LONG-TERM OBSERVATION OF THE WATER CONTENT OF AN ALPINE SNOWPACK

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Abstract. *Relatively little is known about both the infiltration of water in subfreezing snow covers and its influence on the snow strength as well as on release mechanisms of wet snow avalanches. This is partly due to the fact that reliable measurements on wet snow are difficult to perform and therefore our understanding relies mostly on qualitative observations. To get more insight into the properties of wet snow, a quantitative knowledge of the water content in the snow cover has to be known over both a given area (up to now punctually) and longer periods of time. Indeed, the strength of wet snow is said to decrease significantly with a water content above 7% by volume, i. e. near the transition from the pendular to the funicular regime. Over the last few years, systematic measurements of the water content in both time and space were performed on the SFISAR study plot (2540 m a.s.l.) and its surroundings. Over 50 water content profiles representing 518 single measurements were taken and compared with the results obtained by the hand test; the correlation shows a significant discrepancy with the International Classification for Seasonal Snow on the Ground. However, water contents above 6% by volume were rarely measured and the daily variation did not exceed 1 to 2% by volume. On the other hand, the long term observation of the water content shows the importance of the time elapsed since the snow cover first became isothermal. The quite different run-off patterns (5m^2-lysimeter) at the beginning of the melting period end of April in 1993 (~5 mm/-day) and 1994 (~50 mm/day) can be related to both the different structure and the history of the snow cover, influencing the ability of the snow cover to retain and transmit water. However, around 3 weeks after run-offs started to be continuous these differences were fading out. Finally, a few measurements were taken in the starting zone of a wet snow avalanche minutes after it had released. There the gliding plane was within the snow cover and water evidently ran along this failure plane although we could not record water contents above 7.2% by volume, corresponding to a pore volume saturation of 9,9% at a density of 323 kg/m^3.*

1 Introduction

Compared to our understanding of the formation and release of avalanches in dry snow, the knowledge about corresponding mechanisms in wet snow is very poor. Both the water infiltration into and the water retention of a subfreezing snowpack were often observed and described but only qualitatively up to date (e.g. Conway and Benedict, 1994). Even though their influence on the stability of the snowpack is still very poorly known, both the water retention of and the infiltration of water into an inclined subfreezing snowpack are very important regarding the relevant processes leading to wet snow avalanches.. On the other hand, as snowpack runoffs are quite important for hydrological applications, water flow through a mature snowpack is well understood (Marsh, 1991);(Colbeck, 1991). A mature snowpack has experienced the grain growth, density increase and ice layer decomposition usually associated with the first introduction of large quantities of liquid water (Colbeck, 1978). Colbeck (1973) has also well characterized the different water content regimes in wet snow (irreducible-pendular-funicular). In the funicular regime water surrounds the snow grains contiguously, whereas in the pendular regime air exists in continuous paths throughout the pore space. Thus a drastic effect on wet snow strength is expected as the water content approaches the transition from pendular to funicular (Kattelmann, 1984). As water contents corresponding to this transition (6 to 7% by volume) are rarely measured in alpine snowpacks, field measurements of the wet snow strength have not confirmed this assumption unambiguously (Brun and Rey, 1987);(Bhutiyani, 1994). On the other hand, studies on the mechanical properties of wet snow are scarce (Salm, 1982). In summary, most of our knowledge about wet snow stability still relies predominantly on qualitative observations (Conway and Raymond, 1993);(Kattelmann, 1984).

Techniques to measure the water content in the snowpack are mostly destructive. Most of them are quite time consuming and very few may be used to take continuous measurements over longer periods of time (Schneebeli, 1992);(Denoth, 1992). The spatial variability may perhaps be investigated qualitatively with dye tracers. It is also important to realise that even the best measurements of the water content are of little help here - and especially for avalanche forecasting- without good knowledge of both the snowpack structure (layering, grain shape and size, densities, ...) and the prevailing meteorological conditions.

Our approach to get more insight into the evolution of the water content at the beginning of the melting period was to take measurements on the same site punctually but regularly over a longer period of time (~ 2 months). Additional experiments (daily variation on flat and inclined terrain) and event driven measurements (wet snow avalanche) allowed to gather first hand information about infiltrating water into a snow cover and its effects on the formation of wet snow avalanches.

2 Experimental details

Measurements of the volumetric water content were performed with a dielectric device developed at the University of Innsbruck in Austria (Denoth, 1989). The instrument takes advantage of the large difference in the dielectric constant ϵ of water and ice in the frequency range of 10 MHz to 1 GHz. In this frequency range the dielectric constant depends essentially on the density ρ and the water content θ of the wet snow.

For water contents up to 10% by volume and densities $\rho \leq 650$ kg/m^3, the following empirical relation was established (Denoth, 1989):

$$\epsilon = 1 + 1.92\rho + 0.44\rho^2 + 0.187\theta + 0.0046\theta^2 \qquad (1)$$

where ρ is expressed in 10^3·kg/m^3 and θ in % by volume. Thus simultaneous measurements of ρ and ϵ yield the water content θ.

The dielectric device used consists of a tuning and display unit and a plate-like, 13.5x13 cm^2 flat capacitive sensor which may be inserted into e.g. a snowpit wall (full-space measurement). 90% of the volume the probe senses lays within 1.5 cm on both sides of the plate, corresponding to about $0.56 \cdot 10^{-3}$ m^3 (0.56 l). The measuring range extends from $\epsilon = 1$ (air) to $\epsilon = 6.5$ with an overall accuracy $|\Delta\epsilon| < 0.05$. However the limits for reliable results are set by the validity range of equation 1 rather than by the measuring range of the instrument, as for $\theta = 10\%$ by volume and $\rho = 650$ kg/m^3 we get $\epsilon = 4.76$.

The total absolute error $|\Delta\theta|$ on the determination of the water content is -alike θ itself- a function of both ϵ and ρ:

$$|\Delta\theta(\epsilon,\rho)| = \left|\frac{\partial\theta}{\partial\epsilon}\Delta\epsilon\right| + \left|\frac{\partial\theta}{\partial\rho}\Delta\rho\right| \qquad (2)$$

In Figure 1, $|\Delta\theta(\epsilon,\rho)|$ is shown for fixed values of ρ. We assumed $\Delta\epsilon = \pm 0.05$ and put $\Delta\rho$ to either ± 50 or ± 25 kg/m^3. $|\Delta\theta|$ decreases with both increasing ϵ -i.e. water content- and decreasing ρ.

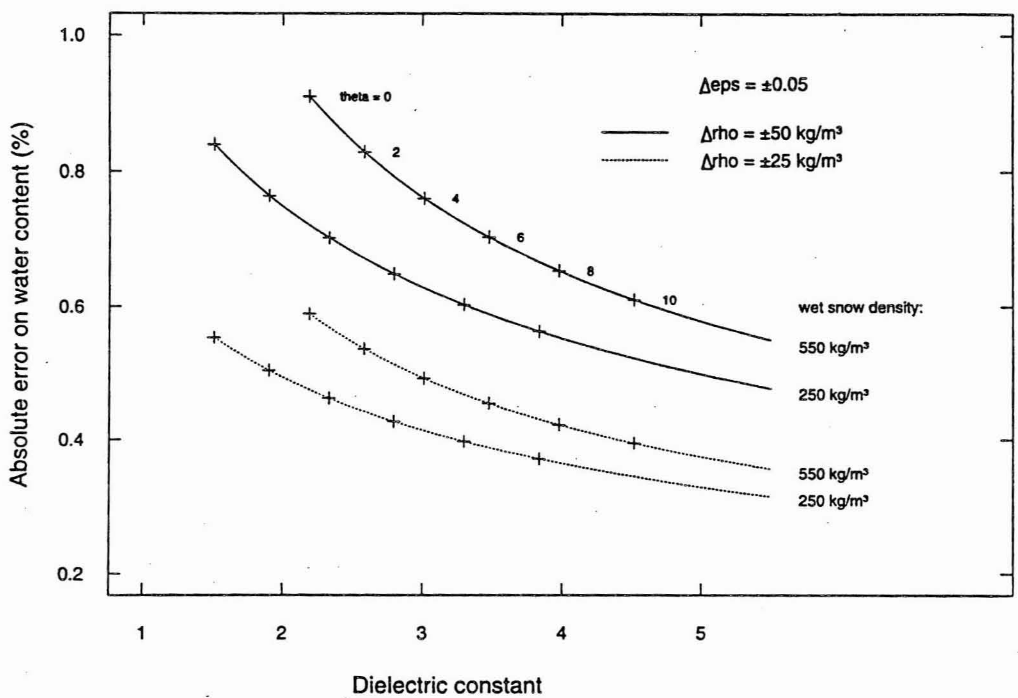

Figure 1. Total absolute error $|\Delta\theta(\epsilon,\rho)|$ on the water content for fixed values of ρ (see also equation 2). We assumed $\Delta\epsilon = \pm 0.05$ and put $\Delta\rho$ to either ± 50 (solid lines) or ± 25 kg/m^3 (dotted lines). The marks (+) correspond to the error on selected values of $\theta(\epsilon,\rho)$.

Obviously, a careful measurement of the snow density may reduce drastically the error on θ, especially at water contents below 3% by volume.
The plate-like sensor of the dielectric device is often inserted vertically into the snow to avoid ponding effects, reducing considerably the vertical resolution. However, taking quasi-instantaneous ($t \leq 15s$) measurements, we usually inserted the sensor horizontally into the snow pit wall of interest. Accordingly a vertical resolution of at least 5 cm could be reached. As far as possible the orientation of the pit walls was chosen in a way to minimize direct insolation. Furthermore, prior to take any measurements, 20 cm or more of snow were removed off the previous pit wall. To take account of the spatial variability of the water content, we usually took two profiles simultaneously about 1 m apart on the same pit wall. For the sake of simplicity, however, profiles presented in this paper were spatially averaged as far as possible.
Ideally the dielectric constant and the snow density should be measured on the same spot to get best results. However, because density is a rather conservative quantity and in order to be able to get water content profiles most rapidly, we usually took separately one or two representative density profiles with ½l-cylindrical probes. Cross checks allow us to set an upper limit of ± 35 kg/m^3 on $\Delta\rho$. This corresponds for a wet snow density of 550 kg/m^3 to an error $\Delta\theta$ of ± 0.72 and ± 0.48% by volume at water contents of 0 and 10% by volume, respectively.
Finally, the dielectric device may also be used to measure the density of dry snow using equation 1 with $\theta = 0$. However, one must be aware of the difficulties arising when measuring in light and loose snow with very different grain shapes.

3 On the interpretation of water content profiles

In the field, the water content is often estimated by hand using a five grade scale. The International Classification for Seasonal Snow on the Ground gives for each grade a corresponding range expressed in % by volume (Colbeck et al, 1990). This classification is based upon the description of the different regimes in wet snow, e.g. pendular (grade 3) and funicular (grade 4) (Colbeck, 1973). From our present knowledge, the transition from the pendular into the funicular regime should have a drastic effect on the wet snow strength (Kattelmann, 1984);(Colbeck, 1982).
However the question arises whether the field results may be used to see that transition! In an attempt to correlate estimated water contents with results obtained with the dielectric device, Martinec (1991) analyzed 518 measurements representing over 50 profiles taken in the surroundings of our institute in 1989 and 1990. The results are shown in table 1 along with the International Classification. There is an obvious discrepancy for the three highest grades, reflecting two facts: First, water contents above 6 to 7% by volume are hardly measured in an alpine snowpack. This may be due to the difficulty to detect and especially characterize thin layers of water saturated snow both by hand or with a measuring device. Second, observers tend to overestimate the wetness of snow as they want to express an increase in water content even though the lower grade may still do it. However, increasing the number of grades would be of little help here.

Grade	Symbol	Term	Int. Classification (% by volume)	SFISAR study (% by volume)
1		Dry	0	< 0.5
2	|	Moist	< 3	0.5 - 2
3	| |	Wet	3 - 8	2 - 4
4	| | |	Very Wet	8 - 15	4 - 5
5	| | | |	Slush	> 15	> 5

Table 1. Definition of the five grade snow wetness scale with the corresponding water contents in % by volume according to the International Classification for Seasonal Snow on the Ground (Colbeck et al, 1990) compared to a SFISAR study (Martinec, 1991).

As an example, we present in Figure 2 a water content profile taken both by hand and with the dielectric device on the SFISAR study plot in the morning of May 31, 1994. The values obtained by hand where converted into % by volume according to either the International Classification or the SFISAR study (see Table 1), allowing for half-grades too. As the observer was involved in the 1989/1990 study, the good agreement with the SFISAR scheme is not too surprising. However, a more rigorous interpretation in terms of the International Classification would obviously lead to wrong conclusions. Hence studies like the one performed at SFISAR may prevent misinterpretations of water content profiles taken by hand.
Unfortunately, hand profile usually show hardly no evidence of layers with potentially higher water contents. Such layers may be expected from the stratigraphic profile also shown in Figure 2. However, although the profile obtained with the dielectric device has a tendency to wiggle right around the position of the ice lenses, one must realise that the error on the water content is very much comparable to the amplitude of the above mentioned wiggles (see Figure 1).
One more point has to be considered when analysing water content profiles: the physically relevant parameter is the saturation S, the percentage of pore volume filled with water. S is the ratio of the water content θ to the porosity Φ and may be expressed in terms of θ, the wet snow density ρ, the density of ice ρ_i and the density of water ρ_w as :

$$S = \frac{\theta}{\Phi} = - \frac{\theta \rho_i}{100 \rho - (100 \rho_i + \theta \rho_w)} \tag{3}$$

In Figure 3 the ratio of S to θ as a function of θ is shown for wet snow densities ranging from 250 to 550 kg/m^3. Wet snow densities often amount to 450 kg/m^3 or more. In this density range, the crude relation S = 2θ may be used to get a rough estimate of the saturation of the pore volume.

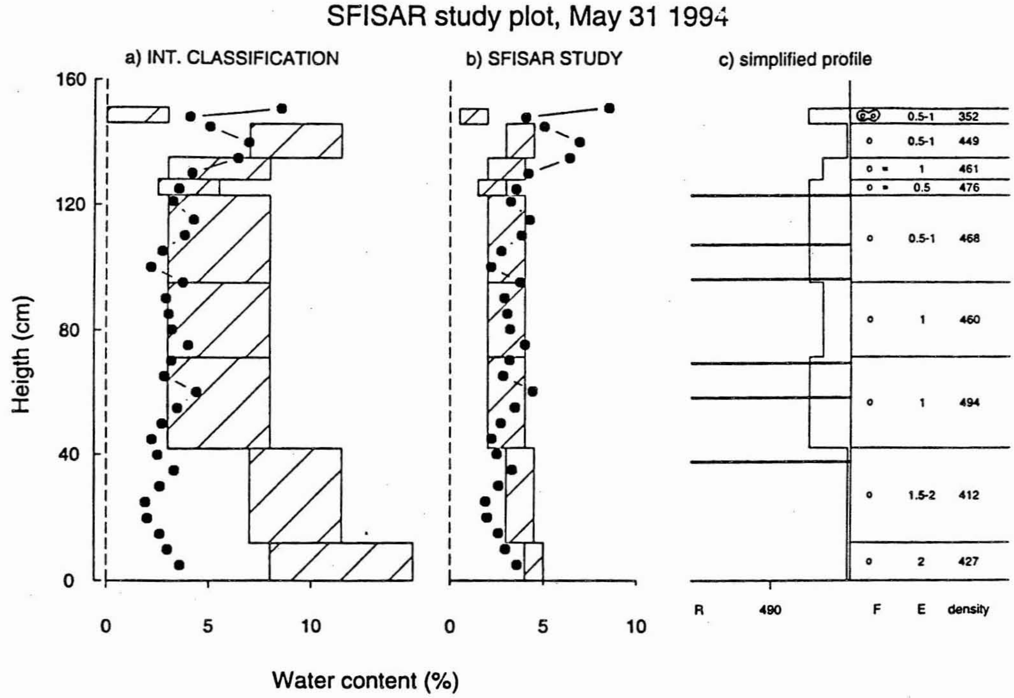

Figure 2. Water content and snow cover profiles taken on the SFISAR study plot (2540 m a.s.l.) in the morning of May 31, 1994. The snowpack was isothermal. Water contents measured with the dielectric device (filled circles) are compared to the estimations made by hand (hatched boxes) and converted according to (see Table 1):
a) the International Classification (Colbeck et al, 1990),
b) a SFISAR study (Martinec, 1991).
c) Also shown is a simplified stratigraphic profile with the position of ice lenses (thick solid lines), hardness R in N (hand test), grain shape F according to Colbeck et al (1990) except for fragmented ice lenses (=), grain size E in mm and density ρ in kg/m^3. Some grain shapes, grain sizes and densities are omitted for the sake of readability.

On the other hand, assuming the transition from the pendular to the funicular regime around S = 0.14 (Colbeck, 1982);(Denoth, 1980) depends only on the wet snow density, Figure 3 shows how this transition shifts towards higher water contents for densities below 450 kg/m^3. Hence it would be advisable to think in terms of the saturation rather than the water content if one is concerned with the strength and stability of a wet snowpack.

4 Measurements of the water content at the SFISAR study plot

In 1993 and 1994, the water content of the snow cover on the SFISAR study plot (2540 m a.s.l.) was studied systematically during the melting period. At this altitude, continuous runoffs as recorded by a 5m^2-lysimeter start around end of April, that is April 27 in 1993 and April 28 in 1994. We followed particularly the evolution of the water content along the profile-line of the avalanche warning group by taking measurements simultaneously to the biweekly snow cover profiles. In 1993, the daily variation of the

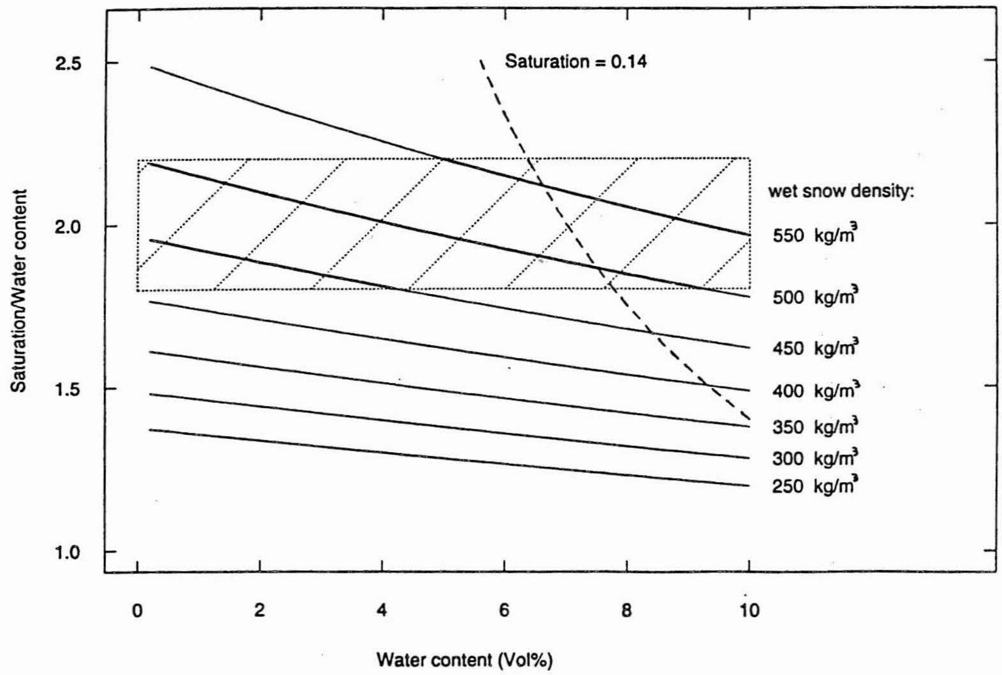

Figure 3. Ratio of the saturation S (percentage of filled pore volume) to the water content θ as a function of the water content for densities ranging from 250 to 550 kg/m^3. The dotted hatched box delineates a $\pm 10\%$-range for the crude relation $S=2\theta$ (see text). The dashed line corresponds to a saturation $S(\theta,\rho)=0.14$, delimiting the transition from the pendular to the funicular regime (Colbeck, 1982);(Denoth, 1980).

water content was observed shortly as well as a few weeks after runoffs started. These measurements were performed on both the flat study plot and an adjacent moderately inclined slope ($\sim 8°$).
In addition, relevant meteo parameters such as temperature, wind, air humidity and others are recorded continuously on the study plot.

4a) Long term observation

In Figure 4 we present snow cover profiles taken one month prior to as well as about two weeks after the start of the melting season in 1993 and 1994. The profiles of the dry snowpack being quite similar, one would not expect to observe a drastically different evolution of the water content profiles in 1993 and 1994. Indeed, the water content profiles measured around mid of May show both a mean water content of roughly $(3\pm1)\%$ by volume for a mean density of 450 kg/m^3. However, in 1994 the profile pattern seems to be more influenced by the presence of numerous ice lenses. Indeed, these lenses or associated discontinuities of the snowpack layering may have been responsible for a huge effect on the snowpack runoff, allowing for lateral inflow into the lysimeter area. As may be seen on Figure 5, the daily runoffs right at the beginning of the melting season are up to an order of magnitude larger in 1994 ($\sim$50 mm/day) than in 1993 ($\sim$5 mm/day).

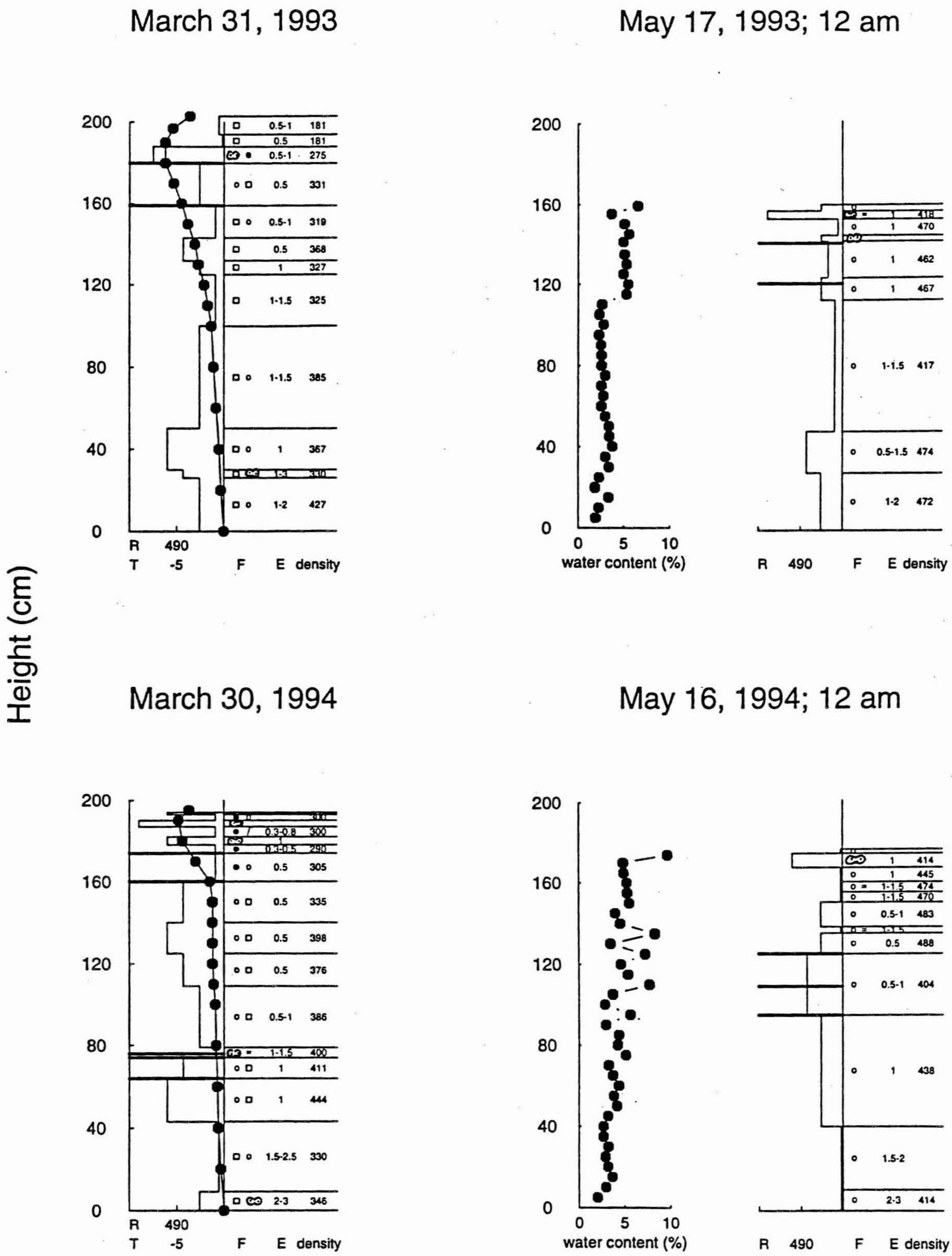

Figure 4. Simplified snow cover profiles (see Figure 2) taken on the SFISAR study plot (2540 m a.s.l.) in 1993 and 1994 one month before as well as two weeks after the melting season started. For subfreezing snowpacks, temperature profiles (T, in °C) are also shown.

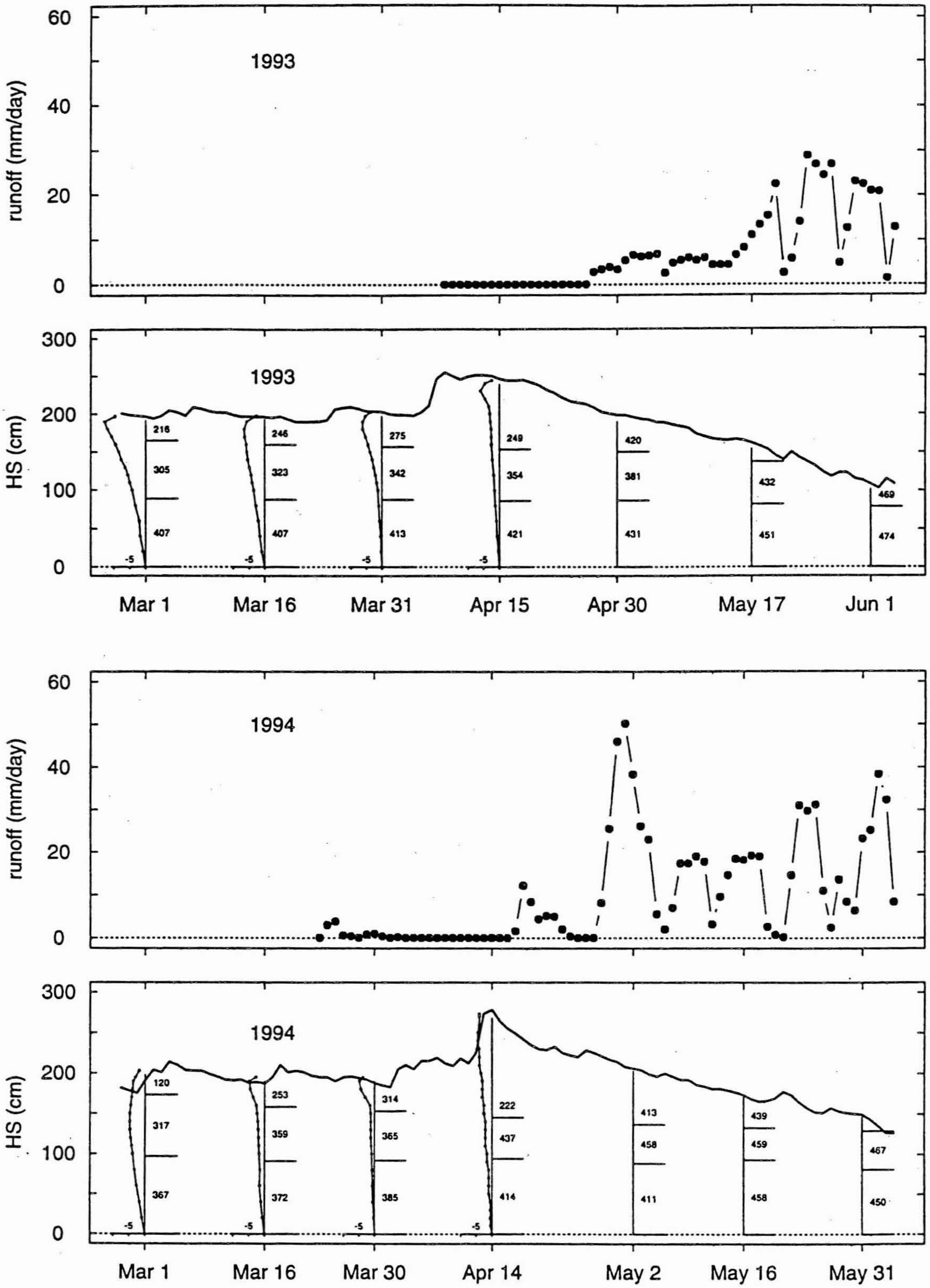

Figure 5. Daily runoffs as recorded by a 5m²-lysimeter in 1993 and 1994 on the SFISAR study plot (2540 m a.s.l.), along with the corresponding snow heights. The temperatures of the biweekly snow cover profiles are only shown for subfreezing snow. The mean densities of selected layers are also shown throughout the chosen period.

Because such a difference could also be due to a larger melting rate resulting from a higher energy input, we decided to estimate roughly the latter for the two years and to compare it to the measured runoffs. In an analysis of the 1992 energy balance at the site of our study plot, Plüss and Mazzoni (1994) show that the predicted runoff from both the measured energy balance and the crude degree-day method (de Quervain, 1979) agree with the measured runoff within 20%. Preliminary results show similarly good agreements for 1993 (Plüss, 1994; private communication). In Table 2 we compare the sum Q_m of the daily runoffs during the first month of the melting period with both the differences ΔHSW of the snowpack water equivalent and the estimated runoff Q_e according to the degree-day method. We split the period in two according to the biweekly snow cover profiles. No corrections were applied for precipitations (rain or/and snow) occurring during that period. Although very crude, these estimates confirm that a large amount of the first runoffs in 1994 must be due to lateral flow into the area of the lysimeter. Nevertheless, as the snowpack ripened the importance of these lateral flows diminished, most probably because of an increase in permeability of the ice lenses still present on May 16, 1994.

Period	Q_m (mm)	ΔHSW (mm)	Q_e (mm)
March 30 to May 16, 1993	93	94	50
May 2 to May 15, 1994	*220*	*80*	*75*
May 17 to May 31, 1993	254	204	242
May 16 to May 30, 1994	*208*	*116*	*136*

Table 2. SFISAR study plot : Comparison of the sum Q_m of the daily runoffs runoffs (in mm) with both the difference ΔHSW of snowpack water equivalent and the estimated runoff Q_e according to the degree-day method (de Quervain, 1979).

Even though we could hardly have predicted the observed runoffs of the melting period 1994, there are several a posteriori indications of this event that might give us some clues to a better understanding of the snowpack response to water infiltration. Between the end of February and the end of March 1994, we recorded several short periods (one to two days) during which the air temperature remained above 0°C at the level of the study plot. One of these periods was marked by the release of a large wet snow avalanche at about 2300 m a.s.l. (see also chapter 5) and two of them coincide with a significant warming up of the snowpack on the study plot. Indeed, the snowpack was generally warmer in 1994 than in 1993 as may be inferred from the temperature profiles shown in Figure 5. Furthermore, the mean density of the middle layers of the snowpack increased by 13.3% and 19.7% in the first half of March 1994 and April 1994, respectively (see Figure 5). Also, the snow cover profile taken on March 30, 1994 shows already a larger amount of medium sized wet grains from 160 cm down to the bottom of the snowpack (see Figure 4). Finally, water runoffs were already recorded weeks before they started to be continuous (see Figure 5). These observations lead to the conclusion that water may have penetrated the snowpack very early in 1994, possibly forming preferential channels or flowing along impeding layers which are still recognizable late in the melting period (see Figure 5).

4b) Daily variations of the water content

In Figure 6 we show the daily variation of the water content at various levels of the snowpack both on flat and moderately inclined terrain (~8°) during the melting season of 1993.

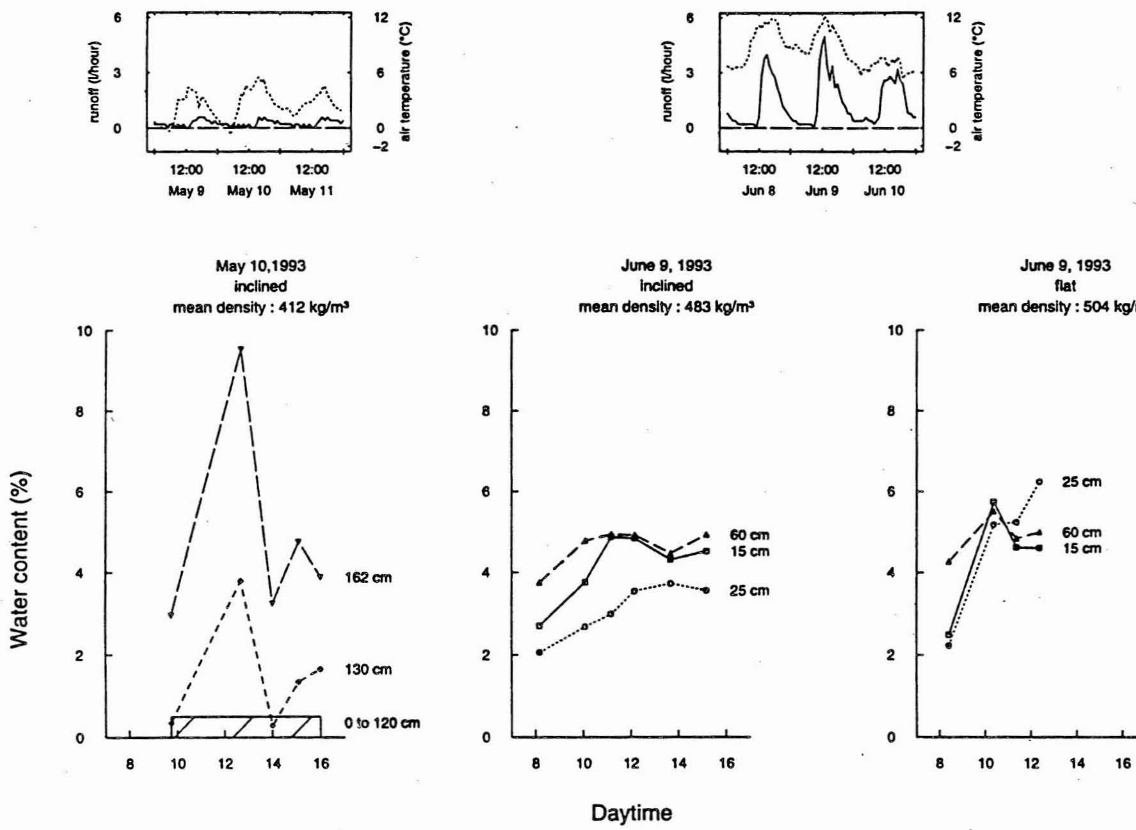

Figure 6. Daily variation of the water content at various heights in the snowpack. Situations for a ripening (5.10.1993) and a mature snowpack (6.9.1993) are shown on both inclined and flat terrain.On top the lysimeter-recordings (solid lines) and the air temperature (dotted lines) during these days are also shown.

On May 10, a thick ice layer at a height of about 130 cm influenced drastically the water content of the snowpack on the inclined terrain. Up to a height of 120 cm the snowpack remained dry, whereas the water content varied considerably in the uppermost 60 cm and showed a strong time dependence, reaching almost 10% by volume around noon at heights above 145 cm. The same ice layer was found that day on the flat study plot also, but the snow layers below were homogeneously wet with a mean water content of (3.7 ± 1.0)% by volume as measured around 9 a.m. This value corresponds closely to the irreducible water content one may expect for wet snow with a

mean density of 444 kg/m^3 (Coléou and Lesaffre, 1994). Clearly, the snowpack was going through its ripening process at that time.
On June 9, the water content profiles taken on both flat and inclined terrain looked quite similar. In fact, the water content increased within a few hours from early morning values near the irreducible range (2 to 3% by volume) to a constant mean value of (5.5 ± 1.0)% by volume, i.e. well within the pendular regime and not much higher than on May 10. Interestingly enough, the early morning water content on flat terrain was markedly lower than on the slope. Such low water contents are often recorded in mature snowpacks (Kattelmann, 1990). On the other hand, the recorded lysimeter-runoffs of the corresponding period were among the highest of the 1993 season. This apparent contradiction reflects either a highly channelled water flow originating during the ripening process of the snowpack and persisting afterwards or a very permeable snow or both.
Although a mature snowpack may be considered homogeneous, some features of the snowpack might persist throughout the melting period. In 1993, a melt-freeze crust around 25 to 30 cm produced such an 'interlayer' of noticeably lower water content. This effect is nicely illustrated on the June 9 daily variation of the water content on the moderate slope and to a lesser extent on flat terrain also.

5 Measurements in the starting zone of a wet snow avalanche

The beginning of March 1994 was marked by four days of snowfall (see Figure 5) followed by a period with temperatures above freezing even at the elevation of our study plot. This warm weather had a strong influence on the stability of the snowpack below 2400 m a.s.l. On March 10 a large wet snow avalanche released on a SE-oriented slope called 'Dorfberg', midway between our institute and the town of Davos. Thus we had the opportunity to take measurements in the starting zone of the avalanche shortly after the event, approaching the crown of the avalanche through defense structures located right above it (see Figure 7). The inclination at the measuring site was 42 degree.
The corresponding snow cover profile along with some water content measurements are shown in Figure 8. A thin ice lamella at 73 cm formed the gliding bed of this avalanche and water could be observed running on top of it. However, the measured mean water content above the ice was once more quite low with (4.5 ± 0.6)% by volume, close to the irreducible value for wet snow of 324 kg/m^3 (Coléou and Lesaffre, 1994) and corresponding to a pore volume saturation of 6.5%. Nevertheless, the profile is suggestive of an noticeable increase in water content above the ice lamella.
The mean hardness of the snowpack amounted to roughly 40 N (Swiss Rammsonde), although the profile taken by hand revealed two harder layers, one of which lay a few cm above the gliding plane. As for dry snow avalanches, the mechanical properties of the snowlayer right above the gliding plane was measured with a 0.2 by 0.25 m shear frame. The mean of 8 measurements yielded a shear strength of 982 Pa corresponding to a stability index for natural releases of 1.4 and to a stability index for skiers of 0.9. However, the validity of the stability index for wet snow is not yet established as this approach was mainly checked for dry snow slabs (Föhn, 1987).

Figure 7. View of the starting zone of the wet snow avalanche released March 10, 1993 on 'Dorfberg' (SE, 2280 m a.s.l., inclination 42°). The snow cover profile and the measurements of the water content were taken at the fracture line of one of the two small slabs to the upper left of the starting zone.

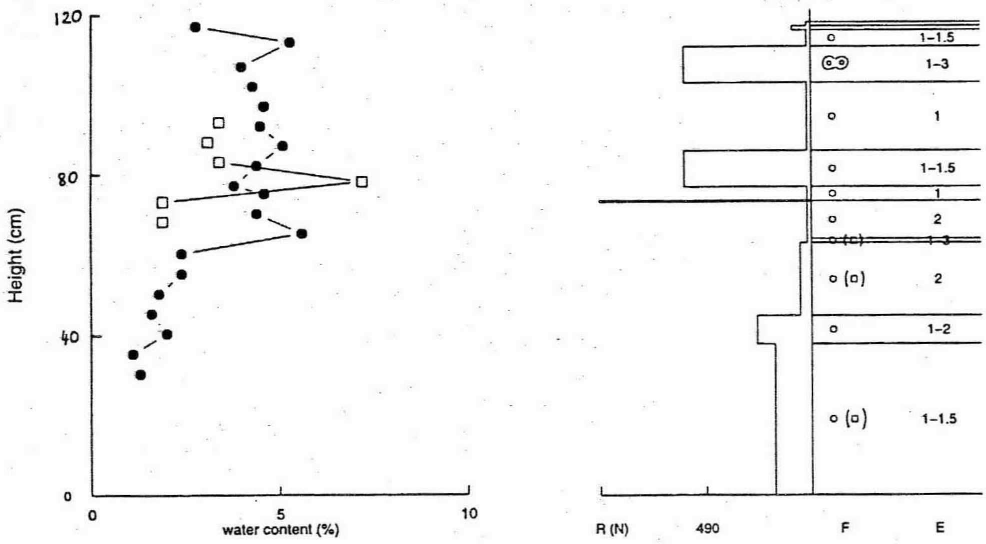

Figure 8. Simplified snow cover profile (see Figure 2) taken around 3 pm in the starting zone of the wet snow avalanche released March 10, 1993 on 'Dorfberg' (SE, 2280 m a.s.l., inclination 42°). The gliding plane was formed by a thin ice lamella lying at a height of 73 cm. One water content profile (filled circles) was taken on a pit wall facing the slope, 5 m apart from the snow cover profile. The other (open squares) on a lateral wall of the snow cover profile. The plate sensor of the dielectric device was always inserted into the snow parallel to the slope.

6 Conclusions

Once water penetrates a snow cover (e.g. during the melt season), its water content varies strongly with time and space. The now available measuring techniques are mostly inappropriate to quantify these dependence reliably and straightforwardly. Thus, as we are faced with a lack of good quantitative data, our knowledge about the processes of both the infiltration of water into and the water retention capacity of a snow cover and accordingly our understanding of the processes leading to the formation of wet snow avalanches are still very poor.

In the field, water content profiles are very often taken by hand. A SFISAR study correlating hand estimates with measured values of the water content showed large discrepancies with a physically based classification scheme (Colbeck et al, 1990). This may be due first to a certain subjectivity of the hand method and second to the fact that water content above 6 to 7% by volume are rarely measured in alpine snowpacks. On the other hand, the dielectric device developed at the University of Innsbruck (Austria) proved to be well suited to take rapidly water content profiles in the field. In order to keep the error on the determination of the water content as small as possible, careful measurements of the wet snow density have to be performed nearby. However, the vertical resolution is still too coarse to allow for detecting water saturated layers thinner than 1 to 2 cm.
Ideally, long term observations of the water content in the snowpack should be done both continuously and over areas as large as possible. Measuring techniques allowing such studies are still under development. However, our punctual but systematic approach, taken together with as much information as possible from other sources, gives a good qualitative insight into relevant processes for both water infiltration into and water retention of a ripening snowpack.
The structure of the snow pack (ice layers, layering, differences in texture and so forth) clearly influences the infiltration of water into the snow. Some structures may even persist over the whole melting season. On inclined terrain, these structures may lead to a water flow predominantly parallel to the slope which in turn increases the probability of wet snow avalanche release.
Because of the difficulty to monitor accurately the infiltration of water into snow, its effect on the stability of a snowpack is still very poorly known. Even the predicted large decrease in strength for snow in the funicular regime has not been unambiguously confirmed in field measurements.

To improve our understanding of the relevant processes in wet snow, further developments of the measuring techniques as well as more numerous systematic studies are needed. Furthermore, new measurements on the mechanical properties of wet snow should be done both in the field and in the laboratory.

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