TEMPORAL AND SPATIAL CHANGES OF A SEASONAL SNOWPACK WITHIN A SMALL SHELTERED SLOPE

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ABSTRACT: We studied the seasonal evolution of a natural snowpack and changes thereof within a small sheltered slope, utilizing non-destructive monitoring systems continuously over more than three months. During the winter season 2012, a permanent installation of a 800 MHz upward-looking ground-penetrating radar (upGPR) provided sub-daily to hourly data about variations in total snow depth, liquid-water content and major stratigraphy at a point in the center of the slope. In addition, to observe the spatial representativeness of these point measurements, we performed radar observations along a 22m aerial tramway once a week using a 1GHz GPR system. The transect crossed the upGPR location and thereby allowed us to put the point measurement in the context of the entire slope. Furthermore, conventional snow pits including densities, liquid-water content measurements and depth probings were recorded next to the tramway right before or after the above-snow measurements. An automated weather station, which was located on a ridge line right above the study slope, provided standard meteorological and snow observations. Utilizing upGPR data together with the tramway measurements, we can determine and time strain rates, new-snow amounts and percolation of liquid water in relation to the prevailing weather conditions and observe both spatial and temporal variability in these properties. The scope of this paper is to demonstrate the potential of non-destructive observations in seasonal snowpacks, to provide further information of the formation of changes in stratigraphy and the variability thereof across a slope.

KEYWORDS: upGPR, tramway GPR, temporal/ spatial variability

1. INTRODUCTION

The layering of the mountain snowpack is one of the key parameters for assessing snow stability (e.g. Schweizer et al., 2003). Monitoring changes in stratigraphy in addition to snow depth and liquid water infiltration is only possible utilizing non-destructive observation methods. Methods not affecting the recorded snowpack are either based on optical sensors (laser scan, time-lapse photography) or on electromagnetic sensors transmitting in the microwave frequency range.

Radar systems, in contrast to optical methods, enable monitoring of internal changes of snowpack properties in addition to the total snow depth (e.g. Marshall and Koh, 2008). So far two different radar applications have been utilized in snow science: (i) from above the snow surface (e.g. Vickers and Rose 1973) and (ii) from underneath the snowpack with sensors buried in the ground (e.g. Gubler and Hiller, 1984) If buried in the ground, radar systems are able to provide continuous data on temporal snowpack evolution (Heilig et al., 2010) at a point, while surface radars can provide detailed information about spatial variations.

In this study, we combined above-surface measurements utilizing a tramway system with continuous point observations utilizing upward-looking radar. Both measurements, from above and beneath the snowpack, were conducted with commercially available impulse radar systems (GPR).

During the winter season 2012 (January-April), we continuously observed temporal snowpack-alternations at a point measurement and compared gathered signal responses on a weekly basis with signals recorded along a 22m transect. Here, we present changes in the total snow depth along the radar transect with respect to point measurements during accumulation and melt conditions. Furthermore, we follow a distinct surface signal after burial for 3 weeks and calculated strains every 0.1m along the transect.

2. METHODS

2.1 Field data

In fall 2011, we buried an upward-looking GPR (upGPR) system level to the ground at the newly developed snow-study site near the Bogus ridge

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line (2100 m a.s.l.) above Boise, Idaho. The test site (Figure 1) is within a small tree-sheltered SE-facing slope (30m x 30m upslope/ cross slope direction). Slope angle varies from about 20 degrees along the upper parts close to the ridge to almost 30 degrees at the lower part of the study site. An automated weather station was located approximately 50m from the slope at the ridge crest. The upGPR is located in the center of the slope. Tramway measurements cross the upGPR location between 15-16m of each transect. We used a RAMAC system (MALA Geoscience, Sweden) with shielded 800 MHz antennas for the upGPR. The antennas were mounted on a linear actuator to move them vertically during each radar recording.
A solar array of 180W with six 30Ah lead batteries provided power to the instrumentation. Utilizing time switches together with a field laptop, we were able to run the whole system autonomously.

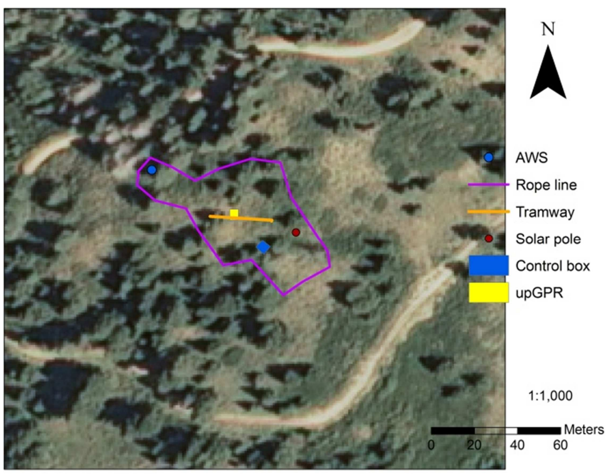

Figure 1: Test site Bogus Basin, Boise, Idaho. The slope is surrounded by trees and centered between two roads, the upper one (upper part of the figure) marks the ridge above the slope. Within the roped area (purple line) installations are displayed in the corresponding colors.

UpGPR measurements were conducted hourly from 9:00h-18:00h and 3 times during the night starting mid-February. From January 1st till then data were only recorded every 3h during daytime due to technical problems. Tramway transects were performed almost every week coincident with conventional snow pits (Fierz et al., 2010) including density and liquid-water-content measurements utilizing a capacitance plate (Denoth et al., 1984). For GPR trace-location, we set a marker on the recorded radargram every 2m and interpolated along these markers. A maximum resolution along the transect of 0.02m distance per trace is possible, but in terms of uncertainties in the interpolation, a smoothing was applied, which reduced the resolution to 0.1m.

2.2 Data processing

Gathered radar data was processed similar as described by Heilig et al. (2010) and Mitterer et al (2011). We applied dewow and band pass filters to reduce clutter and noise and linear gain increasing with travel time to compensate for divergence losses of the radar signal. As described above, the antenna was lifted and lowered twice during each measurement. The resulting data consists of two kinds of signals, (i) with a respective structure corresponding to the vertical movement and (ii) without any vertical oscillations in the signal. Those constant signals in (ii) are caused by system noise (e.g. multiples of the direct wave or antenna ringing) and mask snowpack-related reflections. Applying filter algorithms and lifting corrections enable elimination of these constant signals. All signals originating from within the snowpack show a distinctive movement pattern. After static correction, the resulting radar traces were stacked and the average trace for each radar observation was merged into one radargram (Figure 2). To filter reflections originating from the cover box or surrounding rocks, we applied a moving window filter with a width of 4 weeks. If a sample value of a trace (total 770 samples per trace) remained constant over a time period of 2 weeks in advance and to weeks after a specific measurement, it was considered unrelated to snow and thereby removed.

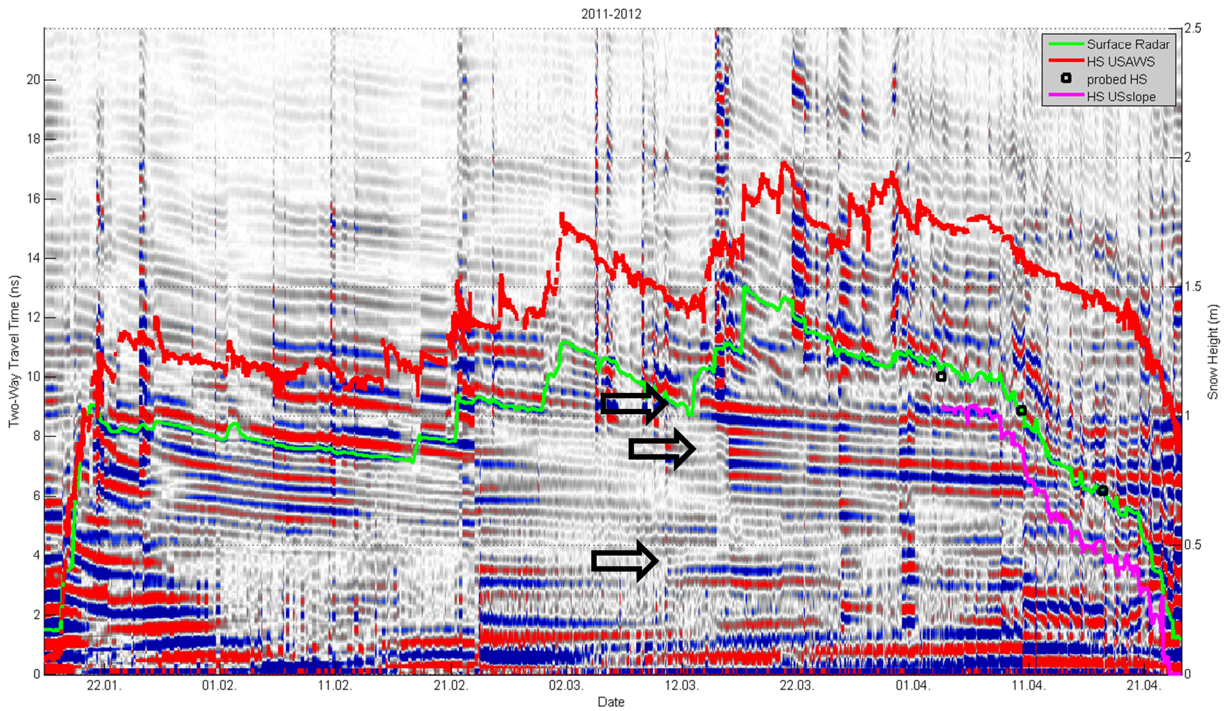

Figure 2: Plot of the entire season of upGPR measurements. Time scale ranges from January 16 until April 27 2012. The radargram is visualized such that positive amplitude values are plotted in red and negative amplitudes in blue, while color saturation corresponds to amplitude intensity. The green line represents the picked snow surface of the upGPR, red line is snow depth measured at the AWS at the ridge, purple line shows an ultrasonic snow-depth sensor installed during the season slightly above the upGPR and black squares indicate probed snow depths right above the upGPR. Black arrows indicate referred signal reflections.

3. RESULTS AND DISCUSSION

In the following, we present results of the upGPR-point measurements and relate some events spatially along the tramway transect. The total snow depth and changes thereof in relation to the upGPR point data are analyzed. Furthermore, we relate snow-depth patterns to precipitation and melt events and determine strains for 1 specific snow layer over 3 weeks.

3.1 Temporal snowpack evolution at upGPR location

Winter 2012 in Idaho was characterized by a dry period in early winter. Initial snowfall in late November was succeeded by a dry interval persisting through mid January, interrupted by 3 days of precipitation at the end of December. As a result an inhomogeneous 0-0.3m thick layer of old snow covered the test site when the first big snowfall event hit the slope starting Jan. 18. Within 3 days more than 1m of new snow covered the test site. After January, only 3 more major snowfall events occurred until late April. The seasonal snowpack at the test site consisted of those 4 major accumulations interrupted by several rain-on-snow and severe melt events. The upGPR plot in Figure 2 represents these circumstances. When precipitation is predominant during upGPR measurements, multiple reflection above the surface in air are evident in the radargram as signal reflection is caused from above the surface as well. Rain can be distinguished from snow by percolating liquid water, which affects deeper layers in the snowpack and thereby results in reflection alternations within the snowpack. Snow fall, however, just has an effect on the surface reflection. Melt events cause similar effects like rain events. The surface-near layers get percolated with liquid water, which increases the permittivity there and generates strong permittivity gradients with the layer beneath, resulting in distinct reflection horizons. These reflections continue as multiples in air. Distinct rain events can be observed in the upGPR plot at the following dates:

Jan. 18, Jan. 25, Feb. 22, Mar 15.
Multiples in air, which are present at other dates not mentioned here, can be related to severe melt events. The first event which caused the stable wetting-front to percolate all the way through the snowpack happened Mar. 6. The following 6 days were characterized by warm temperatures and successive melt events. On Mar. 10 stratigraphy changed at about 0.8m above ground (Fig 2, middle arrow) and at 0.3m (Fig 2, lower arrow). On Mar. 15, a strong rain-on-snow event accumulated liquid water above those layers. The lower layer at 0.3m disappeared with the next melt intrusion to the ground, which happened Mar 25-26. However, the layer at 0.8m and the former surface at ~1.0m, which got buried by new snow starting Mar 13 (Fig 2, upper arrow), remained detectable in the upGPR radargram until those layers melted in late April.

Mitterer et al. (2011) calculated the stored volumetric liquid water content (LWC) utilizing an externally determined snow depth above/close by the upGPR location. This work was performed on a flat site with a slope close to 0 degrees. However, they observed a distinct delay of the two-way travel time (TWT) of the surface reflection during wet-snow conditions. This delay can easily be explained by the decrease in wave speed due to LWC infiltration. While comparing physically measured snow depth to TWT, Mitterer et al. (2011) were able to calculate for volumetric LWC assuming that the measured snow depth matches the snow height above the radar antennas. Additionally, they observed a distinctly pronounced diurnal/nocturnal cycle in the volumetric LWC, reproduced in surface oscillation of the radargram. In this data set, during wet-snow conditions, probed depths match exactly the picked radar snow height, which was converted to depth assuming dry-snow conditions. Furthermore, a distinct diurnal surface increase was not present as well, indicating that liquid water cannot be stored over a longer period within this slope.

3.2 Spatial and temporal variation of snowpack properties along the tramway transect

Figure 4 represents surface heights above ground (in TWT) of the snowpack for all 11 conducted tramway transects in 2012. Such a presentation involves 2 uncertainties for direct comparison:
(i) changes of the ground reflection (e.g. unfrozen - frozen soil, basal melt water) may influence the ground picking and thereby are reproduced in the snowpack presentation;
(ii) alternations of the wave speed among transects are not visible as only recorded TWT are presented.
However, as in the upGPR data set (Fig 2), the probed snow depth is almost exactly matching the picked surface line in April, the assumption of minor wave-speed alternations during melt season seems appropriate. In dry-snow conditions, Mitterer et al. (2011) showed that a mean wave speed for total snow-depth conversion is adequate, if the value is adapted for the seasonal bulk density. The resulting error of this assumption can be neglected.
The range of variability in TWT in Figure 4a is rather small and corresponds well with the point measurements of the upGPR (Fig. 2). There, we observed an almost parallel settlement from Feb. 2-16. Along the transects, only the first snow mound between 8—10m, recognizable for the first two February measurements, caused obvious variability. Afterwards this mound was eroded (Feb. 16), and two larger new-snow events accumulated another 0.25m of snow before the next transect (Feb 23). Again, the respective TWT-values showed parallel increases and the standard deviation (STD) of the subtraction of both measurements remained rather small (#3, Fig. 3). Another large new-snow event including settlement and melt (#5, Feb 28 – Mar 13, Fig. 3) did not change the snow-depth pattern significantly either.

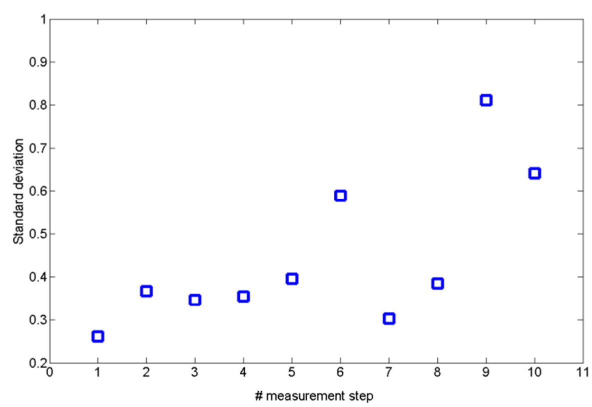

Figure 3: Standard deviation of the difference between 2 successive tramway transects: # 1: Feb 02.-Feb 09, #2: Feb 09-Feb 16, #3: Feb 16-Feb 23, #4: Feb 23-Feb 28, #5: Feb 28-Mar 13, #6: Mar 13-Mar 20, #7: Mar 20-Mar 27, #8: Mar 27-Apr03, #9: Apr 03-Apr 10, #10: Apr 10-Apr17.

However, for the week following Mar. 13, a strong increase in STD is observable (#6, Fig. 3). Within this week a strong rain-on-snow event accompanied with about 0.5m of new snow changed the snow-depth pattern along the transect significantly. While, obviously, during the next 2 weeks melt occurred (Fig. 2), STD-values were comparable to February conditions. Only after early April, melt influenced the snow-depth pattern such that significant differences from one transect measurement to another were detectable. We state that on this slope only rain and very pronounced melt events have a remarkable influence on the snow depth distribution along the radar transect.

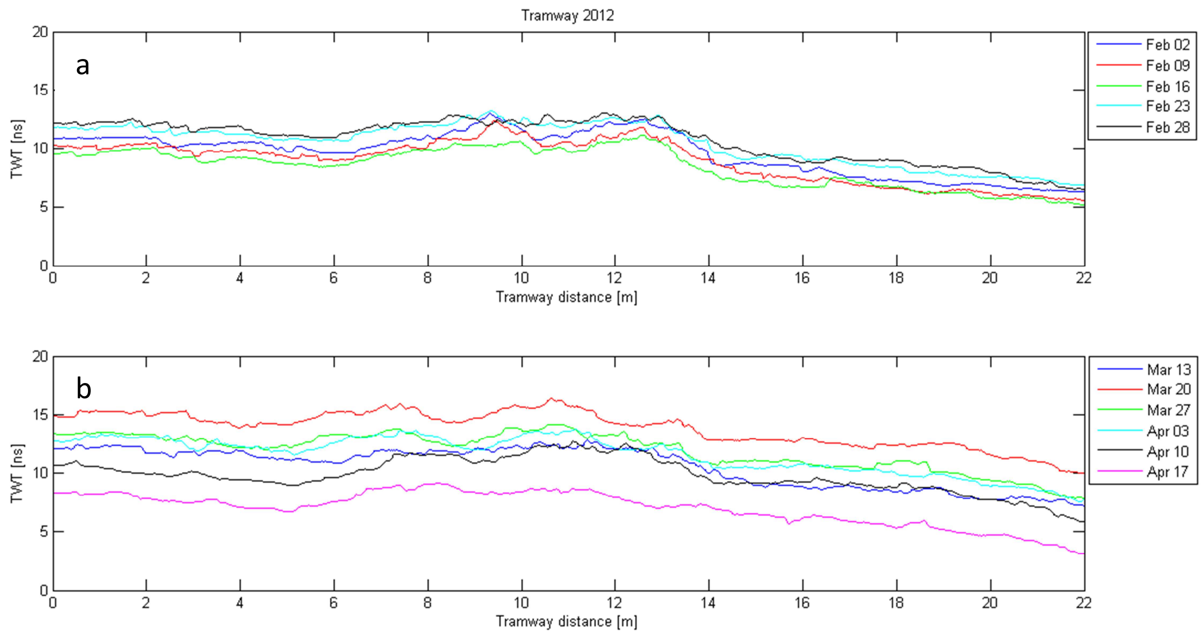

Figure 4: Display of the recorded two-way travel times of the snow depth along the respective transects. The plot (a) represents conditions in February 2012 along the tramway transect and plot (b) conditions, when melt affected the snowpack. Each color stands for one measurement during winter season 2012.

Strain was calculated in accordance to Heilig et al (2010) such that layer thicknesses at time t were subtracted by layer thicknesses at time t+1 for each increment and divided by an averaged thickness over t and t+1. Analyses in Figure 5 were performed on changes of the strain in thickness of the layer between the respective snow surface and the position of the buried former surface before March 13 (Figure 2 upper arrow). As strain for the period from Mar 27 – Apr 03 is oscillating around S=0 and the mean with $\mu_{S2} = 0.04$ is almost a factor of 9 smaller than for the first period ($\mu_{S1} = 0.38$) we conclude that most of the settlement for this layer took place from March 20 – 27. The point measurements at the upGPR confirm this assumption (Fig. 2). The few parts of the transect where strain for the second period is larger than for the first one, most likely, can be related to errors in the layer picking for the March 27 transect. Constructive and destructive interferences in the radar signal are likely due to a high amount of various signal occurrences above the buried surface signal (see Fig 2). In this case, upward-looking radar has advantages compared to above-surface measurements, as the old surface signal in the upGPR did not get inferred by the stratigraphy above.

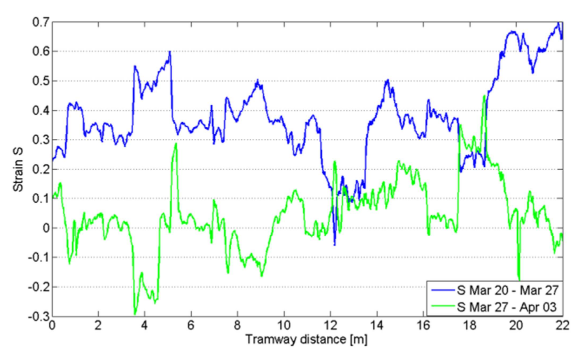

Figure 5: Strain S of the layer above the Mar 13 surface. Blue line represents the strain for the period March 20 – March 27. Green line shows strain for the period March 27 – April 03.

4. CONCLUSIONS

For the first time continuous upGPR observations at a point were successfully combined with weekly spatial measurements from an aerial tramway. The upGPR system shows promising potential for continuous monitoring of snow stratigraphy for the observed test site. Major changes in stratigraphy at this point location were followed along a 22m tramway transect as well. Significant changes in snow-depth patterns were not observed until strong melt occurrences dominated the slope. On the other hand, while accumulation dominates the pattern appears to be very homogenous. In terms of strain, the upGPR location is in a very good agreement to the whole slope. Comparison of TWT and manual depth observations indicate that this sloped site retained very little bulk liquid water, possibly due to lateral movement of water along stratigraphic boundaries.

ACKNOWLEDGMENTS

We would like to thank Andrew Hedrick, Scott Havens, Jake Robertson, and Hank Hetrick for field assistance. This work was funded by NASA grant #NNX10AO02G (NASA New Investigator Program), NASA grant #NNX10AN30A (NASA EPSCoR Program), and NSF grant #0943710 (NSF Hydrologic Sciences Program). A. Heilig is partially funded by DFG grant EI 672/6 as well.

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