MULTI-SCALE SPATIAL VARIABILITY OF A LAYER OF BURIED SURFACE HOAR

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ABSTRACT: Spatial variability of the snowpack exists at different scales. Various studies have investigated and quantified snowpack spatial variability at either the slope scale or the regional scale. This study investigates spatial variability at both of these scales simultaneously. Field measurements were made on a buried layer of surface hoar over a wide range of scales from 0.5 m to 5 km near Davos in the eastern Swiss Alps. The surface hoar layer did exist widespread before burial. At each measurement location, the layer thickness, grain size and stability of the buried surface hoar layer was recorded if the layer was present. At the slope scale fine-resolution measurements were made with a micro-penetrometer. These measurements showed that the surface hoar layer was continuously present at the slope scale. In the surrounding terrain, on slopes of similar aspect, the surface hoar layer was found in 83% of the snow profiles (point observation), and independent of aspect in 72%. However, in an adjacent region, about 12 km to the east, only on 25-30% of the slopes the buried layer of surface hoar was observed. Surface hoar distribution in one region showed a distinct pattern in regard to slope aspect. This could be explained by conditions that likely were responsible for surface hoar destruction before burial: wind and solar radiation. Whereas the surface hoar grain size was initially best predicted by the coordinates and elevation, the best predictor changed to the radiation index (a proxy for the slope aspect). Combining the slope scale measurements with the profile observations showed that within a few 100 m the existence of surface hoar could be extrapolated. But beyond about 500 m extrapolation became merely incidental.

KEYWORDS: spatial variability, snow stability, avalanche forecasting

1. INTRODUCTION

Probably the two 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, complicated 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 variability at the different scales has different causes and importance for avalanche formation and forecasting. Regional avalanche forecasting is typically focused on patterns at the scale of mountain ranges and drainages and seeks to differentiate snow stability between aspects and elevation bands. However, to predict instability or the probability of an avalanche to release, the variability at 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 – in both directions: by favouring and preventing instability (Schweizer et al., 2003a). 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 is usually not known. It is therefore crucial to understand the nature and causes of spatial variability, but not only for one scale but across the scales relevant for avalanche release and forecasting.

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; Föhn, 1989; Jamieson, 1995; Kronholm and Schweizer, 2003;

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Landry et al., 2004), while some 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 are of limited value for operational avalanche forecasting for which the scales must be linked.

Buried layers of surface hoar cause many avalanche accidents (Schweizer and Jamieson, 2001). The spatial distribution of surface hoar existence is difficult to forecast. Hägeli and McClung (2002) studied the spatial characteristics of persistent weak layers across the Columbia Mountains of Western Canada. They showed that layers of buried surface hoar existed over considerable parts, sometimes across the entire mountain range. They proposed that this was in agreement with the spatial extent of the meteorological conditions necessary under which these weak layers develop. Nevertheless, smaller scale variability existed within the mountain range, 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 or a region.

The aim of the present study was to observe and quantify spatial variability of snowpack stability over a wide range of scales from 0.5 m to 10 km in the surroundings of Davos in the Eastern Swiss Alps. Since snowpack stability was in general rather good, it did not depend on terrain. Therefore, we focused on a layer of buried surface hoar that was decisive for snow stability earlier in the winter. 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 an adjacent region.

2. METHODS

During the winter 2002-03 at five occasions, snowpack data were collected in the surroundings of Davos, Eastern Swiss Alps (Figure 1). Davos is located at 1560 m a.s.l. in a valley running north-east to south-west. The study areas were the surrounding ridges and drainages to the west (Hanengretji: HGR), to the north-west (Parsenn: PAR), to the east (Gatschiefer-Pischa: GAT) and to the south (Bärentälli: BRT) (Figure 1). Ridge-tops reach 2600 to 3000 m a.s.l.

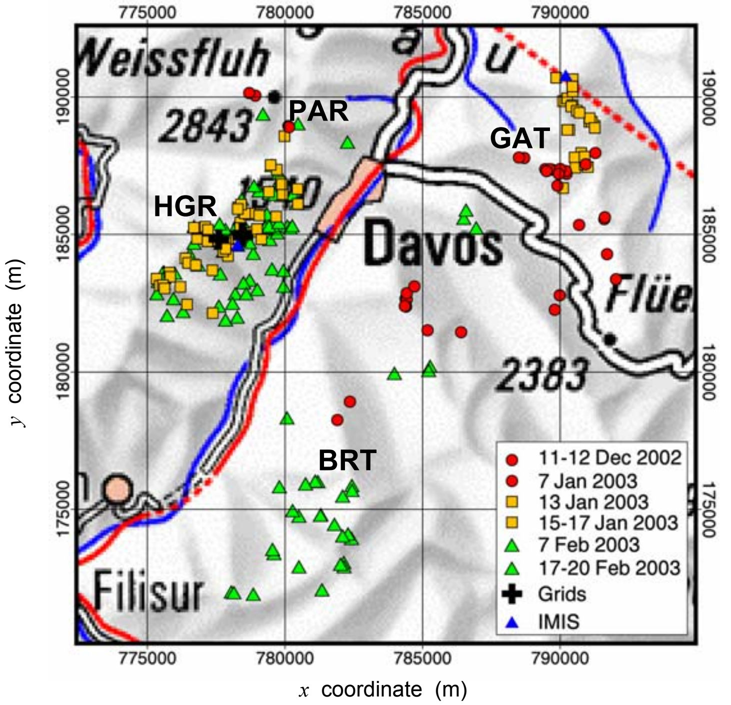

Figure 1: Map of study area around Davos, eastern Swiss Alps with all measurement locations. The Swiss coordinate system is shown with grid lines 5 km apart. The four regions are indicated: Gatschiefer-Pischa (GAT), Parsenn (PAR), Hanengretji (HGR) and Bärentälli (BRT). The crosses indicate the locations of the fine-scale slope measurements (Grids). Also given are the locations of two automatic weather stations (IMIS).

Table 1: Data collection periods and prevailing avalanche danger during field measurements. 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 avalanche danger is described as danger level 1 to 5: Low (1), Moderate (2), Considerable (3), High (4), Very high (5), elevation and aspect.

Period	Date	Number of profiles	Number of Grids	Avalanche danger forecasted	Avalanche danger verified
1	11-12 Dec 2002	23		2, >2400, W-N-E	1, >2400, extreme
2	7 Jan 2003	12		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		4, >1500, all	3-4, >1800, all
5	17-20 Feb 2003	97	1	2, >2200, all	1, >2400, extreme

2.1 Data collection periods

The data were collected over five periods (Table 1). Periods 1 and 2 were during observer training sessions, and the sampling was therefore not as focused as in the subsequent periods. During Periods 3-5 the aim was to verify the regional snowpack stability as previously described (Schweizer et al., 2003b). To enable a multi-scale analysis, the observations at the slope scale, at the drainage scale and at the regional scale were coordinated. Period 3 was the first major period which included 2 fine-scaled slope measurements (Grids 1 and 2). During Period 4 the forecasted level of avalanche danger was High and data collection was limited. The last Period (5) included one fine-scaled slope measurement (Grid 3).

2.2 Scale

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). In the present paper we used the scales as defined in Table 2.

2.3 Field measurements

At the point scale, classical snow cover profiles and penetration resistance measurements were made. The full snow cover measurements 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). Penetration resistance profiles were made with the SnowMicroPen (SMP) (Schneebeli and Johnson, 1998) and provided indirect evidence of the presence or absence of buried surface hoar (Kronholm et al., 2004).

Slope-scale measurements included 113 SMP profiles as described by Kronholm at al. (2004) performed in a cross-shaped grid with nested spacing of the measurement locations. Each grid included 113 SMP measurements with spacing (i.e. distance between measurements) varying from a minimum of 0.5 m in the center of the grid to a maximum of 2 m in the legs of the grid. In the lower left, inner corner of the cross, a snow profile with a rutschblock test was observed. At 12 locations pairs of column type (30 cm × 30 cm) stability tests were made.

Table 2: Definition of scales

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	10 km – 100 km	Spatial snow cover patterns are due to the tracks of individual storms.

2.4 Analyses

For the analysis, each profile was classified in respect to stability into Very poor (1), Poor (2), Fair (3), Good (4) and Very good (5) following the classification scheme proposed by Schweizer and Wiesinger (2001).

To relate the distribution of surface hoar absence or presence to terrain, five variables were considered: x coordinate (east), y coordinate (north), elevation, slope angle and radiation index. The radiation index describes the deviation (in degrees) from the north direction (Birkeland, 2001) and replaced the non-numerical terrain variable aspect.

Comparison of stability or surface hoar existence between regions was made using the non-parametric Mann-Whitney U-Test. A level of significance $p = 0.05$ was chosen to decide whether the observed differences were statistically significant. Univariate and multiple least-square regressions and logistic regressions were used to relate surface hoar size or existence to terrain variables.

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 slightly buried by 16 December 2003 and was covered with a 30-50 cm thick slab by the end of December 2002. Many avalanches with the buried surface hoar layer as failure layer were triggered by recreationists. Occasional triggering continued until mid January 2003, but triggering spots were rare and difficult to localize. By mid January failure initiation probability was low, but propagation potential was still high. This is exemplified by the fact that in Period 3 on 15 January 2003 three avalanches were triggered remotely despite the fact that based on numerous snowpack observations with stability tests median regional snowpack stability was rated as Good (4) typically prevailing when the danger level is Low (Figure 2). However, the stability distribution found in the region HGR was unusually wide compared to the typical distribution for Low (Schweizer et al., 2003b). This agrees well with the above reported triggering conditions and might be typical for a situation when the spatial variability is high due to a buried layer of surface hoar. For backcountry skiing the large spread suggests to consider a wider margin of safety. In the region GAT the stability distribution resembled very much the model distribution of the danger level Low (1) as described by Schweizer et al. (2003b). 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. The difference between the two regions was due to the different presence or absence of the buried surface hoar layer (as will be shown below).

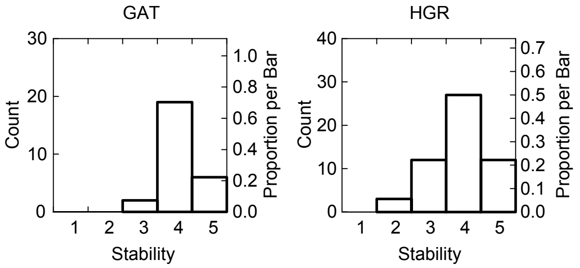

Figure 2: Snowpack stability distribution during period 3 (13-17 January 2003) in the two regions Gatschiefer GAT (left) and Hanengretji HGR (right).

3.2 Surface hoar distribution

Period 1

The surface hoar distribution was initially widespread in the whole Davos region. The first spatial observations were from 11 and 12 December 2002 when 23 manual snow profiles were collected primarily in the GAT region, and occasionally in the PAR and BRT regions. Surface hoar was observed at the surface in all 23 profiles. This clearly shows that surface hoar formation was widespread, and that the spatial patterns in the presence or absence of the surface hoar layer found in subsequent periods are likely to have occurred after Period 1 ended. It is important to note that the surface hoar grain size was significantly smaller in the region GAT (2-3 mm) than in the regions PAR and BRT (4.5-10 mm) ($p = 0.033$ for the mean surface hoar size, $p = 0.002$ for the max surface hoar size). As discussed later, this initial difference in size was possibly decisive for surface hoar existence once the layer was buried.

A multiple linear regression for the maximum surface hoar grain size in the region GAT involving elevation, x and y coordinates, slope angle and radiation index explained 53% of the variance. The best predictor was the x coordinate with a negative regression coefficient, i.e. decreasing surface hoar size with increasing distance to the east. This indicates that the regional-scale trend of larger grain sizes towards the west (in regions PAR and BRT), as mentioned above, was also found at smaller scale within the GAT region.

Period 2

On 7 January 2003, several days after the avalanche activity on the buried surface hoar layer had peaked, 8 profiles in the GAT and 4 in the BRT region were made. The buried surface hoar layer was reported in 3 out of the 4 profiles in the BRT region, and 4 out of the 8 profiles in the GAT region. 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. In the GAT region the decrease was higher than in BRT, possibly due to the smaller surface hoar crystal size observed in GAT during 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. Further, there was a statistically significant trend ($p = 0.028$) indicating higher stability on slopes with more southerly aspects.

Period 3

On the first day of Period 3 (13 January 2003), 113 SMP measurements were made in a grid on a north-facing slope in the HGR region (Grid 1). The buried surface hoar layer was present in all 113 SMP profiles (Kronholm, 2004). The SMP profiles did not provide results on the size of the surface hoar grains. A manual snow profile was recorded on the same slope.

On the same day, 15 additional profiles also primarily in north-facing slopes were made in the HGR region. 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. Correlating terrain parameters with surface hoar grain size showed that elevation and x coordinate consistently were rated as the most or only statistically significant variables. Surface hoar grain size decreased with increasing elevation. From the 4 profiles where no surface hoar was found 3 were located above 2500 m a.s.l. With the highest peaks in the HGR region not reaching higher than about 2600 m a.s.l. these sites were close to the ridge. Therefore, the absence of surface hoar was likely due to destruction by wind. 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 should be made with caution. A multiple linear least squares regression with all terrain variables was statistically significant ($p = 0.028$) and explained 82% of the variance ($R^2 = 0.82$). However, with $N = 16$ and 5 independent variables this result should be interpreted with caution.

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 profiles in the HGR region and 27 profiles in the GAT region. 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) (Figure 3). The number of profiles in the GAT region was too small to analyze the distribution in regard to slope aspect. If the 8 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 8 profiles, no dependence on aspect could be found ($p = 0.97$) (Figure 3).

In the region HGR the layer of buried surface hoar was found in 39 of the 54 profiles.

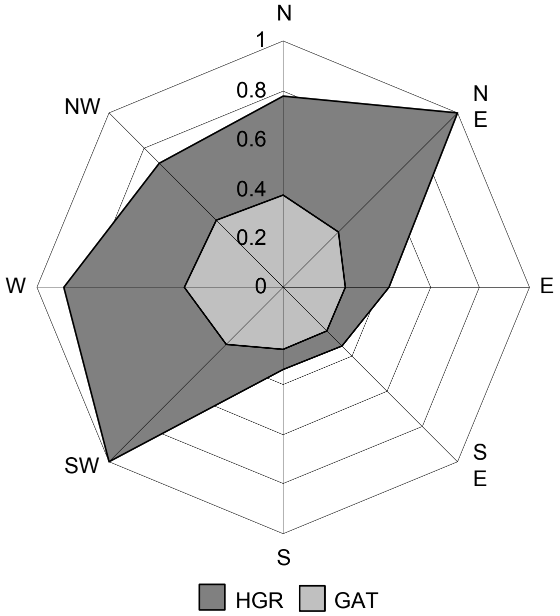

Figure 3: Distribution of surface hoar in regions HGR ($N = 53$) and GAT ($N = 33$) (1 profile each from flat IMIS station location not shown). Axis indicate proportion of profiles in a given aspect in which the surface hoar was found, e.g. for HGR in the northeasterly aspect the surface hoar was found in 100% of all profiles (7 out of 7), whereas in the southeasterly aspect it was only observed in 33% (1 out of 3).

The proportion was about 86% for the aspects in the sector SW over N to NE with NW as the aspect with the lowest occurrence in this sector (71%, Figure 3). In the aspects E to S, the proportion of surface hoar existence was only about 38%. The distribution was almost symmetrical around the NW-SE axis, but not around the N-S axis as would be expected if the presence or absence of surface hoar was controlled primarily by solar radiation. This suggests that other influencing factors such as e.g. wind were present.

The spatial pattern in Figure 3 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, and 2) surface hoar destruction by solar radiation on south-facing slopes. In fact, the dominating wind directions before the surface hoar was buried were northwest and south. Also, field observations on 14-15 December 2002 (not reported in detail here) suggested that the locations where the surface hoar was not observed were all south facing. The fact that the surface hoar was only occasionally observed in the region GAT, where it never grew as large as in the adjacent regions, supports the assumption that destruction by wind and melting due solar radiation caused the different patterns between HGR and GAT.

Terrain variables were related to surface hoar existence by a univariate analysis using the non-parametric Mann-Whitney U-test (contrasting the profiles where the surface hoar was found to the ones where it was absent). Whereas elevation and x and y coordinates were clearly not related to surface hoar existence, the radiation index was found to be just not a statistically significant predictor ($p = 0.054$). Only slope angle was clearly a statistically significant variable ($p = 0.014$). However, slope inclination and radiation index were significantly positively correlated. The correlation, with increasing slope angle towards southerly slope aspects, was likely incidental and/or due to observer preferences.

Alternatively, applying a univariate logistic regression using the radiation index to predict the probability of surface hoar presence was significant ($p \approx 0.04$). Also the slope inclination was a significant predictor for the presence of surface hoar ($p \approx 0.005$). A multiple logistic regression containing all the terrain parameters as independent variables was not significant ($p \approx 0.10$).

For an analysis of surface hoar size in the HGR region, the terrain variables were related to the maximum surface hoar size. Locations where no surface hoar was found were set to 0 mm. The univariate regression analysis showed that x coordinate, elevation, slope angle and radiation index were all statistically significantly related to maximum surface hoar size with the radiation index being the most significant variable. This was confirmed by a multiple regression analysis with the same terrain variables. Again the radiation index was the most significant variable. However, the full regression model only explained about 33% of the variance ($R^2 = 0.32$, $p = 0.002$).

At the end of Period 3 (17 January 2003), 113 SMP measurements were made in a grid on a slope in the HGR region. Analysis of the 113 SMP profiles showed that the layer of buried surface hoar existed at all measurement locations on the slope (Kronholm, 2004).

Combining the SMP results from single

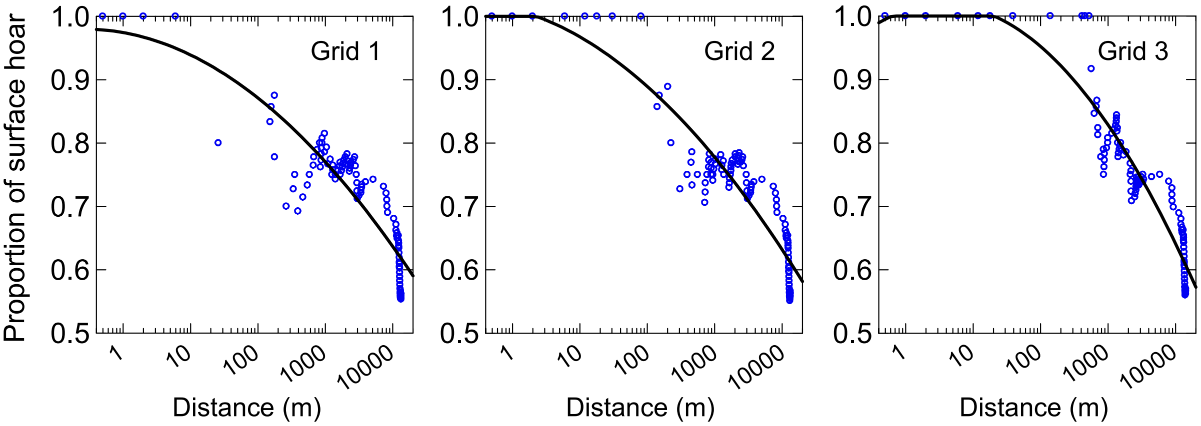

Figure 4: Probability to find surface hoar vs. distance from the fine-scaled slope scale measurements (Grids). For all three grids after a distance of a few 100 m the probability strongly decreases.

slopes with the manual profiles made over the region allowed us to do a spatial analysis spanning a broad range of scales. This showed that within a radius of about 500 m of the slope scale measurements there was a good chance (80%) to find the surface hoar layer in another profile, i.e. extrapolation is likely successful (Figure 4). The most similar conditions were found in the vicinity of Grid 3.

Periods 4 and 5

During the two sampling periods in February 2003 80 Profiles were taken in the HGR region and 28 in the BRT region to the south of HGR. The layer of buried surface was still reported in some of the profiles (HGR: 29%, BRT: 14%), but by that time it was nearly everywhere strongly metamorphosed, difficult to observe and did not show up in stability tests anymore. Consequently, we considered the observations as non-consistent. However, the locations in the region HGR where the surface hoar was observed were used to verify the above models that relate surface hoar size or existence to terrain variables. The multivariate regression analysis performed poorly, and for only 3 out of 23 profiles the predicted surface hoar size was within 2 mm of the observed one. Predicting surface hoar occurrence was more successful (61%).

4. CONCLUSIONS

We have observed and analyzed the spatial distribution of a layer of buried surface hoar. The layer had caused substantial avalanche activity and was decisive for stability evaluation and avalanche forecasting. 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 was particularly wide indicating that spatially varying conditions prevailed. A wide spread seems typical for conditions of a buried surface hoar layer that is relatively stable, but still prone to propagation.

Before the layer was buried its existence was widespread, 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 region GAT east of Davos than in the regions to the west and south.

Three fine-scaled slope measurements using a snow micro-penetrometer showed that the layer of buried surface hoar was present at all measurement locations (18 m x 18 m) i.e. across the whole slope that was tested.

In the surroundings of these grid measurements a large number of snow profiles were made to verify the existence 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 pattern of surface hoar distribution was found in regard to aspect. The layer was least frequently found on southerly slopes and on northwesterly slopes. Northwest is typically the prevailing wind direction of storms. Therefore, and since the surface hoar was present everywhere before burial, it is proposed that the pattern originated from surface hoar destruction due to melting by solar radiation and due to wind. The fact that the surface hoar was hardly found in the region GAT is explained by the initially smaller size of the surface hoar crystals which made survival less likely.

Combining the slope scale measurements with the point observations in the surrounding regions showed that extrapolation of point measurements in regard to surface hoar existence is possible within a radius of a few 100 m. Beyond about 500 m the probability to find the buried layer rapidly decreased to about 50%. Of course, the range within which extrapolation is possible will depend on the particular conditions of surface hoar growth and destruction.

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