OPERATIONAL FORECASTING OF WET SNOW AVALANCHE ACTIVITY: A CASE STUDY FOR THE EASTERN EUROPEAN ALPS

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ABSTRACT: The prognostic operation of detailed snowpack models has recently been objective of extensive research, since many avalanche services start to move from the assessment of the current avalanche danger to forecasts. In this study a new, observationally constrained setup for forecasting the onset of wet-snow avalanche cycles with the detailed snow cover model SNOWPACK is presented and evaluated. Based on data from weather stations and different numerical weather prediction models we demonstrate, that forecasts of the LWC_{index} as indicator for wet-snow avalanche cycles can be useful for operational warning services in some cases, but are so far not reliable enough to be used as single warning tool without considering other factors. In addition, this study indicates some potential for improvement by applying suitable post processing techniques to the output of numerical weather prediction models. Based on the results of this study LWC_{index} predictions will be used operationally by two regional avalanche warning services in Austria starting with the season 2016-2017.

KEYWORDS: forecast, wet-snow avalanches, LWC_{index}, SNOWPACK

1. INTRODUCTION

Many avalanche warning services currently aim to make a transition from assessments of current avalanche danger to forecasts of avalanche danger. The quality of such forecasts heavily relies on information about the future evolution of snowpack stability. For this reason the prognostic operation of detailed snowpack models has recently been objective of extensive research. e.g., in the studies of Bellaire et al. (2011,,2013) simulations with SNOWPACK (Lehning et al., 2002a,b; Lehning and Fierz, 2008; Wever et al., 2015) with meteorological boundary conditions from the 15 km resolution numerical weather prediction (NWP) model GEM15 have been performed for a region in Canada. Their results suggest that such a model chain is beneficial for forecasting new snow amounts, particularly in data sparse regions, but highly depending on bias-correction of the NWP output.

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Also for regions in Canada, Horton et al. (2015) demonstrated the benefits of forcing SNOWPACK with the 2.5 km resolution regional NWP model GEM-LAM for explaining the snowpack stability in case of a buried surface hoar layer.

In Europe, coupling NWP and snow cover models has the longest tradition in France. Within the French model-chain SAFRAN-CROCUS-MEPRA (Brun et al., 1992; Brun et al., 1989; Durand et al., 1999), the meteorological analysis and forecasting system SAFRAN provides meteorological input for the snow cover model CROCUS. CROCUS output is then passed to MEPRA for various snowpack stability calculations. The French model chain simulates snow cover for so-called massifs, covering about 500 km^2 represented on virtual pyramids, i.e. 300 m elevation bands on 8 aspects each. More recently, Quéno et al. (2016) and Vionnet et al. (2016) compared the traditional model chain to the kilometer-scale NWP model AROME (grid spacing: 2.5 km) forcing CROCUS for the French Pyrenees and Alps. Results show that the AROME-CROCUS chain overestimated snow depth due to a strong underestimation of ablation processes (wind and melting), but yielded better spatial distribution of snow cover than SAFRAN–CROCUS.

The aim of this study is to present a new, observationally constrained setup for forecasting snow properties with the detailed snow cover model SNOWPACK (section 2). In particular, we will analyze strengths and weaknesses of currently available operational weather forecasts to deliver meteorological boundary conditions for such forecasts (section 3). The relevance of such snow cover forecasts for operational avalanche services is exemplified by analyzing the forecasted liquid water content index (LWC_{index}), which proved to be a useful indicator for the onset of wet snow avalanche cycles (Mitterer et al., 2013).

2. METHODS

2.1 Retrospective Simulation

Most approaches to generate snow cover forecasts used either only a NWP model or a meteorological analysis in combination with a NWP model to force the snow model. This has the advantage to yield distributed information on a grid, but on the other hand accumulates errors in the modeled snow cover over the entire season.

We therefore propose a weather station based approach, where the snow model in retrospective mode is forced with measured meteorological and snow cover data like air temperature (T_a), relative humidity (RH), wind speed (WS) and direction (WD), incoming solar radiation (ISR), if available incoming longwave radiation (ILR), snow surface temperature (T_{ss}), and snow height (HS). The measured HS is thereby used to drive simulated snow accumulation and ablation, which strongly reduces the long-term accumulation of errors and ensures an adequate initialization of the forecast. As snow model we used version 3.3 of the detailed, physically-based 1-D snow cover model SNOWPACK in operational mode. From the SNOWPACK output, the LWC_{index} was calculated. In the remainder of this paper, the LWC_{index} simulated by the observation-driven SNOWPACK model is called "retrospective LWC_{index}", since it can only be calculated after the meteorological observations are available.

Tbl. 1: Overview of the characteristics of the NWP models used in this study.

Acronym	*NWP Model Description*	*Model Operator*	*Forecast Mode and Post Processing*	*Used parameters*
ALARO	Spectral limited area model ALARO, a further development of ALADIN (Aire Limitée Adaptation dynamique Développement InterNational) for grid spacings below 5km (Gerard et al. 2009). Operated on a 4.8 km grid over Central Europe.	Zentralanstalt fuer Meteorologie und Geodynamik – ZAMG (Austrian Institute for Meteorology and Geodynamics; www.zamg.ac.at)	Operational 72h forecasts, started every 6 hours at 00, 06, 12, and 18 UTC (only the 12 UTC runs are used in this study). Refinement of direct shortwave global radiation, based on high resolution elevation model and bias correction; improved calculation of diffuse shortwave radiation; no bias adjustment of 2 m temperature (and longwave radiation).	T_a, PR, RH, WS, ISR, ILR
COSMO-1	Consortium for small-scale modeling (COSMO) model (Doms and Schaettler, 2002) operated on a 1.1 km grid over the European Alpine Region.	Swiss Federal Office of Meteorology and Climatology – MeteoSwiss (www.meteoswiss.admin.ch)	Operational forecasts, started at 00 and 12 UTC. Only the first 24 hours of each 12 UTC run are used in this study. No post processing.	T_a, PR, RH, WS, ISR, ILR
NEMS4	NOAA Environmental Modeling System (NEMS) operated on a 3 km grid over Europe.	meteoblue (private weather service, Austria; www.meteoblue.com)	Operational 72h forecasts, started at 00 UTC. Only the forecasts 12h to 36h forecasts are used in this study. No post processing by the operator. Additional altitude adjustment of 2 m temperature using constant gradient (0.65 K per 100 m).	T_a, PR, RH, WS, ISR

2.2 Forecast

Starting from the observationally constraint snowpack initialization of the retrospective simulation, up to 72 hour forecasts are generated based on output from three different NWP models. The raw NWP model output is partly post-processed by the provider, but not specifically downscaled to the locations of this study. Only data "from the shelf" of different weather services are used, in order to analyze the performance of snow cover forecasts based on operationally available meteorological forecasts. Tuning and optimization of these NPW input data for detailed snow modeling will be issue of future investigations, based on the results of this study. In Tbl. 1, the three NWP models used are listed together with additional information. In forecast mode, SNOWPACK is forced with simulated T_a, RH, WS, ISR, and precipitation (PR). Some models (ALARO and COSMO-1) additionally provided ILR. The LWC_{index} simulated by the NWP-driven SNOWPACK model is called "prognostic LWC_{index}", since real forecasts can be generated in this setup.

A basic difference between the forecasts from the three different NWP models is that only ALARO actually provides real 72h forecasts. From COSMO-1 only 24h forecasts were available at the time of this study and have been "glued together" to achieve surrogate 48h forecasts. In case of NEMS4, the hours 12 to 36 from forecasts started at 00 UTC have been used, and glued together to give surrogate 72h forecasts, rather similar to COSMO-1. However, all three NWP simulations are entirely independent from the station data used for evaluation in this study.

2.3 Forecast cycle

Fig. 1 a) illustrates the forecast cycle for this evaluation study with daily updates at 12 UTC. In a real-time operational context, this cycle will be slightly modified, since NWP forecasts are not available immediately after their initialization, but with at least 3 hours delay. In addition, many weather services provide up to 4 forecasts per day. Such real-time forecast-cycle will be put into operation by two regional avalanche warning services in Austria starting with the season 2016-2017 (Fig. 1 b).

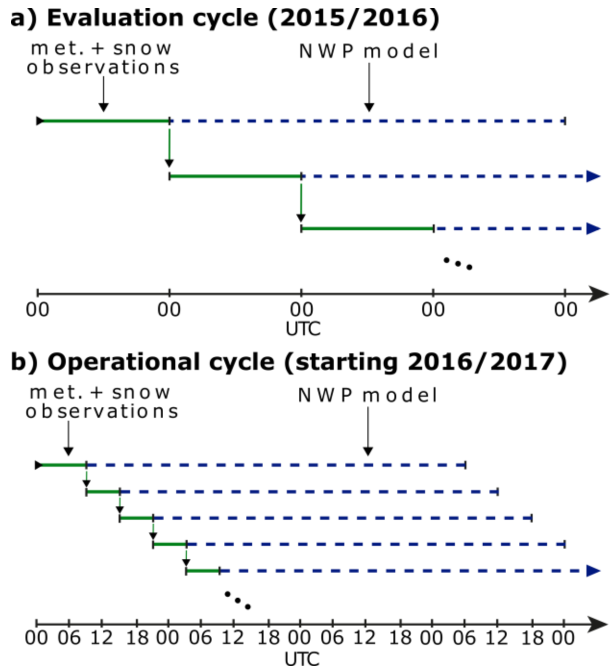

Fig. 1: SNOWPACK forecast cycle for the current evaluation study (a) and for real-time operation (b). Solid lines indicate retrospective SNOWPACK simulations driven by observed meteorological boundary conditions and observed HS and T_{ss}. Dashed lines indicates prognostic SNOWPACK simulations driven by meteorological boundary conditions from a NWP model.

2.4 LWC_{index}

The LWC_{index} was calculated according to Mitterer et al. (2013). The LWC_{index} is based on the bulk volumetric liquid water content of the entire snowpack. The index is normalized by 3% by volume of bulk volumetric liquid water content. With other words, as soon as the LWC_{index} exceeds 1, the entire snowpack has potentially a liquid water content of 3% by volume and gravitational water flow is dominating the flow regime. Observations have shown that this coincides very well with the onset of wet-snow avalanche activity.

2.5 Study regions and periods

Forecasts are generated for the location of three different automatic weather stations in the Eastern European Alps, one being located below the tree line on a plateau of the Hochschwab Massive (SONN, 1523 m a.s.l., 47.587 deg. N, 15.040 deg. E), the second around treeline in the vicinity of the south-facing slopes of the Nordkette near Innsbruck (SEEG, 1921 m a.s.l., 47.306 deg. N, 11.378 deg. E), and the third being a high alpine station (ZUGS, 2960 m a.s.l., 47.406 deg. N, 10.984 deg. E). So far, only the results of stations SONN and SEEG have been evaluated and are presented in this manuscript.

For the evaluation of NWP models, we use station data from the winter season 2015-2016. A brief overview of the quality of the NWP model at the point of the respective station is given by a seasonal statistic (section 3.1). For a more detailed evaluation of the simulated LWC_{index} we selected two periods with pronounced wet-snow avalanche cycles, one being induced by melting in spring (section 3.2), the other being triggered by heavy rain in mid-winter (section 3.3).

3. RESULTS AND DISCUSSION

3.1 *Overview of the NWP performance over the winter season*

Fig. 2 shows a brief overview of the seasonal mean bias and standard error of the ALARO forecasts of T_a and ILR for different lead times (up to 72 hours in steps of 6 hours) with respect to station SONN. We regard these two parameters as the most relevant ones, but other parameters like RH and WS have been evaluated as well (not show). This evaluation demonstrates a rather small positive temperature bias of about 0.5 K, which is not increasing with lead time and an standard error of about ± 2 K, slightly increasing with lead time. This seasonal average temperature error statistics are rather satisfying. However, as will be demonstrated in sections 3.2 and 3.3, this doesn't safeguard from issues with temperature in single cases. The most prominent bias found in this seasonal evaluation is a positive ILR bias of about +35 W/m², which is rather worrying with regard to the energy budget over the entire season. Such systematic bias is a clear candidate to be mitigated with empirical-statistical post-processing techniques in future. However, the subsequent evaluation of two single cases with wet-snow avalanche cycles shows now indication that this bias played there.

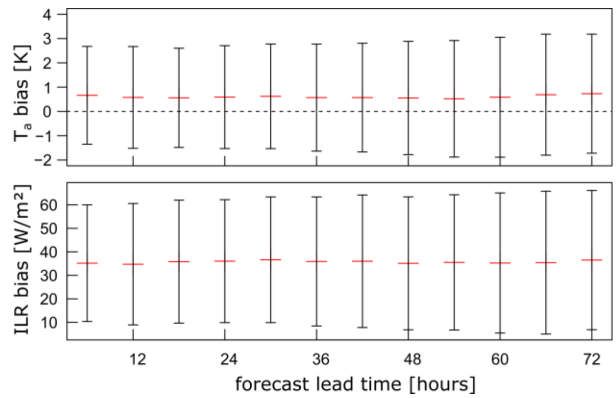

Fig. 2: Error statistics of T_a (upper panel) and ILR (lower panel) for the season 2015-2016. Red lines indicate the seasonal mean bias at different forecast lead times, the black whiskers indicate the respective standard error.

3.2 *Melt event*

A typical spring wet-snow avalanche cycle took place between March 27 and March 28, 2016 in the region around station SEEG (1921 m) on the south-facing slopes of the Nordkette near Innsbruck. On the front of a low-pressure system over the British islands westerly and south-westerly flow brought mild air masses into the eastern alpine region. After an overcast night without substantial cooling of the snow surface, a warm and sunny day led to enough melting to increase the liquid water content above critical levels on the afternoon of March 27. Wet-snow avalanches were observed in the vicinity of the station form March 27 noon until late afternoon. On March 28 avalanche activity faded out.

Fig. 3 shows the LWC_{index} from the retrospective SNOWPACK simulation for a south-facing slope with a slope angle of 38 degrees (black line). In addition the different forecasts are depicted by colored lines. The retrospective LWC_{index} rose to 0.7 on March 26 and subsequently clearly above 1 on March 27, when the avalanche cycle peaked. For this example it proved to be a good indicator for the wet-snow avalanche cycle.

The forecasts for this avalanche cycle (Fig. 3) nicely exemplify to what degree state-of-the-art NWP models are able to represent the meteorological conditions at mountain sites. While one model (ALARO, top row of Fig. 3) shows a slight increase of the predicted LWC_{index} on March 27, it clearly misses to predict onset of the avalanche cycle (LWC_{index} > 1). Another model (COSMO-1, middle row of Fig. 3) shows a stronger increase

(LWC_{index} rises close to 0.8), but this still might be a doubtful signal for an avalanche forecaster and can only be successfully interpreted with plenty of experience and real-time information about the current quality of the NWP model with respect to observations. The third model (NEMS4, bottom row of Fig. 3) delivers a very good match with the retrospective LWC_{index}, and perfectly predicts the avalanche cycle 24 hours before it started (LWC_{index} rises from 0.5 to 1.3 during March 27). Such prediction can be expected to be very helpful for avalanche forecasters.

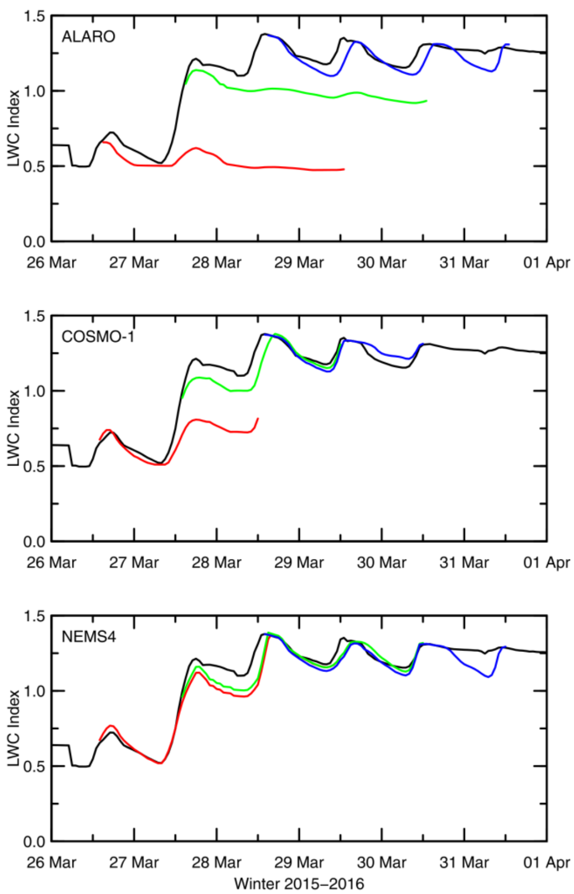

Fig. 3: LWC_{index} from the SNOWPACK simulation driven by observations (black) and NWP model output (ALARO, COSMO-1, NEMS4; different forecasts colored).

Fig. 4 shows the observed and predicted air temperatures for the same period and gives some explanation for the success or failure of the different predictions. ALARO starts off very close to the observation on March 26 at noon, but subsequently models a very cold night due to clear skies in the model, while the actual conditions were cloudy. This results in very low ILR and consequently a large cold temperature bias of more than -5°C, from which the model only slowly recovers during the following day (March 27, onset of avalanche cycle). As a consequence, only minor melting occurred on that day and the predicted LWC_{index} only marginally increased. Contrary, COSMO-1 correctly simulates an overcast night, but remains cloudy on March 27 during the day. As a result, the predicted LWC_{index} corresponds to the retrospective one during the night, but fails to sufficiently rise on March 27 in the afternoon, due to insufficient energy input.

This kind of model error, i.e. not having the clouds exactly on the right place at exactly the right time, is something that has to be expected in any NWP model from time to time and it will be very hard to correct such model errors by post-processing methods.

The third model (NEMS4) happens to catch both the cloudy night and the clear day and consequently predicts the LWC_{index} very well.

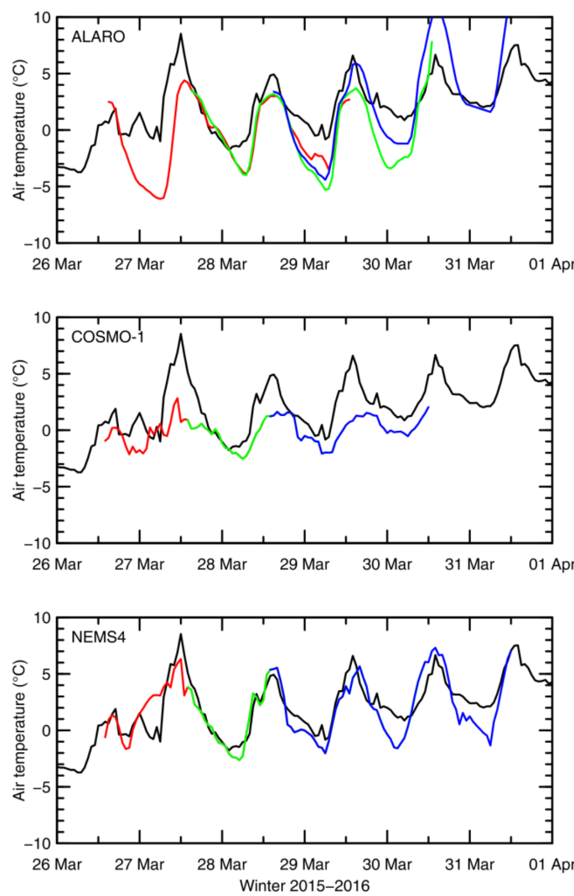

Fig. 4: Observed (black) and modeled (ALARO, COSMO-1, NEMS4; colored) air temperature at station SEEG.

In summary, this example shows that NWP models combined with SNOWPACK have the potential to improve the prediction of the onset of wet-snow avalanche cycles, but that they cannot be expected to provide perfect forecasts in any case (just as NWP models themselves).

3.3 Rain-on-snow event

A typical rain-on-snow event took place on January 24, 2016 in large parts of Austria, including in the region surrounding station SONN (1523 m) in the Hochschwab Massive. After a cold and mainly sunny period, westerly flow brought mild and moist air masses into the study region. From early morning until early afternoon of January 25 a warm front brought about 40 mm precipitation at temperatures rising from +1°C at the beginning of the event to +5°C at the end. Since most of this precipitation fell as rain at elevations around and below 1500 m, the liquid water content of the snow cover rose above critical levels and numerous wet loose-snow avalanches were recorded on the surrounding slopes and valleys with starting zones ranging from 800 m to 1700 m in elevation.

The retrospective SNOWPACK simulation successfully indicated the onset of this avalanche cycle by rising LWC_{index} values from 0 to slightly above 1 around noon. However, all predicted LWC_{index} values failed to indicate this avalanche cycle (Fig. 5).

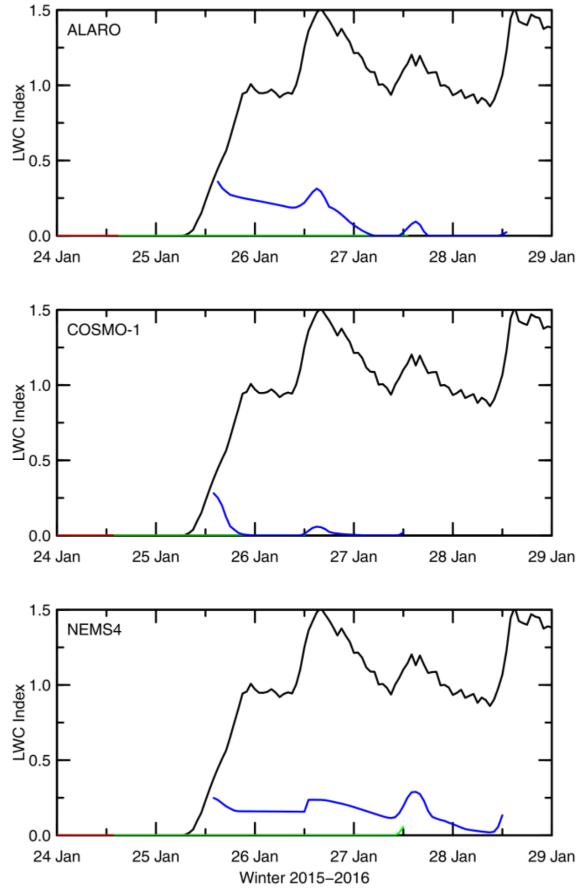

Fig. 5: LWC_{index} from the retrospective (black) and prognostic SNOWPACK simulations (ALARO, COSMO-1, NEMS4; colored).

The reason for this miss was a consistent and large cold bias in all three NWP models, resulting in temperatures below or close to 0°C during the entire precipitation event (Fig. 6). Consequently, the predicted precipitation was interpreted as snowfall by SNOWPACK and the predicted LWC_{index} did not respond at all. Stunningly, the cold bias was not only consistently simulated by all three independent NWP models at SONN, but also about 300 km westward at station SEEG.

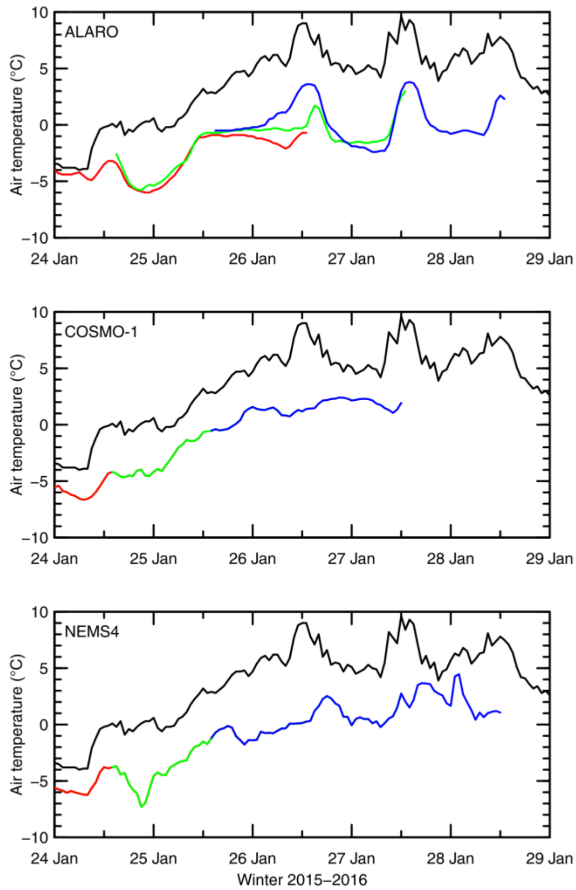

Fig. 6: Observed (black) and modeled (ALARO, COSMO-1, NEMS4; colored) air temperature at station SEEG.

A more detailed analysis of the ALARO predictions (not shown) revealed that during the warm front a strong temperature inversion was simulated near the surface, resulting in cold temperatures close to the model orography. The temperature in the simulated free atmosphere at similar altitudes as station SONN was much warmer and corresponded nicely to the observed temperature at the station. This indicates a common issue of the three NWP models of the study (and probably of most other NWP models as well) with predicting the meteorological conditions at high elevation sites in winter situations with inflow of warm air masses. While the models assume a strong influence of the earth surface, the situation at many high elevation stations corresponds more to conditions in the free atmosphere. Such situations may be accessible to automatic detection and could be corrected by considering model output for the free atmosphere instead of the parameterized surface values. In this case the success-rate of LWC_{index} predictions can probably be increased by suitable post-processing methods.

4. CONCLUSIONS AND OUTLOOK

This study is still work in progress and the results have to be regarded as preliminary. However, they already indicate two major points:

First, forecasts of the LWC_{index} based on NWP "from the shelf" can already be useful for operational avalanche forecast in some situations. However, they are clearly not reliable enough to use them as single warning tool without considering other factors, since model errors can easily prevent the detection of wet-snow avalanche cycle onset by LWC_{index} forecasts. In other words, these forecasts are far away from being able to replace the judgement of an experienced avalanche forecaster. However, they can assist his expert judgement, in particular if the forecaster has some experience with the interpretation of a NWP model and access to real-time monitoring of its quality with respect to observations of the site under consideration.

Second, this study indicates some potential to improve the reliability of LWC_{index} predictions by suitable post processing of NPW output. Based on the results of this study and on further experiences gained in the season 2016-2017, when the LWC_{index} predictions will be used operationally the first time, such improvements are planned.

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