CONTINUOUS MONITORING OF THE SEASONAL SNOWPACK EVOLUTION UTILIZING UPWARD-LOOKING GPR TECHNOLOGY

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ABSTRACT: A temporally continuous observation of the seasonal evolution of the snow stratigraphy at a single site requires non-invasive monitoring technology. Whereas ultrasonic sensors are well established in recording the snow height, they are insufficient to observe internal changes in snowpack stratigraphy. Thus, we implemented an upward-looking ground-penetrating radar (upGPR) system in the ground to monitor snow characteristics from beneath the snowpack. To enable continuous records on a daily basis, the system worked remotely controlled via internet connection and allowed temporally and environmentally independent measurements. The snowpack evolution and its changes were observed throughout a whole winter season from the beginning of December 2009 until the end of April 2010 at the Weissfluhjoch study site (2540 m a.s.l.) above Davos, Switzerland. In addition to determining snow depth under dry-snow conditions and recording settlement of layers above the antennas, the upward-looking GPR system was capable of monitoring water infiltration during a spring day. Continuous seasonal measurements of snowpack characteristics will be useful, among other things, for monitoring snow conditions in avalanche start zones and validating numerical snow cover models more objectively than with manual snow profiles.

1. INTRODUCTION

The layering of the mountain snowpack is one of the key properties when assessing snow stability (e.g. Schweizer et al., 2003). Presently, these data can only by collected with either conventional methods such as manual observations in snow pits, or by more quantitative methods including e.g. the snow micro-penetrometer (Schneebeli and Johnson, 1998). All these methods are destructive and only provide a snapshot in time of snowpack evolution.

With radar systems snowpack properties can be monitored non-destructively (Marshall and Koh, 2008). If buried in the ground, radar systems can even provide continuous data on snowpack evolution. Whereas FMCW radar systems using X- and Ku-band frequencies cannot penetrate a moist snowpack (e.g. Gubler and Hiller, 1984; Gubler and Weilenmann, 1987), C-band systems enable a monitoring under moist conditions (Marshall and Koh, 2008) however under the restriction of lower vertical resolution. Recently, various research has been conducted on the use of ground-penetrating radar (GPR) for recording snowpack properties (e.g. Granlund et al., 2009; Heilig et al., 2009). A pilot study by Heilig et al. (2010) concluded that an upward-looking GPR system (upGPR) is suited for continuous destruction-free monitoring of the snow cover.

During the winter 2009-2010 we used a fully remote-controlled upGPR system to monitor the snowpack evolution at the Weissfluhjoch study site. We will present two examples which are characteristic for mid-winter (dry) and late season (wet) conditions.

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2. METHODS

In autumn 2009 we buried an upward-looking GPR system level to the ground at the study site of Weissfluhjoch (2540 m a.s.l.) above Davos, Switzerland. We used a RIS One GPR instrument (IDS, Pisa, Italy) with shielded 900 MHz antennas. The antennas were mounted on a hydraulic hoist system. The hoist was connected to a pump system with an electric motor to allow vertical movement of the antennas. With remote-desktop software the radar system and the hydraulic lift were remotely controlled. One measurement set consisted of three single measurements. During a single measurement the radar antennas were lifted and lowered vertically several times. Through a vertical movement of the antennas, the data can be processed in a way that the reflections at snow stratigraphy differences can be separated from direct wave and other instrument-related signals.

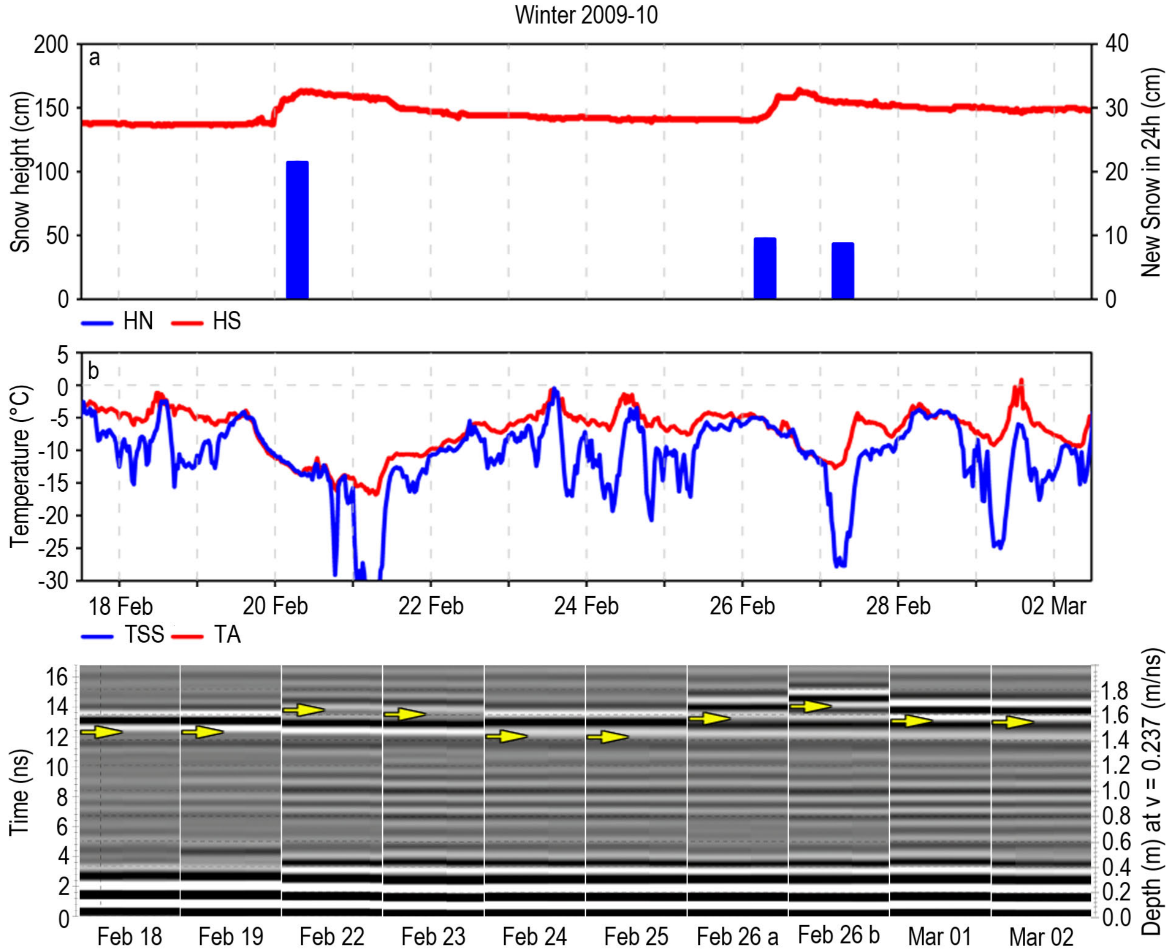

Figure 1: Meteorological conditions and radargrams for the period 18 February - 3 March 2010. (a) snow height (HS, red) and amount of new snow (HN24, blue), (b) air temperature (TA, red) and snow surface temperature (TSS, blue), (c) corresponding radargrams; the left ordinate displays the TWT in ns and the right ordinate shows the calculated snow height utilizing a mean wave speed of $\bar{v}$ = 0.237 m/ns. The yellow arrows indicate the snow surface reflection.

The gathered radar data were processed similarly as described in Heilig et al. (2010) and static corrected such that the snow bottom reflection starts at 0 ns in the profile.

Radar signals were compared to conventionally observed snow stratigraphy. Snow pit observations within a few meters from the radar site were collected according to Fierz et al. (2009). In spring, liquid water content was determined every 5 cm using a plate-type capacity probe (Denoth et al., 1984). Special attention was given to detailed density measurements. Samples taken layer-by-layer using a small (100 cm^3) cylinder were weighed with an electronic balance. At least two measurements per layer were averaged.

3. RESULTS AND DISCUSSION

In the following we will present results on snowpack evolution in winter 2009-2010 for two selected time periods. The first period in mid-winter was characterized by several small snowfall events that covered a wind crust. This allowed us to observe the settling of the new snow. During the second period in late April diurnal melt processes affected the snowpack.

3.1 Dry snow conditions: 18 Feb - 2 Mar 2010

Winter 2009-2010 was characterized by below average snow depth at the test site. Prior to the period we describe below, only two new snow events, both with about 20 cm of new snow, were recorded in January and February 2010. The air temperature was almost exclusively below 0°C.

Two intermediate dry snowfalls occurred on 20 February 2010 and on 26-27 February 2010 (Figure 1a,b). The radar records clearly display the snow height variation during this period (Figure 1c; yellow arrows). Both new snow events and the successive settling of the new snow were well captured. Prior to the first snowfall, the snow surface was influenced by wind. A manual profile conducted two days before classified the surface as a wind crust. The wind crust surface layer consistently caused a reflection although it was covered twice by about 20 cm of new snow. Towards the end of the presented measurement period (2 March 2010) the reflection response of this layer was attenuated. Furthermore, after 26 February 2010 it was hardly possible to distinguish between the reflection response of the snow surface and the signal generated by the former surface. In this case, destructive and constructive interferences occurred because of the relative small bandwidth of the applied radar system. The two layers were now within the vertical resolution limit (ca. 4 cm) of the 900 MHz GPR. Obviously, the phase sequences of the reflection signals at the snow surface and the former, now covered surface were equal and appeared in a phase reversal to the bottom signal (at 0 ns in Figure 1c). Based on observations and modeling results by Arcone et al. (2005), Heilig et al. (2009, 2010) described that a decrease in permittivity as it occurs from snow to air or from dense dry snow to less dense snow generates such a phase reversal to the bottom signal. The phase sequences of the interface above the buried old surface and at the new snow surface (interface to air) are both reversed displayed. As both observed precipitation events took place at conditions below 0°C, we assume that the phase sequence is in correspondence with the prevailing conditions, i.e. that the density decreased remarkably from the old snow surface to the new snow layer and further to air.

The reflection near the bottom was generated by the strong increase in permittivity from air above the antennas to the top of the wooden box and the bottom of the snowpack simultaneously.

The settling of internal layers can be observed as well. For instance, the slight signal at about 11 ns in two-way-travel time (TWT) at 18-19 February 2010 (Figure 1c) decreased in good agreement to the former surface reflection.

3.2 Wet-snow conditions: 28 April 2010

Figure 2 shows the weather conditions for the second case study. Conditions are remarkably different from the above described dry-snow period. The snowpack was isothermal (except when surface layers refroze during nights due to radiative cooling) and affected by melt processes.

Figure 3 presents a time series of radar records of 28 April 2010. The measurements started in the morning after a clear, cold night (Figure 2). Air temperature increased quickly to about 5°C and the snow surface temperate reached 0°C at 10:00 h. In a manual snow profile, recorded at 08:00 h, only the snow temperatures in the upper 10 cm were below 0°C. The melt processes at the study site had started one week prior but outflow at the bottom of the snowpack as recorded with a lysimeter was first observed three days before the 28 April 2010. Therefore, we assume that liquid water was present throughout the snowpack.

As soon as water infiltrates the snowpack a constant wave speed cannot longer be assumed. Here, we keep to the scale for a better comparison but only regard it as a relative scale (Figure 3). The snow depth observed in the manual profile was 170 cm, which is about 10 cm less than calculated with a constant wave speed. Due to the fact that (a) the wave speed changes during the day with ongoing melting and increased liquid water content (LWC), and (b) the total amount of liquid water is not known, it seems to be the best approximation to keep to the wave speed used for dry-snow conditions.

Obviously radar signals occur above the snow surface (Figure 3). These signals are multiples of dominant reflections within the snowpack. They might be suppressed with further processing steps.

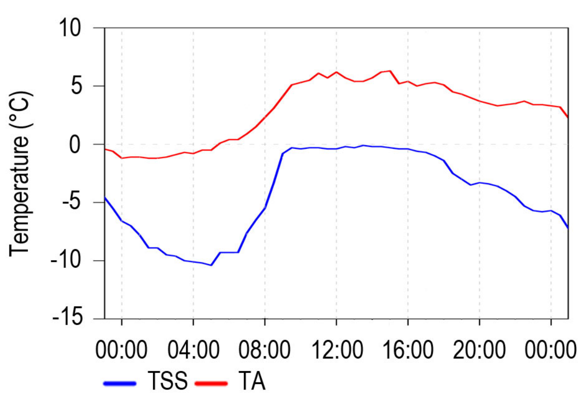

Figure 2: Meteorological conditions for 28 April 2010: air temperature (TA, red) and snow surface temperature (TSS, blue).

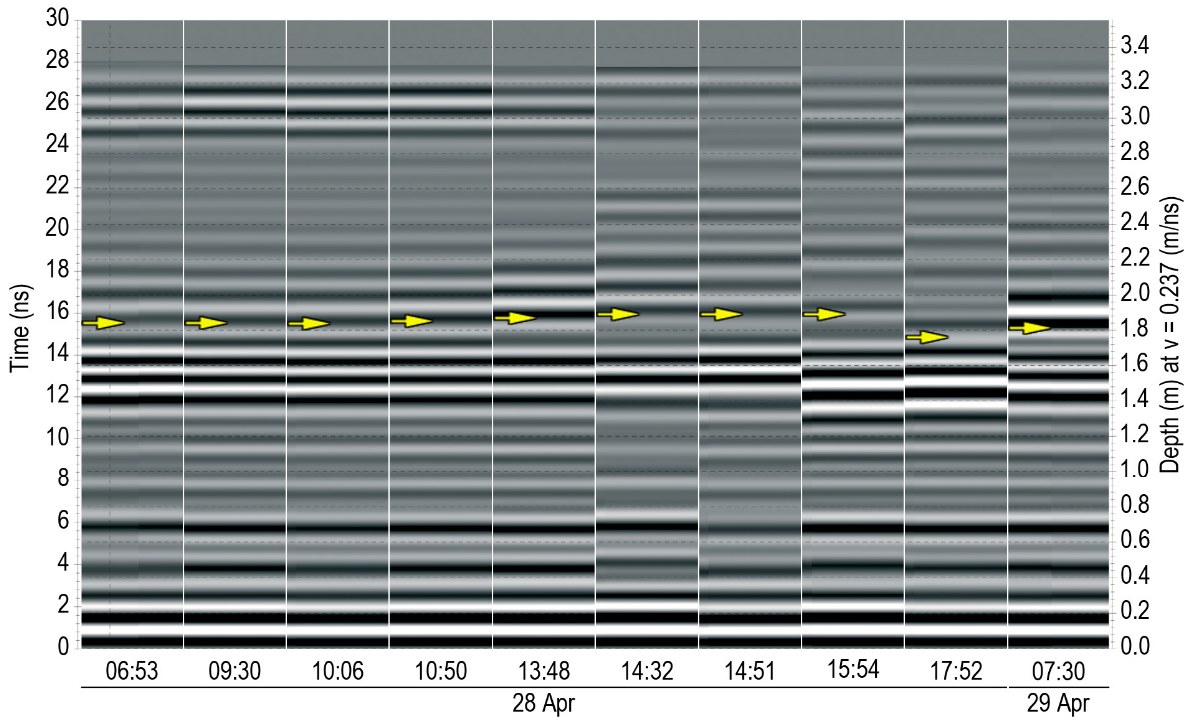

Figure 3: Radargram for 28 April 2010. The left ordinate displays the TWT in ns and the right ordinate shows the calculated snow height utilizing a mean wave speed of $\bar{v}$ = 0.237 m/ns. The yellow arrows indicate the snow surface reflection.

Nevertheless, this data set shows that the dielectrical properties of the snowpack changed during the day which hints to an increasing amount of liquid water during the day. First of all, the wave speed decreases, which is demonstrated by TWT of the surface reflection (Figure 3; yellow arrows). During the day with increasing LWC in the snowpack the radar response of the surface increases in TWT although the nearby measured snow height slightly decreased. The discrepancy results from the decrease in wave speed with increasing dielectric permittivity. Second, the propagation of radar waves is very much attenuated with increasing electrical conductivity in the penetrated medium, which is obviously the case for the surface reflection during the day. These two observations are both indications for the increase in LWC in the snowpack. Additionally, if it is assumed that the average snow density remains unchanged at the beginning of the melt season, and if a continuous external snow depth measurement is available, it might be possible to assess the increase in LWC below specific layers using the alternation in TWT of those specific layers. This method seems promising for quantifying LWC within the snowpack continuously without influencing possible infiltration patterns. Furthermore, the radar records show a decrease in TWT of the brightest reflection in the time series, in particular from 14:51-15:44 h. The previous days, the liquid water accumulated above several crusts and ice lenses located between 130 and 160 cm. Below these layers conventional measurements showed almost no liquid water. In the late afternoon of 28 April 2010 the melt water started to percolate through these layers from 11.5 ns down to about 10.5 ns (Figure 3).

The next morning (29 April 2010) the surface reflection appeared as a bright signal response, which was caused by the refreezing of the near-surface layers during the night resulting in a remarkable crust. The phase structure at that morning corresponded well with the expected conditions, namely in a phase sequence equal to the snow-bottom reflection.

4. CONCLUSIONS

We presented selected examples of continuous radar monitoring of the snowpack throughout a whole winter season from beneath the snowpack. By the use of a remotely controlled upward-looking radar arrangement (upGPR), we were able to monitor the temporal evolution of the snowpack from January until beginning of May 2010.

Although preliminary, the analysis shows that it is feasible to observe changes in snowpack properties at a single site over time. We followed the snow surface covered by two new snow events and monitored the settling close to the former snow surface. The upGPR was also capable to record the subsequent attenuation of the reflection as the density difference to the surrounding layers decreased. Under dry-snow conditions, the snow depth evolution can be monitored using the upGPR. Of course, snow depth can be recorded much simpler by ultrasonic or laser beam sensors, but to record snow depth in areas where these sensors are difficult to mount, such as avalanche start zones, upGPR offers an alternative solution.

In wet-snow conditions, the consecutive radar records taken during a single day demonstrate that monitoring the evolution of LWC (e.g. the advance of a wetting front) seems feasible with the upGPR-system. Nevertheless, determining the liquid water content of the snowpack above the radar antennas was not possible, as this would require a simultaneous, continuous snow depth measurement right next to the antennas.

The upGPR system shows promising potential for continuous monitoring of snow stratigraphy which would be useful for objectively validating and – through data assimilation – improving numerical snow cover models, as well as for assessing snow slope instability in a specific avalanche path (local forecasting).

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REFERENCES

Arcone, S.A., Spikes, V.B. and Hamilton, G.S., 2005. Phase structure of radar stratigraphic horizons within Antarctic firn. Ann. Glaciol., 41: 10-16.

Denoth, A., Foglar, A., Weiland, P., Mätzler, C., Aebischer, H., Tiuri, M. and Sihvola, A., 1984. A comparative study of instruments for measuring the liquid water content of snow. J. Appl. Phys., 56(7): 2154-2160.

Fierz, C., Armstrong, R.L., Durand , Y., Etchevers, P., Greene, E., McClung, D.M., Nishimura, K., Satyawali, P.K. and Sokratov, S.A., 2009. The International Classification for Seasonal Snow on the Ground. HP-VII Technical Documents in Hydrology, 83. UNESCO-IHP, Paris, France, 90 pp.

Granlund, N., Lundberg, A., Feiccabrino, J. and Gustafsson, D., 2009. Laboratory test of snow wetness influence on electrical conductivity measured with ground penetrating radar. Hydrology Research, 40(1): 33-44.

Gubler, H. and Hiller, M., 1984. The use of microwave FMCW radar in snow and avalanche research. Cold Reg. Sci. Technol., 9(2): 109-119.

Gubler, H. and Weilenmann, P., 1987. Seasonal snow cover monitoring using FMCW radar, Proceedings ISSW 1986, International Snow Science Workshop, Lake Tahoe, California, U.S.A., 22-25 October 1986. ISSW Workshop Committee, Homewood, CA, USA, pp. 87-97.

Heilig, A., Eisen, O. and Schneebeli, M., 2010. Temporal observations of a seasonal snowpack using upward-looking GPR. Hydrol. Process.: in press, doi: 10.1002/hyp.7749.

Heilig, A., Schneebeli, M. and Eisen, O., 2009. Upward-looking ground-penetrating radar for monitoring snowpack stratigraphy. Cold Reg. Sci. Technol., 59(2-3): 152-162.

Marshall, H.-P. and Koh, G., 2008. FMCW radars for snow research. Cold Reg. Sci. Technol., 52(2): 118-131.

Schneebeli, M. and Johnson, J.B., 1998. A constant-speed penetrometer for high-resolution snow stratigraphy. Ann. Glaciol., 26: 107-111.

Schweizer, J., Jamieson, J.B. and Schneebeli, M., 2003. Snow avalanche formation. Rev. Geophys., 41(4): 1016, doi:10.1029/2002RG000123.