On estimating avalanche danger from simulated snow profiles

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ABSTRACT: Estimating avalanche danger is the primary goal of avalanche warning services. Typically avalanche danger is estimated based on a variety of information such as manual snow profiles, avalanche observations as well as weather data. However, this required information is often not available especially in data sparse areas, which are common in Canada. It has been shown that coupled snow cover and numerical weather prediction models can provide such information on the snow cover. For this study we simulated the snow cover for three elevation bands – alpine, tree-line, below tree-line – at Glacier National Park, B.C., Canada for the winter season 2012-2013 between December and March. Snow cover simulations were performed using the Swiss snow cover model SNOWPACK forced by weather data from the Canadian high-resolution numeric weather prediction model GEM-LAM. Experienced forecasters estimated the regional avalanche danger (Low to Extreme) daily during the same period for the three elevation bands. Multivariate classification trees were used to estimate the avalanche danger from the simulated profiles. Classification trees were built using four parameters derived from the simulated profiles. These four parameters were the new snow amounts – maximum over 24-hours and 3-days – as well as measures for the likelihood of triggering and the expected avalanche size – based on a skier stability index and the depth of a critical layer. A comparison of the avalanche danger estimated from the simulated profiles with the forecasted avalanche danger showed that the avalanche danger was estimated correctly with an accuracy of 77% for the alpine, 76% for tree-line and 70% below tree-line – overall accuracy about 74%. Although the simulated avalanche danger tends to be slightly underestimated, especially for the alpine and tree-line, such a model chain can be a valuable tool for avalanche warning services especially for data sparse areas.

KEYWORDS: avalanche warning, avalanche forecasting, avalanche danger, SNOWPACK, snow cover simulations, numerical weather prediction, data sparse areas.

1 INTRODUCTION

Avalanche warning services combine local snow cover and regional avalanche observations with past, present and future weather conditions to estimate the regional avalanche danger for the day. However, this comprehensive information is often not available, especially in data sparse areas.

Advanced snow cover models such as the Swiss snow cover model SNOWPACK (Bartelt and Lehning, 2002; Lehning et al., 2002a, 2002b) or the French model CROCUS (Brun et al., 1989, 1992) simulate the formation and evolution of the snow cover based on meteorological input data. Hence, these models can provide the required information on the snow cover including stratigraphy as well as stability.

However, snow cover models require meteorological data as input. This input is typically provided by automated weather stations (Lehning et al., 1999; Durand et al., 1999), but the number of automated weather stations measuring all essential parameters to force the snow cover models is often limited, notably in Canada. Forcing snow cover models with forecasted weather data from numerical models has been shown to be an alternative (e.g. Durand et al., 1999; Bellaire et al. 2011, 2013; Bellaire and Jamieson, 2012) to the conventional forcing with data from automatic weather stations.

SNOWPACK as well as CROCUS use stability routines to estimate the snow cover stability based on mechanical properties (Schweizer et al., 2006) or use expert rule systems such as MEPRA (Giraud, 1992). In addition to the stability, MEPRA estimates the natural avalanche risk on a six level scale – very low, low, moderate increasing, moderate decreasing, high and very high – and the accidental avalanche risk, i.e. human triggered, on a 4 level scale – very low, low, moderate, high. Both assessments are based on the output of the snow cover model CROCUS.

Schirmer et al. (2009) used the output from SNOWPACK to estimate avalanche

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danger on a 5-level scale ranging from Low to Extreme with a cross-validated success rate of 73%. However, for this study SNOWPACK was forced with weather data from automatic weather stations.

This study shows how snow cover simulations forced by data from a numerical weather prediction model can be used to estimate the regional avalanche danger on a the widely accepted five level avalanche danger scale from Low to Extreme. Such a model chain consisting of a snow cover model and a numerical weather prediction model additionally combined with a statistical model would represent an operational tool for avalanche warning services to estimate avalanche danger not only in data sparse areas.

2 DATA & METHODS

2.1 Snow cover simulations

For this study we forced the Swiss snow cover model SNOWPACK with hourly forecasted weather data from the Canadian numerical weather prediction model GEM-LAM, the limited area version of GEM (Global Environmental Multiscale, Côté et al., 1998, Zadra et al., 2008). GEM-LAM (WEST) provides weather data on a grid with a horizontal resolution of 2.5 km, which is covering the southern two-thirds of the Canadian provinces of Alberta and British Columbia. We used the same forecasted weather parameters as suggested by Bellaire et al. (2011). Data were used from the grid point located a Latitude 51.2432 N and Longitude -117.6982 W (n_i = 441, n_j = 233). The grid point has an elevation of 1684 m a.s.l. This grid point is the closest to a study plot (1905 m a.s.l.) maintained by the Avalanche Control Section Rogers Pass at Mt. Fidelity, Glacier National Park, B.C., Canada (Figure 1).

Snow cover simulations were carried out for flat terrain at three elevation bands alpine, tree-line and below tree-line. We adjusted the forecasted air temperature for each elevation band according to a dry adiabatic lapse rate, i.e. ± 1°C/100 m depending on the elevation difference between the elevation of the grid point and the corresponding elevation band. All other meteorological parameters remained unchanged,

The elevation for tree-line and below tree-line for which the simulations were carried out was chosen based on experience, i.e. 1900 m and 1500 m a.s.l, respectively. For the elevation of the alpine we defined a 400 km^2

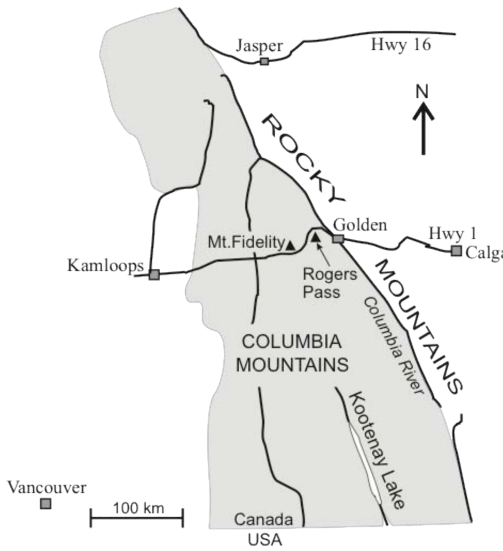


Figure 1: Map of the Columbia Mountains, British Columbia, Western Canada. Mt. Fidelity study plot is located at 1905 m a.s.l., west of Golden. Glacier National Park covers and area (1350 km^2) about 10 km North and South of the Trans Canada Highway (Hwy #1) roughly between Mt. Fidelity and 10 km East of Rogers Pass.

domain (20 km x 20 km) with the GEM-LAM grid point as the center point and searched for the maximum elevation within this domain using a 90 m digital elevation model (SRTM-90). The elevation for the alpine simulation, i.e. 2370 m a.s.l., was then defined as the average between the maximum elevation (2740 m a.s.l.) within the 400 km^2 domain and 2000 m a.s.l., the typical elevation for tree-line in this region.

Simulated critical layers were identified using the implemented stability algorithm as described by Schweizer et al. (2006). Based on the skier stability index Sk_{38} (Föhn, 1987; Jamieson, 1995) of the identified critical layer we calculated the RB_{calc} - a measure of the likelihood of triggering – according to Jamieson (1995):

$$RB_{calc} = \min(3.2 \times Sk_{38} + 1, 7) \qquad (1)$$

In addition to the RB_{calc} the depth of the simulated critical layer was extracted from the simulation. We used the simulated profile at noon to extract stability information on the critical layer from the simulation and used this as the stability of the corresponding day. Therefore we assume the simulated Sk_{38} does not change significantly over a 24-hour period.

New snow amounts, i.e. 24-hours (HN_{24}) and 3-days (HN_{3d}), were calculated by

Table 1: Estimated (public bulletin) avalanche danger (Low to Extreme) between December 2012 and March 2013 (121 days) per elevation band alpine (AL), tree-line (TL) and below tree-line (BTL) at Glacier National Park, B.C., Canada. Median avalanche danger for each elevation band is highlighted bold.

Elevation Band	Avalanche Danger				
	Low	Moderate	Considerable	High	Extreme
	%	%	%	%	%
AL	0	28	**54**	17	1
TL	9	30	**49**	12	0
BTL	26	**48**	21	3	0

SNOWPACK for each model time-step, i.e. every three hours.

3.2 Avalanche danger ratings

The regional avalanche danger – Low, Moderate, Considerable, High and Extreme – for Glacier National Park, B.C., Canada was estimated daily by experienced forecasters for three elevation bands – alpine, tree-line and below tree-line. We used forecasted avalanche danger from the pubic bulletin of the winter season 2012-2013 between December and March. Summary statistics of the estimated avalanche danger for each elevation band are shown in Table 1. The median avalanche danger for this period was estimated as Considerable for the alpine and tree-line and Moderate below tree-line. For each elevation band, avalanche danger ratings were available for a total of 121 days. In the following we will refer to this forecasted avalanche danger from the public bulletin as estimated avalanche danger.

3.3 Avalanche Size

To estimate the potential avalanche size (destructive) from the critical layer depth, the avalanche size of 1149 natural and skier-triggered avalanches from Mike Wiegele Helicopter Skiing in the Columbia Mountains of British Columbia was compared to the corresponding slab thickness (Figure 2). An exponential model was fitted to the median values of each size class. Avalanche size (*Size*) can then be calculated based on the depth of the critical layer (*Depth*; in meters) identified by SNOWPACK such as:

$$Size = \frac{\ln(\frac{Depth}{0.08})}{0.8} \qquad (2)$$

Calculated avalanche sizes were rounded to integers, i.e. full sizes only.

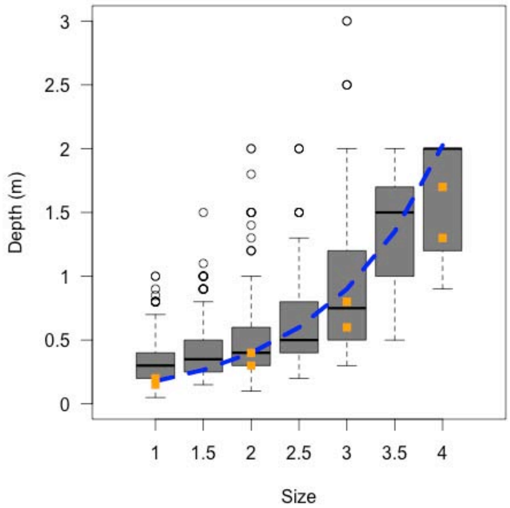


Figure 2: Distribution of slab thickness per avalanche size (destructive) of 1149 avalanches (natural and skier triggered) observed in the Monashee and Cariboo Mountains of British Columbia, Canada. Blue dashed line shows an exponential fit through the median values of each size class. Filled squares (orange) show the theoretical upper and lower range of slab thickness per full avalanche size as given by McClung (2009). Boxes span the interquartile range. Whiskers correspond to 1.5 times the interquartile range. Open circles indicate outliers.

3.4 Classification tree analysis

To estimate the avalanche danger from the simulated profiles we used a multivariate classification tree analysis (Breiman et al., 1998). A minimum of 20 observations was required in order for a split to be attempted. Nodes with 7 or less data were not split further.

Variables used for classifying avalanche danger were RB_{calc}, avalanche size as well as new snow amounts HN_{24} and HN_{3d}.

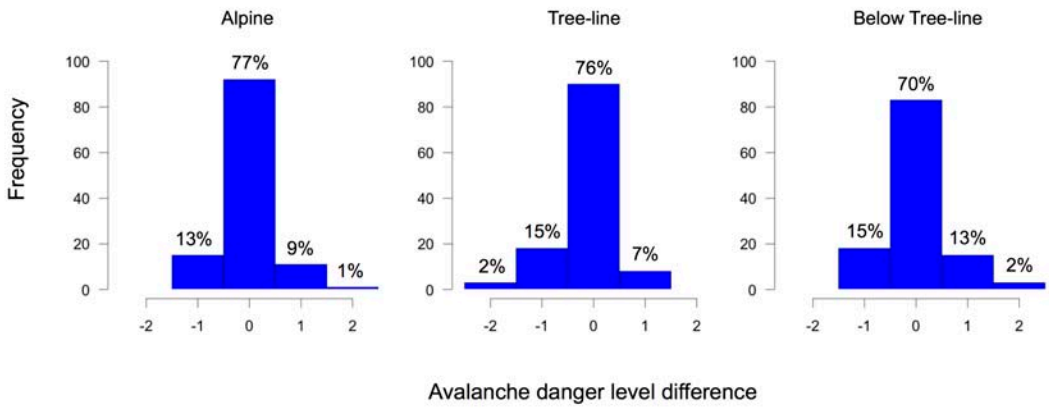


Figure 4: Validation results of the modeled avalanche danger. Shown are the differences between modelled and estimated avalanche danger (N = 119 days) for each elevation band – Alpine, Tree-line, Below Tree-line. Negative values represent an under-estimation (modelled avalanche danger < public bulletin) and positive values an over-estimation (modelled avalanche danger > public bulletin) of the avalanche danger. Zero indicates a perfect match. Percentages for the 119 days and calculated difference are given above each column. The avalanche danger level was transferred from a categorical to a numerical variable (Low = 1, Moderate = 2, Considerable = 3, High = 4, Extreme = 5).

For the classification tree analysis we used the maximum value of HN_{24} and HN_{3d} of each day instead of using the values of a single profile to capture storm events occurring during the day. Classification trees were built for each elevation band, i.e. alpine, tree-line and below tree-line, for 119 days between December 2012 and March 2013 (121 days total). Two days – 25 December 2012 and 26 December 2012 – were excluded due to missing forecasted weather data. The classification trees were 10-fold cross-validated.

4 RESULTS

4.1 Avalanche danger model – Classification trees

Multivariate classification trees for the alpine, tree-line and below tree-line are shown in Figure 3. For all elevation bands RB_{CALC} seems to classify best followed by the maximum values of HN_{24} and HN_{3d} and avalanche size (Size).

Note that an additional split (HN_{3D} > 39) was added manually for the alpine classification tree to improve the model accuracy (see Discussion section for details).

4.2 Verification of modeled vs. estimated avalanche danger

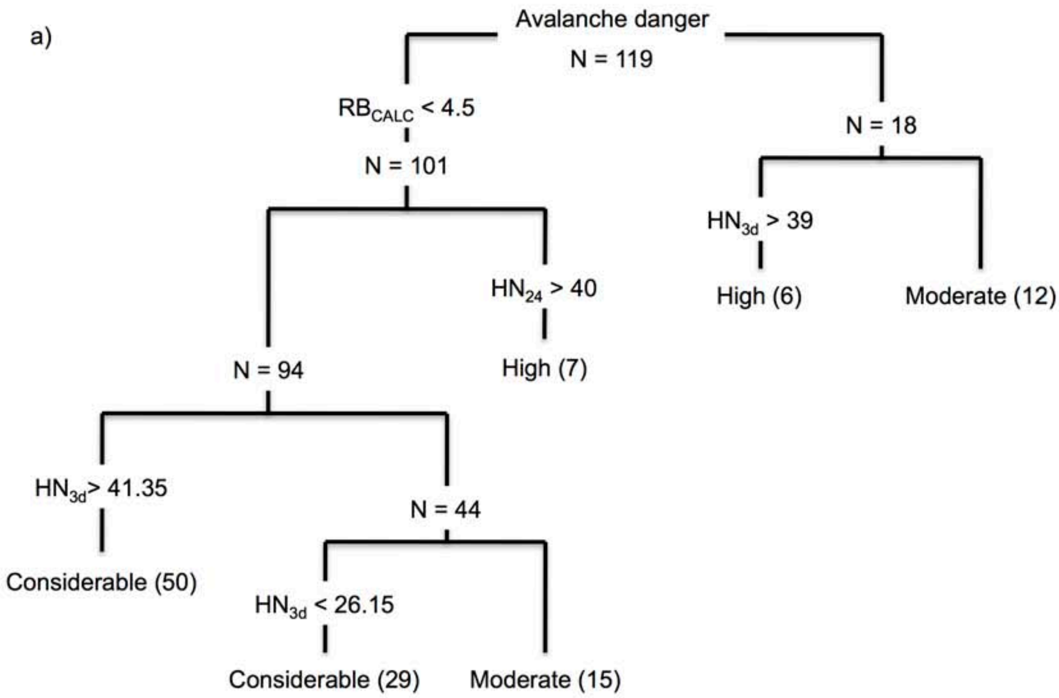
After the avalanche danger was modeled for each elevation band using the classification trees displayed in Figure 3 we applied two empirical expert rules as a quality check. First, if the avalanche danger at tree-line is modeled higher than the alpine, the modeled avalanche danger of the alpine is set to the modeled avalanche danger at tree-line. Second, differences in avalanche danger of more than one step between the alpine and tree-line as well as tree-line and below tree-line are not allowed. In these cases the lower avalanche danger was increase by 1 level. These two rules were applied in 3 cases for the alpine, in 6 cases for tree-line and in 9 cases for below tree-line.

To verify the accuracy of the modeled avalanche danger we assigned numerical values to each danger level, i.e. Low = 1, Moderate = 2, Considerable = 3, High = 4 and Extreme = 5 and subtracted the estimated avalanche danger from the modeled avalanche danger. Frequency distributions of the difference between modeled and estimated avalanche danger for each elevation band are shown in Figure 4.

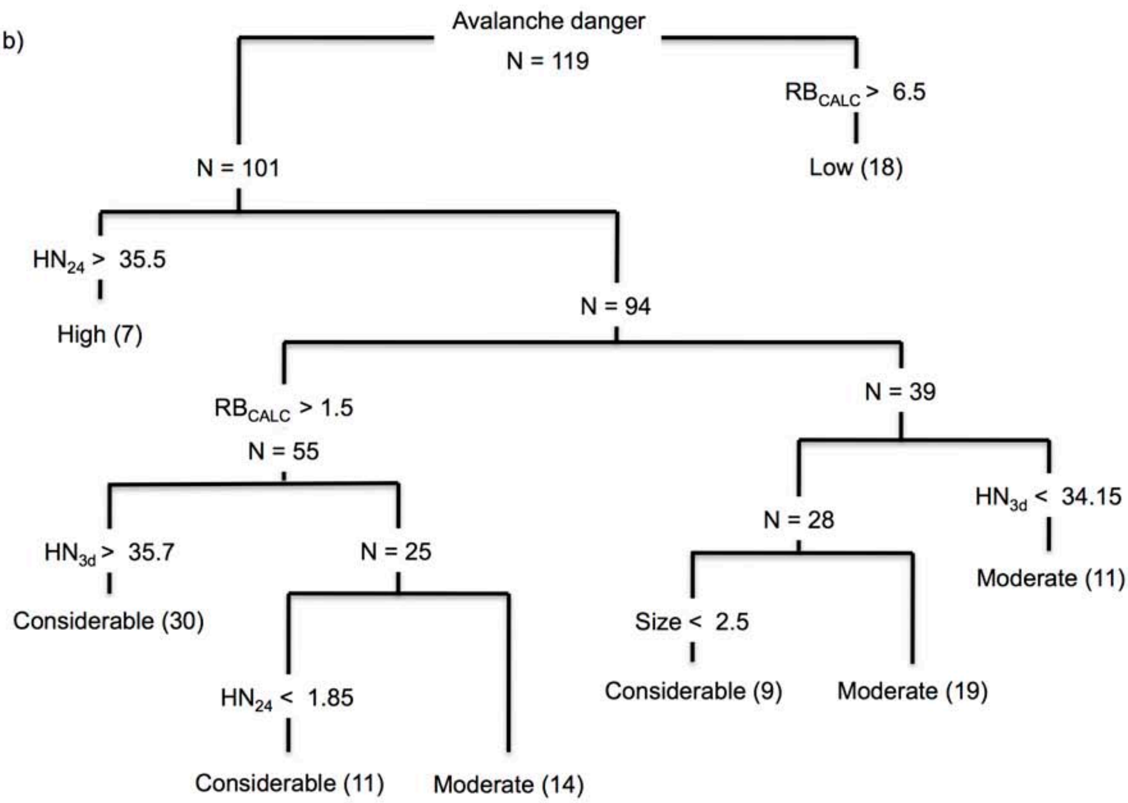
For the alpine the modeled and estimated avalanche danger was the same in 77% of the 119 days, i.e. the difference was zero (Figure 4). The accuracy for the modeled avalanche danger at tree-line and below tree-line was found to be slightly lower, i.e. 76% and 70%, respectively. In other words, the avalanche danger was modeled correctly for about three quarters of the days for all three elevation bands.

During the remaining days where avalanche danger was not modeled correctly the model tends to underestimate the avalanche danger for the alpine and tree-line – negative difference – and tends to over-estimate the avalanche danger below tree-line – positive difference. However, in most cases the modeled avalanche danger was found to be within one step of the danger level from the public bulletin.

a)


Avalanche danger
N = 119
RBCALC < 4.5
N = 101
N = 18
HN3d > 39
High (6)
Moderate (12)
HN24 > 40
High (7)
N = 94
HN3d> 41.35
Considerable (50)
N = 44
HN3d < 26.15
Considerable (29)
Moderate (15)

b)


Avalanche danger
N = 119
RBCALC > 6.5
Low (18)
N = 101
HN24 > 35.5
High (7)
N = 94
RBCALC > 1.5
N = 55
N = 39
HN3d > 35.7
Considerable (30)
N = 25
HN24 < 1.85
Considerable (11)
Moderate (14)
N = 28
HN3d < 34.15
Moderate (11)
Size < 2.5
Considerable (9)
Moderate (19)

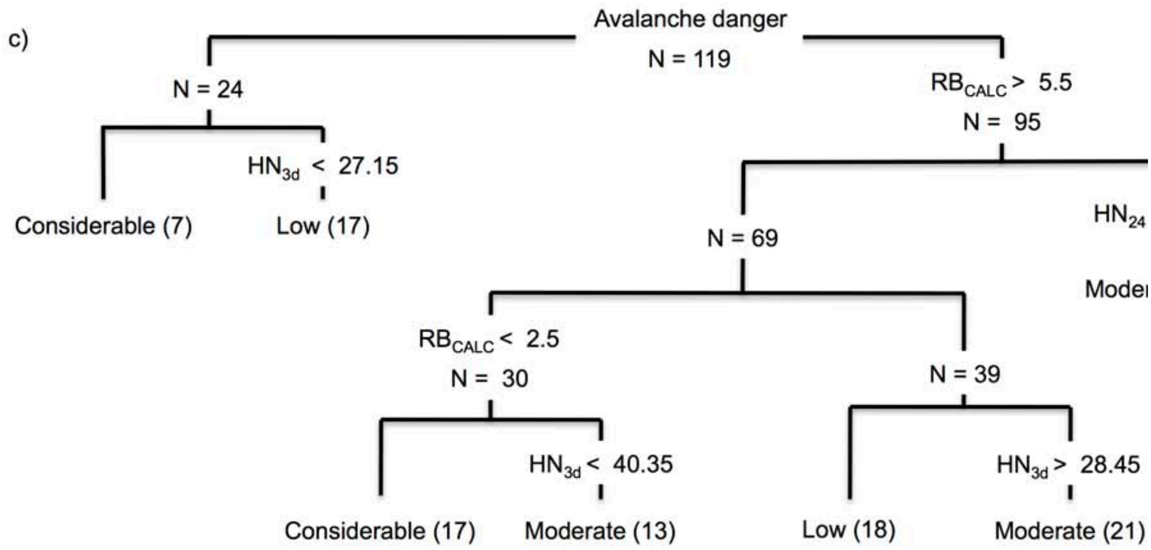


Figure 3: Classification trees used to classify avalanche danger (Low to Extreme, N = 119) for a) the alpine, b) tree line and c) below tree-line. Trees were built based on RB_{CALC}, avalanche size (Size) as well as 24-hour (HN_{24}) and 3-days (HN_{3d}) new snow amounts. Threshold values for the new snow amounts are given in centimeters. RB_{CALC} and avalanche size are indices on a scale from 1 to 7 for the RB_{CALC} and 1 to 5 for the avlanche size. Above each node the number of available cases for the split are given as well as the number of cases remaining in the leaf of the each split.

5 DISCUSSION

The avalanche danger is defined by the likelihood of triggering and the expected size of an avalanche. An avalanche release indicates low snow cover stability and consequently critical avalanche conditions. However, not every avalanche release corresponds to High or even Extreme avalanche danger. Therefore, the likelihood of triggering as well as the potential avalanche size are key parameters for modeling avalanche danger and need to be derived from the simulations.

For this initial study we estimated the likelihood of triggering by deriving the RB_{calc} from the simulated Sk_{38} (Eq. 1). As already shown by Bellaire and Jamieson (2012) critical layers were modeled by SNOWPACK forced with forecasted weather data with a fair accuracy. It has been shown by Schweizer et al. (2006) that the skier stability index SK_{38} in combination with structural index, i.e. lemons or yellow flags, can be used to identify critical layer within simulated profiles. However, the accuracy of the SK_{38} and therefore the corresponding values of the RB_{calc} has not been verified yet.

A relation between the destructive avalanche size and slab thickness, i.e. depth of the critical layer, was developed (Figure 2). Up to a size 2 our empirical relation is in alignment with the theoretical values found by McClung (2009). To reach an avalanche of size 3 or 4, our regression for median slab thickness were thicker than McClung's (2009) theoretical values for size 3 and 4 avalanches. However, McClung (2009) concluded for his data set that entrainment could explain such differences.

The multivariate classification tree analysis showed that the RB_{calc} classified best followed by the new snow amounts (HN_{24} and HN_{3d}) and the avalanche size (Figure 3). Avalanche danger strongly depends on the presence and absence of critical layers as well as on critical new snow amounts, both have been shown to be modeled with fair accuracy (Bellaire et al., 2011, 2013; Bellaire and Jamieson, 2012). The shown classification trees only present one possible model, which is in addition only based on one winter season. Therefore, threshold values as well as nodes and splits will change once more data are used. On the first view the displayed trees suggest some over-fitting especially for the lower splits, e.g. Figure 3a last split $HN_{3D} < 26$. However, this specific split is related to storm snow problems, which sometimes last longer than 3 days, i.e. the new snow amounts of the last 3-days were small, but previously a large storm brought larger amounts of snow and the avalanche condition remained Considerable.

The accuracy of the estimated avalanche danger using the above described values as classifiers was found to be 77% for the alpine 76% for tree-line and 70% for below tree-line (Figure 4). Although, this is a good agreement these values are only based on one winter season. More winters with different conditions are required for verification. If the two expert-rules are not applied to the modeled avalanche danger the accuracy decreases from 77% for the alpine to 75%, from 76% to 72% for tree-line and from 70% to 66% for below tree-line. Although these differences seem fairly small the two expert-rules further prevent large underestimation of the modeled avalanche danger, i.e. differences of 2 or even 3 steps between modeled and estimated avalanche danger occur more often.

Without the manually added split for the alpine classification tree (Figure 3a) the model accuracy would drop from 77% to 72%. In addition, most days with estimated High avalanche danger would be classified as days with Moderate avalanche danger.

6 CONCLUSIONS

This study investigated the possibility of deriving avalanche danger ratings from snow cover simulations. Snow cover simulations were forced by forecasted data from a high-resolution numerical weather prediction model. The likelihood of triggering as well as the avalanche size was estimated from the snow cover simulations.

Multivariate classification tree analysis was used to classify snow cover simulations based on a measure of the likelihood of triggering, the avalanche size as well as 24-hour and 3-days new snow amounts. The avalanche danger was modeled correctly with an accuracy of 77% for the alpine, 76% for tree-line and 70% for below tree-line.

Despite the fact that this initial study is only based on one winter season and therefore needs further validation and verification, such a model chain supplemented with additional statistical analysis shows promising potential to become a valuable forecasting tool. Such a tool could assist avalanche warning services worldwide especially in data sparse areas where information on the snow cover is limited.

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