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Point observations of liquid water content in natural snow – investigating methodical, spatial and temporal aspects

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Abstract

Information on the amount and distribution of liquid water in the snowpack is important for forecasting wet snow avalanches and predicting melt-water run-off. Considerable spatial and temporal variations of snowpack wetness exist. Currently, available information relies mostly on point observations. Often, the snow wetness is estimated manually using a hand test. However, quantitative measures are also applied. We compare the hand test to quantitative measurements and investigate temporal and small-scale spatial aspects of the snowpack wetness. For this, the liquid water content was measured using dielectric methods, with the Snow Fork and Denoth wetness instrument in the Swiss Alps, mostly above tree-line. More than 12 000 water content measurements were observed on 30 days in 85 locations. The qualitative hand test provides an indication of snowpack wetness, although snowpack wetness is often over-estimated and quantitative water content measurements are more reliable. If the measured water content is very low, it is unclear if the snow is dry or contains small quantities of liquid water. In particular during the initial melt-phase, when the snowpack is only partially wet, it is important to consider spatial aspects when interpreting point observations. One measurement taken at a certain measurement depth may significantly deviate in 10–20% of the cases from snowpack wetness in the surrounding snow. Not surprisingly, diurnal changes in snowpack wetness are significant in layers close to the snow surface. At depth, changes were noted within the course of a day. From a single vertical profile, it was often unclear if these changes were due to the heterogeneous nature of water infiltration. Based on our observations, we propose to repeat three measurements at horizontal distances greater than 50 cm. This approach provides representative snow wetness information for horizontal distances up to 5 m. Further, we suggest a simplified classification scheme of snowpack wetness by introducing five wetness types of the snowpack incorporating both vertical and horizontal liquid water content distribution.

TCD

4, 1967–2011, 2010

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1 Introduction

The distribution and amount of liquid water in snow is an important characteristic of a snowpack. It influences mechanical properties of snow and snow stability (e.g. Armstrong, 1976; Kattelmann, 1985). In snow hydrology, snowpack wetness is an important factor in forecasting the onset of melt-water run-off (Jones et al., 1983) or reservoir management (Kattelmann and Dozier, 1999). Currently, snowpack wetness is mostly observed in point observations, near adjacent automatic weather stations, in study plots or in manual snow profiles.

In Switzerland, most of the available snowpack information is based on manual snow profiles. These profiles are observed by researchers, avalanche professionals and observers of the Swiss snow observation network. Profile locations include potential avalanche slopes, but also level study-plots, at all elevations and aspects. The number of these profiles is large (annually about 1000 snow profiles, mostly in dry snow). In particular, slope profiles are important information for the avalanche warning service to provide the national avalanche hazard forecast (Schweizer and Wiesinger, 2001). Profiles observed at level study-plots are a source of information to assess the water outflow of the snowpack.

In the large majority of the profiles the liquid water content is estimated by a hand test for each stratigraphic snow layer according to Swiss and international observational guidelines (WSL, 2008; Fierz et al., 2009, Table 1). However, the estimation of the water content provides difficulties even for experienced observers (Martinec, 1991b; Fierz and Föhn, 1994). Consideration must also be given to spatial aspects of water flow through snow (e.g. Colbeck, 1979; Marsh, 1988; Conway and Benedict, 1994).

Our objectives for this study are threefold: (i) to investigate the reliability of point observations in relation to temporal and small-scale spatial variability, and (ii) to compare the technique of estimating the water content with measurements using dielectric methods and (iii) to explore if wetness observations over a wider area and region are a valuable addition to wet snow avalanche forecasting.

TCD
4, 1967–2011, 2010

2 Background

2.1 Liquid water in snow

The formation of liquid water at the snow surface depends on the energy balance in a given slope. Slope aspect and elevation are particularly significant for incoming net short wave radiation. Once melting at the snow surface starts, water begins to penetrate the snowpack rapidly, in particular if water is routed through vertical flow fingers (Waldner et al., 2004). The advance of the wetting front is seldom uniform. Even under laboratory conditions it is difficult to obtain a homogeneous water content distribution (Brun, 1989). Often, water flows in isolated thin flow channels (e.g. Marsh, 1988; Schneebeli, 1995) until larger flow structures develop and the full snowpack is wet (Kattelmann and Dozier, 1999). The infiltration pattern depends on snow structure, but also on snow temperature, slope angle and the amount of liquid water entering the snowpack (Conway and Benedict, 1994; Fierz and Föhn, 1994). Generally, gravitational forces dominate water flow. However, slope-parallel flow within the snowpack has also been observed (Wankiewicz, 1979). This is often observed when ice-layers or capillary barriers exist where layers consisting of fine grains overly layers of coarse grains (Jordan, 1994; Waldner et al., 2004).

Wet snow metamorphism commences as soon as liquid water is present. Wet snow metamorphism is faster when the water content is higher (Colbeck, 1997). The introduction of liquid water into snow leads to changes in grain shape (Brun, 1989; Coléou and Lesaffre, 1998), grain coarsening (Raymond and Tusima, 1979; Brun, 1989; Marsh, 1987) and an increase in bulk density (Marshall et al., 1999; Jordan et al., 2008). Important feed-back mechanisms exist between snow metamorphism, hydraulic conductivity and water flow (Jordan et al., 2008).

The amount of liquid water influences the mechanical properties of snow. Relatively small amounts of liquid water may reduce the strength of snow. Techel et al. (2008) observed a strength decrease in layers consisting of temperature-gradient snow (such as facets or depth hoar) at a lower water content ($\theta < 3$ vol.%) than Colbeck (1982), who describes a loss in strength at approximately 8 vol.%.

2.2 Estimation and measurement of liquid water in snow

In the field, the estimation of the liquid water content by hand test is an integral part of manual snow profile observations (Fierz et al., 2009; WSL, 2008). The snow wetness is estimated by gently squeezing a snow sample with the gloved hand and observing the reaction to it as well as by using a magnifying lens to detect if liquid water is present (Table 1). Measuring snow temperature may assist in deciding whether a snow sample is dry or not.

Methods to quantitatively measure the liquid water content in snow include: centrifugal separation, melting calorimetry, freezing calorimetry, alcohol calorimetry and the dilution method (summarized in Stein et al., 1997). These methods are destructive and rather time-consuming making them impractical in the field.

In recent years, the water content has often been measured making use of the different dielectric constants of air ($\epsilon_i' \approx 1$), ice ($\epsilon_i' \approx 3.15$) and water ($\epsilon_i' \approx 86$) (Frolov and Macharet, 1999). The dielectric permittivity is measured by capacitance (e.g. Denoth, 1994) or time domain reflectometry (e.g. Stein et al., 1997; Schneebeli et al., 1998; Waldner et al., 2001). In the micro-wave region (1 MHz to 10 GHz) the permittivity of ice depends mostly on snow density and wetness (Frolov and Macharet, 1999; Louge et al., 1998). In this study, we use predominantly the Snow Fork instrument (SnF, Sihvola and Tiuri, 1986; Toikka, 2009) and sometimes the Denoth wetness instrument (Dn, Denoth, 1994) for a comparison.

Snow Fork and Denoth wetness meter

The sensor of the Snow Fork (SnF, Fig. 1, Toikka, 2009) is a two-pronged steel fork with a length of 75 mm. It works like a microwave resonator. The resonant frequency lies between 500 and 1000 MHz. Three electrical parameters: resonant frequency f, attenuation and 3-dB bandwidth B are measured. From these, both the real and the imaginary part of the complex dielectric constant of snow (ϵ' and ϵ'', respectively) are calculated (Toikka, 2009). No density sampling is needed.

$$\epsilon' = \left(\frac{f_{\mathrm{air}}}{f}\right)^2, \tag{1}$$

$$\epsilon'' = \frac{B-(0.04f-16)}{f}\epsilon', \tag{2}$$

Semi-empirical equations are then used to calculate of the liquid water content (θ_{SnF}).

$$\theta_{\mathrm{SnF}} = -0.06 + \left(0.06^2 + \frac{\epsilon''}{0.0075f}\right)^{0.5}, \tag{3}$$

The SnF has been used in a variety of studies exploring, for instance, the spatial wetness distribution (Williams et al., 1999), snow characteristics in Antarctica (Kärkäs et al., 2005) or the wetness in ski tracks (Moldestad, 2005). The insertion of the Snow Fork compresses the surrounding snow, which increases snow density by approximately 1–2% (Sihvola and Tiuri, 1986).

The Denoth wetness instrument (Dn, Fig. 1, Denoth, 1994) was used as a reference to the wetness as measured with the Snow Fork. The plate-like sensor unit of the Dn has a width of 13 cm and a length of 13.5 cm. To calculate the liquid water content θ_{Dn}, values related to the permittivity of air (A) and snow (S) need to be measured as well as the snow density (ρ in kg m^{-3}). With these, the dielectric constant of snow can be calculated and the liquid water content derived (Martinec, 1991a):

$$\theta_{\mathrm{Dn}} = 4.69\left(k\log\frac{S}{A} - 2\frac{\rho}{1000}\right), \tag{4}$$

where k is a sensor-specific calibration constant. The Denoth wetness meter has been used in several field studies, for example to monitor the changes in snowpack wetness

TCD
4, 1967–2011, 2010

during the melt period (Martinec, 1991a; Kattelmann and Dozier, 1999). Data obtained from the Denoth meter has also been compared to modeled liquid water content (Mitterer et al., 2010).

The accuracy of θ-measurements by dielectric methods is approximately ±0.5 vol.% (Sihvola and Tiuri, 1986; Fierz and Föhn, 1994). Sensors may be affected by solar radiation if the sensor is placed close to the snow surface (Lundberg et al., 2008).

These methods are destructive to the snow sample and also require the excavation of a snow-pit, which causes a local disturbance in the water flow (Fig. 2).

More recently, non-destructive measurement methods like ground-penetrating radar installed upward-looking at the snow-ground interface have been applied to measure snow wetness in a snowpack (Heilig et al., 2009). Satellite remote sensing is a suitable method to distinguish between areas of a dry and a wet snow surface (e.g. Gupta et al., 2005)

3 Scope and aim

This study addresses the spatial and temporal validity of point observations in wet snow by considering short-term temporal and small-scale spatial aspects as well as different measurement designs. The common hand test method of estimating the water content (Fierz et al., 2009) is compared to quantitative measurements based on dielectric methods.

The following hypotheses are investigated:

1. Whether the estimation of the liquid water content by hand in the field is a sufficient measure to observe point-specific water content of the snowpack.

2. Whether the correct estimation of the liquid water content by hand depends on other layer characteristics like hardness or grain shape.

3. Whether comparable measurements of snowpack wetness can be achieved by either measuring before digging a snow pit or at the side-wall of a snow profile.

TCD
4, 1967–2011, 2010

4. Whether small-scale spatial variability in water content distribution must be considered when interpreting wetness profiles.

Based on the obtained results we propose a robust sampling strategy in the field. For practical purposes, we introduce a simplified snow wetness classification, which incorporates information on vertical and horizontal wetness distribution.

4 Methods and data

Most of the data analyzed was collected in winter and spring 2008/2009 and spring 2009/2010 in Alpine terrain in Switzerland in the Fribourg and Western Bernese Alps and Pre-Alps, the region of Davos and in the Lower Engadin (Fig. 3). The majority of these observations were carried out in potential avalanche terrain (slopes steeper than 30°) above tree-line.

4.1 Field methods

All measurements were carried out in a seasonal snowpack. The focus was on sampling a data-set consisting of diverse topographic, snowpack and wetness conditions. Slope selection was dictated by safety concerns, as many observations were carried out during periods of wet snow avalanche activity.

In 2009, the focus was on measuring diurnal wetness changes and the comparison of measured and estimated water content. At first, θ was measured horizontally (Sect. 4.1.1, Fig. 4a). This was followed by the excavation of a snow-pit and θ-measurements made on a shaded side-wall of the snow-pit (Fig. 4b). Last, a manual snow profile was observed (WSL, 2008). Observed parameters included layer thickness, hardness, wetness as well as grain shape and size following the standard observational guidelines (WSL, 2008; Fierz et al., 2009). Snow temperatures were measured using a calibrated, digital thermometer with an accuracy of ±0.5 °C (Milwaukee Stick Thermometer TH310). Data on snow stability, which was also collected, is

TCD

4, 1967–2011, 2010

Point observations of liquid water content in wet snow

F. Techel and C. Pielmeier

not subject of this paper (Techel and Pielmeier, 2009). Measurements were carried out in the morning and repeated in the afternoon in the same slope at a distance of approximately 3–5 m.

In 2010, changes in snow wetness over several days and the distribution of water within the approximate area of a snow profile according to Swiss observational guidelines were of prime interest. θ was measured mostly by inserting the Snow Fork vertically into the snow in cross-sections of 5 m width. These were followed by a manual snow profile and a snowpack stability test.

The qualitative estimation of liquid water content (mWC) was part of the standard observation procedure in all manual snow-profiles (WSL, 2008; Fierz et al., 2009, Table 1). Primarily, the Snow Fork (Sihvola and Tiuri, 1986; Toikka, 2009) was used to quantitatively measure the liquid water content. The Denoth wetness meter (Denoth, 1994) was used to allow a comparison between the two instruments.

4.1.1 Sampling design for liquid water content measurements in a natural snowpack with the Snow Fork

Liquid water content was measured in one of the following three ways:

- *horizontal* – These preceded all slope profiles. Three measurements beside each other were taken. The distance between measurements was 20 cm (across the slope) with horizontal measurement intervals of 5 cm into the snowpack (Fig. 4a, Table 2).

- *profile* – These accompanied all slope profiles. Measurements were undertaken beside a manual snow profile and always on a side wall of the snow-pit. Measurements were slope- and layer-parallel, and generally made less than 50 cm away from *horizontal* measurements. Vertical measurement intervals were 5 cm and the distance between the three measurement rows was 20 cm (Fig. 4B, Table 2)

- *vertical* – This measurement lay-out was carried out to observe spatial variability

TCD
4, 1967–2011, 2010

of water content distribution. The vertical distance between consecutive measurements was 5 cm, the horizontal distance (across the slope) 50 cm (Fig. 4c, Table 2).

Measurement spacing and extent apply the concept by Blöschl (1999). The support, the integrated volume of a measurement device (Blöschl, 1999), is approximately 47 cm^3 for the Snow Fork.

The idea behind horizontal measurements was that we did not know if water would be running in front of the probe. However, with the fast measuring speed of the Snow Fork, we believe that this is rarely the case. It took less than 2 min to measure one vertical profile (15 single SnF measurements). As can be seen in Fig. 5, there is often a clear distinction from wet to dry layers implying that water running ahead of the SnF is not a problem.

4.1.2 Comparison of Denoth wetness meter and Snow Fork device

Denoth and Snow Fork (Fig. 1) devices were compared through two or three Denoth and four to six Snow Fork measurements adjacent to each other. The measurements were always undertaken on a side-wall of a snow-pit and parallel to the layer stratigraphy. The horizontal and vertical distance between measurements was 5 cm. Snow densities were sampled directly above and below the Denoth placement using a 100 cm^3 density cutter and a digital scale.

4.2 Data

Snow wetness was measured using the Snow Fork in more than 80 different locations in a variety of measurement designs and wetness conditions in natural snowpacks.

Measurements in winter and spring 2008/2009 targeted small-scale variability (within 40 cm), diurnal changes in wetness within the same slope and compared estimated and measured snow wetness. To achieve this, more than 7000 measurements were taken accompanying manual snow profiles using the *horizontal* (Fig. 4a) and *profile* measuring modes (Fig. 4b, Table 3). These were recorded in more than 2500 different measurement depths or layers.

In spring 2010, the focus was on investigating the wetness variability at spatial scales of up to 5 m. *Vertical* measurements (Fig. 4c) were carried out in 25 locations. The comparison of Snow Fork and Denoth instrument is based on measurements in 134 different snow layers made in *profile* mode (Table 3).

4.3 Data analysis

The water content measured with the Snow Fork (θ_{SnF}) was calculated using Eqs. (1), (2) and (3). Recorded values ranged from 0 to 23.6 vol.%. Following the recommendation of the Snow Fork manual (Toikka, 2008), measurements with $\theta_{\text{SnF}} > 10$ vol.% may not be accurate. However, as these values often corresponded to areas of high snowpack wetness, they were not excluded from analysis but considered as 10 vol.%. The calculation of the water content using the Denoth instrument (θ_{Dn}) uses Eq. (4). The snow density ρ is based on the mean of two observations.

The relationship between estimated water content (wetness index, mWC) and measured liquid water content (θ_{SnF}) used the conversion shown in Table 1. If θ_{SnF} was within ± 0.5 vol.% of a class limit, this is considered as an intermediate (half) index class and not considered as a false classification or measurement.

Snow wetness was often non-normally distributed. Therefore, the median and the interquartile range are considered as robust measures of central tendency and data distribution. If several measurements are available the median θ is used.

Linear regression models were derived for θ and the Pearson coefficient of determination r^2 was calculated. Spatial correlation was investigated using the coefficient of determination r. For categorical variables (mWC), the Spearman correlation r_s was used.

Data was tested for significant differences using non-parametric tests (Mann Whitney U-test, Kruskal-Wallis H-test, sign-test, Crawley, 2007). The level of significance was $\alpha \leq 0.05$.

Linear interpolation is applied in the contour plots (as in Fig. 5) and is described in the *R*-package *graphics* (R, 2009)

5 Results

5.1 Liquid water content measurements using Snow Fork and Denoth wetness instrument

In a variety of snow wetness situations ranging from dry to wet snow, the liquid water content as measured with the Snow Fork (θ_{SnF}, in vol.%) is generally higher than by using the Denoth meter (θ_{Dn}, Fig. 6a). Snow wetness from these devices are strongly correlated:

$$\theta_{SnF} \approx 1.06 \cdot \theta_{Dn} + 1.0 \qquad (r^2 = 0.78, p \leq 0.001) \tag{5}$$

These results are similar to previous studies, in which strong positive correlations between either measuring device were observed (Denoth, 1994; Williams et al., 1999; Frolov and Macharet, 1999). These results imply that Snow Fork and Denoth instrument will generally provide similar measures of liquid water content.

In dry snow (hand test *dry* and snow temperature $\leq -0.5\,^{\circ}$C), we investigated the effect of snow density (ρ) on the measured water content. The Snow Fork recorded a median $\theta_{SnF} = 0.8$ vol.% (standard deviation $\sigma = 0.2$ vol.%, $n_{SnF} = 487$). The Denoth wetness device showed lower values $\theta_{Dn} = 0.1$ vol.% ($\sigma = 0.17$ vol.%, $n_{Dn} = 281$). Measured water content in dry snow is generally 0.65 vol.% higher using the Snow Fork than with the Denoth meter (Fig. 6b). In dry snow poor positive correlations between θ and ρ were observed:

$$\theta_{SnF} = 0.0019\rho + 0.32 \qquad (r^2 = 0.28, p < 0.001) \tag{6}$$

$$\theta_{Dn} = 0.0019\rho - 0.33 \qquad (r^2 = 0.11, p < 0.05) \tag{7}$$

TCD
4, 1967–2011, 2010

5.2 Influence of sampling design

Liquid water content measurements made before digging a snow-pit (*horizontal* mode, Fig. 4a) and following manual snow profile observations (*profile* mode, Fig. 4b) were compared for 86 locations.

For locations with low water content (median $\theta_{SnF} < 1.3$ vol%, dry or barely moist snow), there was no significant difference between either mode of measuring the water content. In moist and wet snow ($\theta_{SnF} \geq 1.3$ vol%), however, *horizontal* measurements were significantly wetter than the measurements at the side-wall following snow pit excavation. The median difference is 0.43 vol.% ($p = 0.03$). While this is a statistically significant difference, it is within the range of measurement uncertainty (±0.5 vol.%, Sihvola and Tiuri, 1986; Fierz and Föhn, 1994).

In our data-set, 2% of the recorded values were higher than 10 vol.%. These high values were more frequently observed when we measured across layer boundaries in an undisturbed snowpack before digging the snow-pit than in layer-parallel measurements taken at the sidewall of a snow profile. In *horizontal* measurements, θ-values greater than 10 vol.% occur more frequently in layers relatively close to the snow surface and when neighboring measurements also showed high values.

5.3 Qualitative snow profile observations in wet snow

Manually estimated water content (mWC) and liquid water content measured with the Snow Fork (θ_{SnF}) were compared for 314 layers. mWC and θ_{SnF} were strongly correlated ($r_s = 0.73$, $p \leq 0.001$). The number of layers with correctly estimated water content *mWC* decreases with increasing θ_{SnF} (Fig. 7a, b). These results are similar to an earlier study (Martinec, 1991b). Both, Martinec (1991b) and our results, show that dry layers are normally well described, while wetter layers are often incorrectly classified (30% in our study for wet layers). Very few layers were estimated as being *very wet*. In these layers, mWC was always overestimated.

TCD
4, 1967–2011, 2010

Parameters observed in manual snow profiles include observations of layer hardness, grain shape and size. The wetness in layers consisting of coarse melt-freeze-particles (MF, snow class MF, Fierz et al., 2009) is more frequently falsely estimated (33% of cases) than in layers consisting of fine precipitation particles and snow which has undergone low-temperature gradient metamorphism (LTG, snow classes PP, DF, RG, 13%) or coarse medium to high temperature gradient metamorphosed grains (TG, snow classes FC, DH, 13%). Neither hardness nor grain size seem to influence the correct estimation of the water content. The wetness range in MF is much greater than in LTG or TG layers (MF: 0–10 vol.%; LTG/TG: 0–5.5 vol.%). $\theta_{SnF} > 3$ vol.% is more frequently observed in MF (> 20% of cases) and rarely in LTG/TG (< 4% cases). LTG layers estimated as being *wet* were almost always overestimated. The error rate in snow estimated as being *wet* is smallest in TG snow (20%).

Hardness of snow is influenced by the liquid water content. This can be observed by comparing the hardness (hand hardness test, Fierz et al., 2009) with estimated and measured water content. A negative correlation exists in layers classified as MF ($r_s = -0.70$ for mWC, $r_s = -0.43$ for θ_{SnF}, $p \leq 0.001$). Not surprisingly, the transition from *dry* (frozen) to *wet* infers a significant hardness decrease. There is no clear trend for TG. However, all TG layers estimated as being *wet* ($n = 6$), or measured as being wet ($\theta_{SnF} > 3$ vol.%, $n = 9$), have a hand hardness of 1. This is significantly softer than the dry hand hardness ($p \leq 0.01$).

The results indicate that in particular grain shape (and size) and layer hardness may unconscientiously influence even experienced observers when estimating the liquid water content.

5.4 Temporal changes in snow wetness: morning versus afternoon

The snowpack wetness is compared in 33 locations between morning and afternoon. Afternoon measurements were conducted approximately 3–5 m away from morning observations.

Seen over the full data-set, significant diurnal changes occurred within the upper 10 cm of the snowpack ($p < 0.05$, Fig. 8a). This is not surprising, as measurements were carried out when day-time warming was expected. If the change in snowpack wetness is analyzed for each location individually, the median snowpack wetness (excluding the uppermost 10 cm) changed significantly in only nine cases ($p < 0.05$). Surprisingly, six of these nine wetness profiles showed decreasing values (Fig. 8b). These significant changes always involved a transition from dry or barely moist snow (median $\theta^{m}_{\mathrm{SnF}} \leq 1.3$ vol.%, third quartile $\theta^{q3}_{\mathrm{SnF}} \leq 1.9$ vol.%) to moist or wet snow ($\theta^{m}_{\mathrm{SnF}} \geq 1.2$ vol.%, $\theta^{q3}_{\mathrm{SnF}} \geq 1.9$ vol.%) or vice versa, where both the changes in median and third quartile are significant ($p \leq 0.001$). We have only one explanation for the profiles where overall water content decreased during the day: the snowpack was in the initial phase of wetting with very irregular water infiltration patterns (vertical flow channels). By chance, our morning observations were conducted in regions of wetter snow when the surrounding snow was still predominantly dry (see also Fig. 5). For the cases, where wetness increased throughout the profile, it is unclear if this is also due to flow channels or if the wetting front advanced over larger areas (Fig. 8c).

These measurements show that there is considerable uncertainty due to spatially heterogeneous water distribution in the initial part of the melt-phase. Even if we are considering just the six observations, where overall snowpack wetness decreased during the day, this represents almost 20% of the measurements.

5.5 Spatial variability in water content distribution

The variability of measured liquid water content (θ_{SnF}) was investigated at horizontal distances of 10–40 cm and 50–500 cm. The difference between measured θ_{SnF} at measurement spacings of 10 and 20 cm is significantly less than at 40 cm or greater ($p < 0.001$, Table 4). Variability in about half the cases is similar to, or less than the measurement accuracy ($\theta \pm 0.5$ vol.%). However, even at horizontal spacings of 20 cm, 20% of the measurements differ by more than 1 vol.% and 10% of the measurements differed by more than 1.8 vol.%. While the correlation between measurements at various measurement distances is moderate to strong (Fig. 9a), considerable variations in θ_{SnF} are noted within horizontal cross-sections of 5 m (Fig. 5). However, significant differences between the median θ_{SnF} in each vertical column existed in only five of the twenty-five grids ($p \leq 0.05$).

Variability in θ_{SnF} increases marginally with greater measurement spacings (Fig. 9b). The variability (expressed as the interquartile range) as a function to the median water content within 5 m distance (θ_{5m}) is much smaller at $\theta_{5m} < 1.3$ vol.% than at $\theta_{5m} \geq 1.3$ vol.% (± 0.16 and ± 0.52 vol.%, respectively, $p < 10^{-16}$, Fig. 9b, c).

5.6 Temporal evolution of snowpack wetness in spring 2010

The evolution of snowpack wetness during spring 2010 for southerly aspect slopes above tree-line is shown in Figs. 10 and 11. The snowpack was shallow with snow depth often less than 1 m and dominated by soft, coarse-grained faceted layers due to the relatively dry winter with sustained cold periods. The snowpack was predominantly dry and cold with snow temperatures mostly below –1 °C on 18 March (Fig. 10a). Water infiltration was slow the following day too (Fig. 10b, Fig. 10c). On 20 March two grids were measured: the first at higher elevation showed a relatively dry snowpack with first weak flow channels (Fig. 10d), while the second, measured later in the afternoon and at lower elevation, was already moist to the ground (Fig. 11a). Four days later, on 24 March the snowpack was moist or wet throughout (Fig. 11b). This first wetting of the snowpack coincided with wide-spread wet snow avalanching in the region of Davos (Fig. 3). A cold period with new snow (Fig. 11c) was followed by further melting (Fig. 11d). Subsequent avalanching from southerly aspect start zones was minor and related to shallow failures of the surface snow.

6 Discussion

6.1 Measurement methods

The Snow Fork and the Denoth wetness instrument are comparable instruments to measure the water content of snow. Based on our experiences, the Snow Fork has some advantages. Particularly useful is its long arm allowing measurements at depth without previously disturbing the water flow by digging a snow-pit. Water might flow down along the instruments arm when inserting the Snow Fork vertically. However, with consecutive measurements being conducted within seconds, our measurements show that this is not truly a problem.

If the main interest is the water content distribution or the detection of lateral flow patterns, the *vertical* or *horizontal* measurement mode may be appropriate (see Fig. 4). It should be considered that the water content is measured over the length of the sensor (75 mm). Thus, thinner layer specific observations are not possible.

The *vertical* mode of measuring the snow wetness using the Snow Fork is an efficient method causing relatively small disturbances in the snowpack. This measurement design may be used as a comparison to non-destructive snow wetness measurement methods like the ground penetrating radar looking upward from the snow-soil interface (GPR, Heilig et al., 2009). Advantages to GPR are that measurements using the Snow Fork are not bound to one location. On the other hand, undertaking measurements in steep slopes at times of increased avalanche risk may be potentially dangerous to observers.

When estimating the wetness of snow layers by hand test, it is important to observe stratigraphic layers always on a shaded side-wall of a snow-pit (WSL, 2008). This is of particular importance when observing wet snow profiles (as less water will flow into a side-wall than a front-wall of a snow-pit, see Fig. 2) or when the slope is exposed to strong solar radiation. Snow temperature measurements may be an indicator for dry snow, although small amounts of liquid water may be measured in snow in temperatures below 0 °C ($\theta < 1$ vol.%, this study, also Kattelmann and Dozier, 1999). An

TCD
4, 1967–2011, 2010

additional help in the field may be the fact that snow wetness seldom exceeds 8 vol.% in natural snowpacks (Martinec, 1991b; Fierz and Föhn, 1994; Kattelmann and Dozier, 1999). Layers which contain water contents greater than this, are normally relatively thin or may be observed in vertical flow paths (as in Fig. 5). Thus, estimated snowpack wetness would be expected to lie mostly in the dry, moist or wet range ($\theta \leq 8$ vol.%).

The estimation of liquid water content in the field is difficult, even for experienced observers. As with other observed parameters like the hardness of snow layers, the hand test often provides information on relative differences rather than absolute values. Thus, estimated snow wetness must not be interpreted strictly according to the international guidelines but should be understood as an indication only (Fierz and Föhn, 1994). Expanding a previous study (Martinec, 1991b), we investigated the effect of layer characteristics like hardness or grain shape on snow wetness estimation. It seems that it is more difficult to correctly estimate the wetness in layers consisting of melt-freeze particles. The liquid water content of melt-freeze-crusts undergoing melting is particularly hard to estimate. We assume that the reason for this is the larger range of snow wetness (θ0–10 vol.%) and hardness. In particular at low water content when the ice matrix is still frozen for the most part, water cannot be seen using a magnifying lens and the squeeze test is not suitable in such hard layers. While layer hardness and grain shape seem to influence wetness estimates, they are very hard to quantify. In cases where it is necessary to quantitatively interpret the estimated wetness, we propose a rough guide which is based on the initial study by Martinec (1991b) (Table 5).

Additionally to methodical aspects, the spatial variability must be considered when interpreting point observations. This is particularly valid in the case of a partially wet snowpack (as shown in Fig. 5).

6.2 Snowpack observation in wet snow conditions: integrating spatial aspects

We have seen that small-scale spatial aspects should not be neglected when interpreting snow wetness in point locations. Due to a lack of data at greater spatial distances than 5 m, we can only assume that a 5 m wide cross-section is a good representation of the snowpack wetness in a given slope. The median and interquartile range from a 5 m wide cross-section is a robust indicator of snow wetness at a certain snow depth and we might be interested how many measurements are required to achieve a good correlation to these measures.

Randomly selecting a single measurements already yields strong correlations to the median (θ_{5m}, $r^2 > 0.83$). The difference is less than 0.5 vol.% in more than 60% of the cases. If the interest in snow wetness is simply estimating the wetness class according to Table 1, then in more than 90% of cases this measurement would be within ±0.5 classes, regardless if compared to the median or the interquartile range (Fig. 12a–c shows the results for the comparison to the median). However, as was observed in 2009 (Fig. 8), one observation or several within 40 cm horizontal distance (Sect. 5.4) do not always capture a robust picture of snow wetness.

The median water content observed in three measurements at regular intervals of 50 cm, 100 cm or 200 cm (θ_{m3}) is very strongly correlated to θ_{5m} ($r^2 > 0.93$). θ_{m3} is in more than 70% of the cases within 0.5 vol.% of θ_{5m} and in more than 98% within ±0.5 mWC-classes. The interquartile range within 5 m sections is generally very well represented by the minima and maxima of three values (95% within ±0.5 mWC-class, Fig. 12d–f shows the results for the measurements at 100 cm distance). With an increase in measurement spacing, the minima and maxima tend to fall outside the interquartile range of 5 m cross-sections.

Measuring more than one wetness profile may provide a more robust picture of snow wetness in a given slope, particularly when the snowpack is in the initial part of the melt-phase. The recorded snow wetness will differ less from θ_{5m} if θ_{m3} is used rather than just one measurement ($p < 0.05$). Using the 80 cm long arm of the Snow Fork, little time is required to measure three vertical wetness profiles (less than five minutes). Thus, within a few hours it is easily possible to investigate snow wetness in several different locations.

TCD
4, 1967–2011, 2010

6.3 Advancement of the wetting front in spring 2010

The measurements of snowpack wetness during spring 2010 were conducted on slopes of all aspects (illustrated for southerly aspects in Fig. 10 and 11). This information was available for the SLF avalanche warning team during the March melt-phase and was considered as very helpful to assess the advancement of the wetting front. The first significant period of water infiltration into the lower parts of the snowpack coincided with intense avalanche activity in both the springs of 2009 and 2010.

It is of note that very wet horizontal layers, as in Fig. 5, were absent during the avalanche cycle in spring 2010. We suspect that this is due to the snowpack structure, which contained few spatially expanded possible capillary barriers, like fine-over-coarse grained layer boundaries. Also, clear patterns of larger vertical flow paths could not be observed.

6.4 Qualitative description of the wetness of a snowpack

As has been discussed before, the reliable estimation and measurement of snow wetness in the field is difficult. Temporal changes in the amount and distribution of liquid water in snow may occur rapidly. Therefore, it might be more practical and sufficient for avalanche forecasting and snow hydrology purposes to use a very general description of the wetness of a snowpack. Based on our observations, we propose five wetness profile types, which may be based on estimated or quantitatively measured water content. It could also be based simply on the distinction between dry and not-dry snow. We suggest that surface layers are not included in this classification as these show significant changes during the diurnal freeze-melt-cycles. The classification incorporates both vertical and horizontal wetness distribution.

The snowpack is dry before the melt-phase (Fig. 13, type 1). With continued input of liquid water through melt or rain, snowpack wetness increases. Initially, only a part of the snowpack is wet while some areas remain dry. The wetting may follow a “step-and-fill-pattern” (Conway and Benedict, 1994) (Fig. 13, type 2). Often, in a snowpack consisting predominantly of coarse-grained temperature-gradient snow, preferential flow fingers will penetrate the snowpack relatively quickly and water may temporarily flow laterally along capillary barriers (Marsh, 1988) (Fig. 13, type 3). At this stage, first water outflow at the base of the snowpack may be observed. With continued water infiltration the snowpack will be fully wet and homogenize (Jordan et al., 2008) (Fig. 13, type 4). Once drainage channels are well established, water outflow will respond quickly to additional input of melt-water (Carran et al., 2002). A special case is the situation that the snowpack begins to refreeze or new snow falls on an already wet snowpack after a melt-event (Fig. 13, type 5).

We propose this very simplified classification and are aware that more variations will exist. However, such a basic classification can facilitate the description of the snowpack wetness, in particular for practical purposes. One advantage of such a classification is that the distinction between dry and not dry snow will likely be more accurate than the estimated wetness classes. Additionally, it describes the spatial wetness distribution which currently is not included in a snow profile observation. The spatial wetness distribution may be observed when excavating a snow pit.

7 Conclusions

Methodical, spatial and temporal aspects must be considered when observing snow wetness in the field and interpreting wetness information.

The method of estimating the liquid water content by hand test can not be regarded as a reliable method to record snow wetness if absolute values are of interest (hypothesis 1). If it is necessary to quantitatively interpret the qualitative wetness recordings, Table 5 may provide a rough aid for conversion. The hand test is more suited to record the relative wetness differences within one profile (Fierz and Föhn, 1994) and the difference between dry and not dry snow. Our study expands previous research (Martinec, 1991b) by incorporating snow layer properties like hardness, grain shape and size. Differences in correctly estimated wetness existed in layers consisting of different grain shape, however no conclusive results were obtained (hypothesis 2).

Quantitative measurement methods are generally a more reliable indicator of snow wetness at a given point within the snowpack. If the measured liquid water content is low (less than approximately 1.0–1.5 vol.%), the measured wetness should be interpreted with caution. In such cases, we believe, that the snow could be either dry or contain small quantities of liquid water. If the presence of very wet layers is of interest and an instrument like the Snow Fork is available, measurements should be undertaken before excavating a snow pit. Otherwise, only small differences existed between measurements made on the shaded side-wall of a snow-pit or in a previously undisturbed snowpack (hypothesis 3).

Vertical measurements of snow wetness using the Snow Fork are efficient and cause a relatively small disturbance of the snowpack. This method may prove particularly valuable for the comparison with radar measurements of snow wetness.

Site selection is important to observe representative wetness information. Of particular importance are slope aspect, slope inclination, elevation and the distance to rocky areas. Still, the small-scale spatially heterogeneous distribution of dry and wet areas within the snowpack may lead to unrepresentative results. Our observations showed that approximately every fifth to tenth wetness profile was a poor representation of the surrounding snow wetness (hypothesis 4). Therefore, to achieve robust snow wetness data for a certain slope and aspect, we propose to observe several measurements at horizontal distances greater than 50 cm. Because our measurement extent was limited to 5 m, we can not give conclusive results on spatial correlation of liquid water content. As far as we are aware, this is the first study quantifying the variability of liquid water distribution in a snowpack at scales up to 5 m.

Based on our observations on spatial variability in snow wetness, we proposed a snowpack-wetness classification. We see this as a first step towards the development of a wet snow classification scheme as exists for the assessment of dry snow profiles (Schweizer and Wiesinger, 2001). Incorporating additional snowpack properties like the state of wet snow metamorphism (grain shape), snow layering and snow

TCD
4, 1967–2011, 2010

temperature may improve the value of such a classification for avalanche forecasting purposes and could also assist in flood forecasting during snow melt periods.

To our knowledge, there is currently no reliable, economical and practical alternative available to the hand test to measure snow wetness in the field. Therefore, we propose that future research should investigate possibilities of developing a practical, hand-held instrument to quantitatively measure the liquid water content in snow (similar to a digital thermometer). Further, it would be of advantage to know the distribution of liquid water content at the slope-scale to allow better interpretations of point observations in wet snow. Combined real-time information on snow surface and snowpack temperature, wetness and water outflow measured in representative slopes would be a valuable instrument for avalanche or flood forecasting purposes.

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References

Armstrong, R.: Wet snow avalanches, in: Avalanche Research and Snow Characteristics, edited by: Armstrong, R. and Ives, J., San Juan Mountains, Colorado, University of Colorado INSTAAR, Occasional paper 19, 256 p. Boulder, CO, pp. 67–82, 1976. 1969

Blöschl, G.: Scaling issues in snow hydrology, Hydrol. Proc., 13, 2149–2175, 1999. 1976, 1995

Brun, E.: Investigation on wet-snow metamorphism in respect of liquid-water content, Ann. Glaciol., 13, 22–26, 1989. 1970

Carran, W., Hall, S., Kendall, C., Carran, A., and Conway, H.: Snow temperatures and water outflow during rain and melt; Milford Highway, New Zealand, in: Proceedings International Snow Science Workshop, Big Sky, Montana, 2002, pp. 173–177, 2002. 1987

Colbeck, S.: Water flow through heterogeneous snow, Cold Reg. Sci. Technol., 1, 37–45, 1979. 1969

TCD

4, 1967–2011, 2010

Point observations of liquid water content in wet snow

F. Techel and C. Pielmeier

Colbeck, S.: An Overview of Seasonal Snow Metamorphism, Rev. Geophys., 20, 45–61, 1982. 1971

Colbeck, S.: A review of sintering in seasonal snow, US Army Cold Regions Research and Engineering Laboratory Report, 97–10, 1997. 1970

Coléou, C. and Lesaffre, B.: Irreducible water saturation in snow: experimental results in a cold laboratory, Ann. Glaciol., 26, 64–68, 1998. 1970

Conway, H. and Benedict, R.: Infiltration of water into snow, Water Resour. Res., 30, 641–650, 1994. 1969, 1970, 1986

Crawley, M.: The R book, John Wiley & Sons Ltd., 1st edition, 2007. 1977

Denoth, A.: An electronic device for long-term snow wetness recording, Ann. Glaciol., 19, 104–106, 1994. 1971, 1972, 1975, 1978

Fierz, C. and Föhn, P.: Long-term observation of the water content of an Alpine snowpack, in: Proceedings International Snow Science Workshop 1994 Snowbird, Utah, USA, pp. 117–131, 1994. 1969, 1970, 1973, 1979, 1984, 1987

Fierz, , R. L., Durand, Y., Etchevers, P., Green, E., McClung, D., Nishimura, K., Satyawali, P., and Sokratov, S.: The International Classification for Seasonal Snow on the Ground, IHP-VII Technical Documents in Hydrology N83, IACS Contribution N1, UNESCO-IHP, Paris, 2009. 1969, 1971, 1973, 1974, 1975, 1980, 1994, 1998, 2005, 2010

Frolov, A. and Macharet, Y.: On dielectric properties of dry and wet snow, Hydrol. Process., 13, 1755–1760, 1999. 1971, 1978

Gupta, R. P., Haritashya, U. K., and Singh, P.: Mapping dry/wet snow cover in the Indian Himalayas using IRS multispectral imagery, Rem. Sens. Environ., 97, 458–469, 2005. 1973

Heilig, A., Schneebeli, M., and Eisen, O.: Upward-looking ground-penetrating radar for monitoring snowpack stratigraphy, Cold Reg. Sci. Techn., 59, 152–162, 2009. 1973, 1983

Jones, E., Rango, A., and Howell, S.: Snowpack liquid water distributions using freezing calorimetry, Nord. Hydrol., 14, 113–126, 1983. 1969

Jordan, R.: Effects of capillary discontinuities on water flow and water retention in layered snowcovers, in: Proceedings of Snowsymp, International Symposium on Snow, Manali, India, pp. 157–170, 1994. 1970

Jordan, R., Albert, M., and Brun, E.: Physical processes within the snow cover and their parametrization, in: Snow and climate: physical processes, edited by: Armstrong, R. and Brun, E., surface energy exchange and modeling, Cambridge University Press. pp. 12–69, 2008. 1970, 1987

TCD

4, 1967–2011, 2010

Point observations of liquid water content in wet snow

F. Techel and C. Pielmeier

Kärkäs, E., Martma, T., and Sonninen, E.: Surface snow properties and stratigraphy during the austral summer in western Dronning Maud Land, Antarctica, Polar Res., 24, 55–67, 2005. 1972
Kattelmann, R.: Wet Slab Snow Instability, in: Proceedings International Snow Science Workshop, 24–27 October 1984, pp. 102–108, 1985. 1969
Kattelmann, R. and Dozier, J.: Observations of snowpack ripening in the Sierra Nevada, California, U.S.A., J. Glaciol., 45, 409–416, 1999. 1969, 1970, 1973, 1983, 1984
Louge, M., Foster, R., Jensen, N., and Patterson, R.: A Portable Capacitance Snow Sounding Instrument, Cold Reg. Sci. and Technol., 28, 73–81, 1998. 1971
Lundberg, A., Granlund, N., and Gustafsson, D.: "Ground Truth" snow measurements – review of operational and new measurement methods for Sweden, Norway, and Finland, in: Proceedings 65th Eastern Snow Conference, Fairlee (Lake Morey), Vermont, USA, pp. 215–237, 2008. 1973
Marsh, P.: Grain growth in a wet Arctic snow cover, Cold Reg. Sci. Technol., 14, 23–31, 1987. 1970
Marsh, P.: Flow fingers and ice columns in a cold snowcover, in: Proceedings Western Snow Conference, 18–20 April 1988, Kalispell, Montana, pp. 105–112, 1988. 1969, 1970, 1987
Marshall, H., Conway, H., and Rasmussen, L.: Snow densification during rain, Cold Reg. Sci. Technol., 30, 35–41, 1999. 1970
Martinec, J.: Flüssiger Wassergehalt in der Schneedecke im Gebiet Davos-Weissfluhjoch, April–Juni 1988 (Liquid water content in the snowpack in the region of Davos-Weissfluhjoch, April–June 1988), internal report 663 (unpublished), WSL Institute for Snow and Avalanche Research SLF, Davos, 1991a. 1972, 1973
Martinec, J.: Schneefeuchtigkeit mit dem Denoth-Gerät im Vergleich mit dem Handtest, Messungen 1989, 1990 (Snow wetness with the Denoth-tool in comparison to the hand test, measurements 1989, 1990), internal report 667 (unpublished), WSL Institute for Snow and Avalanche Research SLF, Davos, 1991b. 1969, 1979, 1984, 1987, 1998, 2005
Mitterer, C., Hirashima, H., and Schweizer, J.: Wet-snow instabilities: comparison of measured and modelled liquid water content and snow stratigraphy, Ann. Glaciol., submitted, 2010. 1973
Moldestad, D.: Characteristics of liquid water content and snow density in a cross-country race ski track, Bull. Glaciol. Res., 22, 39–49, 2005. 1972
R: R: A Language and Environment for Statistical Computing, R Foundation for Statistical Com-

puting, Vienna, Austria, ISBN 3-900051-07-0, 2009. 1978
Raymond, C. and Tusima, K.: Grain coarsening of water saturated snow, J. Glaciol., 22, 83–105, 1979. 1970
Schneebeli, M.: Development and stability of preferential flow paths in a layered snowpack, IAHS-AIHS Publ., 228, 89–96, 1995. 1970
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. 1971
Schweizer, J. and Wiesinger, T.: Snow profile interpretation for stability evaluation, Cold Reg. Sci. Technol., 33, 179–188, 2001. 1969, 1988
Sihvola, A. and Tiuri, M.: Snow fork for field determination of the density and wetness profiles of a snow pack, IEEE Transactions on Geoscience and Remote Sensing, GE-24, 717–721, 1986. 1971, 1972, 1973, 1975, 1979
Stein, J., Laberge, G., and Lévesque, D.: Measuring the dry density and the liquid water content of snow using time domain reflectometry, Cold Reg. Sci. Technol., 25, 123–136, 1997. 1971
Techel, F. and Pielmeier, C.: Wet snow diurnal evolution and stability assessment, in: Proceedings International Snow Science Workshop, edited by: Schweizer, J. and Van Herwijnen, A., 27 September to 2 October 2009, Davos, Switzerland., pp. 256–261, 2009. 1975
Techel, F., Pielmeier, C., Schneebeli, M.: The first wetting of snow: Micro-structural hardness measurements using a snow micro penetrometer, in: Proceedings International Snow Science Workshop, Whistler, B.C., Canada, 21–27 September 2008, pp. 1019–1026, 2008. 1970
Toikka: Snow Fork – manual, Ins.toimisto Toikka Oy, Espoo, Finland, 20 p., 2008. 1977
Toikka: Snow Fork – a portable instrument for measuring the properties of snow, Ins.toimisto Toikka Oy, Espoo, Finland, http://www.toikkaoy.com/, 2 p., 2009. 1971, 1972, 1975
Waldner, P., Huebner, C., Schneebeli, M., Brandelik, A., and Rau, F.: Continuous measurement of liquid water content and density in snow using TDR, in: Proceedings Second International Symposium and Workshop on Time Domain Reflectometry for Innovative Geotechnical Applications, Evanston, Illinois, USA, 5–7 September 2001, edited by: Dowding, C., Infrastructure Technology Institute at Northwestern University, Evanston, Illinois, USA, pp. 446–456, 2001. 1971
Waldner, P., Schneebeli, M., Zimmermann, U., and Flühler, H.: Effect of snow structure on water flow, Hydrol. Process., 18, 1271–1290, 2004. 1970
Wankiewicz, A.: A review of water movement through snow, in: Proceedings of the modeling

TCD
4, 1967–2011, 2010

of Snow Cover Runoff, edited by: Colbeck, S. and Ray, M., CRREL Special Report, pp. 222–252, 1979. 1970

Williams, M., Sommerfeld, R., Massman, S., and Rikkers, M.: Correlation lengths of meltwater flow through ripe snowpacks, Colorado Front Range, USA, Hydrol. Process., 13, 1807–1826, 1999. 1972, 1978

WSL: SLF-Beobachterhandbuch: Regionale Beobachter, Hangprofiler, Geländebeobachter, WSL Institute for Snow and Avalanche Research SLF, Davos, 2008. 1969, 1971, 1974, 1975, 1983, 1994, 1998

TCD

4, 1967–2011, 2010

Point observations of liquid water content in wet snow

F. Techel and C. Pielmeier

Table 1. Hand test for the qualitative estimation of liquid water content (mWC) and the approximate range of liquid water content (θ). The detailed description is taken from the International Classification of Seasonal Snow on the Ground (Fierz et al., 2009, p. 8). This classification is also used in Swiss observational guidelines (WSL, 2008). Half index classes may also be used. t_s – snow temperature.

Wetness content	Index (mWC)	Description	θ [vol. %]
Dry	1	$t_s \leq 0.0\,^{\circ}$C. Disaggregated snow grains have little tendency to adhere to each other when pressed together.	0
Moist	2	$t_s = 0.0\,^{\circ}$C. The water is not visible, even at 10× magnification. When lightly crushed, the snow has a tendency to stick together.	0–3
Wet	3	$t_s = 0.0\,^{\circ}$C. The water can be recognized at 10× magnification by its meniscus between adjacent snow grains, but water cannot be pressed out by moderately squeezing the snow in the hands.	3–8
Very wet	4	$t_s = 0.0\,^{\circ}$C. The water can be pressed out by moderately squeezing the snow in the hands, but an appreciable amount of air is confined within the pores.	8–15
Soaked	5	$t_s = 0.0\,^{\circ}$C. The snow is soaked with water and contains a volume fraction of air from 20 to 40%.	>15

TCD
4, 1967–2011, 2010

F. Techel and C. Pielmeier

Table 2. Spacing and extent of measurement lay-outs as shown in Fig. 4 (concept according to Blöschl, 1999). x-direction corresponds to horizontal distance, y-direction is distance between consecutive measurements as in Fig. 4a, and z-direction is equivalent to snow depth measured vertically (in cm, Fig. 4b, c).

Mode	Extent	Spacing		
		x	y	z
	[cm]	[cm]	[cm]	[cm]
profile	40	20	–	5
profile	300	10	–	5
horizontal	40	20	5	–
vertical	500	50	–	5

TCD

4, 1967–2011, 2010

Table 3. Data overview: shown are the number of days (n_{day}), locations (n_{loc}), measurement depths (n_{depth}) and single measurements (n) for the various measurement modes (Fig. 4) using the Snow Fork (SnF), and for the comparison between SnF and Denoth instrument (Dn).

Mode	n_{day} (n_{loc})	n_{depth}	n
horizontal	24 (60)	>1300	>3500
profile	26 (63)	>1200	>3500
vertical	10 (26)	330	>3500
Dn-SnF comparison	8 (11)	134	251–637

TCD
4, 1967–2011, 2010

Table 4. Number of pairs of liquid water content measurements (n) and median difference between measured liquid water content $\Delta\theta_{\mathrm{SnF}}$ at a variety of horizontal distances (Δx).

Δx [cm]	n	$\Delta\theta_{\mathrm{SnF}}$ [vol.%]
10	164	0.28
20	4036	0.26
40	1625	0.42
50	3013	0.45
100	2697	0.46
150	2379	0.47
200	2067	0.50
250	1752	0.50
300	1437	0.49
350	1134	0.48
400	837	0.51
450	549	0.48
500	272	0.54

Table 5. Proposition of interpretation of manually estimated water content (hand test as per guidelines WSL, 2008; Fierz et al., 2009). The proposition from Martinec (1991b) (θ_{Martinec}, $n = 518$, 9 observers) is compared to our study (θ, $n = 314$, 4 observers). This interpretation may apply only to experienced observers estimating the liquid water content. θ, measured with the Snow Fork, is corrected by -0.8 vol.%.

Hand test (mWC)	Signature	θ_{Martinec} [vol.%]	θ [vol.%]
Dry	1	< 0.5	< 0.5
Moist	2	0.5–2	0.5–2
Wet	3	2–4	2–4.5
Very Wet	4	4–5	4.5–6
Slush	5	> 5	–

TCD
4, 1967–2011, 2010

F. Techel and C. Pielmeier

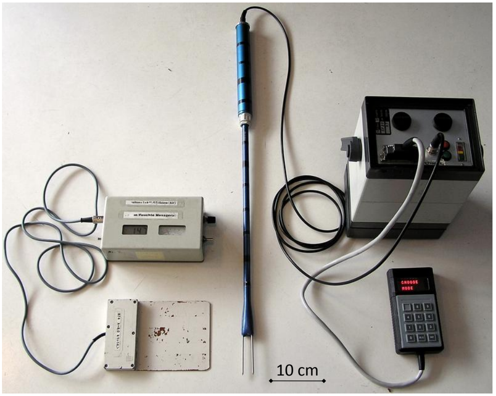

Fig. 1. Denoth (left) and Snow Fork (right) measurement devices.

TCD
4, 1967–2011, 2010

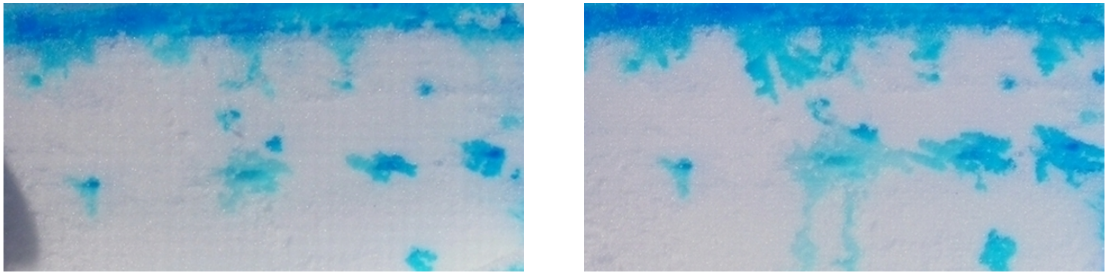

Fig. 2. Response of water flow in a slope. Shown are 50 cm wide frontal views of the pit-wall facing down-slope in experiments using dye-tracers. The left photo was taken immediately after cutting a pit-wall, the right picture approximately 30 s later. The size of the wet area at the pit-wall increased rapidly due to water flowing from lateral flow channels into the pit-wall.

TCD
4, 1967–2011, 2010

F. Techel and C. Pielmeier

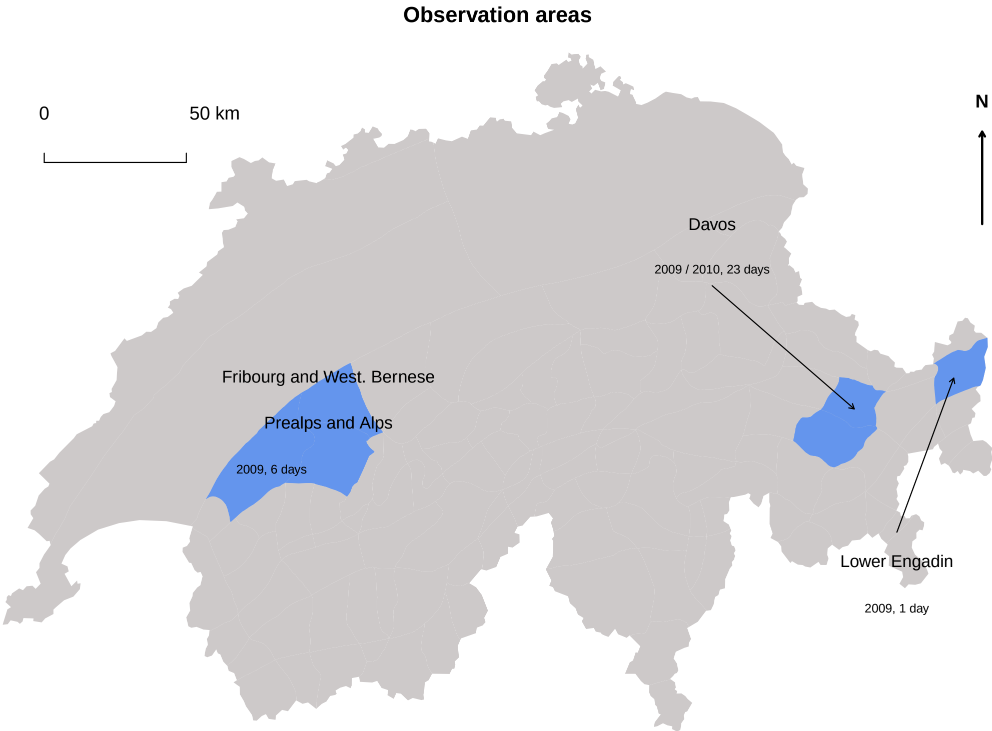

Fig. 3. Map showing Switzerland (grey) and the regions (blue), where measurements were conducted in 2009 and 2010. The number of days is shown, when measurements were carried out. The majority of measurements were taken in the region surrounding Davos.

TCD
4, 1967–2011, 2010

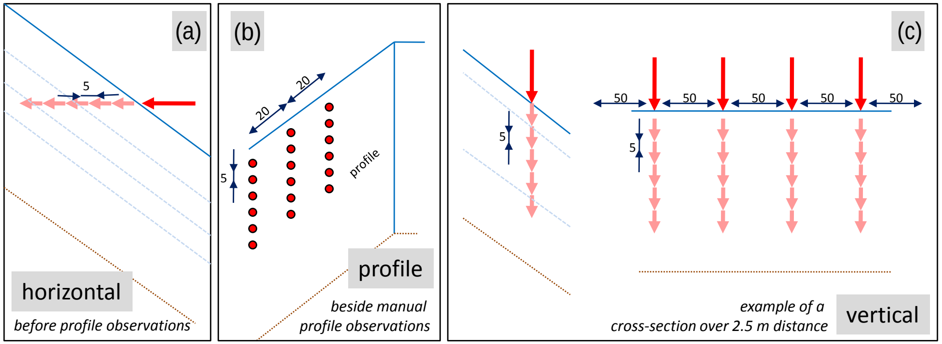

Fig. 4. Liquid water content measurements: sampling design for horizontal, profile and vertical measurements. **(a)** horizontal measurements in 5 cm steps to a depth of 75 cm. **(b)** observations adjacent to manual snow profile, vertical distance 5 cm, slope-parallel distance 20 cm. **(c)** vertical measurements for spatial variability observations, measurement steps 5 cm, horizontal distance 50 cm. Refer also to Table 2 for extent and spacing of measurements.

TCD
4, 1967–2011, 2010

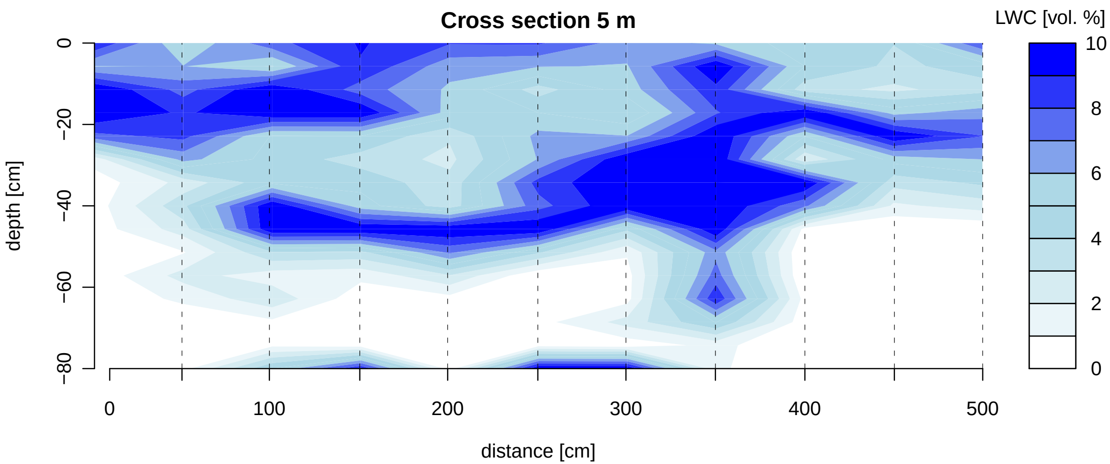

Fig. 5. Contour plot showing cross-section of snow wetness (θ) to a depth of 80 cm over 5 m wide areas across the slope. Measurements were conducted at horizontal intervals of 50 cm (lines) with a vertical spacing of 5 cm. 4 April 2009, S aspect, 2660 m, 30°. θ, measured with the Snow Fork, is corrected by −0.8 vol.% (this corresponds to the median measured water content in dry snow).

TCD
4, 1967–2011, 2010

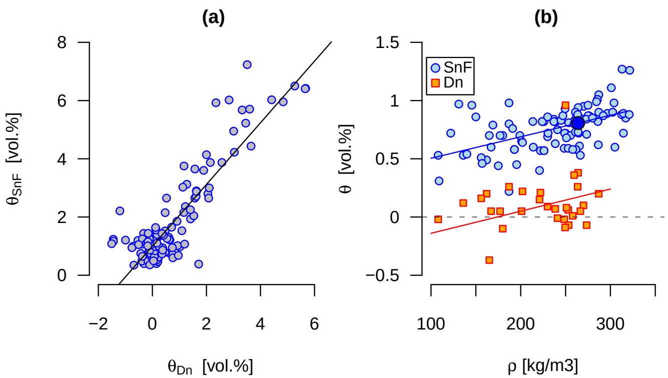

Fig. 6. Comparison of measured liquid water content using the Denoth (θ_{Dn}) and the Snow Fork (θ_{SnF}) instruments in **(a)** all wetness conditions ($n = 134$) and in **(b)** in dry snow as a function of snow density (ρ). Linear regression models are shown in both plots. The median off-set of the θ_{SnF} for the dry snow data is marked by the dark-blue dot ($\rho = 250\,\mathrm{kg\,m^3}$, $\theta_{SnF} = 0.8$ vol.%).

TCD
4, 1967–2011, 2010

F. Techel and C. Pielmeier

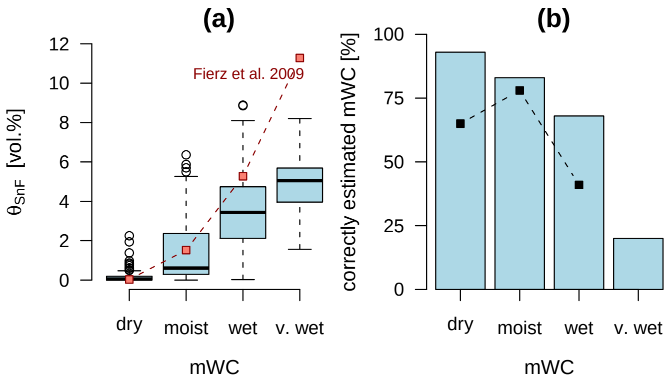

Fig. 7. (a) Box-plot comparing estimated liquid water content (mWC) and water content measured with the Snow Fork (θ_{SnF}, $n = 318$, 4 observers). As comparison the mean for each class is shown based on the conversion given in Fierz et al. (2009). **(b)** shows the frequency that mWC was correctly estimated (light blue bars). For comparison, data by a previous study is shown (black dashed line, black squares Martinec, 1991b, $n = 518$, 9 observers). θ_{SnF} is corrected by -0.8 vol.% (this corresponds to the median measured water content in dry snow).

TCD
4, 1967–2011, 2010

Point observations of liquid water content in wet snow

F. Techel and C. Pielmeier

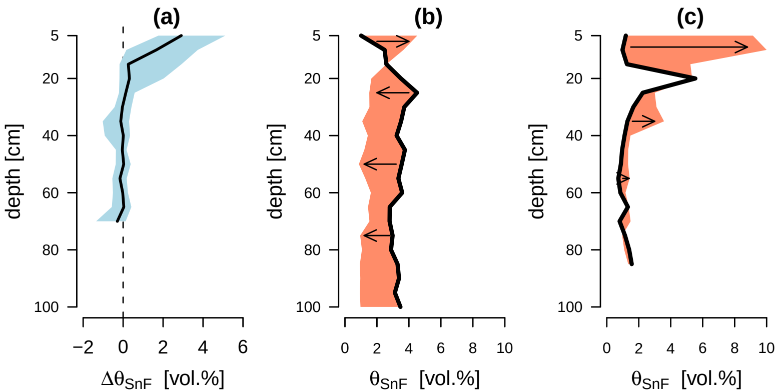

Fig. 8. (a) Difference between morning and afternoon liquid water content (θ_{SnF}), measured in 33 locations. Positive values indicate an increase in θ_{SnF} from morning to afternoon. Depth is given in cm below snow surface. The median is the bold line, the shaded area represents the interquartile range. **(b)** and **(c)** example of profiles with significant changes in θ_{SnF} during the day. The bold line represents the morning measurements (median of 3), the shaded area and the arrows indicate the change during the day.

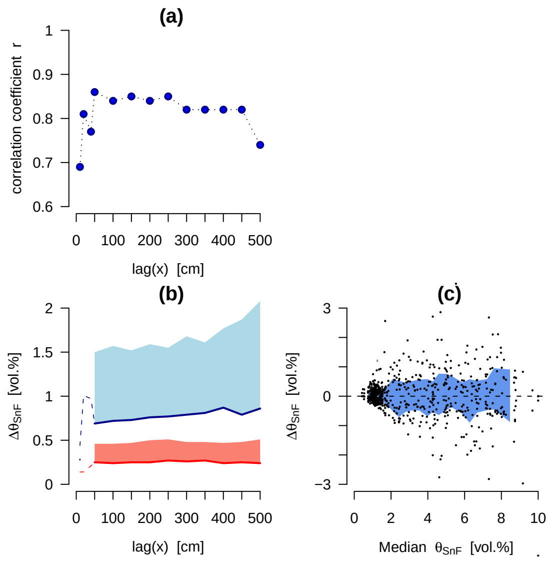

Fig. 9. Variability in measured water content as a function of lag-distance between measurements and water content. **(a)** Pearson correlation coefficient r for all measurement pairs with the same lag distance lag (x). **(b)** Difference in liquid water content ($\Delta\theta_{SnF}$) between measurement pairs at lag distance (x). Compared are the median (bold line) and the range between median and the third quartile for each lag distance (shaded area). The data-set is split into measurements where the median θ of the measurements taken over 5 m was less than 1.3 vol.% (lower values, red) and more than 1.3 vol.% (higher values, blue). **(c)** Difference between median water content and the first and third quartile (always measured within 5 m distance, $\Delta\theta_{SnF}$). The shaded area highlights the interquartile-range averaged over 25 measurements.

TCD
4, 1967–2011, 2010

Point observations of liquid water content in wet snow

F. Techel and C. Pielmeier

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

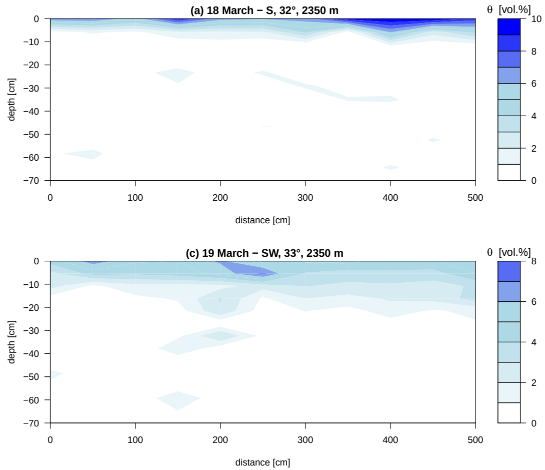

Fig. 10. State of snow wetness, 18–20 March 2010 on southerly aspect slopes at similar altitudes in the beginning of the melt phase. Contour plots showing cross-sections of snow wetness (θ) to a depth of up to 70 cm over 5 m wide areas across the slope. All observations were observed in shallow snowpack areas at similar elevations (2000–2300 m) in southerly aspect slopes (SE, S, SW). θ, measured with the Snow Fork, is corrected by −0.8 vol.% (this corresponds to the median measured water content in dry snow). θ-values greater than 10 vol.% are shown as 10 vol.%.

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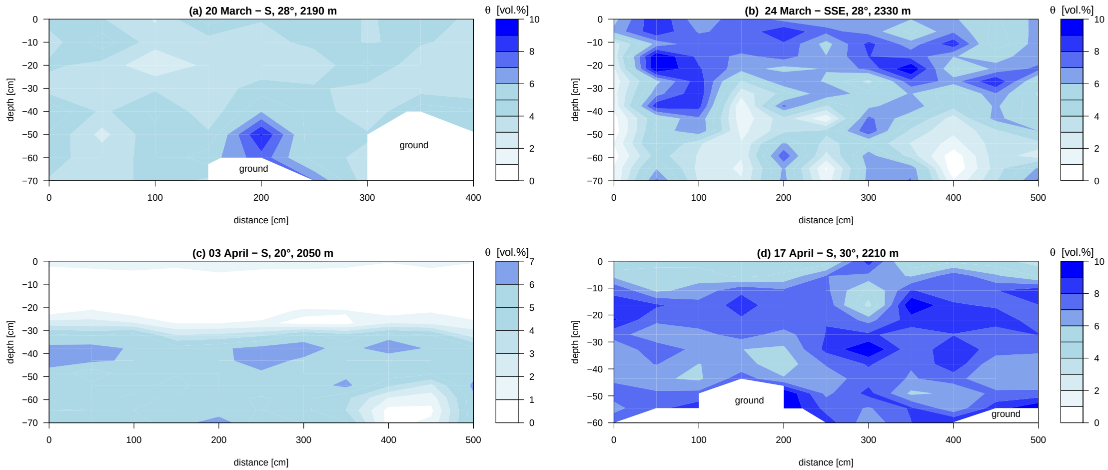

Fig. 11. Evolution of snow wetness during melting from 20 March till 17 April 2010 on southerly aspect slopes at similar altitudes. Contour plots showing cross-sections of snow wetness (θ) to a depth of up to 70 cm over 5 m wide areas across the slope. All observations were observed in shallow snowpack areas at similar elevations (2000–2300 m) in southerly aspect slopes (SE, S, SW). θ, measured with the Snow Fork, is corrected by −0.8 vol.% (this corresponds to the median measured water content in dry snow). θ-values greater than 10 vol.% are shown as 10 vol.%.

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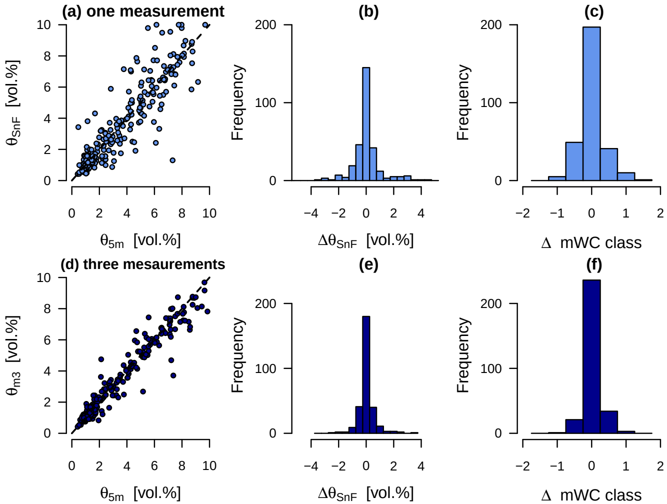

Fig. 12. Comparison between measurement samples and the median of a 5 m cross-section at a certain depth θ_{5m}. Upper row plots **(a–c)** show the comparison for one randomly selected measurement to θ_{5m}, lower row plots **(d–f)** compare the median of three measurements (θ_{m3}) observed at 1 m horizontal distance to θ_{5m}. Scatter-plots show the absolute values (a, d), the histograms the difference between θ-values ($\Delta\theta$, plots b and e) and the difference in wetness classes (Δ mWC) using the international classification (Fierz et al., 2009, plots c, f).

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

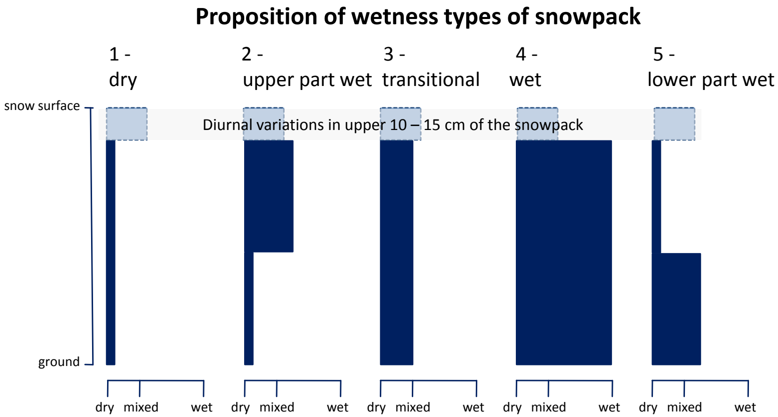

Fig. 13. Wetness classification incorporating vertical and horizontal water content distribution. The x-direction shows the percentage of the snow which has been wetted, where dry/wet is fully dry or fully wet and mixed consists of both dry and wet regions. The y-direction shows the vertical distribution of snow wetness. Diurnal changes occur mostly within the upper-most 10–15 cm of the snowpack and are not considered in this classification.

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