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ScienceDirect
Cold Regions Science and Technology 47 (2007) 207–223
cold regions science and technology
www.elsevier.com/locate/coldregions

Snow cover spatial variability at multiple scales: Characteristics of a layer of buried surface hoar

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Received 22 August 2006; accepted 20 September 2006

Abstract

With the aim of a multi-scale analysis, we simultaneously observed snowpack stratigraphy and stability at three scales: the slope scale, the regional scale and the mountain range scale. The minimum spacing between measurements was 0.5 m and the maximum extent was about 17 km. Field measurements were made during five periods near Davos in the eastern Swiss Alps and focused on a layer of surface hoar. The layer was initially observed on the snow surface where it showed a high degree of spatial continuity. After burial the layer was less spatially continuous. Snow stability and its variation depended on the existence and size of the surface hoar layer. At the slope scale, measurements were made with a micro-penetrometer at a high spatial resolution and showed that the layer of buried surface hoar was spatially continuous at the slope scale. At the regional and mountain range scale various patterns in surface hoar size and presence were observed. A spherical semivariogram model fitted to the regional data gave a range of 500–1500 m. At the mountain range scale the distance of autocorrelation increased to around 10 km. The different lengths of autocorrelation indicate that the observed variability was the result of several physical processes with different typical scales.

Keywords: Snow cover; Snow stability; Spatial variability; Avalanche forecasting; Scale; Geostatistics

1. Introduction

Two of the most prominent properties of the mountain snowpack are its layering and a high degree of lateral or spatial variability. It is believed that wind turbulence over steep, complex terrain and highly variable solar radiation are the main causes of this variability (Colbeck, 1991; Sturm et al., 1995). The temporal evolution of snow stability and the spatial variability represent two main challenges in avalanche forecasting (McClung, 2002).

Spatial variability of snowpack properties exists at different scales from the scale of a bond between snow crystals (10^{-4} m) to the scale of a mountain range (10^5 m). The scales defined in Table 1 are particularly relevant for avalanche forecasting. The variability at the different scales has different causes and degrees of importance for avalanche formation and forecasting. Regional avalanche forecasting is typically focused on patterns at the scale of mountain ranges and seeks to differentiate snow stability between different aspects and elevations. However, to predict instability or the probability of an avalanche to release, the variability at

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doi:10.1016/j.coldregions.2006.09.002

Table 1
Definition of scales investigated

Scale	Length	Characteristics
Layer or point scale	1 cm − 0.5 m	The scale of the typical snow layer thickness
Snowpack scale	0.5 m − 5 m	The scale of the typical snow cover thickness
Slope	5 m − 100 m	The size of typical avalanche slopes Radiation is constant due to constant aspect
Basin/ drainage	100 m − 1 km	Area with slopes of different aspects, inclinations and elevations. Radiation varies; precipitation is constant
Region	1 km − 10 km	Precipitation varies
Mountain range	0 km − 100 km	Spatial snow cover patterns are due to the tracks of individual storms

the slope scale needs to be known. Though the dry-snow slab-avalanche release process occurs at the slope scale, the sub-slope scales directly influence avalanche formation by affecting failure initiation and fracture propagation (Schweizer et al., 2003a). The effect can either favor or prevent instability — mainly depending on the relation of the length scale of variation to the critical length of the initial failure (estimated to be on the order of 0.1–10 m) (Schweizer, 1999). The standard method to assess snowpack instability is to do local observations of snow stratigraphy and perform a stability test. However, the extrapolation of the test results is hindered by spatial variability, which can usually not be quantified. It is therefore crucial to understand the nature and causes of spatial variability, not only for one scale, but across the scales relevant for avalanche release and forecasting.

Blöschl and Sivapalan (1995) review scale issues related to snow hydrology, and Blöschl (1999) proposes a framework applicable for all studies dealing with scale issues. The framework operates with three types of scales: process scale, measurement scale and model scale. The measurement scale and the model scale are identified by the scale triplet: support, spacing and extent. The support of a measurement is the length, area or volume of the sample. The spacing is the distance between measurements and the extent is the total distance across the sampling area. In this study, there is a scaling issue in regard to scaling of a process measured with different supports (i.e. snow stability inferred from different methods) since spatial variability is a function of measurement support, i.e. a variable that has high variation measured at one support might have less variation measured at a larger support (e.g., Blöschl, 1999). To give an intuitive meaning to the different scales studied here, logical names were given to each of the scales used (Table 1).

In addition, the scaling of stability itself presents a problem. Three scales that are often used in avalanche forecasting are point stability, slope stability and regional snowpack stability. Point stability is proportional to the additional load (usually dynamic) a small (compared to a slope), isolated snow block will withstand before fracturing. Slope stability is inversely proportional to the probability that an avalanche will release on a given slope. Regional snowpack stability is proportional to the probability and frequency of avalanche release in a given region. For avalanche forecasters and recreationists, it is relevant to know the relation between point stability, slope stability and regional snowpack stability.

Since the first notable study by Conway and Abrahamson (1984) several authors have described and partly quantified spatial variability at different scales. Most studies were focused at the slope scale (Birkeland et al., 1995; Campbell and Jamieson, in press; Föhn, 1989; Jamieson, 1995; Kronholm and Schweizer, 2003; Landry et al., 2004; Stewart and Jamieson, 2002). Various point (stability) observations were made using different grid-type measurement layouts. A few studies have approached the regional scale or mountain range scale (Birkeland, 2001; Hägeli and McClung, 2003; Schweizer et al., 2003b). All these studies provided a better insight into the problem, but considered only one scale at a time.

Buried layers of surface hoar frequently form the failure layer of dry-snow slab avalanches (Schweizer and Jamieson, 2001). Knowledge of the spatial distribution of surface hoar would therefore be valuable for avalanche forecasters. Optimal growth of surface hoar crystals can be estimated from meteorological conditions (wind, humidity and temperature conditions) (e.g., Hachikubo, 2001). Due to the spatial variations of these parameters the spatial distribution of surface hoar existence is difficult to forecast. For complex alpine terrain, Feick et al. (in press)) showed that for estimating surface hoar growth conditions the local wind regime needs to be known with high spatial resolution (≤ 10 m). Hägeli and McClung (2002) studied the spatial characteristics of persistent weak layers across the Columbia Mountains of Western Canada. They showed that when layers of buried surface hoar formed they could extend over considerable areas, sometimes across several mountain ranges. They proposed that this coverage was in agreement with the spatial extent of the meteorological conditions necessary for these weak layers to develop. Nevertheless, smaller scale variability existed within the mountain ranges, in particular in regard to aspect and elevation. Birkeland (2001) and Schweizer et al. (2003b) quantified snowpack stability variations due to aspect and elevation across a small mountain range.

As mentioned above, wind and solar radiation are considered as major snow cover process drivers. Sturm and Benson (2004) proposed meteorological conditions (mainly wind and temperature) in combination with topography and vegetation to be the chief agents of snow layer heterogeneity. More specifically, for surface hoar growth and destruction, the focus of this paper, the micrometeorological conditions near the snow surface are crucial. All agents that affect the micrometeorology should be considered as process drivers and included as explanatory variables into the statistical analyses. However, as a complete distributed modeling approach was beyond the scope of this paper, and as most of the variables cannot easily be extrapolated to complex alpine terrain from scarce point observations, we will mainly consider terrain parameters as being the process drivers.

The aim of the study was to observe and quantify the spatial variability of snowpack stratigraphy and stability over a wide range of scales from 0.5 m to 10 km in the surroundings of Davos in the Eastern Swiss Alps. During most of the study period a layer of buried surface hoar was the major concern for snow stability evaluation and avalanche forecasting. In the present paper, we focus our analysis on the spatial variability of this layer. The surface hoar was at the snow surface at the beginning of our observations, and after it was buried by subsequent snowfalls, was sampled four times during the following two months. We compared fine-scaled quasi-continuous snowpack measurements from three slopes to point observations on adjacent slopes of similar aspect within the same region as well as to slopes in a

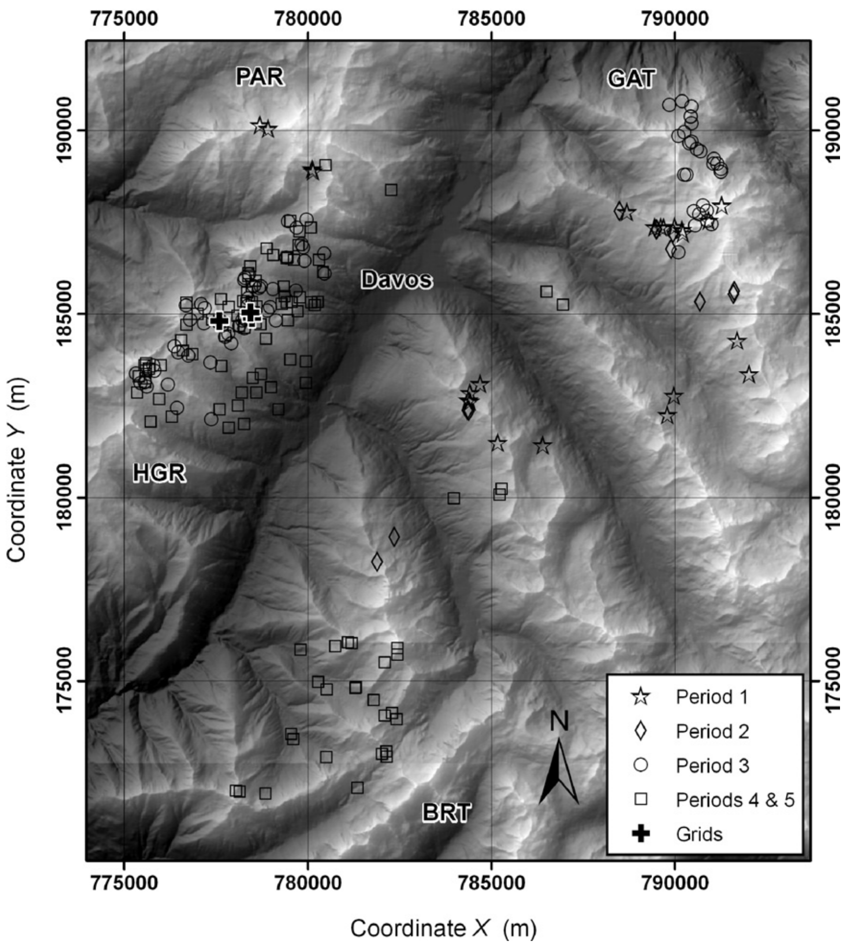

Fig. 1. Map of study area around Davos, eastern Swiss Alps with all observation and measurement locations. The Swiss coordinate system is shown with grid lines 5 km apart. The four regions are indicated: Gatschiefer–Pischa (GAT), Parsenn (PAR), Hanengretji (HGR) and Bärentälli (BRT). The crosses (grids) indicate the locations of the slope and snowpack scale measurements DHM25©2006 swisstopo (DV033492).

neighboring region across the valley about 12 km to the east-north-east. We will describe (1) the snowpack stability variation and (2) the patterns of surface hoar occurrence from the snowpack scale to the regional scale. The surface hoar observations will be related to terrain variables assumed to be process drivers. Finally, we will quantify the spatial variability with geostatistical methods using the semivariogram and an autologistic regression model.

2. Methods

2.1. Study area

Snowpack data were collected around Davos, Eastern Swiss Alps (Fig. 1). Davos is located at 1560 m a.s.l. in a valley running north-east to south-west. The four regions investigated were the surrounding ridges and drainage basins to the west (Hanengretji: HGR), to the north-west (Parsenn: PAR), to the east (Gatschiefer–Pischa: GAT) and to the south (Bärentälli: BRT) of Davos (Fig. 1). Ridge-tops reach 2600 to 3000 m a.s.l. in all regions.

2.2. Data collection periods

The data were collected during the winter 2002–2003 whenever the weather and the avalanche conditions were favorable, the snowpack was sufficiently interesting and the resources needed for a spatial study were available. This resulted in five separate sampling periods (Table 2). Initially, during periods 1 and 2 only limited resources were available and sampling was therefore limited. Nevertheless, these data were retained since they provided insight into layer characteristics before burial of surface hoar. Period 3 was the first major sampling period which included two fine-scaled slope measurements (grids 1 and 2). During period 4 the forecasted level of avalanche danger was High (second highest level on the 5-level danger scale) (Meister, 1995) and data collection was therefore limited. The last period (5) included one fine-scaled slope scale measurement (grid 3).

2.3. Field methods

Snow cover stratigraphy and stability were sampled at a number of locations in each region. At each measurement location, either a full manual snow cover profile or a penetration resistance profile was made. The full snow profile observation included grain type and size, hand hardness index for each layer, snow temperature and ram hardness (Colbeck et al., 1990). In addition, a rutschblock test was performed as described by Schweizer (2002). For the analysis, each manual profile was subsequently classified by the authors in respect to stability into very poor (1), poor (2), fair (3), good (4) and very good (5), following the point stability classification scheme proposed by Schweizer and Wiesinger (2001). Penetration resistance profiles were made with a snow micro-penetrometer (SnowMicroPen: SMP) (Schneebeli and Johnson, 1998). These profiles provided indirect but reliable evidence of the presence or absence of buried surface hoar (Kronholm et al., 2004). Both types of measurements have a small spatial support compared to the process scale (slope). The support is about 20 mm^2 for the SMP (the area of the measuring tip) and 3 m^2 for the snow profile (the area of the rutschblock test). In this study we therefore consider both manual profiles and SMP profiles as measurements at the point scale (Table 1).

Table 2
Data collection periods and prevailing regional avalanche danger during field measurements

Period	Date	Number of manual profiles	Number of Grids	Avalanche danger	
				Forecasted	Verified
1	11–12 Dec 2002	23	0	2, > 2400, W–N–E	1, > 2400, extreme
2	7 Jan 2003	12	0	2, > 1800, all	3, > 2400, NW–N–SE
3	13 and 15–17 Jan 2003	81	2	2, > 2000, all	1, > 2000, all
4	7 Feb 2003	14	0	4, > 1500, all	3–4, > 1800, all
5	17–20 Feb 2003	97	1	2, > 2200, all	1, > 2000, extreme

The forecasted avalanche danger is given as issued in the public bulletin. The verified avalanche danger is based on observer's assessment and analysis of snow profile data. The regional avalanche danger is described as danger level 1 to 5: Low (1), Moderate (2), Considerable (3), High (4), Very High (5), elevation above which the level prevails, and sector of aspects (clockwise): part of the compass with the highest danger. If, for the sector of aspects, "extreme" is given, this means that the danger only prevails on a few extremely steep, shady and rocky slopes; whereas "all" means in all aspects.

2.4. Measurement locations

To enable a multi-scale analysis, the observations at the slope scale, at the regional and mountain range scale were coordinated. For the variability at the slope scale, SMP measurements were made in a cross-shaped grid with an extent of 19 m (Kronholm et al., 2004). Each grid included 113 SMP measurements with spacing varying from a minimum of 0.5 m in the center of the grid to a maximum of 2 m in the arms of the grid. In the lower left, inner corner of the cross, a snow profile with a rutschblock test was observed. The grids were restricted to slopes with a northerly aspect. We expected these slopes to provide the best chance of making measurements on a slope with the buried layer of surface hoar. Furthermore, by selecting a slope not directly exposed to solar radiation, temporal (diurnal) variations were negligible. An overview of the study area with the locations for the manual snow cover profiles and the grids is shown in Fig. 1.

The spatial variability at the regional and mountain range scale was observed with snow profiles. These observations could not be distributed evenly over the study area due to numerous restrictions, first of all, safety concerns. For the same reason, measurement locations cannot exactly be predefined. However, the sampling was systematical insofar as each two-person field team was assigned a certain area, an elevation range and an aspect sector in which the team had to do the snowpack observations on a daily basis. The sampling location restrictions for each team were determined in the morning before the sampling day, based on snow stability conditions and sampling locations on the previous days (Schweizer et al., 2003b). On a given day, between 4 and 11 field teams made observations.

2.5. Snowpack variables

For each period, we investigated the spatial variability of a) snowpack stability, b) the existence (presence or absence) of a specific layer of surface hoar, and c) where the surface hoar layer was observed in the manual profiles, the size of the surface hoar crystals. The spatial variability of presence and size of the studied surface hoar layer was related to terrain and meteorological variables.

2.6. Terrain variables

The terrain parameters studied were the coordinate X (east), coordinate Y (north), elevation, distance to ridge, and slope inclination and aspect (Table 3). The location coordinates X and Y were studied to see if any large-scale trends were present at the regional and mountain range scale. The coordinates for each sampling location were determined in the field using a combination of GPS receivers and 1:25,000 maps. The elevation ELV and the distance to ridge D were investigated because we considered these to be indicative for the wind field: Locations at higher elevations and closer to a major ridge were assumed to be more influenced by wind than lower elevations and locations far from major ridges.

Table 3
Independent variables used in logistic and linear least squares regression models

Number	Variable	Abbreviation	Unit	Scale
1	Elevation	ELV	m	Basin
2	X-coordinate	X	m	Region
3	Y-coordinate	Y	m	Region
4	Slope inclination	ψ	degrees	Slope, Basin
5	Radiation index (slope aspect)	RI	degrees	Basin
6	Distance to ridge	D	m	Slope, Basin
7	Solar radiation	R_s	–	Basin
8	Neighborhood probability	P_{NN}	–	Basin

The non-numerical variable aspect was replaced by a numerical variable, the radiation index, which describes the absolute deviation from north. Solar radiation is a daily total for 1 January normalized by the maximum radiation possible that day. The neighborhood sum is used for the autologistic regression to take into account the spatial autocorrelation. Also given is the approximate scale at which the variable is supposed to cause spatial variability.

We did not consider orientation to predominant wind direction (lee, windward, cross-loaded). Elevation was determined in the field by a combination of an altimeter and 1:25,000 maps. Distance to ridge was determined by digitizing major ridgelines from a 1:25,000 map and calculating the distance from each sampling location to a major ridge in a GIS. The determination of major ridges in the study area was partly subjective and relied on our knowledge of the area. Despite a significant correlation between ELV and D ($R^2=0.37$, $p<0.001$) we chose to include both variables in the analyses. Our choice was legitimate as the stepwise regression analyses described below always included only one of the variables in the best regression model. Slope inclination and aspect were determined with inclinometer and compass in the field, and were considered in the analysis because of their influence on the radiation at a location. The non-numerical terrain parameter slope aspect was described by the radiation index RI. The radiation index RI described the absolute deviation (in degrees) from the north direction (Birkeland, 2001) and was calculated from the slope aspect. Other terrain variables that might influence the surface hoar layers such as ground cover properties (e.g. vegetation and roughness) were not considered.

2.7. Meteorological variables

The only meteorological variable that was considered was solar radiation (Table 3). The incoming solar radiation R_s was determined for all sampled locations for 1 January based on the measured slope inclination and aspect at each location. Shadow effects due to terrain as well as reflections from adjacent slopes were not considered in the calculations, and the cross correlations between R_s and slope inclination ψ, which were both included in the regression analyses, were neglected. The solar incidence angle (angle between the slope-normal and the solar beam) for a given slope inclination and aspect was calculated according to Oke (1987). We chose 1 January since we assume the radiation conditions on that day as representative for the period between the burial of the surface hoar layer and our observations in January. The calculated daily radiation at each sample location was normalized by the potential maximum value for that day, giving a dimensionless index for potential solar radiation.

Although other meteorological conditions such as wind and precipitation, will affect the distribution of surface hoar, we did not investigate the effect of these variables in the present paper.

2.8. Regression analyses

To investigate the influence of the chosen terrain and radiation variables on the presence or absence of surface hoar we used uni- and multivariate logistic regression models. Standard logistic regression models assume the responses at each site to be independent when in fact the responses may be spatially autocorrelated (e.g., Wu and Huffer, 1987). A common way of incorporating spatial autocorrelation in the logistic regression model is to introduce an additional parameter describing the degree of spatial correlation in the data. This model is called autologistic regression model. To represent possible autocorrelation in the presence of surface hoar in the statistical model we used P_{NN} the inverse-distance weighted probability sum that the surface hoar is present at the five nearest observation sites:

$$P_{NN} = \frac{\sum_{i=1}^{5} w_i P_i}{\sum_{i=1}^{5} w_i} \qquad (1)$$

where P_i is 1 if the surface hoar is present, and 0 elsewhere, and the weight $w_i = 1/d_i$, is the inverse distance d_i from the observation point to the neighbor i. Any number of neighbors could have been used to calculate P_{NN}. We chose five to keep the distance to the neighbor sites relatively small in order to include only local effects in the variable. Five neighbor sites were considered to be enough to make the variable reasonably robust to possible errors in the observations.

The influence of the variables on the surface hoar grain size was investigated using uni- and multivariate linear least squares regression. For these analyses, the grain size was set to 0 mm for measurement locations where the surface hoar layer was not observed. Stepwise forward and backward selection of the best model was done by including a term if its significance value was ≤ 0.15 and excluding a term if its significance value was > 0.15.

Explicit spatial analyses were made using the semivariogram. Following Goovaerts (1997), the spatial patterns of presence or absence of surface hoar were considered as indicator variables. We did this by setting the indicator variable Z_{ind} as 1 for location where surface hoar was observed and 0 for all other locations. From this constructed variable an experimental indicator semivariogram γ was calculated by

$$\gamma(h) = \frac{1}{2m(h)} \sum_{i=1}^{m(h)} \{Z_{ind}(x_i) - Z_{ind}(x_i + h)\}^2 \qquad (2)$$

where $m(h)$ is the number of point pairs separated by the lag distance h, and $x_i = (X_i, Y_i)$ is the spatial location of the observations.

Comparison of stability or surface hoar existence between regions was made using the non-parametric Mann–Whitney U-Test. Observed differences were judged to be statistically significant where the level of significance is $p < 0.05$.

2.9. GIS analysis

The regression models that explained most of the observed surface hoar size in the HGR region was modeled in a Geographical Information System (GIS). A digital elevation model (DEM) with a pixel size of 25 m was used to derive aspect and slope inclination for the area. The radiation index RI was calculated from the aspect and distance to ridge D was calculated as the shortest distance from a measurement location to the nearest ridge.

3. Results

3.1. Snowpack stability

Snowpack stability in late December 2002 and early January 2003 was strongly influenced by the presence of a buried surface hoar layer. The surface hoar formed in the first half of December 2002 and became shallowly

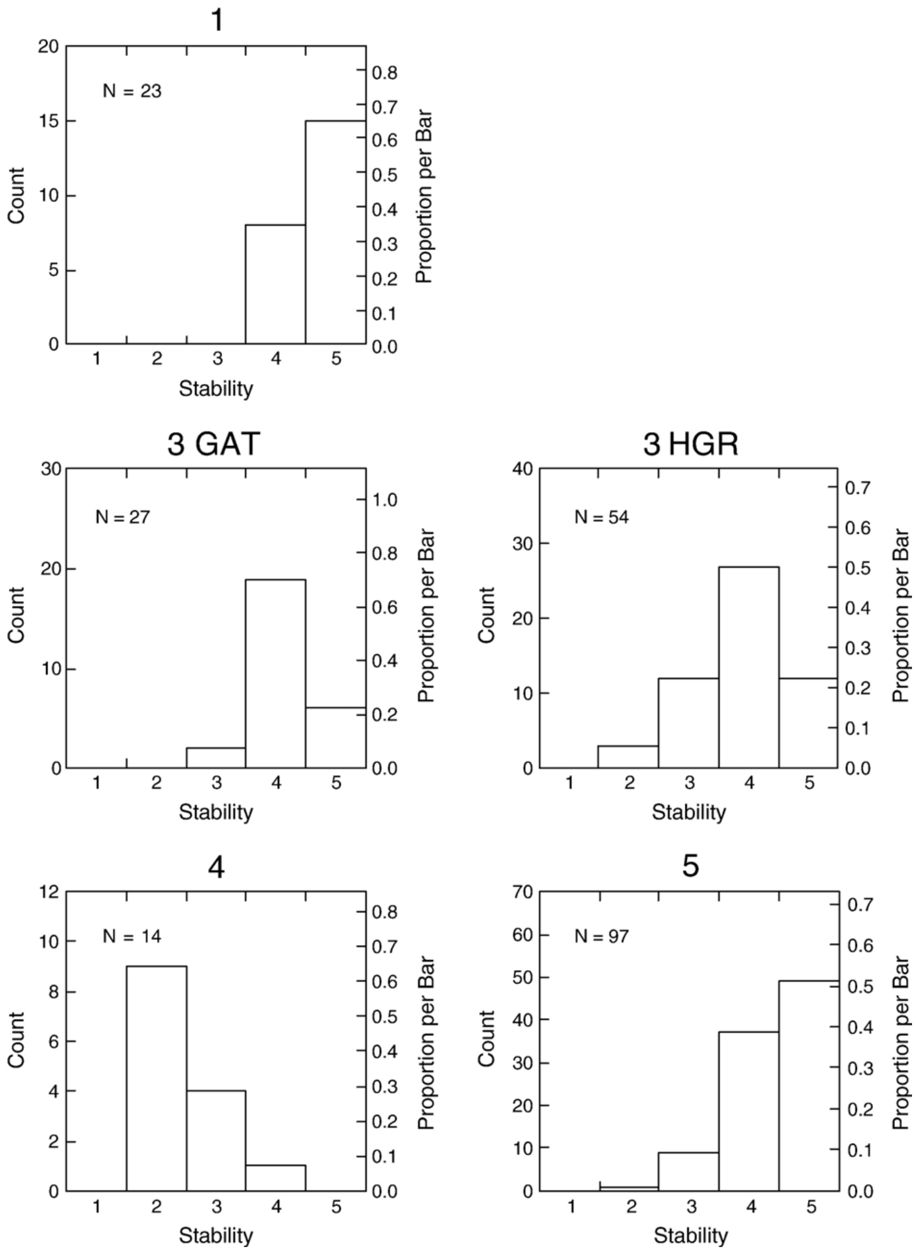

Fig. 2. Snowpack stability distributions for periods 1 and 3–5. The stability is given as 1 to 5 (1= very poor, 2= poor, 3= fair, 4= good, 5= very good). For period 3 the stability is shown for the two regions Gatschiefer GAT (left) and Hanengretji HGR (right).

buried by 16 December 2003 and was covered with a 40–60 cm thick slab by the end of December 2002. Many avalanches (10–20 in total) were triggered by recreationists with the buried surface hoar layer as the failure layer in the area of Davos. Occasional triggering (1–3 per week) continued until mid January 2003, but at that time triggering spots were rare and difficult to predict. By mid January 2003 failure initiation probability was low, but propagation potential was still high. This condition was exemplified by the fact that during period 3 on 15 January 2003 three avalanches were triggered remotely by our observers.

The regional stability distributions as found during the five sampling periods are shown in Fig. 2. The forecasted and verified danger levels are compiled in Table 2. The verified danger level results from the observers' estimate of the regional danger at the sampling day and the stability distribution found from profile analysis as compared to the standard distributions for the various danger levels found by Schweizer et al. (2003b).

In period 1, before the burial of the surface hoar layer, the stabilities of the majority of the profiles were rated as very good (5) and the observers agreed that the danger level was Low. During period 2 the number of profiles ($N=12$) was insufficient for analysis. However, there was a trend for higher stability on slopes with more southerly aspects ($p=0.028$).

In period 3, about two weeks after burial of the critical layer of surface hoar the median stability was good (4). This indicates that the avalanche danger was Low according to the typical stability distribution established by Schweizer et al. (2003b). However, the spread of stability in the region HGR was unusually wide compared to the typical distribution for Low. On the other hand, at the same time in the region GAT the stability distribution (Fig. 2) resembled very much the model distribution of the danger level Low. Though there was no statistically significant difference between the regions (Mann–Whitney U-test, level of significance $p=0.18$), there were clearly more poor and fair profiles in HGR than in GAT.

For the sampling day of period 4 the forecasted danger level was High (4). Though observations were restricted by the prevailing danger level the median stability found was poor (Fig. 2). The avalanche activity had peaked the day before and for the sampling day most observers rated the danger level as 3–4 (Table 2). During period 5 in mid February 2003 rather stable conditions prevailed with a median stability throughout the regions of very poor (Fig. 2) corresponding to a danger level of Low, or even somewhat less (Table 2).

In a univariate least squares regression analysis none of the explanatory variables (Table 3) were significantly related to the stability in the region HGR in period 3. Using stepwise forward and backward multivariate least squares regression with the stability as dependent variable, the best model found included the coordinate X, radiation R_s and distance to ridge D. However, this model was not significant ($p=0.09$) and only explained a small part of the stability variation ($R^2=0.15$).

3.2. Surface hoar distribution and size

3.2.1. Period 1

The first observations were from 11 and 12 December 2002 when 23 manual snow profiles were collected in a wide range of elevations and aspects. Most were collected in the GAT region (13) and a few in the other three regions (Table 4). In all profiles surface hoar was observed on the surface (Table 4).

Table 4
Surface hoar observations for each of the regions in the five periods

Period	Region	Number of profiles		SMP	SH presence in manual profiles	
		Total	Manual		N	%
1	Total	23	23	0	23	100%
	BRT	6	6	0	6	100%
	GAT	13	13	0	13	100%
	HGR	0	0	0	–	–
	PAR	4	4	0	4	100%
2	Total	12	12	0	7	58%
	BRT	4	4	0	3	75%
	GAT	8	8	0	4	50%
	HGR	0	0	0	–	–
	PAR	0	0	0	–	–
3	Total	307	81	226	45	56%
	BRT	0	0	0	–	–
	GAT	27	27	0	6	22%
	HGR	280	54	226	39	72%
	PAR	0	0	0	–	–
4 & 5	Total	224	111	113	28	25%
	BRT	28	28	0	4	14%
	GAT	2	2	0	0	0%
	HGR	193	80	113	23	29%
	PAR	1	1	0	1	100%

The surface hoar grain size was smaller in the region GAT (2–3 mm) than in the regions PAR and BRT (4.5–10 mm) which were pooled for analysis to get enough data for a sound analysis. The difference in size was statistically significant (U-test) between the GAT and the PAR/BRT regions both for the mean surface hoar size E_{mean} ($p=0.033$) and in particular for the maximum surface hoar size E_{max} ($p=0.002$).

A multiple stepwise linear regression for the maximum surface hoar grain size in all profiles recorded during period 1 using terrain variables 1–6 (Table 3) as possible predictors was significant ($p<0.001$) and explained 66% of the variance. The location coordinates and the distance to ridge D were the only three significant variables left in the selected regression model. The best regression model selected by multiple stepwise linear regression for the mean surface hoar size E_{mean} included the same variables (X, Y and D) but explained less of the variance ($R^2=0.49$, $p=0.004$). The coefficients for X and Y were negative, demonstrating the regional difference of smaller surface hoar crystals in the GAT region (to the north and north-east of the PAR and BRT regions) mentioned above.

Looking at the GAT region alone ($N=13$), only the terrain variable Y was correlated (positively) with E_{max} ($R^2=0.47$, $p=0.009$). The coordinates (X, Y) were the only variables involved in the best linear prediction model for the mean surface hoar size E_{mean} and explained 63% of the variance ($R^2=0.63$, $p=0.007$).

3.2.2. Period 2

On 7 January 2003, several days after the avalanche activity on the buried surface hoar layer had peaked, eight profiles in the GAT and four in the BRT region were made (Table 4). The buried surface hoar layer was reported in three out of the four profiles in the BRT region, and four out of the eight profiles in the GAT region (Table 4). The number of profiles was too low for a sound analysis, but the percentage of profiles where the surface hoar layer was observed had decreased from period 1.

While buried surface hoar was observed in profiles on most aspects, profiles where the buried surface hoar was not observed were only located on southerly aspects.

3.2.3. Period 3

During period 3 a total of 307 profiles were made (Table 4). These were located in the HGR region (280 profiles) and GAT region (27 profiles). On the first day of period 3 (13 January 2003), 113 SMP measurements were made in a grid on a north-facing slope at 2525 m a.s.l. in the HGR region (grid 1). A manual snow profile was recorded on the same slope. The buried surface hoar layer was present in all 113 SMP profiles, demonstrating spatial continuity of the surface hoar layer at the slope scale. The SMP profiles provide some indication of the surface hoar grain size by calculation of the microstructural element length (Johnson and Schneebeli, 1999). However, this variable did not correlate well with grain size observations from manual profiles (Kronholm, 2004, p. 106), and we have therefore not used the results here. A further analysis of the SMP signal with focus on extracting the grain size is outside the scope of this paper.

On the same day, 15 additional profiles also primarily in north-facing slopes were made in the HGR region. This subset of the data provides a possibility for analyzing a more spatially and temporally homogeneous dataset than the full dataset: all profiles were from shady slopes within a smaller area and all were collected on one day. By using this dataset, we are able to sort out the effect of aspect and the radiation variables and focus more on other terrain variables. In 12 out of the total 16 profiles the layer of buried surface hoar was found. Maximum grain size ranged from 1 to 30 mm with a median of 15 mm. Univariate regression analysis on each of the variables 1–7 (Table 3) with mean surface hoar grain size showed that elevation and the X coordinate were the only statistically significant variables. For the maximum surface hoar size the Y coordinate was also a significant variable. However, the best stepwise multiple regression model included the three variables X, D and ψ and explained 83% of the variance ($p<0.001$).

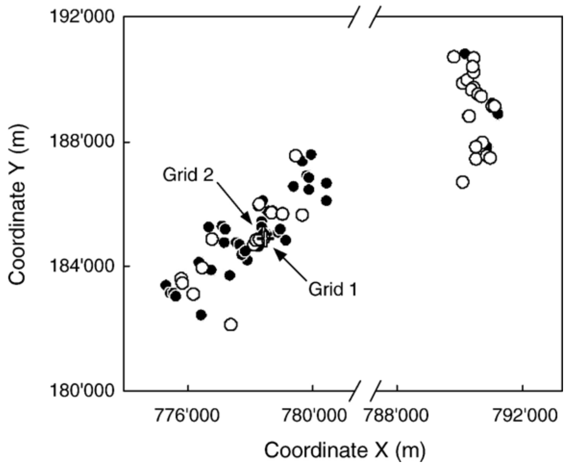

Fig. 3. Sampling locations during period 3 in the HGR region and the GAT region. Open circles (○) indicate the location of profiles where surface hoar was not observed and filled circles (●) indicate profiles where surface hoar was observed. Crosses (+) indicate the locations of the grids.

In the subsequent days of period 3, 65 manual profiles were collected in all aspects covering the regions HGR and GAT, giving a total of 54 manual profiles in the HGR region and 27 manual profiles in the GAT region (Table 4, Fig. 3). The manual profiles showed that the surface hoar was only occasionally observed in the region GAT (23% of the manual profiles), whereas it was still widespread in the region HGR (72% of the manual profiles, Fig. 4). The number of profiles in the GAT region was too small to analyze the distribution with regard to slope aspect. If the eight profiles made in the GAT region during period 2 were pooled with the profiles from period 3, the proportion of profiles where the surface hoar was observed increased to 32% (11 out of 34). Still, by including these eight profiles, no dependence on the variable solar radiation R_s could be found ($p=0.97$).

In the region HGR, the layer of buried surface hoar was found in 39 of the 54 profiles (72%, Table 4). The proportion was about 86% for the aspects in the sector south-west over north to north-east with north-west as the aspect with the lowest occurrence in this sector (71%, Fig. 4). In the aspects east to south the proportion of surface hoar existence was only about 38%.

Applying univariate logistic regression to the observations in the HGR region ($N=54$) showed that radiation index, slope inclination and solar radiation R_s were significantly related with surface hoar absence or presence (Table 5). Autologistic regression analysis

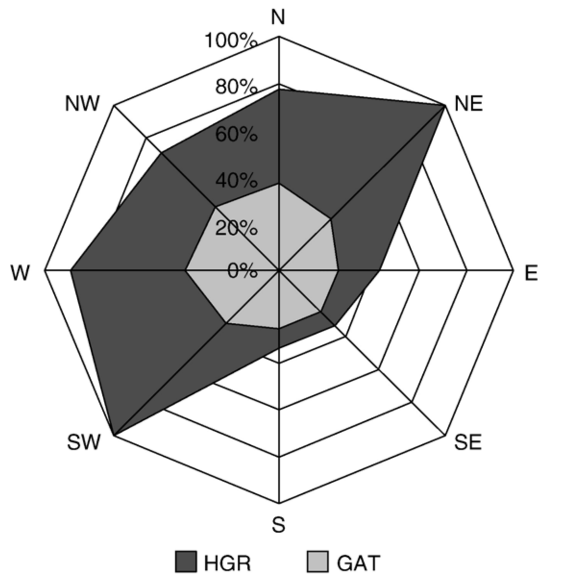

Fig. 4. Distribution of surface hoar in regions HGR ($N=53$) and GAT ($N=33$) (2 profiles from flat locations not included). Axes indicate proportion of profiles in a given aspect in which the surface hoar was found, e.g. for HGR in the northeasterly aspect the surface hoar was found in 100% of all profiles (7 out of 7), whereas in the southeasterly aspect it was only observed in 33% (1 out of 3).

revealed that the neighborhood sum P_{NN} was not a significant predictor. A multivariate logistic model including two of the significant variables in the univariate analysis, RI and inclination, correctly predicted 87% of the surface hoar locations and 60% of the locations where surface hoar was not observed ($p=0.007$). However, a stepwise multiple regression suggested that the best model included only inclination ($p=0.005$) indicating that surface hoar was less frequently found on steep slopes. This model correctly predicted surface hoar presence or absence for 82% of the locations where surface was present, and for 60% of the locations were it was absent. For the observations in the GAT region ($N=27$) a stepwise selection of the best multivariate logistic regression model predicting the locations of surface hoar presence or absence based on all 8 investigated parameters (Table 3) showed that the coordinate X and the slope inclination provided the best model ($p=0.009$). When observations from the HGR and GAT regions were combined, the best model included the X coordinate, slope inclination, solar radiation R_s and the neighborhood variable P_{NN} ($p<0.001$).

Table 5
Significance and classification accuracy for univariate and multiple logistic and autologistic regression models on the presence of surface hoar in the HGR region during period 3 ($N=54$)

Variable(s)	p-value	Classification accuracy
ELV	0.46	0.69
X	0.46	0.39
Y	0.34	0.57
ψ	0.005	0.76
RI	0.031	0.76
D	0.77	0.39
R_s	0.023	0.74
P_{NN}	0.50	0.65
ψ+RI	0.007	0.80

For comparison, the a priori probability of surface hoar presence was 72%.

Table 6
Regressions for the surface hoar maximum grain size observed in all profiles ($N=54$) in the HGR region during period 3

Predictor (s)	p-value	R^2
RI	<0.001	0.20
X	0.009	0.12
Y	0.050	0.07
ψ	0.034	0.08
ELV	0.12	0.05
D	0.58	0.01
R_s	<0.001	0.22
ψ+RI+X+Y+ELV+D+R_s	<0.001	0.40
R_s+X+D	<0.001	0.36
RI+X+D	<0.001	0.36

For an analysis of surface hoar size in the HGR region, the correlation between independent variables 1–7 (Table 3) and the maximum surface hoar size E_{max} was investigated (Table 6). The univariate regression analysis showed that the coordinate X, slope angle, radiation index and solar radiation were all significantly related to E_{max} with the radiation dependent variables R_s and RI being the most significant variables. Stepwise multiple regression suggested the best model to include solar radiation R_s, coordinate X and distance to ridge. Accordingly, maximum surface hoar size should decrease with increasing solar radiation and increasing distance to ridge, and increase with increasing coordinate X (towards east). As much of the variation (36%) was explained by a model including RI instead of R_s.

At the end of period 3 (17 January 2003), another 113 SMP measurements were made on a north-east-facing slope (grid 2, 33°, 2480 m a.s.l.) about 150 m from the slope with grid 1 (Fig. 3). The buried surface hoar layer was again present in all SMP profiles on the slope (Kronholm, 2004, p. 99; Kronholm et al., 2004). Combining the results from the SMP measurements in the two grids with the manual profiles made over the region allowed us to do a spatial analysis spanning a large range of scales (Tables 2 and 7). However, the clustering of 226 SMP measurements within a small spatial extent (two slopes approximately 180 m apart) had too much

Table 7
Minimum spacing and maximum extent of the manual observations during period 3

Region	Minimum spacing (m)	Maximum extent (km)
HGR	26 (0.5)	6.3
GAT	10	4.1
HGR + GAT	10 (0.5)	16.9

When the SMP measurements were also included, the minimum spacing was 0.5 m as indicated in the brackets.

weight in a spatial analysis compared with the 54 manually observed profiles recorded over the remaining HGR region during period 3. Instead of using all 226 SMP measurements in the spatial analysis, we therefore selected 15 measurements from each grid, thus combining 30 instead of 226 SMP measurements with the 54 manually observed profiles. When enough data are present, and the sampling scheme used results in strong clustering, as was the case here, it is common to include only some data (Goovaerts, 1997). The 15 retained profiles were selected from a line through the grid such that 1) all spacings used in the grid (0.5 m to 2 m) were present in the selected data and 2) the full extent of 19 m was represented by the 15 measurements.

Using the data from the HGR region, an indicator sample semivariogram was calculated using the surface hoar presence/absence data from 54 manually observed profiles and 30 SMP measurements (Fig. 5a). A spherical semivariogram model fitted to the data gave a range of 570 m and a nugget ratio (nugget/sill) of 20% indicating a relatively strong spatial structure in the data. If the SMP measurements were not included, the spatial structure of the data was not as obvious but could still be identified (Fig. 5b): The range was around 550 m and the relative nugget was 76%. In the GAT region the spatial structure was not as well defined as in the HGR region and the range was somewhat longer; around 1500 m (Fig. 5c). When the data from the HGR and GAT regions were pooled, the lag distance of the sample semivariogram was extended to 16 km (Fig. 5d). This resulted in a change in the range to around 10 km.

3.2.4. Periods 4 and 5

During period 4 the forecasted avalanche danger was High, thus limiting the data collection to a total of 14

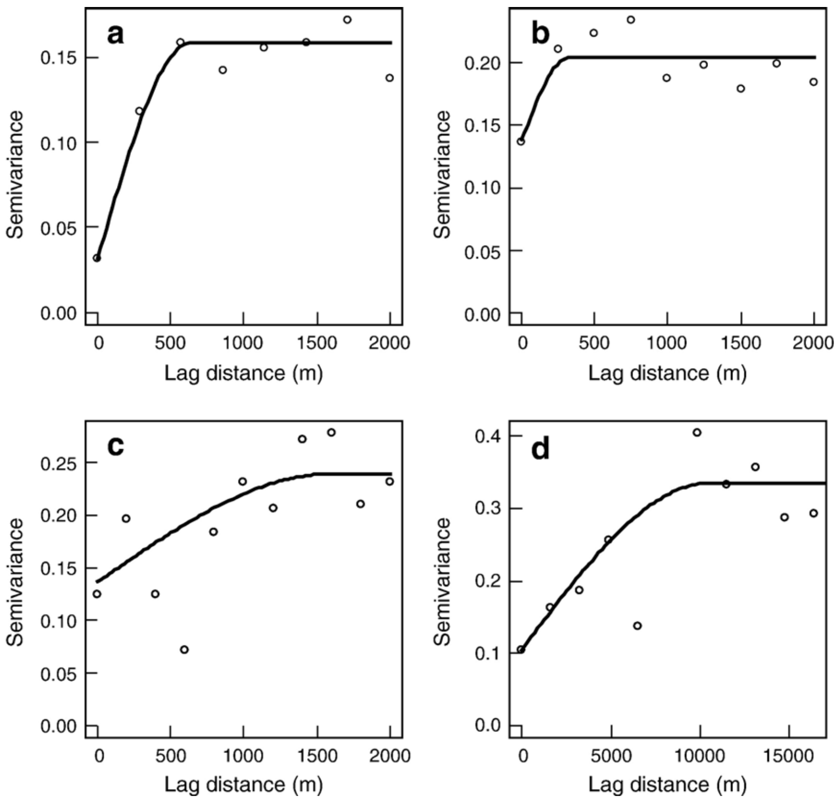

Fig. 5. Sample (○) and model (—) indicator semivariogram for surface hoar presence during period 3. a) Using results from 30 SMP profiles and 54 manual profiles in HGR. b) Using only results from the 54 manual profiles in the HGR region. c) Using only the 27 manual profiles in the GAT region. d) Using the 30 SMP profiles and the 54 manual profiles in the HGR region together with the 27 manual profiles in the GAT region.

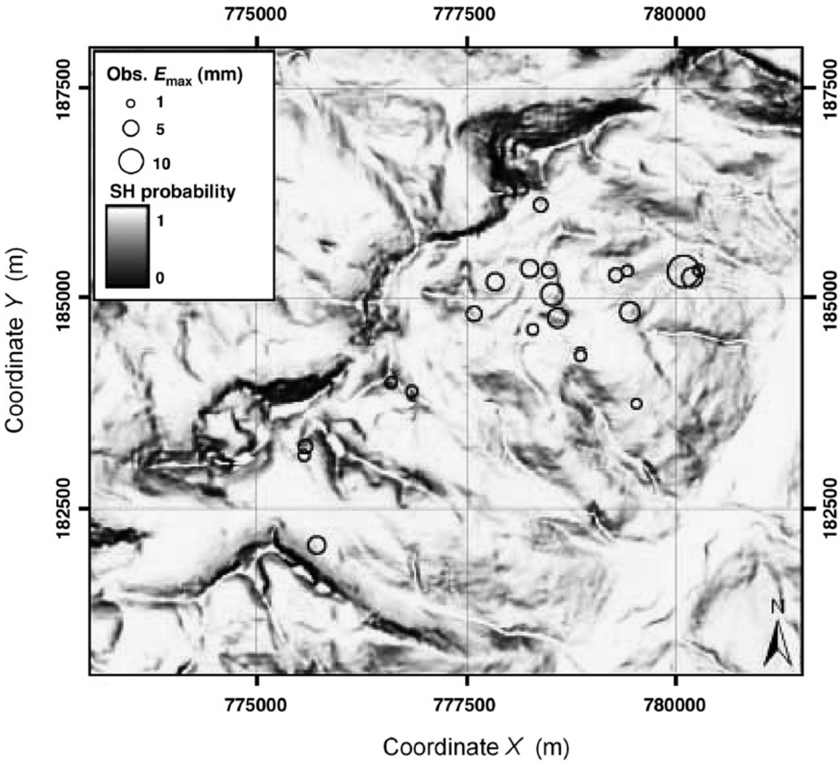

Fig. 6. Predicted probability for the existence of surface hoar based on the logistic multivariate analysis of observations from HGR during period 3 ($8.95-0.206\psi-0.0082$ RI, Table 5). The 23 observations from periods 4 and 5 where the surface hoar was observed are shown with open circles (○) scaled to the size of the observed grain size DHM25©2006 swisstopo (DV033492).

profiles which were collected from all four regions. The number of measurements in each region was too low for a sound statistical analysis. Based on the burial depth of the surface hoar layer (80–100 cm), we assume that little change occurred with respect to existence of the layer of buried surface hoar between periods 4 and 5 (10 days). Pooling of the data from periods 4 and 5 therefore seemed reasonable.

During the two sampling periods in February 2003, 80 manual profiles were taken in the HGR region, 28 in the BRT region to the south of HGR, two in GAT and one in PAR (Table 4). The layer of buried surface hoar was still reported in some of the profiles (HGR: 29%, BRT: 14%), but by that time it was strongly metamorphosed nearly everywhere, difficult to observe in profiles and rarely (in 6% of the cases) was the failure layer that showed up in the stability test. Consequently, we considered the observations of surface hoar presence and size as being more affected by the skill of the observers than in the previous observation periods. A stepwise logistic regression on variables 1–8 (Table 3) for the HGR and the BRT regions showed that the presence of surface hoar was not dependent on terrain or radiation. Only the neighborhood probability P_{NN} was included in the logistic regression models selected by stepwise regression. This was the case when each region was analyzed individually and when they were pooled, and was also the case for linear regression models on the surface hoar size E_{max}.

The locations in the region HGR where the surface hoar was observed in periods 4 and 5 ($N=23$) were used to verify the models derived from the observations in period 3 that related surface hoar existence and size to terrain variables. The logistic regression including radiation index RI and inclination (Table 5) correctly predicted surface hoar presence for 18 out of the 23 locations (78%)(Fig. 6). If only the slope inclination was used, the model performance decreased to 74%. The multivariate regression predicting surface hoar size E_{max} (Table 6) performed poorly: A linear regression of predicted and observed surface hoar sizes gave $R^2=0.09$. The predicted value of the surface hoar sizes was generally overestimated with a mean bias of 3.5 mm. The result was that for only five out of the 23 locations the predicted surface hoar size was within 2 mm of the observed size.

On 19 February 2003 a third fine-scaled slope measurements was done on a south-west-facing slope (grid

3, 35°, 2590 m a.s.l.) about 880 m from the slopes where the previous grid measurements were taken. Again, at all 113 measurement locations the layer of buried surface hoar was found, indicating that the surface hoar presence was still consistent at the slope scale. The logistic models derived from the observations in period 3 predicted surface hoar presence on this slope. The best multivariate linear model predicted a surface hoar size of 7.5 mm whereas the observed size was 5 mm.

Table 8 summarizes the results focusing on the three scales (slope, region and mountain range) in order to show the various trends at the three scales during the five observations periods.

4. Discussion

4.1. Snowpack stability

Snowpack stability found by profile analysis agreed well with the verified danger level (observers' assessment) that was typically somewhat lower than the forecasted danger level. During period 3, the snow stability distribution was unusually wide for Low avalanche danger. The discrepancy was confirmed by three avalanches which were remotely triggered by skiers on 15 January 2002. The triggering conditions found during this period (low failure initiation probability, high propagation potential) might be typical for a situation when the spatial variability at the basin to regional scale is high due to a buried layer of surface hoar. For backcountry travelers the large spread in stability warrants a wider margin of safety than for conditions with smaller spread.

The lack of significant correlations between snowpack stability and any of the explanatory variables in the HGR region during period 3 seems obvious when the avalanche danger is Low. With Low avalanche danger, the possible triggering locations are so rare that no patterns can be described, for example in terms of a sector of aspects or an elevation band where the highest danger prevails.

4.2. Surface hoar distribution and size

In period 1 the surface hoar was present at the surface in all 23 profiles. These observations, which were made in a wide range of elevations and aspects, indicate that surface hoar formation was widespread at the regional and mountain range scales. Similar observations were made by Hägeli and McClung (2002) in the Columbia mountains in Canada. From the observations we conclude that the spatial patterns in the presence or absence of the surface hoar layer found in subsequent periods were caused by various surface hoar destruction processes after period 1 ended.

The surface hoar crystals were smaller in the GAT region than in PAR/BRT region. Regression analysis results reflected this mountain range scale pattern (Table 8). The initial difference in size was possibly decisive for surface hoar existence once the layer was buried. The cause for the size discrepancy remains unclear.

In period 2, after burial of the surface hoar layer, the layer was less frequently found in the GAT region than in BRT region. This pattern might be due to the initially smaller size of the surface hoar in the GAT region. In addition, the layer had mainly disappeared on southerly aspects, indicating that solar radiation was important for the surface hoar disappearance. Destruction could either have been directly when the surface hoar was on the surface, or indirectly after burial by increasing temperature in the snowpack and thus increasing the speed of metamorphic processes responsible for rounding of the surface hoar grains. Furthermore, smaller surface hoar crystals may have been overlooked by the observers, especially if the layer was no longer decisive for stability and therefore did not produce fractures in the stability tests.

In 75% of the 16 profiles taken in shady slopes on the first day of period 3 in the HGR region, the layer of buried surface hoar was observed. Surface hoar grain size decreased with increasing elevation. A similar pattern was observed in period 1 before the surface hoar was buried, when the size decreased closer to the ridges. From the four profiles where no surface hoar was found, three were located above 2500 m a.s.l. just below the highest peaks and ridges in the HGR region at 2600 m a.s.l. This observation suggests that the absence of surface hoar may be due to destruction by wind, which generally increases closer to the ridges, or result from the initially smaller size. Grain size increased to the east, contrasting the regional trend found during period 1. However, during period 1 no measurements were made in the HGR region, and a direct comparison was therefore not possible.

In period 3, we found a strong mountain scale trend: In the GAT region the layer of buried surface hoar was only occasionally found whereas it was still widespread in the HGR region. This pattern was in agreement with the initial pattern of surface hoar size before burial (cause) and the stability pattern (consequence).

At the regional scale, there were no patterns of surface hoar presence in the GAT region. It remains unclear whether the surface hoar was infrequent due to destruction before burial or due to disappearance through metamorphism after burial. The small initial size supports both causes. However, in the HGR region a strong dependence on slope aspect was found. The distribution was almost symmetrical around the north-west–south-east axis (Fig. 4). If the presence or absence of surface hoar was controlled primarily by solar radiation, a symmetrical distribution around the north-south axis would be expected. The aspect-dependent pattern of surface hoar presence for the HGR region might be due to two effects: 1) partial surface hoar destruction by strong north-westerly winds just prior to final burial on 17 December 2002. This is supported by measurements showing that the dominant wind directions were from northwest and south before the surface hoar was buried. 2) Surface hoar destruction by solar radiation on south-facing slopes. This is supported by field observations on 14–15 December 2002 (not reported here) which suggested that the locations where the surface hoar was not observed were all south-facing. Further, the logistic regression model with radiation index and inclination as independent variables performed surprisingly well.

Besides radiation, slope angle proved to be the best predictor for surface hoar presence and to a lesser degree also for surface hoar maximum crystal size (period 3, HGR region). Surface hoar was less frequently found (and smaller) on steeper slopes. This result might be due the increased sky view with decreasing slope angle and hence increased surface cooling due to net outgoing long-wave radiation. In regard to site selection for field observations when surface hoar is a concern, the results of the regression analyses confirm that study sites should be sheltered, have a wide sky view (CAA, 2002) and possibly north-facing aspect.

In contrast to period 1 when the surface hoar grain size was best predicted at the regional scale by the coordinates and the distance to ridge, the best predictor changed to radiation during period 3 as the surface hoar layer aged. This indicates the increasing influence of radiation with increasing age of the surface hoar. This observation is intuitive because wind will only be active in surface hoar destruction before the layer is buried, whereas radiation will remain active in destruction even after burial by supplying energy to drive metamorphic processes in the snowpack. The multiple regression model including all variables only explained about 40% of the variance of surface hoar size in period 3 (Table 6). This proportion is considerably less than the regression model for the observations made on the first day of the period, which explained 84%. On the first day of period 3 the profiles were made primarily on shady slopes. The different accuracy of the regression models was expected since the grain size observations from the northerly slopes sampled on the first day were expected to be less variable between slopes than the results obtained using all measurements from period 3 with data from all aspects.

Birkeland (2001) investigated variation of stability test scores, and found that between 20% and 30% of the variance of stability could be explained by terrain variables, a somewhat higher percentage than found in the present study. Still, our results indicate that more of the variance could be explained by the models for surface hoar size than for stability. This supports the observation that stability is more variable than layer characteristics such as grain type and size (Kronholm, 2004).

Combining the slope and the regional scale in a geostatistical analysis, the resulting variograms suggested that the data were spatially autocorrelated up to a distance of about 500 m in the HGR region and 1500 m in the GAT region (Fig. 5). This indicated that extrapolations of observations of surface hoar could be made out to 500 m on average without taking terrain variables into account such as done in the regression models described above. However, the range within which extrapolation is possible will depend on the particular conditions of surface hoar growth and destruction. For example, knowing that aspect was important for the occurrence of surface hoar, an extrapolation of an observation on a north-facing slope to a south-facing would not make sense although the two locations were close together (e.g. on either side of a ridge). The semivariogram analysis also demonstrated that the estimated distance of spatial autocorrelation depends on the scale analyzed as pointed out by Blöschl (1999). At the mountain range scale the distance of autocorrelation increased to around 10 km from the 500–1500 m at the regional scale due to the distinct difference in surface hoar presence between the two regions. These values of the length of spatial autocorrelation coincide approximately with the lower bounds of the corresponding scales (Table 1). An indicator semivariogram at the slope scale would have shown a line of no semivariance because all observations on each of the investigated slopes were the same (surface hoar observed). The different lengths of autocorrelation indicate that the observed variability is the result of several physical processes with different typical scales. A discontinuous semivariogram exhibiting steps has been proposed for such a multi-scale analysis (Blöschl, 1999).

The number of points included in the sample semivariograms, especially for GAT alone, was rather small and the range estimates may accordingly be uncertain. However, they can still be used as best estimates.

Table 8
Summary of surface hoar observation results divided in study periods and observation scale

Period	Slope scale	Regional scale	Mountain range scale
1	–	Size: – HGR/PAR: No trends – GAT: Y significant predictor Presence: – Present everywhere	Size: – Strong trend decreasing from HGR/PAR to GAT: X, Y, D Presence: – Present everywhere
2	–	Presence: – Decreased compared to previous period	
3	2 grids: continuously present	Size: – HGR: RI, X, D – GAT: no dependence on radiation/aspect Presence: – HGR: dependence on radiation/aspect: RI, ψ – GAT: X, Y	Presence: – Strong difference in presence between HGR and GAT – X, ψ, R_s, P_{NN}
	Indicator semivariogram: HGR: range around 500 m. HGR+GAT: range around 10 km		
4 and 5	1 grid: continuously present	Size and presence: – P_{NN} – No dependence on terrain/meteorological variables in either region	Size and presence: – P_{NN} – No dependence on terrain/meteorological variables in either region – No difference in presence between HGR and BRT

The parameters involved in the best uni- or multivariate regression of the surface hoar size and presence are shown, where relevant.

Results from the present study therefore suggest that slopes are the smallest unit for homogeneous observations of surface hoar presence or absence. Further, if extrapolation within the basin scale is possible as our results suggest, snowpack observations and stability tests will probably reveal useful information for stability evaluation during the course of a backcountry trip, which typically covers the basin scale.

In periods 4 and 5, surface hoar was no longer frequently observed and neither its presence nor its size was related to the investigated terrain and meteorological variables. However, the neighborhood probability was a significant predictor of both presence and size. While it was not clear why the neighborhood probability was correlated to observed surface hoar size, the neighborhood probability was significant because of the low a priori probability of surface hoar. The average neighborhood probability was low and hence predicted that surface hoar was not present at any locations, a result that closely matched the observations. In period 3 in the HGR region, the neighborhood probability was not a significant predictor. However, this did not mean that the data were not spatially autocorrelated (the semivariogram analysis showed autocorrelation), but rather that the variation was due to terrain-related drivers creating distinct spatial patterns. When the analysis was extended to the mountain range scale (including the HGR and the GAT region), the neighborhood parameter became significant. This was likely due to the distinct difference in surface hoar presence between the two regions: when the terrain variables were no longer good predictors of the locations of surface hoar, the neighborhood parameter was additionally used as a predictor in the best logistic model. A more advanced measure of neighbor probability may have provided a better predictor variable. Because of the strong dependence of both size and presence of the surface hoar, such an improved neighborhood predictor could be calculated with observations from neighboring locations with similar aspect.

The data from periods 4 and 5 were used to test the regression models derived with the data from period 3 (region HGR) (Fig. 6). Whereas the presence of the layer of buried surface hoar was well predicted, the size was poorly predicted. Due to the temporal development, about one month between observations, the absence could not be predicted and the lack of agreement in surface hoar size is not surprising. In order to improve predictions of surface hoar evolution, a temporal variable could be included in the models.

5. Conclusions

We have observed and analyzed snowpack stability variation and the spatial distribution and grain size of a layer of buried surface hoar. The layer caused substantial avalanche activity and was decisive for stability evaluation and avalanche forecasting during a one-month period. The stability distribution found some time after the avalanche activity had peaked, showed that the stability could be rated as good, but that the spread of stability was wide, indicating that at the regional scale spatially varying conditions prevailed. Good median (regional) stability, but wide spread may be typical for conditions with a layer of surface hoar that has been buried for several weeks: failure initiation has become unlikely, but fracture propagation potential is still high due to its collapsible structure (Jamieson and Schweizer, 2000).

Before burial the layer was observed in all sampling locations, indicating that the atmospheric conditions were such that it grew everywhere. However, it was observed that the surface hoar size before burial was significantly smaller in the GAT region east of Davos than in the regions to the west and south.

After burial of the surface hoar, a large number of snow profiles were observed to describe the patterns of occurrence of the layer. Whereas the layer was found to be present in over 70% of the profiles in the region HGR it was mainly absent in the region GAT. In the region HGR a distinct aspect-dependent pattern of surface hoar distribution was found. The layer was least frequently found on south-facing and on north-west-facing slopes. North-west is typically the prevailing wind direction of storms. Therefore, and since the surface hoar was present everywhere before burial, it was proposed that the pattern originated from surface hoar destruction due to destruction by solar radiation and due to wind. The fact that the surface hoar was hardly found in the region GAT was explained by the initially smaller size of the surface hoar crystals which made survival less probable, both before and after burial.

Relating surface hoar size to terrain variables for the region HGR explained about 80% of the variance for the northerly slopes on day 1 of period 3 and 36% for all slopes (independent of aspect). Describing and predicting surface hoar occurrence instead of size revealed better results.

A geostatistical analysis using the indicator semivariogram combined the slope scale measurements with the profile observations at the regional scale. A spherical semivariogram model fitted to the data of the HGR region gave a range of around 500 m and a nugget ratio of about 20%. This result–achieved without taking terrain variables into account–indicated that extrapolation of observations of surface hoar could be made out to on average 500 m. Of course, smaller scale patterns may still be found. These may be due to variations in terrain such as the slope aspect.

The multi-scale geostatistical analysis showed that the spatial autocorrelation length depends on the scale analyzed. For example, if slope scale measurements suggest a range of about 10 m (Kronholm, 2004, pp. 111–114), that does not mean that the layer is not present or has strongly different properties beyond 10 m, but rather reflects the extent of the measurement grid. At the mountain range scale the distance of autocorrelation increased to around 10 km from the 500–1500 m at the regional scale. This suggests that the observed variability was caused by several process drivers with different typical scale.

Our findings on the spatial structure of a surface hoar layer are specific to the particular layer we observed. However, we expect that the spatial structure of different layers will as well reflect the physical processes that are responsible for the growth and destruction of surface hoar.

Acknowledgements

We are grateful to all our colleagues at SLF who made field observations during the winter 2002–2003. The helpful comments by the reviewers are gratefully acknowledged.

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