DISTRIBUTED MODELLING OF SNOW COVER INSTABILITY AT REGIONAL SCALE

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ABSTRACT: Forcing snow cover models with high resolution numerical weather prediction models has provided new insight into the spatial distribution and temporal evolution of, for instance, snow depth and snow water equivalent in mountainous terrain. Tough, of particular interest to avalanche forecasting services are spatial patterns of snow instability. However, it is presently unclear what level of model complexity is required to obtain snow instability information such that the locations where the danger is most pronounced can be identified. Alpine3D is a spatially distributed (surface), three-dimensional (atmospheric) model for analyzing and predicting dynamics of snow-dominated surface processes in mountainous topography. We forced Alpine3D with gridded meteorological data for the region of Davos, Switzerland (~ 20 km x 20 km; 100 m grid spacing) with the aim to identify spatial patterns of potential instability with regard to slope elevation and aspects. We simulated the snow cover using SNOWPACK – implemented in Alpine 3D – to identify spatial patterns across the model domain for two winters between 2016 and 2018. The winter season 2016-2017 was a below-average winter in terms of snow depth and hence persistent weak layers existed throughout the entire study region. In contrast, the winter season 2017-2018 showed above-average snow depth with few critical weak layers. General patterns of the two winters were reproduced by the simulations. Despite the high computational costs spatially distributed model chains show promising potential for supporting operational avalanche forecasting.

Keywords: snow instability, avalanche forecasting, spatial variability, snow cover modelling

1. INTRODUCTION

Snow cover models have become valuable tools for avalanche warning services. They can provide additional information on the seasonal mountain snow cover in terms of stratigraphy and stability as observations are often 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 Météo-France being the most progressive service in terms of model implementation (Lafaysse et al., 2013). Although several studies have shown that snow cover simulations are useful for assessing avalanche danger (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 French model CROCUS (Brun et al., 1989, 1992) that was recently implemented into SURFEX, a highly detailed surface modelling platform (Vionnet et al., 2012), and the Swiss snow cover model SNOWPACK (Bartelt and Lehning, 2002; Lehning et al., 2002a, 2002b). 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; Lehning et al., 1999). The model chain SAFRAN-CROCUS-MEPRA simulates the snow for virtual slopes of various aspects and elevations of so-called massifs with an area of about 500 km^2, where SAFRAN provides the meteorological input and MEPRA estimates the snow cover stability.

SNOWPACK is implemented into Alpine3D a spatially (surface), three-dimensional (atmospheric) model for analysing and predicting dynamics of snow-dominated surface processes in mountainous topography. With Alpine3D it is possible to spatially simulate the evolution of the snow cover – similar to SURFEX – in any given domain and topography. SNOWPACK – as well as CROCUS – were already successfully driven with output from numerical weather prediction models (e.g. Bellaire and Jamieson, 2013b, Vionnet et al., 2012). This allows forecasting the evolution of the snow cover. However, so far validation of such model chains mainly focused on snow height and stratigraphy (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).

We therefore aimed to evaluate whether spatially distributed snow cover simulations provide valuable snow instability information in space and time. In a first step, we forced Alpine3D with

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measured meteorological input data, to avoid uncertainties inherently present in weather forecasts.

2. DATA AND METHODS

In the following we describe the general setup of the Alpine3D simulations as well as how the simulated snow profiles were analyzed.

2.1 Alpine3D – Domain and meteorological input

Simulations with Alpine3D were performed for a domain (Fig. 1) of 21.5 km x 21.5 km located in the eastern Swiss Alps. The domain roughly corresponds to the avalanche warning region around Davos as defined by the Swiss avalanche warning service. A digital elevation model as well as a land use class is required as input for Alpine3D. We used a digital elevation model with a grid spacing of 100 m. The land use classes correspond to PREVAH code (https://models.slf.ch/). The required meteorological input data, i.e. air temperature, relative humidity wind speed and direction were extrapolated from 10 automated weather stations (IMIS) using MeteoIO (Bavay and Egger, 2014). Liquid precipitation is also required as input and is measured at most of the stations. Since these measurements are prone to large errors due to e.g. under-catch of solid precipitation, we instead used SNOWPACK to simulate the snow cover at the location of the 10 automated weather stations for both winter seasons and extracted hourly precipitation amounts. Incoming short-wave and long-wave radiation were extrapolated from measurements at Weissfluhjoch (WFJ) above Davos (Fig. 1). The Alpine3D simulations were initiated with no snow on the ground on 1 October and continued until 1 April of each winter season.

2.2 Alpine3D – Output

At each grid point within the domain – except for grid points where the land use class corresponds to either water, settlement or forest – a simulation with SNOWPACK was performed. Due to the relatively small grid spacing (100 m) and the large domain (46,225 grid points) SNOWPACK output was only written for pre-selected points. We randomly sampled points for north-facing (315° to 45°), east-facing (45° to 135°), south-facing (135° to 225°) as well as west-facing slopes (225° to 315°) with either a slope angle between 10° and 20° or 30° and 40°, for elevations below and above 2000 m a.s.l. For each of these 16 classes 200 points were randomly selected. South-facing slopes with a slope angle between 30° and 40° below 2000 m rarely exist within our domain, so we only had 64 points in that particular class. In total, we analysed 3064 grid points, for which 3-hourly SNOWPACK output was available.

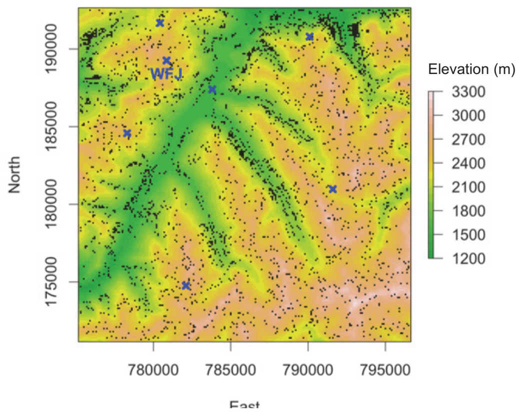

Figure 1: Surface elevation of the Alpine3D domain (100 m digital elevation model) used for this study. Black squares show the location of the randomly selected slopes. Blue crosses show the location of the automated weather stations used for extrapolation. In addition to the 7 stations located within the domain, 3 stations outside the domain were used for extrapolation. Axes are labelled with Swiss coordinates (in meters).

2.3 Snow cover characteristics and analysis

We analyzed spatial snow cover simulations of two winter seasons. The winter season 2016-2017 was a below-average winter in terms of snow depth, hence prominent persistent weak layers existed throughout the entire study region. In contrast, the winter season 2017-2018 showed above-average snow depth with few critical weak layers.

To quantify these differences in snow stratigraphy we used the threshold sum approach by Schweizer and Jamieson (2007) as applied by Monti et al. (2014) for simulated profiles. Hence for each layer within the top 100 cm we calculated the number of variables in the critical range. All layers with 5 or 6 variables in the critical range we considered as potentially critical. Once per week from October to end of March of each season, we then calculated the total number of potentially critical layers per profile. Finally, we determined a monthly value by taking the median of the weekly profiles to analyze the evolution of the winter in terms of snow stratigraphy.

As a second measure we calculated the percentage of layers consisting of persistent crystal types, i.e. facets, depth hoar, surface hoar and rounding facets per profile by simply summing up the thicknesses of the persistent layers and dividing it by the total snow depth times 100 (100% = fully faceted).

3. RESULTS

3.1 Number of critical layers

The evolution of the median monthly number of potentially critical layers per aspect, slope and elevation class for the winter seasons 2016-2017 and 2017-2018 is shown in Figures 2 and 3, respectively. For both winter seasons differences in snow stratigraphy are more pronounced between the two elevation classes than between the four different aspects.

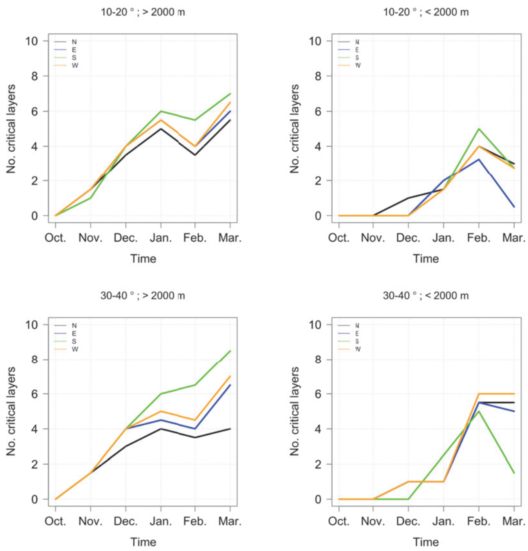

Figure 2: Median number of critical layers per month between October 2016 and March 2017 for slopes of 10-20° above 2000 m, 10-20° below 2000 m, 30-40° above 2000 m as well as 30-40° below 2000 m for the four cardinal aspects (North, East, South and West). Slopes (N = 200) within each class were randomly selected throughout the domain (Fig. 1).

The median number of critical layers above 2000 m a.s.l. during the winter season 2016-2017 started to gradually increase from November to January followed by a decrease in February; in March the number increased again. This evolution was the same for all aspects above 2000 m. The number of critical layers for slopes below 2000 m started to increase later in the season, i.e. in December and January depending on the aspect. After peaking in February, the number of critical layers decreased in March 2017.

During the winter season 2017-2018 the number of critical layers above 2000 m started to increase early in the season and peaked for the first time around November 2017 to decrease almost to zero in January 2018. For the rest of the season, the number increased again. Below 2000 m the number of critical layers increased during October and then almost stayed the same with only a minor further increase until the end of March 2018.

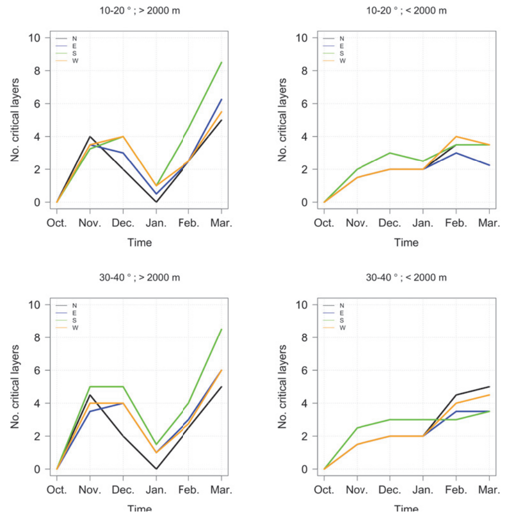

Figure 3: Median number of critical layers per month between October 2017 and March 2018. Same classification and colour coding as described in Fig. 2.

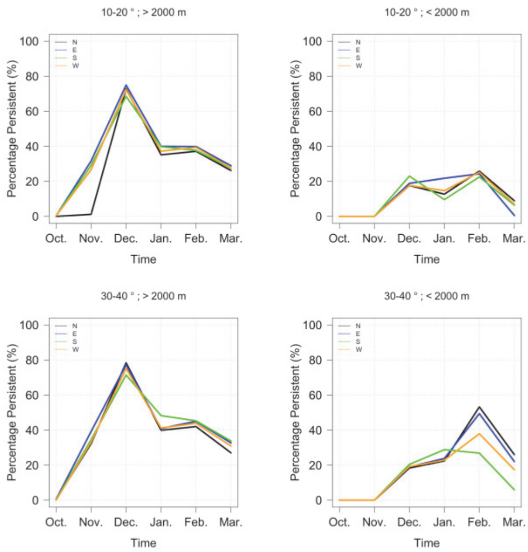

Figure 4: Percentage of persistent layers, i.e. layers consisting of facets, depth hoar, surface hoar and rounding facets per profile (100% = fully faceted) for the winter season 2016-2017 between October and March. Classification and colour coding as described in Fig. 2.

3.2 Percentage of persistent layers

The percentage of persistent layers in the simulated profiles also did not depend on slope angle for both seasons (Fig.s 4 and 5). During both winter seasons the percentage of persistent layers within the snow cover peaked in December, but was almost twice as high in 2016 compared to 2017, i.e.~ 80% to ~40%, respectively. Below 2000 m the maximum percentage of persistent layers was reached earlier in the 2017-2018 season than in the year before, i.e. in December and February, respectively. Both seasons showed about the same percentage of persistent layers below 2000 m (~20-30%).

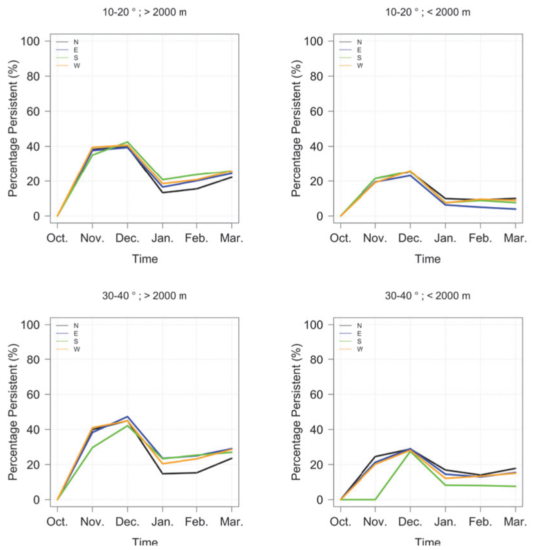

Figure 5: Percentage of persistent layers for the winter season 2017-2018 between October and March. Same representation as described in Fig. 4.

4. DISCUSSION

The Alpine3D simulations reproduced some of the features and general trends observed for the two distinct winter seasons, i.e. a shallow snow cover in 2016-2017 associated with many persistent layers and an above average snow cover in 2017-2018 with fewer persistent layers. Furthermore, the number of critical layers in the top 100 cm decreased significantly during the winter season 2017-2018 in January. This is most likely due to the fact that during this period frequent storms accumulated new snow layers so that the upper portion of the snow cover mainly consisted of non-persistent grain types.

However, it is rather counterintuitive that south-facing slopes above 2000 m tend to show more faceting than north-facing slopes of the same elevation. A comparison of mean monthly meteorological input variables, i.e. snow surface temperature, air temperature and incoming short-wave radiation as well as snow depth are shown in Fig. 6. The snow depth tended to be slightly lower on the south-facing slopes compared to

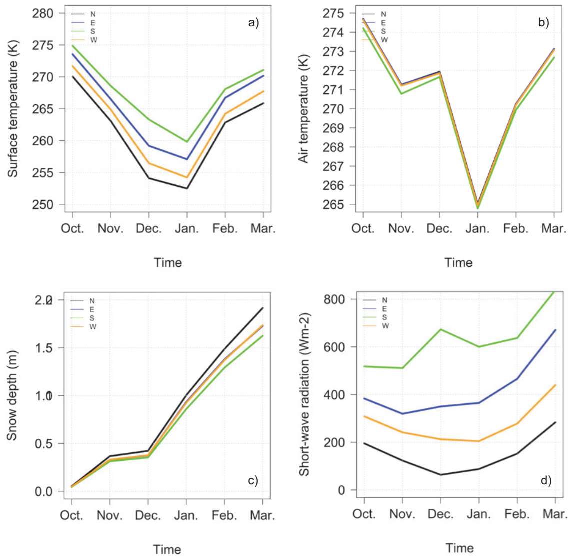

Figure 6: Mean meteorological parameters and snow depth for the winter season 2016-2017 for October to March for slopes with a slope angle of 30-40° above 2000 m. (a) Mean monthly snow surface temperature, (b) mean monthly air temperature, (c) mean snow depth, and (d) mean monthly incoming short-wave radiation for the cardinal aspects N (black), E (blue), S (green), W (orange).

the north-facing slopes, which would favour faceting. However, the air temperature was surprisingly slightly lower for the south-facing slopes. The incoming short-wave radiation was found to be about 3 times larger on the south facing slopes compared to north-facing slopes, which might favour crust formation, which in turn might cause increased faceting. Still, it remains unclear for the time being, why the snow cover on the south-facing slopes includes slightly more persistent layers than the snow cover on the north-facing slopes. An in-depth analysis of various south- and north-facing profiles is required to clarify this point.

The simulations showed that the old snow problem in 2016-2017 was present mainly above 2000 m, in line with field observations. Also, in 2017 there was a prominent avalanche cycle on 9 March, when the number of critical layers in the upper snow cover above 2000 m for steep slopes was still on the rise (4 to 8 depending on aspect), and the percentage of facets in the snow cover had reached a steady value of about 30-40%. In 2018, there was a major snow storm on 22 January with comparatively fewer avalanches. The number of critical layers above 2000 m was then also a little lower (1-3) and the percentage of facets was also lower (20-30%). While clearly we still need to define clear thresholds to discriminate between rather stable and rather unstable condition, these qualitative results suggest that there are differences in modelled snow stratigraphy in line with observed differences in avalanche activity.

6. CONCLUSIONS

We conducted Alpine3D simulations for two distinct winter seasons for the region of Davos, i.e. a domain of approximately 20 km x 20 km with a horizontal grid spacing of 100 m. The winter season 2016-2017 was characterized by below-average snow depth and hence more persistent layers existed in the snow cover. In contrast, the winter season 2017-2018 showed above-average snow depth with fewer persistent layers. The Alpine3D simulations in general reproduced these observed differences between the two winter seasons.

However, differences in snow stratigraphy, with respect to slope aspect were minor, and occasionally counterintuitive. These findings might be related to (a) the small differences in simulated snow depth between slopes of different aspect, but also to (b) how we tried to quantify snow stratigraphy. In general, it is not straightforward to quantitatively analyse snow layering with regard to snow instability. Most likely, more prominent differences in snow depth can only be achieved by taking into account varying snow deposition due to the interaction of wind and terrain. Clearly, further work is needed before distributed modelling of the snow cover can provide those prominent differences in snow stratigraphy and hence snow instability that are typically observed in complex mountainous terrain.

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