}$, the red line to $W \sim 30 \text{ mm h}^{-1}$ and the blue line to $W \sim 100 \text{ mm h}^{-1}$. Note that the vertical coordinate refers to the depth of the top section of the acrylic ring to which the measurement refers. As an example, any measurement that corresponds to a depth equal to 8 cm is the average LWC observed between depths of 8 and 10 cm. This convention is consistent with Figs. 1 and 3.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Capillary barriers in snow

F. Avanzi et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

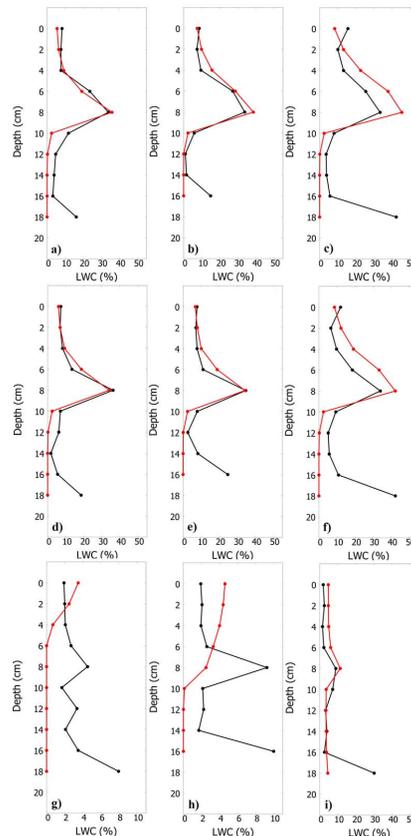


Figure 5. A comparison between observed profiles of volumetric liquid water content (black lines) and those simulated using SNOWPACK (red lines). Panels (a, b, c) refer to samples FC1, FC2 and FC3. Panels (d, e, f) refer to samples FM1, FM2 and FM3. Panels (g, h, i) refer to samples MC1, MC2 and MC3. Note that panels (g, h) have a different horizontal range from the others. The vertical coordinate refers to the depth of the top section of the acrylic ring to which the measurement/simulation refers.