FORECASTING SNOW AVALANCHE DAYS FROM METEOROLOGICAL DATA USING CLASSIFICATION TREES; GRASDALEN, WESTERN NORWAY

Kalle Kronholm [1,2,]*, Dagrun Vikhamar-Schuler [3], Christian Jaedicke [1], Ketil Isaksen [3],
Asgeir Sorteberg [4] and Krister Kristensen [1]

[1] Norwegian Geotechnical Institute, Oslo, Norway
[2] International Centre for Geohazards, Oslo, Norway
[3] Norwegian Meteorological Institute, Oslo, Norway
[4] Bjerknes Centre for Climate Research, Bergen, Norway

ABSTRACT: Avalanches pose one of the most serious problems to infrastructure and people in the mountains in Norway. Processes leading to avalanche release are deterministic but the time and place of avalanche release is notoriously difficult to predict. Statistical approaches using meteorological parameters to predict the probability of natural avalanche release provide an alternative to deterministic prediction. We used classification trees to predict days with and without avalanches in the valley of Grasdalen in Western Norway based on meteorological parameters. A database with avalanche observations from almost 30 years was spatially and temporally coupled to grids of wind, precipitation and temperature. The grids were used because they provided more temporally consistent datasets than measurements from a local weather station. Avalanches were observed on 254 days and the same number of non-avalanche days was randomly selected. The optimal classification trees gave misclassification rates of 15% for all avalanche days, 18% for days with dry avalanches and 13% for days with wet avalanches. The most important meteorological parameters for the classification were the five-, one- and three-day sum of precipitation. Then followed wind speed, either measured as the maximum or mean over five days, three days or one day. Finally, daily temperature was important for the classification both alone and through a degree day parameter. Based on realistic scenarios for precipitation and temperature, our results imply that avalanche frequency will increase in the future. Further studies are needed to quantify this increase.

KEYWORDS: Avalanche release, climate, precipitation, wind, temperature

1. INTRODUCTION

Avalanches pose one of the most serious problems to infrastructure and people in the mountains in winter. Historically, avalanches have taken more lives than any other natural hazard in Norway. Every winter houses are destroyed and roads are closed due to avalanches. To avoid loss of lives and to decrease the number and time of road closures, avalanche warnings are issued in regular intervals in the most threatened parts of the country. The warnings are based primarily on meteorological data and are additionally based on knowledge about parameters that lead to high probability for natural avalanche release, such as critical thresholds for precipitation values (e.g. Bakkehøi, 1987).

Processes leading to avalanche release are deterministic (Schweizer and others, 2003) but the large spatial and temporal variations in input parameters make exact prediction of time and place of natural avalanche release nearly impossible. Stochastic approaches using meteorological variables to predict the probability of natural avalanche release have therefore been investigated in a number of studies using various methods. Classification trees using meteorological parameters to split between avalanche days and non-avalanche days were first reported by Davis and others (1999) in a study area in an intermountain avalanche climate (Mock and Birkeland, 2000) in California. They found that various parameters related to precipitation were the best at splitting avalanche days from non-avalanche days, but did not use the constructed trees for prediction. Later, Hendrikx and others (2005) used similar

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* *Corresponding author address:* Kalle Kronholm, P.O. Box 3930 Ullevaal Stadion, N-0806 Oslo, Norway; Phone: +47 2202 3050; E-mail: kalle.kronholm@ngi.no

classification trees in New Zealand and specified the optimal size of the trees to be used for warning. They also found that precipitation related parameters provided the best split between avalanche days and non-avalanche days. A thorough review of the literature can be found in Hendrikx and others (2005). Classification trees have never been used at the current study area in Western Norway.

In Norway significant warming has been observed in the whole country since the 1960s (Hanssen-Bauer and Førland, 2000). In addition, annual precipitation in Norway has increased statistically significantly (5% level) in 9 of 13 regions and no region shows a negative trend. The largest increase is found in north-western regions of Norway, especially during winter and spring (Hanssen-Bauer, 2005). These changes are expected to continue with noticeable changes predicted even in a relatively short horizon within the next 50 years (Hanssen-Bauer and others, 2003). While average values of precipitation and temperature will likely change, the most dramatic changes are expected in the extreme events of both precipitation and temperature (Hanssen-Bauer and others, 2003).

The present study was partially motivated by municipalities requesting more and more detailed information about if and how the avalanche activity will change in response to the predicted climate changes. If the predicted changes in avalanche frequency are significant, the municipalities may have to adjust their land zone planning routines for the future climate. In this study, we develop classification trees to relate meteorological parameters to the number of days with observed avalanches. The developed models may be used to qualitatively investigate the effect of climate change on avalanche release frequency.

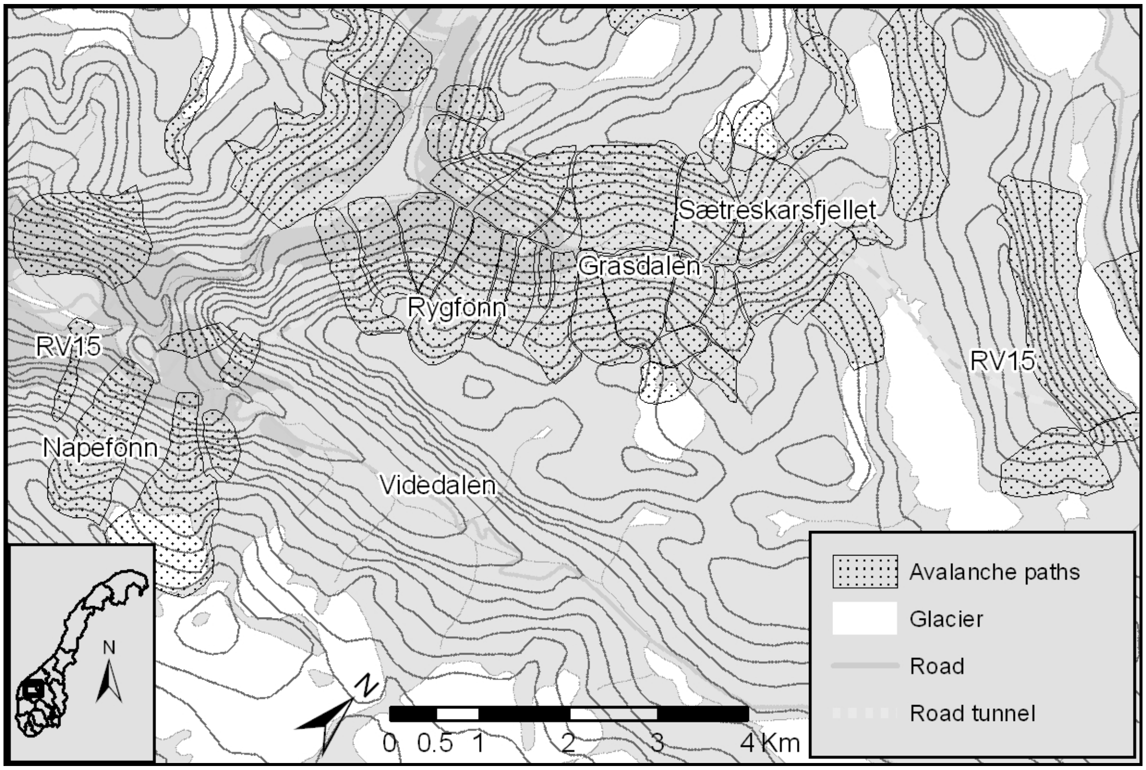

Figure 1: Map of the study area with the most frequent slide paths and the main road (RV15) through the valley of Grasdalen. The Napefonn, Rygfonn and Sætreskarsfjellet avalanche paths are controlled. Contour lines are 20 m apart. The insert shows Norway and the location of the study area.

2. METHODS

2.1. Study area

The national road RV15 is the main transport corridor between the city of Stryn in the northern part of western Norway and the city of Otta in eastern Norway. In addition to being the primary road for people it is also the main transport corridor for goods and services produced on the coast. This study focuses on a 10 km long stretch of road along RV15. This stretch of road starts at around 100 m a.s.l. at the western end in the valley of Videdalen and reaches more than 900 m a.s.l. at the eastern end (Fig. 1) after passing through the valley of Grasdalen. Peaks in the area reach between 1220 and 1800 m a.s.l.. Despite three tunnels, a number of avalanche paths threaten the road from above (Fig. 1). Avalanches in the area are mainly direct-action, meaning that they are released during or briefly after a storm. Three of the avalanche paths (Ryggfonn, Napefonn and Sætreskardsfjellet; Fig. 1) have been artificially controlled since the 1980's. Different types of weather observations have been made in Grasdalen and on a nearby peak. However, for reasons described below, we do not use the data for the analysis.

2.2. Avalanche observations

Avalanche observations from Grasdalen have been recorded in more than 50 separate avalanche paths by several persons on an irregular basis from the 1974-1975 winter season to the present (2006). Throughout this period the recording practice has changed a number of times, resulting in a somewhat heterogeneous dataset. However, the following relevant parameters for each observed avalanche were recorded when possible: a) the name of the slide-path with a map of the run-out zone and the release area; b) date and time of release; c) trigger type (natural or artificial); d) avalanche type (wet, dry or both). Weather conditions often limited the observations, and estimates of these parameters were given instead. In these cases a measure of accuracy was given for each parameter. In the present paper we investigate the differences in release factors for the wet and dry events separately and for all events together.

For observations lacking some of the parameters and measures of accuracy, we tried to estimate these from the notes in clear text, which followed most observations. For some observations this was not possible, and in these cases we gave our best estimate of the missing parameter and attached the lowest measure of accuracy which we felt confident with. For over half of the observations no trigger type was recorded, but based on the limited human activity in the release areas and the consistent recording when using explosives we feel confident that these were natural releases. The post-processing of the data recorded in the database may have introduced errors into the database, but more importantly has also helped increase the overall data quality.

The dataset used for the analysis was selected from the total dataset based on certain restrictions on the data quality. First, we use observations from 1975 to 2003 since these have been through the best quality check. Further, only observations for which the release time was certain to within ±12 hours were considered. Finally, only natural releases were considered in this analysis.

After selecting the reliable event data, we assigned an avalanche index *AI* to each avalanche day. Because size information was not given for all observed avalanches, the *AI* was calculated as the number of reliable avalanche observations on a given day. In the present paper we do not distinguish between days with many avalanches and days with few, because if an avalanche event was significant enough to be recorded, it may have potentially threatened the road. The meteorological variables for the days when avalanches were observed are discussed below.

2.3. Meteorological data

Meteorological data has been collected manually and by automated stations in the area since 1975. However, the collected data was very heterogeneous due to 1) different observers for the manual measurements, 2) different sensors through the observation period for the automated measurements, and 3) varying degrees of data quality. To avoid these problems we decided to use other sources of meteorological data. Using the three data sets described below also allowed us to analyze the meteorological parameters responsible for avalanche release on the national scale, which was a second aim of the study, but not described in this paper.

Table 1: Investigated meteorological parameters related to temperature and precipitation.

Abbreviation	Unit	Description
rr1day	mm	Precipitation on the avalanche day
rr3day	mm	Three day sum of precipitation ending at the end of the avalanche day
rr5day	mm	Five day sum of precipitation ending at the end of the avalanche day
tam	°C	Daily mean air temperature
posDegDays	°C	The sum of the daily mean temperature on days with positive temperatures since the beginning of the season
negDegDays	°C	The sum of the daily mean temperature on days with negative temperatures since the beginning of the season
posDegDays5d	°C	The five day sum of the daily mean temperature on days with positive temperatures ending at the end of the avalanche day
negDegDays5d	°C	The five day sum of the daily mean temperature on days with negative temperatures ending at the end of the avalanche day
frostInterval	-	Number of freeze-thaw cycles (crossings of 0°C) preceding the avalanche release in the current winter season
coldPeriod	-	Number of periods with more than 5 continuous days without precipitation and with temperatures < 5°C
rainOnSnowEvent	-	Number of days with rain on the snow cover

The first two datasets contained nationwide daily values in a 1 km x 1 km grid from 1961 to the present of precipitation (met.no, 2004; Tveito and others, 2005) and temperature (Tveito and others, 2000; met.no, 2004). These datasets were generated from values recorded at a number of irregular placed locations throughout the country. The weather station network density decreases with elevation, and together with the interpolation algorithm, this leads to overestimated precipitation values at higher elevations. From these datasets, we calculated a number of meteorological parameters for each recorded avalanche event (Table 1). The start of the winter season was defined as 1 November.

The third dataset contained re-analyzed values of 6-hourly wind speed and direction in 10 m above ground from the Environmental Modeling Center (NCEP) covering Norway with a approximately 250 km x 250 km grid from 1948 to present (Kistler and others, 2001). From this dataset, we calculated a number of wind-related meteorological parameters (Table 2).

Table 2: Investigated meteorological parameters related to wind.

Abbreviation	Unit	Description
wndspd1day	$m\ s^{-1}$	Average wind speed on the day of the avalanche
wndspdmax1day	$m\ s^{-1}$	Maximum wind speed on the day of the avalanche
wndspd3day	$m\ s^{-1}$	Three day average wind speed ending at the end of the avalanche day
wndspdmax3day	$m\ s^{-1}$	Three day maximum wind speed ending at the end of the avalanche day
wndspd5day	$m\ s^{-1}$	Five day average wind speed ending at the end of the avalanche day
wndspdmax5day	$m\ s^{-1}$	Five day maximum wind speed ending at the end of the avalanche day

The parameters in Tables 1 and 2 were sampled from the meteorological grids at locations corresponding to the highest point in the release area in each avalanche path. For each avalanche day with $AI > 1$ the meteorological variables from each event were averaged to arrive at only one set of meteorological parameters.

2.4. Non-avalanche days

To compare meteorological parameters from avalanche days with the parameters on days without avalanches, we picked a number of days without avalanches in the following way: First, the number of non-avalanche days N_{none} had to be equal to the number of avalanche days N_{aval} to give a balanced model. Further, we attempted to keep the number of selected non-avalanche days on any given month equal to the number of avalanche days in the same month. This was not always possible because some months had avalanches on more than half of the days, leaving less than half for the non-avalanche days. For these few cases, we picked the nearest day in either the previous or following month. In picking the non-avalanche days we disregarded the type of avalanches that were observed. In other words, days with observed avalanches of any type were never selected as non-avalanche days. Finally, non-avalanche days were never selected twice, meaning that all non-avalanche days were unique.

For each non-avalanche day the same meteorological parameters as for the avalanche days were generated from the meteorological grids (Tables 1 and 2). In addition to being temporally specific, the non-avalanche dataset was also location-specific because the meteorological parameters come from spatially distributed grids. We chose the non-avalanche day locations at the coordinates of a meteorological station in the upper part of Grasdalen (Fig. 1). The location was not in the centre of the observed avalanche paths, but was chosen to enable a comparison with data from the meteorological station (results not shown here).

2.5. Classification trees

In a first exploratory data analysis, we investigated whether the meteorological parameters for the days with avalanches were different from the parameters on the days without avalanches. Comparisons were made using the Kruskal-Wallis test with p-values ≤ 0.05 considered significant.

Rather than seeking an explicit global linear model for prediction or interpretation, tree-based models seek to split the data, recursively, at critical points of the determining variables in order to partition the data into groups that are as homogeneous as possible within, and as heterogeneous as possible between. The results often lead to insights that other data analysis methods tend not to yield.

We used binary classification trees to distinguish between days with avalanches and days without avalanches based on the meteorological parameters listed in Tables 1 and 2. Trees were grown using Gini values to decide the splits and node heterogeneity was measured by deviance. First the trees were over-fit by growing them to produce perfect classification results and then pruned to their optimal size using 10-fold cross-validation (Breiman and others, 1984; Hendrikx and others, 2005). The goodness of the optimal classification trees were described with the percent of misclassified days with equal weights for misclassified avalanche days and misclassified days without avalanches.

Due to the larger setting of this study, as described above, it was not only important to know how well each tree managed to classify the days, but equally important to find the meteorological parameters most significant for avalanche release. We did this by focusing mainly on the first three nodes of the classification trees since these provide the most important splits and kept the analysis simple despite some trees which were rather complicated. Normally, classification tree analyses are done by looking only at the parameter that is the best for each split. However, to investigate if other parameters would have been almost as good for a split, and hence important for avalanche release, we reported the three best parameters for the splits.

3. RESULTS

The database contained 886 avalanche observations. After the selection criteria were applied, 805 events were left for analysis. These avalanches were observed on 254 days. Dry snow avalanches were observed on 125 days and wet avalanches on 76 days. Some days had observations of both wet and dry avalanches and some days had only observations where the avalanche type was not recorded. The distribution of the avalanche index on the avalanche days (all types) was heavily skewed towards days with few observed avalanches and on only a few days more than 20 avalanche events were observed.

The exploratory analysis showed that many of the analyzed meteorological parameters were significantly different for avalanche days and non-avalanche days (Table 3). Only *negDegDays*, *coldPeriod* and *rainOnSnowEvent* were not significantly different for either of the three data sets. The precipitation and wind parameters were significant for all three datasets, though the wind parameters had a higher significance for the datasets including all avalanches and only dry avalanches than for the wet avalanches. Not unexpected, the temperature parameter *tam* was only significant for the dataset with wet avalanches. Based on this preliminary analysis we expected that the selected meteorological parameters would provide a good data set for splitting between avalanche days and non-avalanche days.

The optimal classification tree using all 254 avalanche days and 254 non-avalanche days as dependent variables and all meteorological parameters as independent variables misclassified 15.4% of the events (Fig. 4). In the first split almost half of the non-avalanche days (123) and 32 avalanche days were separated from the rest based on *rr5day* < 5.2 mm. The second best variable for the first split was *rr1day* and the third was *rr3day* (Table 4), indicating the strong control the precipitation has on avalanche release in the study area. This means that if the *rr5day* parameter had not been included the *rr1day* would have been used instead, so just because *rr1day* was not used to split the events at any notes this does not mean that it was not an important parameter. The second split on the right branch involved the *tam* parameter, which correctly classified 103 days as non-avalanche days if *tam* ≥ 0.975 °C. The small misclassification error in this branch (10.4%) indicates that with little snow and with temperatures above freezing, the chance of avalanche release is small. The final split in the right branch also involved a temperature parameter. The second split in the main left branch was a wind speed parameter (*wndspd5day*) followed by two temperature parameters (*negDegDays5d* and *negDegDays*). The selection of precipitation, wind and temperature parameters in the first three splits indicates the wide range of conditions that lead to avalanche release.

The tree built using only days with dry avalanches used fewer days (N_{aval} = 125) and misclassified more days (18%) than the tree using all 254 avalanche days. Yet, the three best parameters used to split in the first three nodes were similar (Table 4). The most noticeable differences were that *rr3day* and *wndspd1day* were no longer important for the first three nodes, and that *frostInterval* and *negDegDays* were now important and *frostInterval* actually used to split a node.

Table 3: P-values for the Kruskal-Wallis test checking whether the distribution of parameters for avalanche days and for days without avalanches are the same. Values in **bold** are significant ($p \leq 0.05$).

Variable	**All**	**Dry**	**Wet**
rr1day	**<0.001**	**<0.001**	**<0.001**
rr3day	**<0.001**	**<0.001**	**<0.001**
rr5day	**<0.001**	**<0.001**	**<0.001**
posDegDays	**<0.001**	**0.015**	0.61
negDegDays	0.20	0.78	0.87
posDegDays5d	**0.0417**	0.0065	0.28
negDegDays5d	**<0.001**	0.0025	0.96
frostInterval	**<0.001**	0.0078	0.055
coldPeriod	0.28	0.51	0.55
tam	0.76	0.31	**0.046**
rainOnSnowEvent	0.056	0.095	0.85
wndspd1day	**<0.001**	**0.0017**	**0.0057**
wndspdmax1day	**<0.001**	**<0.001**	**0.0014**
wndspd3day	**<0.001**	**<0.001**	**0.0054**
wndspdmax3day	**<0.001**	**<0.001**	**0.015**
wndspd5day	**<0.001**	**<0.001**	**0.0011**
wndspdmax5day	**<0.001**	**<0.001**	**0.0043**

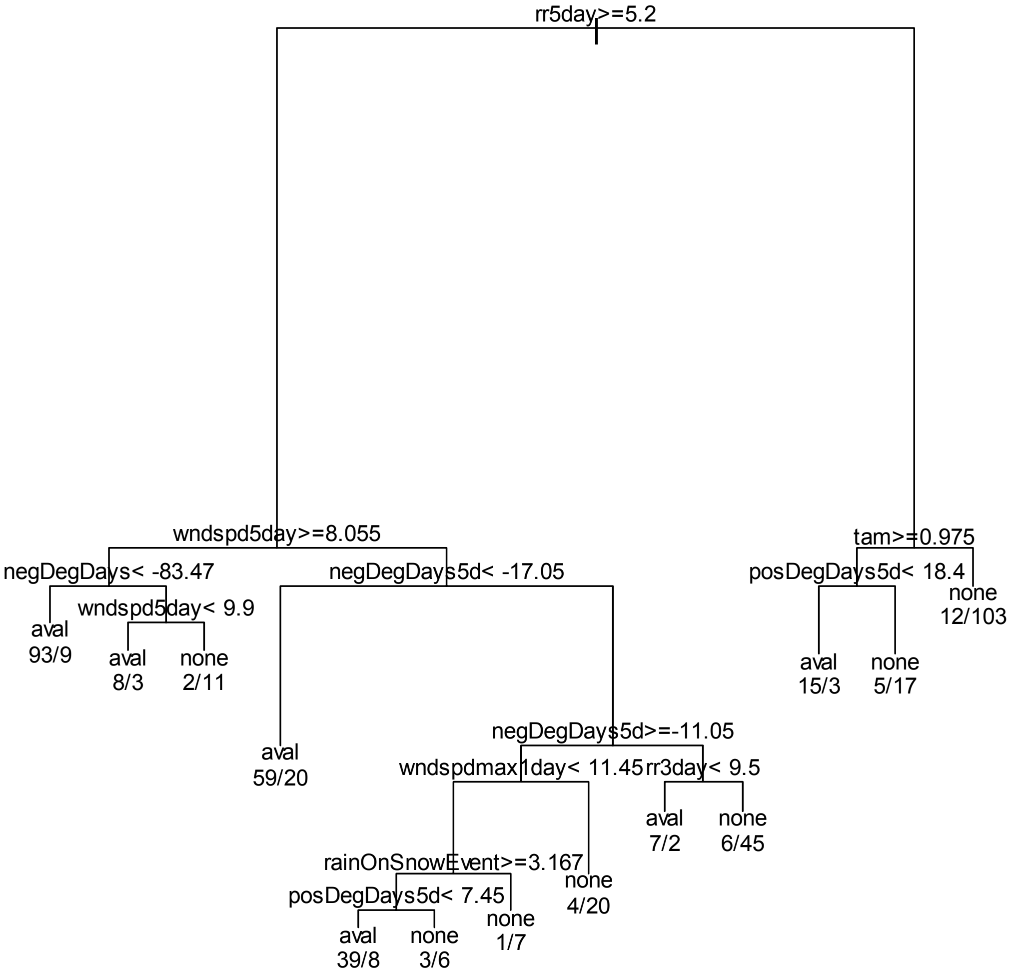

Figure 4: Classification tree grown when all avalanche observations were considered together ($N_{\text{aval}} = N_{\text{none}} = 254$). The tree had a misclassification rate of 15.4%. At each node events evaluated as true are sent to the left and false events to the right. In the leaves of the tree "none" indicate days classified as non-avalanche days and "aval" indicate days classified as avalanche days. Below the predicted class are the number of observed days shown as $n_{\text{aval}}/n_{\text{none}}$. The vertical length of the tree branches is proportional to the ability of each node to split correctly.

Despite the lowest number of days with avalanches ($N_{\text{aval}} = 76$) the tree build for days with wet snow avalanches gave the lowest misclassification rate (13.2%). The primary split was still done with the *rr5day* parameter, and as for the trees using all observed avalanches and days with dry avalanches the *rr1day* parameter was also important (Table 4). However, the two next splits were mainly dominated by temperature related parameters unlike for the previous trees, which were dominated by wind and temperature related parameters. Specifically, the *rainOnSnowEvent* parameter, which was not important in the previous trees and also not significantly different between avalanche and non-avalanche days, split the second left node and *posDegDays5d* which only had minor importance in the previous trees split the second right node. For the release of wet snow avalanches it therefore appears that the precipitation parameters and to some degree the wind parameters are important, but that parameters related to days with warm temperatures play a more important role than when considering all events together and certainly compared to the days with dry avalanches.

Table 4: Meteorological parameters used in the first three splits for trees grown using all meteorological parameters as variables. The best predictor (Predictor place = 1) was the one used to construct the tree. Also shown are the two best alternative predictors.

Avalanche type	**Predictor place**	**Node number**		
		1	**2, left**	**2, right**
All	1	*rr5day*	*wndspd5day*	*tam*
	2	*rr1day*	*wndspdmax5day*	*wndspd1day*
	3	*rr3day*	*rr1day*	*posDegDays5d*
Dry	1	*rr5day*	*wndspd5day*	*frostInterval*
	2	*wndspdmax5day*	*wndspdmax5day*	*tam*
	3	*rr1day*	*negDegDays*	*posDegDays5d*
Wet	1	*rr5day*	*rainOnSnowEvent*	*posDegDays5d*
	2	*rr1day*	*posDegDays*	*tam*
	3	*wndspdmax3day*	*wndspd5day*	*posDegDays*

4. DISCUSSION

Some errors may have entered the analysis through the use of meteorological data from the grids instead of using data from meteorological stations. For example, the precipitation grid data may not have been able to capture effects of topography on the local precipitation rates. The precipitation rates used to construct the trees may therefore underestimate the actual peak precipitation rates. However, for precipitation over multiple days, we expect this underestimation to be limited. Similarly, the temperature grid may not reflect fully the large temperature gradients expected from the large elevation differences in the area. The wind speed estimates from the reanalysis are probably systematically too low compared to reality and do not include local topographical effects that might influence both the direction and speed. However, they provide homogeneous time series and a good indication of the daily large scale flow. The procedure of calculating meteorological parameters for a fixed location for the non-avalanche days may also have an effect on the results, but although we did not investigate this effect by calculating the meteorological data from another location within the study area, we expect the effect to be negligible. Especially for the coarse resolution wind speed data a change in location of a few kilometers would not generate different values unless the location changed from one cell to another. For the precipitation and temperature grids with a resolution of 1 km x 1 km another location may have resulted in different calculated values. Yet, because these grids were constructed using kriging and triangulation (met.no, 2004), the difference from one grid cell to the neighbors is small. Moving the location of the non-avalanche days to other locations within the study area would therefore not result in large changes in the calculated meteorological parameters. Due to the inhomogeneous data recorded locally by the weather station and manually, we think that the use of the grid data was a better option.

The constructed trees gave misclassification rates of around 15%, which was comparable to the best trees constructed by Hendrikx and others (2005). This is surprising as their area was about 10 times as large. Within their study area they collected data from two weather stations, but their analyses use precipitation and temperature data from one station and pressure data from the other station. Their stations therefore do well at capturing the important meteorological parameters. Davis and others (1999) over fit their trees, and did not report misclassification rates. For forecasting purposes models with misclassification rates less than 20% are generally accepted (Föhn, 1998). The trees produced in this study could therefore be used for forecasting.

The precipitation parameters were the most used variables for splitting between avalanche days and non-avalanche days (Table 4). This indicates that precipitation is the most important variable in triggering avalanches in the study area, backing up observations that most avalanches are direct action, meaning that they are released during or shortly after storms pass over the area. The releases are due to an increase in shear stress of weak layers in the snow cover, caused by the weight of the new snow. The strong dependence of avalanche release on precipitation explains the success of single parameter threshold criteria for the probability of avalanche release, such as the probability approach suggested by Bakkehøi (1987) for the study area. This criterion relates the probability of avalanche release in a particular avalanche path to the summed three or five day precipitation. Such criteria are in active use in avalanche warning for RV15. The *rr5day* splitting value of 33.45 mm for the dry snow avalanches seems reasonable and alone correctly classifies almost 25% of the observed avalanche days but alone misclassifies almost 55% (Fig. 5). However, the values of 5.52 mm for all avalanches (Fig. 4) and 5.55 mm for the wet snow avalanches are surprisingly low and require further investigation.

After precipitation wind speed was the parameter most often used to split between avalanche and non-avalanche days, either as the mean or maximum, but mainly over a period of five days. The release of avalanches after periods of strong winds is well known and is caused by the wind transported snow increasing the stresses in the snow cover in the same way as new snow load. A parameter combining wind speed – possibly to the fourth power – and precipitation as suggested by Davis and others (1999) may provide another good explanatory parameter and could be investigated in further studies.

Temperature-related parameters such as positive and negative degree days and the number of freeze-thaw cycles were also used for some splits, but the interpretation of these parameters was not straight forward and they must be investigated further. The number of rain on snow events was strongly temperature related and was not surprisingly important for the release of wet avalanches. Rainwater may penetrate the snow cover to a layer with low permeability or to the ground, and cause a reduction in the strength of the snow above this layer by destruction of the bonds between snow crystals. High temperatures may have a similar effect by producing meltwater that may percolate through the snowpack, but may also have a stabilizing effect on the snow cover by decreasing the time for snow grains to produce strong bonds and decrease the time that weak layers are present in the snowpack. The analysis of all avalanche data (Fig. 4) indicates that the stabilizing effect of reasonably warm temperatures may be more important in the study area than the destabilizing effect that may release wet avalanches, as the temperature parameter was found to have only minor importance in the release of wet slides.

Norway is expected to experience considerable changes in climate over the next 100 years (Hanssen-Bauer and others, 2003). For certain purposes, such as land hazard zoning and cost-benefit analyses of tunnels in avalanche terrain, it will be important to know how a change in climate will affect the release frequency of avalanches. The results presented here suggest that to predict changes in avalanche frequency, one must first predict how precipitation and wind will change in the future. While this is no simple task, it is encouraging that the simple variables based on only one meteorological parameter showed a higher degree of control over avalanche release frequency than more complex variables involving multiple meteorological parameters as these would be even harder to predict for the future. In the study area, the yearly precipitation and the number of days with high precipitation events are predicted to increase. Using the classification trees found in this study qualitatively, the predicted change in precipitation will mean an increase in the number of days with avalanche events along RV15. However, further studies will have to test this against other statistical models. To be useful for society, such an analysis must give a quantitative estimate of the expected changes in future avalanche frequency. This will be pursued in a future study.

5. CONCLUSIONS

Based on classification trees aimed at splitting avalanche days and non-avalanche days using meteorological parameters derived from precipitation, temperature and wind grids, we have reached the following conclusions:

- Precipitation was the most important parameter for avalanche release in the study area, mainly if given as five, one or three-day sum. Precipitation was followed in importance by wind speed and temperature parameters.

- Based on a set of simple meteorological parameters it can reasonably well be predicted whether a day will have avalanches or not.
- Predicted climate change with an increased number of days with high precipitation will lead to an increase in avalanche days.

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