COMPARISON OF MEASURED AND MODELED SNOW COVER LIQUID WATER CONTENT TO IMPROVE LOCAL WET-SNOW AVALANCHE PREDICTION

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ABSTRACT: Wet-snow avalanches can be difficult to forecast. However, recent studies have suggested that an index (LWCindex) related to the mean liquid water content of the entire snowpack can be used to predict the onset of periods with high wet-snow avalanche activity. Since this index has not yet been verified, we compared modeled and measured liquid water content to wet-snow avalanche activity for four winter seasons at the Dorfberg test site, above Davos, Switzerland. Using the 1-D snow cover model SNOWPACK, we simulated snow stratigraphy, the mean liquid water content and water infiltration within the snowpack. Simultaneously, we used an upward-looking ground penetrating radar (upGPR) to derive mean liquid water content of the snow cover and monitor changes in percolation depth. Measurement and simulations agreed fairly well and showed that increased wet-snow avalanche activity started when the mean liquid water content of the snowpack reached 0.01 and a significant diurnal increase in liquid water content was observed. In three out of four melt seasons, the first arrival of water at the bottom of the snowpack coincided with the onset of high wet-snow avalanche activity. Overall, these results suggest that the mean liquid water content index can be used to predict wet-snow avalanche activity. The model approach might be particularly helpful for narrowing down the period of temporary avalanche mitigation measures (e.g., preventive closures) since conditions favoring wet-snow avalanches usually persist only for a short period of time. Combined with a numerical weather prediction model, this approach may allow for effective wet-snow avalanche forecasting.

KEYWORDS: wet-snow avalanches, avalanche forecasting, liquid water content

1. INTRODUCTION

Wet-snow avalanches, which mostly release spontaneously, can be destructive and cause considerable damages to infrastructure. When considering natural releases only, they cause around half of the fatalities (Schweizer and Lütschg, 2001). In addition, wet-snow avalanches are difficult to control with traditional preventive mitigation measures and therefore closures remain the only applicable temporary mitigation measure for local authorities. To limit closure times, it is of paramount importance to accurately predict periods of increased wet-snow avalanche activity. While for rain-on-snow events this period is immediately after the onset of rain (Conway and Raymond, 1993), timing of wet-snow instability during on-going melting represents the crux of the matter.

In past years, various research projects aimed to improve our knowledge on measuring (Heilig et al., 2015; Mitterer et al., 2011; Okorn et al., 2014; Schmid et al., 2014) and modeling (Wever et al., 2014; 2015) the amount and movement of water percolating through the snowpack – knowledge which is important to better predict periods with high wet-snow avalanche activity.

Rather than using only air temperature as predictive parameter, Mitterer and Schweizer (2013) used the energy balance to better predict days with high wet-snow avalanche activity. Results showed that enhanced predictions rely on correct simulations of both the energy input and the cold content of the snowpack. Consequently, these advances led to more physically based approaches in determining periods with high wet-snow avalanche activity on national and regional scales. Mitterer and Schweizer (2014) and Wever et al. (2016) used both the 1-D snow cover model SNOWPACK to calculate indices based on energy

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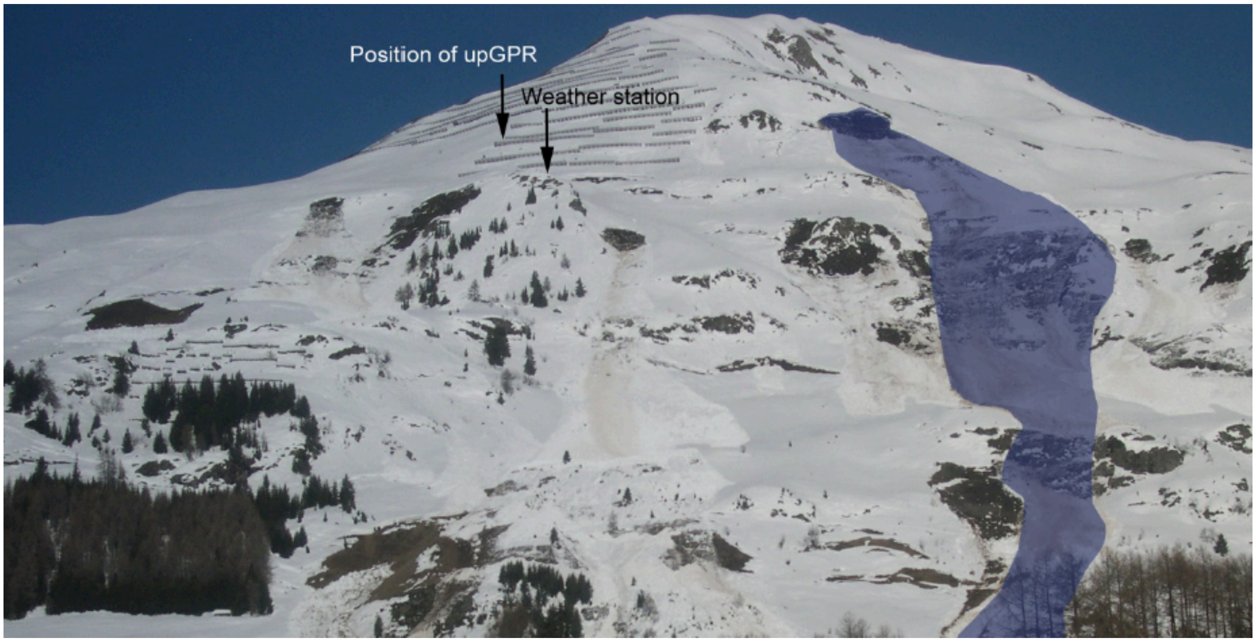

Fig. 1: Study site at Dorfberg above Davos, Switzerland. upGPR and automatic weather station are located on top of the observed avalanche slope. Photo taken on 3 March 2012, blue polygon marks largest avalanche during that avalanche cycle (same Photo as in Schmid et al. (2012)).

and mass balance (Mitterer et al., 2013) or the concentration of liquid water content within the snowpack. The performance of both indices was better than statistically based models including meteorological parameters (Peitzsch et al., 2012) or air temperature only. While simple approaches often correctly predicted avalanche days, they suffered from high false-alarm rates. More complex approaches tended to have a slightly lower probability of detection, higher probability for detecting non-events and a lower false-alarm rate.

Nevertheless, both modeling approaches by Mitterer et al. (2013) and Wever et al. (2016) have not yet been verified with measurements and/or avalanche observations at the path-scale.

Schmid et al. (2014) and Heilig et al. (2015) demonstrated the potential of upward-looking ground-penetrating radar (upGPR) in tracking wetting front advances, determining concentration of water within the snowpack and calculating bulk liquid water contents. We therefore combined the upGPR measurements and the indices simulated with SNOWPACK and compare both to highly resolved wet-snow avalanche activity data for the Dorfberg avalanche path above Davos, Switzerland.

2. DATA AND METHODS

2.1 Study site

Upward-looking ground penetrating radar (upGPR) measurements were performed at the study site Dorfberg above Davos (Switzerland) at an elevation of 2230 m a.s.l (Fig. 1). The location of the upGPR is next to a well-known wet-snow avalanche path on a gently inclined (22°), southeast-facing slope. As of the season 2012-2013, we mounted two ultrasonic range gauges on a wooden cross beam directly above the upGPR. An automatic weather station (AWS) 90 vertical meters below the position of the radar provides information on several weather and snowpack properties. The station records all necessary input parameters to drive the 1-D snow cover model SNOWPACK (e.g. Wever et al., 2015).

2.2 Wet-snow avalanche activity

Avalanche activity was monitored from the valley bottom with time-lapse photography (van Herwijnen et al., 2013) for the winter seasons 2011-2012 to 2014-2015. Photos were taken every 15 minutes as long as daylight permitted visibility. All avalanches within our data set released during good visibility. The photos were then loaded into a geographical information system (GIS). We used the GIS *Monoplotting* software (Bozzini et al., 2011) to transform the oblique photos (Fig. 1) of avalanche releases into georeferenced polygons. With this procedure, we obtained the area and the length of the avalanche and the slope angle at the fracture line. We used the area of the polygons (avalanched area) to describe avalanche activity (Stoffel et al., 1998). During the winter season 2013-2014 no wet-snow avalanches were observed at the Dorfberg field site.

2.3 upGPR measurements and calculations of liquid water content

Fig. 2 shows a sketch of the setup of the upward-looking ground-penetrating radar (upGPR) at the Dorfberg slope site. During the four winter seasons 2011-2012 to 2014-2015 we recorded radar data of the snowpack at a 30 minutes interval during the day. For the winter season 2011-2012 the 30 minutes interval was set from 09:30 to 18:30 hours with no measurements during the night. From winter 2012-2013 on, the radar conducted measurements every three hours during night (21:00 to 08:30 hours) and switched back to 30 minutes intervals during the day.

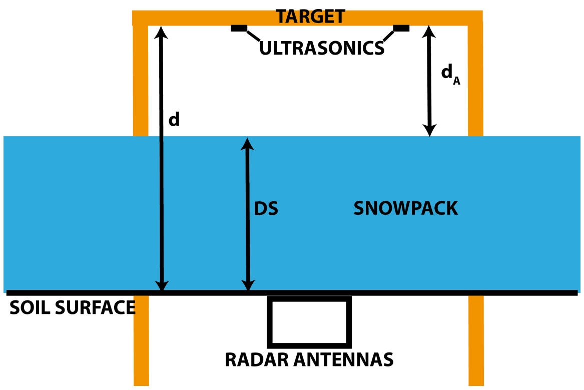

Fig. 2: Sketch showing the setup for the upGPR measurements at the Dorfberg site. The wooden construction holding the ultrasonic sensors is displayed in orange.

We processed the radar data as described in Schmid et al. (2014) using a semi-automated picking algorithm to determine the two-way travel time ($\tau_{\text{snow surface}}$) of the snow surface reflection. Since the cross beam holding the ultrasonic sensors above the radar antennas constantly showed a clear reflection signal, we picked the position of this signal as well and calculated the $\tau_{\text{cross beam}}$ to the cross beam (Fig. 2). Although we had snow thickness (DS) information recorded with two ultrasonic sensors directly above the radar, we decided to derive snow thickness values above the radar from the radar signal itself, as the signal from the ultrasonic sensors was very noisy and prone to errors. To determine DS, we used the known height of the cross beam above the radar antennas (d) and the fact that the relative dielectric permittivity of air is constant with $\varepsilon_a = 1$ (Heilig et al., 2015). Combined with the picked $\tau_{\text{snow surface}}$ of the snow surface and $\tau_{\text{cross beam}}$ of the cross beam we can calculate DS using $DS = d - d_A$ where $d_A = \frac{1}{2} c_0 (\tau_{\text{cross beam}} - \tau_{\text{snow surface}})$ with c_0 the speed of light in vacuum. The cross beam was mounted in autumn 2012 and therefore we have no available data on measured snow thickness (DS) above the radar antennas for the winter season 2011-2012 and consequently no radar measurements of the bulk volumetric liquid water content (see below).

To derive the bulk volumetric liquid water content ($\theta_{\text{v,b}}$) we used the approaches presented in detail by Schmid et al. (2014) and Heilig et al. (2015): The speed of electromagnetic waves in a wet snowpack is slower compared to a dry snowpack. We calculated the amount of water within the snowpack from the change in speed of the electromagnetic wave in wet snow using $\tau_{\text{snow surface}}$ and DS compared to the speed in dry snow (Mitterer et al., 2011).

2.4 Simulated bulk liquid water content and wet-snow instability indices

We used the 1-D physics-based snow cover model SNOWPACK to obtain the $\theta_{\text{v,b}}$ and thereof the $\text{LWC}_{\text{index}}$ (Mitterer et al., 2013) and the Max_{LWC} (Wever et al., 2016). To run the model, we used air temperature, relative humidity, incoming shortwave and longwave radiation, wind direction, wind speed, and snow height. Except for winter season 2011-2012, snow height was not recorded at the AWS, but directly above the location of the upGPR (Fig. 1). In order to compare the simulations with the location of the radar, we adjusted the simulations to a 22° steep southeast-facing slope by taking into account changes in incoming solar radiation. Within SNOWPACK we used two different schemes for modeling the water transport. The first scheme is based on a simple bucket approach, depending on simulated snow density; the second scheme solves Richards' Equation for water flow in porous media (Wever et al., 2014) and allows to mimic more complex flow behaviors (e.g. capillary barriers).

3. RESULTS AND DISCUSSION

3.1 Comparison of measured and modeled bulk volumetric liquid water content

Fig. 3 shows the comparison of measured and modeled bulk volumetric liquid water content for three winter seasons 2012-2013 to 2014-2015. For both water transport schemes, simulations and measurement agreed fairly well; the agreement was particularly good for values of $\theta_{v,b} < 0.02$. For higher values of liquid water content, measured $\theta_{v,b}$ was higher than modeled one – independent of the water transport scheme used in the model.

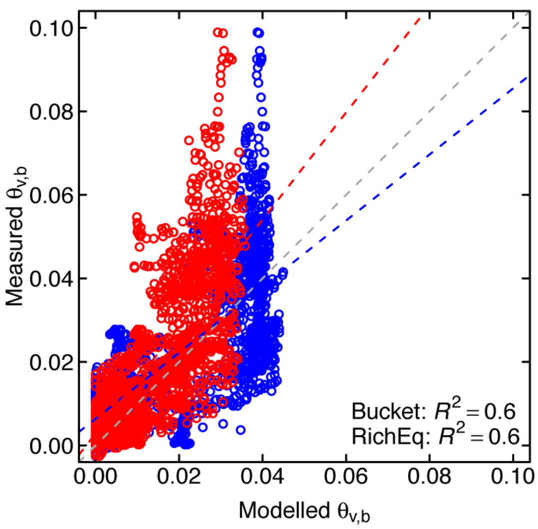

Fig. 3: Hourly values of measured vs. modeled bulk volumetric liquid water content for the three winter seasons 2012-2013 to 2014-2015. Blue circles represent values obtained with SNOWPACK run in bucket mode, while red circles refer to values obtained with the Richards' Equation mode. Grey dashed line represents 1:1 line, blue (bucket) and red (RichEq) dashed line show linear regression models.

Fig. 4b shows the measured and modeled evolution of $\theta_{v,b}$ for the winter season 2014-2015. The radar started to record an increase in $\theta_{v,b}$ on 8 March 2015, with a sharp rise on 18 March 2015 exceeding a value of 0.01, followed by a steady increase until the end of March 2015. Until the beginning of April, $\theta_{v,b}$ obtained with both water transport schemes of SNOWPACK qualitatively agrees with the pattern of measured $\theta_{v,b}$ (Fig. 4b). Differences between measurement and simulations arise after 10 April 2015: While both simulation schemes show a strong increase in $\theta_{v,b}$ (>0.03), the values derived from the radar increase more steadily reaching 0.03 on 12 April 2015. After this sharp rise, the snow cover became ripe, i.e. snow stratigraphy was characterised mostly by melt forms. In addition, both simulations and measurement indicate diurnal cycles, however, with varying absolute values.

During the winter season 2014-2015, radar-derived values of $\theta_{v,b}$ were in general higher than modeled values (Fig. 4b). These absolute differences are mostly driven by the residual amount of water. For the two water transport schemes these varying values are based on the parameterisations used within the schemes. While the bucket approach uses a density-driven parameterisation for the residual water content and generally allows residual liquid water contents around 0.04, the Richards' Equation approach allows for a more pronounced drainage and lower values of residual water content (Fig. 3). The radar-derived values behave more similar to the Bucket mode and do not show such a pronounced drainage as the Richards' Equation mode (Fig. 4b). When considering diurnal changes in $\theta_{v,b}$ only (not shown), differences are less pronounced; in other words modeled and measured changes in $\theta_{v,b}$ are in good agreement which is important for wet-snow instability, since large changes in $\theta_{v,b}$ will weaken the snowpack.

3.2 Wet-snow instability indices and avalanche activity

During winter 2014-2015, wet-snow avalanche activity started on 18 March 2015 and peaked the next day. Two subsequent periods of high activity occurred at the end of March and in mid April (Fig. 4a). The first days with avalanche activity (18-19 March; 23 March; 31 March) coincided well with days when the radar and SNOWPACK in both water transport modes measured and modeled $\theta_{v,b} > 0.01$. During the last period (mid April), avalanche activity agreed very well with a radar-derived value of $\theta_{v,b} \geq 0.03$. SNOWPACK in both modes modeled the increase towards values of $\theta_{v,b} \geq 0.03$ three days too early (9 April 2015).

This pattern of coincidence for the thresholds of $\theta_{v,b} \geq 0.01$ and $\theta_{v,b} \geq 0.03$ was also found for the winter seasons 2011-2012 (Tbl. 1). In both winter seasons the Dorfberg avalanche path experienced at least two major avalanche cycles. In 2012-2013, only one major period of high avalanche activity took place, when $\theta_{v,b}$ reached 0.01. However, both, radar and model simulated the increase towards this value slightly too late (Tbl. 1).

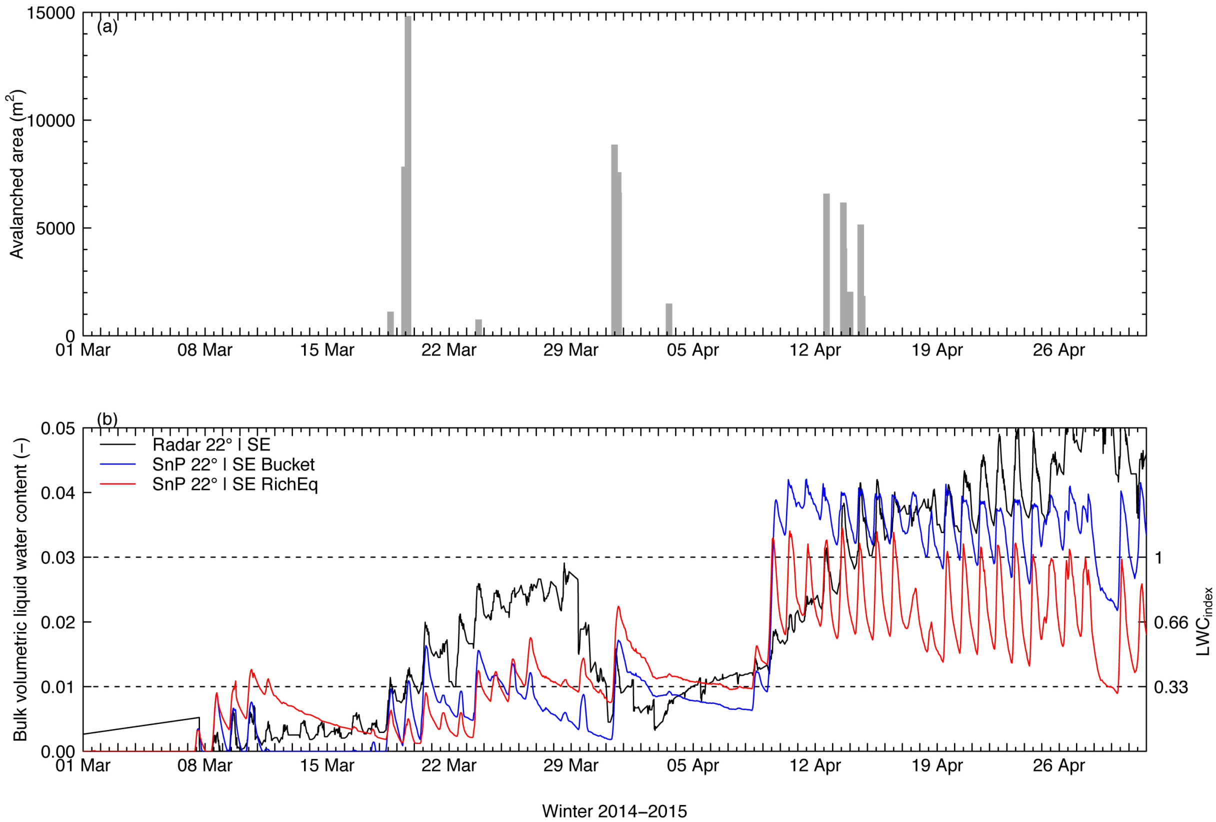

Fig. 4: (a) Avalanche activity and (b) bulk volumetric liquid water content derived from the radar signal (black) and modeled with SNOWPACK (SnP) using the bucket water transport mode (blue) and the Richards' Equation mode (red) for the location of the radar at the Dorfberg test site. Dashed lines show threshold values for the LWC_{index} (right y-axis).

Accordingly, applying the threshold values for the LWC_{index}, i.e. $\theta_{v,b} \geq 0.03$, suggested by Mitterer et al. (2013) would lead to a large number of misses and a low probability of detecting wet-snow avalanche days on Dorfberg (Fig. 4). In fact, the two-stepped threshold pattern differs from the outcomes in Mitterer et al. (2013) and Mitterer and Schweizer (2014), where a $LWC_{index} \geq 1$ (equivalent to $\theta_{v,b} \geq 0.03$) or a distinct increase of the index towards 1 indicated the beginning of wet-snow avalanche activity with good predictive performance. In the data set used for this study, predicting wet-snow avalanche days for the winter season 2014-2015 with a $LWC_{index} \geq 1$ fails in terms of probability of detection (POD). POD improves for both measurement and model, when using a $LWC_{index} \geq 0.33$ (equivalent to $\theta_{v,b} \geq 0.01$). Still, the well-known problem of high false-alarm rates, deteriorate the overall skill. Overall, the best performance showed the Max_{LWC} approach proposed by Wever et al. (2016) used with bucket mode (not shown here).

The reason for the observed two-stepped threshold pattern of LWC_{index} might be associated with the dominating water flow regime shortly before wet-snow avalanche activity starts. In other words, when the LWC_{index} reached values of 0.33, preferential flow paths might have dominated the water flow; while on days where avalanche activity agreed with a $LWC_{index} \geq 1$, matrix flow fully wetted the entire snowpack. The observed and modeled time when the snowpack was fully wetted for the first time underlines this assumption (Tbl. 1). This implies that knowing only the amount of water is not enough for predicting wet-snow avalanches at the avalanche-path scale. We need to know the evolution of snow stratigraphy to evaluate whether preferential or matrix flow will produce wet-snow instabilities. Based on that knowledge, the threshold for the LWC_{index} can be adjusted.

Furthermore, the differences compared to the studies by Mitterer et al. (2013) and Mitterer and Schweizer (2014) might be due to scale issues. The latter analyzed the connection of wet-snow avalanche days and LWC_{index} on a national and

Tbl. 1: Overview on timing for avalanche activity, measured and modeled thresholds of $\theta_{v,b}$ during the four winter season 2011-2012 until 2014-2015. Agreement of $\theta_{v,b}$ values of radar and models with wet-snow avalanche activity is marked in bold.

Winter	*Onset avalanches*	*$\theta_{v,b\text{ - Radar}}$*		*$\theta_{v,b\text{-SnP}}$ ≥1*		*$\theta_{v,b\text{-SnP}}$ ≥3*		*Snowpack wet SNOWPACK*	
		≥1	≥3	Bucket	RichEq	Bucket	RichEq	Bucket	RichEq
2011-2012	First cycle: **24 Feb** Second cycle: **29 Feb**	No radar measurements		**24 Feb**	**24 Feb**	**29 Feb**	**29 Feb**	01 Mar	29 Feb
2012-2013	01 Mar	08 Mar	15Apr	09 Mar	09 Mar	15 Apr	15 Apr	25 Dec	25 Dec
2013-2014	No avalanches	10 Mar	14 Mar	09 Mar	09 Mar	12 Mar	12 Mar	13 Mar	13 Mar
2014-2015	First cycle: **18 Mar** Second cycle: **12 Apr**	**18 Mar**	**12 Apr**	**18 Mar**	08 Mar	09 Apr	09 Apr	10 Apr	10 Apr

regional scale using a large dataset of avalanche observations and averaged values of LWC_{index}. The good agreement of $LWC_{index} \geq 1$ with avalanche activity in their studies suggests that knowing the energy input and amount of water within the snowpack is sufficient to detect wet-snow avalanche activity at regional scale. At this scale, differences between periods with either dominating preferential flow or matrix flow regime might cancel out by combining several model results at various elevation bands (Mitterer et al., 2013).

4. CONCLUSIONS

We used high-quality avalanche observations to evaluate the performance of the LWC_{index} to predict wet-snow avalanches. For this purpose, we compared modeled and measured liquid water content, the basic ingredient of the LWC_{index}, to wet-snow avalanche activity for four winter seasons at the Dorfberg test site, above Davos, Switzerland. We used upward-looking ground penetrating radar (upGPR) to derive volumetric bulk liquid water content ($\theta_{v,b}$) and concurrently modeled $\theta_{v,b}$ with SNOWPACK using two different water transport schemes. The temporal evolution of measured and modeled $\theta_{v,b}$ was qualitatively in good agreement. While absolute values may differ significantly, diurnal changes in $\theta_{v,b}$ agreed fairly well. Based on measured and modeled $\theta_{v,b}$ we found a distinct pattern for explaining days with wet-snow avalanche activity. When there were two wet-snow avalanche cycles in one winter season, the onset of avalanche activity for the first cycle coincided with a $LWC_{index} \geq 0.33$ and for the second cycle with a $LWC_{index} \geq 1$. We observed this pattern for both, measured and modeled LWC_{index}, which confirms the validity of the modeled index.

We hypothesize that the different threshold values of LWC_{index} correspond to different prevailing water flow regimes. For values around 0.33 preferential flow paths may dominate the water routing to the snow-soil interface. As soon as the LWC_{index} reaches one, it is more probable that matrix flow governs the routing system. Consequently, the threshold for LWC_{index} depends on the flow regime, which in terms depends on snow stratigraphy.

From this analysis at the avalanche path scale we can conclude that knowing both the evolution of the snowpack and the amount of water are particularly important for pinpointing the period of temporary avalanche mitigation measures (e.g., preventive closures). Combined with a numerical weather prediction model (Bellaire et al., 2016; Gobiet et al., 2016), this approach may allow for effective wet-snow avalanche forecasting.

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