REGIONAL FORECASTING OF WET SNOW AVALANCHE CYCLES: AN ESSENTIAL TOOL FOR AVALANCHE WARNING SERVICES?

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ABSTRACT: Wet-snow avalanches are relatively poorly understood and difficult to forecast. By definition, liquid water is required in the snow cover, thus predicting the liquid water content of the snow cover is of paramount importance for wet-snow avalanche forecasting. While assessing wet-snow instability through field measurements is difficult, physically based snow cover models, such as SNOWPACK, can be used to estimate the amount of liquid water within the snow cover using meteorological input. Indeed, an index based on the liquid water content of the snow cover was recently suggested for the onset of wet-snow avalanching (LWC_{Index}). If snow cover models are forced with data from automated weather stations (AWS), only a now-cast is possible. For this study, we therefore force SNOWPACK with data from the high-resolution numerical weather prediction (NWP) model COSMO and investigate whether forecasting regional patterns of the onset of wet-snow avalanche activity is feasible. To validate the index, we compared simulations performed at the location of numerous AWS in the Swiss Alps with wet-snow avalanche observations from the corresponding region. Results show that the onset of wet-snow avalanche activity can be simulated with the snow cover model SNOWPACK while forced with data from automated weather stations (now-cast). Bias corrections are required prior to forcing SNOWPACK with only NWP data. However, similarly good results compared to simulations with station data only were achieved by first forcing SNOWPACK with data from automated weather stations and then adding the forecasted data. While using this setup the onset of wet-snow avalanching for two different climate regions in Switzerland was reproduced.

Keywords: avalanche forecasting, wet-snow avalanche, snow cover modelling, numerical weather prediction

1. INTRODUCTION

Snow cover models have become valuable tools for avalanche warning services. They can provide additional useful information on the seasonal mountain snow cover in terms of stratigraphy and stability where observations are sparse in time and space. However, the extent to which snow cover simulations are implemented into the operational routine differs significantly between avalanche warning services – with France probably having the most progressive service (Lafaysse et al., 2013). Although it has been shown that snow cover simulations can be used for avalanche danger assessments (e.g., Giraud, 1992; Schweizer et al., 2006, Schirmer et al., 2010; Bellaire and Jamieson, 2013a) they are rarely used operationally.

The two most advanced snow cover models are the Swiss snow cover model SNOWPACK (Bartelt and Lehning, 2002; Lehning et al., 2002a, 2002b) and the French model CROCUS (Brun et al., 1989, 1992) that was recently implemented into Surfex, a highly detailed surface modelling platform (Vionnet et al., 2012). Both models treat snow as a three-component material consisting of ice, water and air. The snow cover model SNOWPACK was developed to simulate the snow cover at locations of automated weather stations (AWS). If the meteorological input is provided by AWS, only a now-cast is possible (Lehning et al., 1999). The model chain SAFRAN-CROCUS-MEPRA simulates the snow over on so-called massifs of about 500 km^2, where SAFRAN provides the meteorological input and MEPRA estimated the snow cover stability.

SNOWPACK – as well as CROCUS – were already successfully coupled to numerical weather prediction models (e.g. Bellaire and Jamieson, 2013b, Vionnet et al., 2012) allowing forecasting the evolution of the snow cover. However, so far validation of such model chains mainly focused on snow height and stratigraphy

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(e.g. Bellaire et al., 2011, 2013c; Bellaire and Jamieson, 2013b; Vionnet et al., 2012) and rarely on stability (e.g. Bellaire and Jamieson, 2013a).

Mitterer et al. (2013) suggested and partly verified an index for the onset of wet-snow avalanching (LWC_{Index}). The liquid water content of the entire snow cover was simulated with SNOWPACK for the location of automated weather stations across Switzerland. Wever et al. (2016) forced SNOWPACK with data from automated weather stations located in the Alps, Central Andes and Pyrenees. They found a local liquid water content of 5-6% within the snow cover to be a better predictor for wet-snow avalanche activity compared to other methods like the daily mean air temperature or the daily sum of the positive energy balance. In addition, the location or depth within the snow cover was found to be related to the size of wet-snow avalanches. However, in both studies SNOWPACK was forced with weather station data, hence only a now-cast was possible. A different approach was used by Helbig et al. (2015) who used NWP data to calculate wet-snow probability maps for the entire Swiss Alps based on a probability density function derived from detailed avalanche occurrence data. While their model performed reasonably well, they only used two meteorological parameters and noted that including snow cover information would likely improve the model performance.

In this study, we therefore aim at forecasting the LWC_{Index}, to assess future regional wet-snow avalanche activity by forcing SNOWPACK with data from a high-resolution NWP model. For this initial study, a proof of concept, we focus on the Swiss Alps and a time period from October 2013 to June 2014.

2. DATA

2.1 Numerical Weather Prediction (NWP) model

We used the numerical weather prediction model COSMO. The COSMO model (formerly 'LM', Doms and Schaettler, 2002) is currently in operational use by different European weather forecasting services (Germany, Switzerland, Italy, Poland, Romania, Greece and Russia). COSMO is a non-hydrostatic limited-area model developed and maintained by the COnsortium for Small scale MOdelling (COSMO, www.cosmo-model.org). For our study, we used data from the Swiss Version of COSMO with a horizontal resolution of 1.1 km (COSMO-1). The COSMO-1 domain extends about 1000 km in east-west direction and about 700 km in north-south direction with the Alps in its centre. COSMO-1 became fully operational in March 2016, is initiated 8 times a day with a lead-time of up to 33 hours.

2.2 Automated Weather Stations (AWS)

To assess the performance of COSMO-1 during winter we compared forecasted meteorological parameters – relevant for snow cover evolution – to historical COSMO-1 runs performed daily at 00 UTC at MeteoSwiss. Forecasted data were mainly compared with data from a network of automated weather stations located between 1500 m and 3000 m a.s.l. across the Swiss Alps (Intercantonal Measurement and Information System: IMIS; Lehning et al., 1999). The IMIS stations were designed to provide additional meteorological and snow cover data for avalanche services and are therefore located at representative locations. In addition, we used high quality radiation data measured at the study plot Weissfluhjoch (2540 m a.s.l.) above Davos (Eastern Swiss Alps).

2.2 Avalanche Observations

Trained observers record avalanche observations on a daily basis within each forecasting region across Switzerland. We used observations from the two sub-regions Grisons (Eastern Swiss Alps) and Valais (Western Swiss Alps). Observers record single avalanches as well as multiple avalanches; for the latter the exact number of avalanches is unknown. However, the aspect on which the avalanches were observed is recorded in both cases. To estimate the daily avalanche activity, based on avalanche observations, we calculated the number of avalanches per day and sub-region by counting the number of recorded aspects implying that at least one avalanche had to be observed on the corresponding aspect.

3. METHODS

3.1 Liquid Water Content – LWC_{Index}

The LWC_{Index} presented by Mitterer et al. (2013) is defined as:

$$LWC_{Index} = \frac{\overline{\theta_{w,c}}}{0.03} \qquad (1)$$

where $\overline{\theta_{w,c}}$ is the modelled, average volumetric liquid water content of the entire snow cover. A LWC_{Index} of 1 indicates that water will percolate through the snow cover, since a liquid water content of 3% represents the starting value of the transition from the pendular to the funicular regime. Mitterer et al. (2016) define a LWC_{Index} of > 1 and/or an increase of > 0.6 over 24-hours as critical for wet-snow avalanching.

3.2 SNOWPACK

The Swiss snow cover model SNOWPACK (Version 3.3.0) was forced with forecasted data (COSMO-1) as well as IMIS data (IMIS). COSMO-1 forecasted data of the first 23 hours after initiation at 00 UTC were used to create a daily time series with hourly time steps and were used to force the snow cover model SNOWPACK. Snow cover simulations were carried out for a level site, i.e. the location of the IMIS stations as well as on virtual north-facing (38° incline, 0° azimuth) and south-facing slopes (38° incline, 180° azimuth).

SNOWPACK can be driven using various combinations of input parameters. We chose to force SNOWPACK using COSMO-1 forecasted incoming shortwave and longwave radiation, precipitation, air temperature and relative humidity, wind speed and direction. When using IMIS data, SNOWPACK was forced with outgoing (reflected) shortwave radiation, surface temperature as well as measured snow height instead of incoming radiation and precipitation, respectively. The setup for the IMIS stations represents the most stable setup, which was validated in many studies and serves as reference.

4. RESULTS

4.1 Local verification

A comparison of forecasted (COSMO-1) and measured key meteorological parameters for the snow surface energy balance, i.e. air temperature, incoming shortwave and longwave radiation, is shown in Fig. 1. COSMO-1 tends to have a general cold bias, i.e. air temperatures are too low. The incoming shortwave radiation is generally overestimated and the incoming longwave radiation underestimated. The mean error (ME) for the period between October 2013 and June 2014 was -1.8 °C for the air temperature, 14.1 W m^{-2} for the incoming

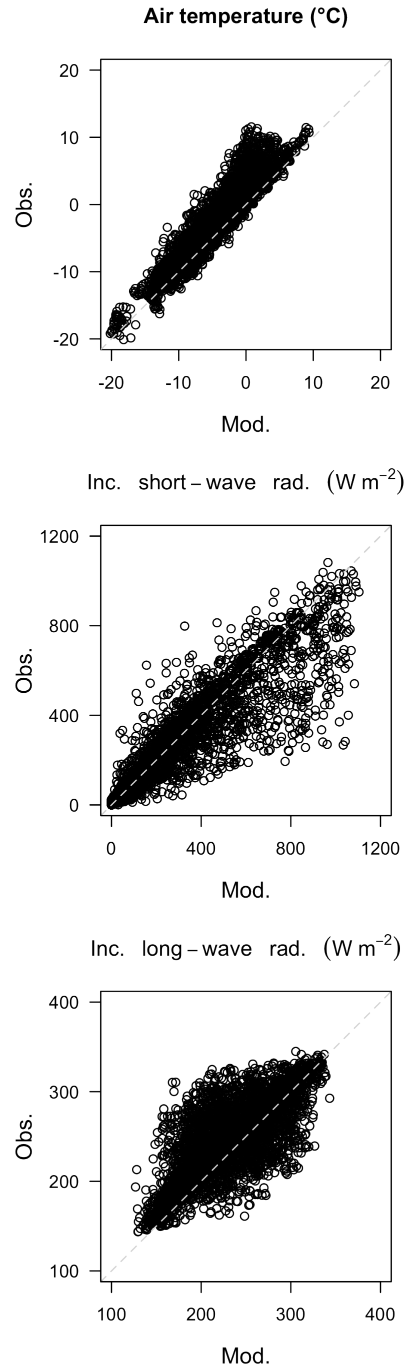

Fig. 1: Comparison of hourly modelled/forecasted (Mod.) and observed (Obs.) a) air temperature, b) incoming shortwave radiation and c) incoming longwave radiation for the experimental site Weissfluhjoch for the winter season 2013-2014 between October and June. Dashed line shows the one-to-one relation.

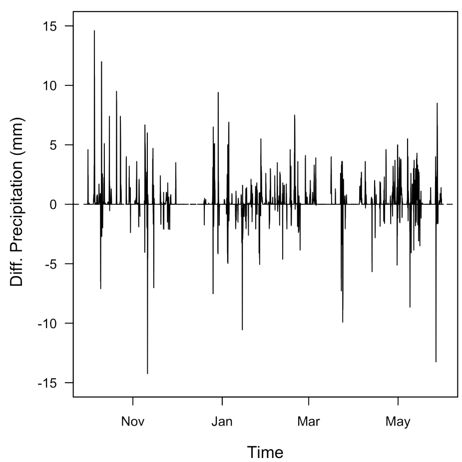

Fig. 2: Difference between modeled (COSMO-1) and calculated (SNOWPACK) precipitation amounts (3-hour sums) at Weissfluhjoch for the winter season 2013-2014. Negative values indicate too small and positive values too high precipitation amounts.

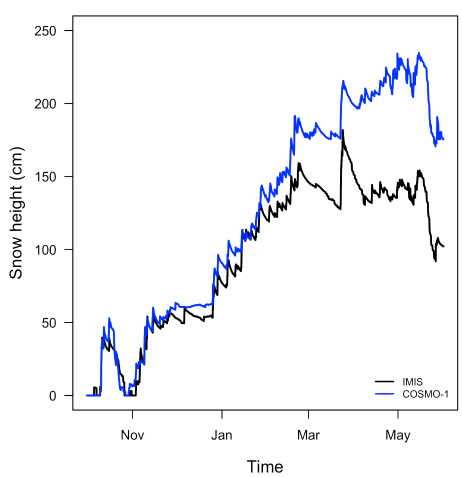

Fig. 3: Comparison of the SNOWPACK simulated snow height with input data from the IMIS station (black) and with forecasted data from COSMO-1 (black) for Weissfluhjoch experimental site between October 2013 and June 2014.

shortwave radiation and -49.2 W m^{-2} for the incoming long wave radiation. Note that elevation differences between station and COSMO-1 model grid point were corrected with a wet-adiabatic lapse rate of 0.65 °C/100 m.

For the simulation of the snow cover an accurate precipitation forecast is of paramount importance. A comparison of calculated (SNOWPACK) and forecasted (COSMO-1) precipitation for the winter season 2013-2014 at Weissfluhjoch is shown in Fig. 2. Negative values of the difference (Mod. - Obs.) indicate too little while positive values indicate too much precipitation. Overall, COSMO-1 tends to overestimate precipitation. For the investigated period a total amount of 745 mm of precipitation (rain and snow) was calculated from SNOWPACK and 1075 mm were forecasted by COSMO-1.

Snow heights simulated with the snow cover model SNOWPACK forced with measured input data (IMIS) and forecasted data (COSMO-1) are shown in Fig. 3. The simulated snow height using forecasted COSMO-1 data seems to be in good agreement with the simulation using measured input data until the end of February. Subsequently, SNOWPACK forced with COSMO-1 data overestimates the snow height by 50 to 70 cm. The latter can be explained by the overestimation of precipitation for the same period as well as the general cold bias of COSMO-1.

Since the LWC_{Index} is averaged over the entire snow cover, it strongly depends on the total snow height. Hence, an accurate simulation of the snow height is essential. It is therefore not surprising that the LWC_{Index} derived from SNOWPACK simulations using only COSMO-1 data was substantially lower than the SNOWPACK simulation forced with station data (compare black and blue lines in Fig. 4).

To overcome the issue, we therefore suggest using a now-cast based on SNOWPACK simulations forced with station data (IMIS) in combination with a 24-hour forecast using COSMO-1 data. This removes accumulated forecasting errors, i.e. minimizing the error throughout the season, while still being able to forecast the LWC_{Index}. Therefore, SNOWPACK was initiated with IMIS data as described above, but stopped daily at midnight. A SNOWPACK output file containing snow profile information was written and used to initiate the next SNOWPACK run using forecasted COSMO-1 data as input. In other words, a daily 24-hour forecast was performed. In the following, we refer to this setup up as IMCO.

A comparison of the simulated LWC_{Index} for (a) SNOPWACK forced with IMIS data, (b) SNOWPACK forced with only COSMO-1 data, and (c) SNOWPACK forced with both IMIS and COSMO-1 data (IMCO) is shown in Fig. 4. In addition to the simulation at the level location of the IMIS station, simulations were carried out for a north-facing and a south-facing slope. A critical value ($LWC_{Index} > 1$) during the period of February to April 2014 was reached only for the simulation at the south-facing slope during early March. Furthermore, the simulation using only COSMO-1 data did not reach the critical value of the LWC_{Index}. However, the combination of a simulation with IMIS data and COSMO-1 data (IMCO) shows good agreement with the reference run, i.e. IMIS data only. Note that although IMIS data were used to generate initial profiles the IMCO run still uses forecasted data as input, i.e. in this setup a 24-hour forecast of the onset of wet-snow avalanche activity would have been possible.

4.2 Regional verification

Wet-snow avalanche activity for two forecasting regions in Switzerland, i.e. Grisons (~7000 km^2) and Valais (~5000 km^2) as well as the simulated LWC_{Index} are shown in Fig. 5. Simulations with SNOWPACK were carried out with data for the IMIS station, with COSMO-1 data as well as combined simulations with IMIS and COSMO-1 data (IMCO). The LWC_{Index} was averaged over 27 IMIS stations for the region of Grisons and 33 IMIS stations for the region of Valais. Wet-snow avalanche activity in both regions started with a minor cycle by the end of February. The main wet-snow avalanche activity began early March until the end of the month, interrupted in both regions by a few cold days towards the end of the month. Avalanche activity in March starts a few days earlier in Valais than in Grisons.
As already shown above for the local verification at Weissfluhjoch the reference run (IMIS) as well as the combined run (IMCO) are in good agreement with the observed avalanche activity. The stand-alone simulation with COSMO-1 data did not capture the onset of wet-snow avalanche activity due to the propagation of forecast errors. In both regions the model (IMCO) was also able to capture the break in avalanche activity by the end of March.

5. DISCUSSION

A model – not only snow cover models – can only be as good as the input data. Therefore, we compared measured meteorological parameters against their forecasted counterparts. A general cold bias was found for the forecasted COSMO-1 data as well as a general overestimation for the incoming shortwave radiation and an underestimation for the longwave radiation

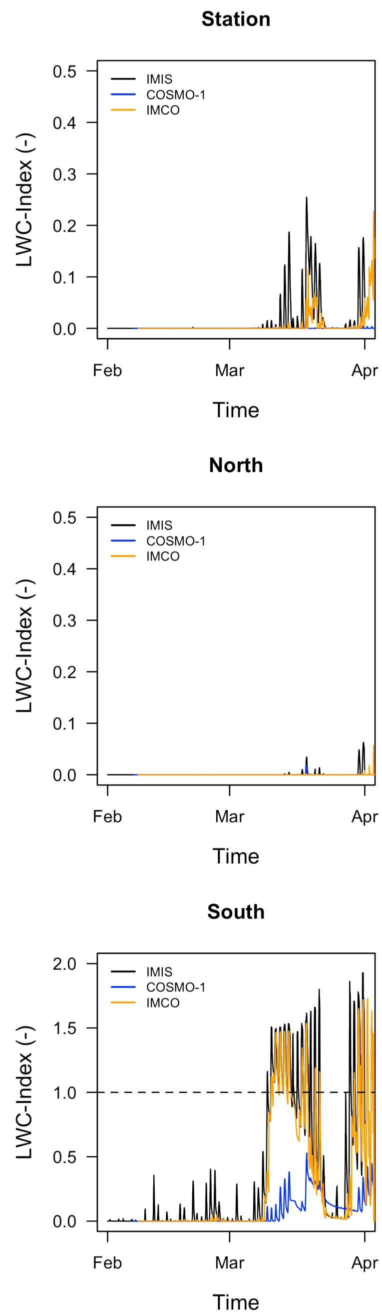

Fig. 4: LWC_{Index} simulated between February and April 2014 at Weissfluhjoch. Shown are simulations for (a) the level location of the station, (b) a north-facing slope as well as (c) a south-facing slope. Different lines refer to different input data to force SNOWPACK simulations: IMIS data (black), COSMO-1 data (blue) as well as a combination of IMIS and COSMO-1 data (IMCO, orange). Horizontal dashed line is located a LWC_{Index} = 1 indicating the critical value of LWC_{Index} based on a liquid water content of 3%.

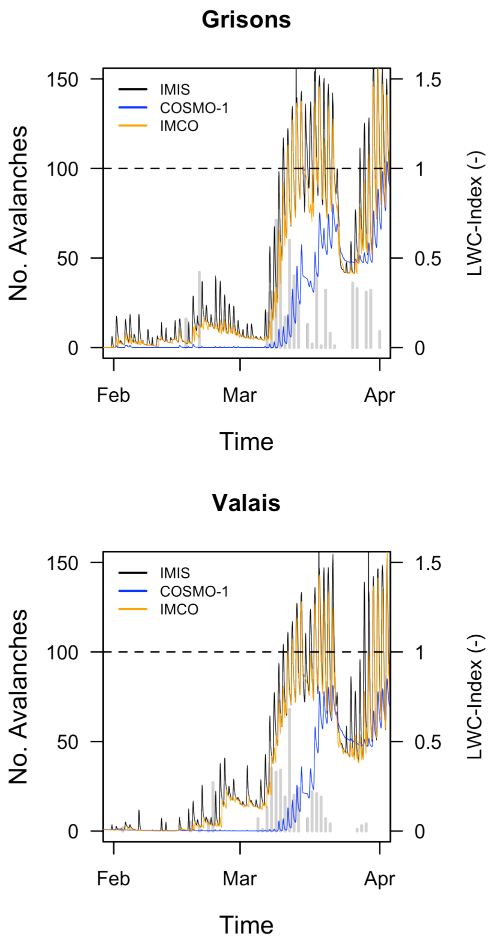

Fig. 5: Simulated LWC_{Index} averaged for (a) the location of 27 IMIS stations in Grisons and (b) 33 locations for Valais. Shown are SNOWPACK simulations using station data (IMIS), COSMO-1 data (blue) and IMCO data (orange). Grey vertical bars show the number of observed wet-snow avalanches per day. Dashed horizontal line is located at 1, the critical value for the LWC_{Index}.

(Figure 1). The horizontal resolution of NWP models has significantly increased during the last years. Theoretically, higher horizontal resolution should allow one to forecast small-scale weather events such as convective precipitation or local wind systems. Indeed so-called convection permitting models (i.e., operational models with a resolution on the order of 1 km) show considerably improved skill scores when compared to their coarse-resolution counterparts (e.g., Weusthoff et al., 2010). However, the physical formulations especially for turbulence and radiation, of currently available NWP models have been developed based on knowledge from flat and idealized terrain (Rotach and Zardi, 2007). Therefore, typically model output statistics (MOS) or bias corrections are often applied to the direct model output to correct the shortcomings of the model introduced by the model physics and underlying terrain. Future improvement will therefore have to include bias corrections for relevant meteorological parameters such as air temperature, precipitation as well as radiation.

While running SNOWPACK with forecasted NWP data it is strongly advised to use the forecasted precipitation amounts, because NWP models often use simplified parameterizations for the snow cover especially for the snow height. COSMO-1 tends to be too wet (Fig. 2) resulting – also in combination with the cold bias – in too much snow and hence an overestimation of the simulated snow height. Precipitation processes triggered or modified by orography are of course most challenging – even if considerable progress has been made in recent years (Richard et al., 2007). Thus, reliable point forecasts from high-resolution NWP in complex terrain – although by far the best we can obtain and more representative than a point observation – still remain a great challenge.

Bias corrections for the NWP forcing data are required if SNOWPACK needs to be run in a real forecasting mode, e.g. in data sparse areas. Without bias corrections best results were achieved by using AWS data forced SNOWPACK runs for initiation. This is especially true for the prediction of the liquid water content of the entire snow cover since the calculation of the LWC_{Index}, strongly relies on the simulated snow height.

Long-term data sets of high quality avalanche observations especially during the start and the end of winter season are rare. Therefore, the quantitative validation of the LWC_{Index} on the regional and local scale (Gobiet et al., 2016) remains challenging. However, the validation of wet-snow avalanche activity for the two regions of the Swiss Alps with a good network of observers shows good qualitative agreement between the forecasted LWC_{Index} and the observed wet-snow avalanche activity. Note that the COSMO-1 data were not bias corrected. A bias correction should further enhance the performance of the IMCO model chain in terms of timing of wet-snow avalanche activity.

6. CONCLUSIONS

To predict wet-snow avalanche activity, we forced the snow cover model SNOWPACK with input data from a network of automated weather stations (IMIS) as well as data from the numerical weather prediction model COSMO-1. The onset of wet-snow avalanche activity was estimated by simulating a recently developed index based on the average volumetric liquid water content of the entire snow cover (LWC_{Index}).

As already shown in previous studies, SNOWPACK forced with data from automated weather stations, is capable of predicting wet-snow avalanche activity with good agreement to observations. However, up to now only a now-cast was possible using AWS data. Although forcing SNOWPACK with forecasted data from COSMO-1 shows promising potential, not only for wet-snow avalanche activity; nevertheless bias corrections of key parameters for the evolution of the snow cover are required. Using SNOWPACK simulations forced with data from automated weather stations as initial state and subsequently adding forecasted data removes the accumulated bias. By using a combination of measured and forecasted data wet-snow avalanche activity was forecasted with good qualitative agreement for two different mountain regions in Switzerland. Coupled state-of-the-art snow cover and high-resolution numerical weather prediction models combine snow cover, stability and weather information – the key ingredients for avalanche forecasting – in an integral way and represent a powerful tool for avalanche warning services.

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