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SPATIAL VARIABILTY – SO WHAT?

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ABSTRACT: Since the landmark papers of Conway and Abrahamson many studies have tried to quantify spatial variability. Many different methods have been used and the studies covered a variety of scales. Accordingly, some results appear contradictory, suggesting that the degree of spatial variation varies widely. This is not surprising, and is partly due to the methodology used and of course, due to varying natural conditions. Spatial variability is doubtless an inherent property of the snowpack. One important result seems to be that the layering is less variable than, for example, the stability of small column tests. Whereas it is often perceived that the results of the studies were not conclusive, it seems clear that they completely changed our view of spatial variability. We realized the importance of scale issues. For example, the variation will strongly depend on the measurement scale – the so-called support – of the method (SnowMicroPen vs. compression test vs. rutschblock test). Geostatistical analysis has been introduced and used to derive appropriate input data for numerical models. Model results suggest that spatial variation of strength properties have a substantial knockdown effect on slope stability and that the effect increases with increasing spatial correlation. The focus on scale has also revealed that spatial variations can promote instability or inhibit it. With the awareness of scale we can now address the causes of spatial variability. Many processes such as radiation and wind act at several scales. The most challenging process is probably wind that might hinder prediction of variability at the slope scale. However, at the regional scale, already today, many avalanche forecasting services try to address differences in respect to slope aspect. We will review the present state of knowledge, discuss consequences for avalanche forecasting and snow stability evaluation, and recommend future research directions.

KEYWORDS: snow mechanical properties, snow slope stability evaluation, avalanche formation, avalanche forecasting, spatial variability, numerical modeling

1. INTRODUCTION

The way spatial variability has been analyzed and treated since the early snow studies differs. Early snow researchers knew that the snow cover varied in space, and even suggested that wind was the most significant cause of the variability (Seligman, 1936). However, the research was more focused on describing the basic properties of the snow cover at a single location and its evolution in time, than worrying about spatial variability. This meant that observed variations in snow cover properties such as strength were primarily seen as the result of measurement errors. Only few spatial investigations were done. For example, Neher (Bader et al., 1939) did series of ram profiles and temperature measurements in different aspects and elevations, and Bradley (1970) studied the dependence and timing of deep slab instabilities on slope aspect.

When McClung (1979; 1981) presented a model of snow slab avalanche release based on fracture mechanical principles, he indirectly introduced a spatial component. Fracture mechanics assumes that there is no perfect material and describes whether and how a fracture grows from an initial imperfection in the material. In spatial variability terms, applied to avalanche release, the weak layer consisted of areas of lower than average strength (imperfections) and areas of about average or higher than average strength (everywhere else). This was used more as a conceptual model incorporating fracture

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mechanical principles rather than an actual model of the snow cover.

It was Conway and Abrahamson (1984) who first put stability-related observed variations in a spatial context. They measured shear strength along the fracture lines of recently skier triggered avalanches, and on slopes that had not failed. Along fracture lines, they found large variations between adjacent measurements, in particular some of their tests failed before completion. They assigned these measurements to so-called deficit zones where the shear strength was less than the gravitational stress. They concluded that the basal region (the weak layer or interface below the slab) of an avalanche may contain deficit areas and pinning areas. If a deficit area was found by a test, the slope was considered as likely unstable. Subsequently, Conway and Abrahamson (1988) used spatial statistics to derive the failure probability based on the size of deficit zones.

Conway and Abrahamson's papers triggered two things: (1) The hunt for deficit zones was open, and (2) the representativity or validity (and hence the usefulness) of stability tests became widely questioned. However, the importance of the spatial structure and its scale in the context of avalanche formation got lost in most of the research that followed. During the 1990s field results were rarely analyzed using spatial statistics. One exception is a study by Chernouss (1995) who presented autocorrelation functions for snow depth, snow density and strength from spatial measurements in the Khibini mountains to derive a probabilistic model of avalanche release (Chernouss and Fedorenko, 1998).

Currently, the focus is less on the validity of point observations. Rather, it is recognized that the spatial variability is important for slope stability evaluation and avalanche formation, and should be investigated and described in detail for that purpose. Summing up, snow cover variability with regard to snow slope stability has been investigated in many studies. Interpretation of the results varies widely. At the extremes of the different interpretations are two contradicting views: regular vs. irregular (Sturm and Benson, 2004): some studies suggest that the snow cover consists of well behaved and laterally homogeneous layers with properties that can be perfectly extrapolated. Other studies describe the layers as being so variable that cross-correlation of layers (finding the same layers) and extrapolation of layer properties is impossible for distances of kilometers or as little as tens of meters. The truth is probably somewhere in between, as suggested by Sturm and Benson (2004).

In the following we will review studies on spatial variation of strength and stability properties at scales from slope scale to mountain range scale. The aim is to summarize and discuss previous studies in order to arrive at a description of our current knowledge. Although a number of studies have investigated the spatial variability of snow bulk properties such as snow water equivalent, we will only review those if they are of relevance to snow cover stability. Before the review, we will introduce some basics on spatial variation and the concept of scale. Based on our review we will highlight key points about spatial variability, its interpretation and consequences on snow slope stability evaluation.

2. DEFINITIONS

It is well known that the snow cover is spatially variable. The most obvious form of snow cover spatial variability is the snow depth. However, for snow stability evaluation purposes, snowpack bulk properties such as snow depth are not as relevant as the properties of individual layers within the snowpack (Colbeck, 1991). In this paper our focus is therefore on layers within the snowpack.

2.1 Layer

A thorough discussion of the definition of a "layer" is outside the scope of the present paper, but it must briefly be mentioned because it is important for studies of spatial variability (see e.g., Pielmeier and Schneebeli, 2003). A layer can be described as "a stratum of snow that is different in at least one respect from the strata above and below" (Colbeck et al., 1990). This description leaves open the definition of both the property of interest and the magnitude of difference necessary. For snow stability evaluation studies, the mechanical properties of the layers are of interest. The exact definition of "different" decides the level of detail and may differ between studies depending on their purpose. A profile made to accompany a snow stability test result may include only a few types of layers; those that are potential weak layers, those that are potential slabs and the rest, resulting in relatively few layers. On the other hand, a profile made to verify the result of a snow cover model may include a larger number of layers. In addition, the number of layers found by a study is determined by the method used to define each layer. For manually recorded snow profiles the skill of the observer and the time spent on the profile are decisive. More generally, the layer resolution is determined by the sample support, as discussed below.

Spatial variability of snowpack layers is manifested through the presence of individual layers in the slope-perpendicular direction and through appearance and disappearance (pinching) of layers in the slope-parallel (lateral) directions. More succinct spatial variability may be exhibited in individual layers by spatial variation of layer properties such as thickness, density, grain size and strength in both the slope-perpendicular and the lateral directions at a level of detail that is below that used to define layer boundaries for the study, as described above. In the present paper, we focus on studies that have described the lateral variations of mechanical properties of individual layers.

2.2 Scale and scale issues

Blöschl and Sivapalan (1995) review scale issues related to snow hydrology and set up a useful framework for spatial variability studies. They defined the scale triplet as the spacing (the distance between measurement locations), the extent (the longest distance between two measurement locations, or the area covered by the study) and the support (the area or volume over which each measurement is integrated). In Nature, processes act over a typical scale (or a range of scales) called the process scale. Spatial variability studies attempt to measure and describe the process scale, but depending on the scale triplet of the study, the result, called the measurement scale may be different from the process scale. Similarly, studies with different scale triplets may find different measurement scales. Some recent spatial variability studies have used this framework to describe the sampling methodology of the study.

3. SLOPE SCALE STUDIES

Table 1 summarizes slope scale variability studies. The properties measured are given as well as the main results. Most studies measured either point stability, shear strength or penetration resistance and reported, among other findings, the coefficient of variation (CV): a non spatial measure of variation. Coefficients of variation were about 15-25% for shear strength measured with a support of the order of 100 cm^2, and 50% for penetration resistance measured with a much smaller support of less than 1 cm^2. Stability variations were of the order of 30-50% (CV) again depending on the test area. As there are more sources of variation for point stability (at least slab and weak layer properties) the higher variation found in stability tests is not surprising. Of particular interest are the results about the representativity of Rutschblock tests. On rather sheltered slopes a rutschblock test score was in 98% of the cases found to be within ±1 degree of the slope median. This high portion decreased to about 70-80% if avalanche start zones were tested.

Only recently, true geostatistical analyses have indicated that at the slope scale typical weak layer properties are autocorrelated over a length of several meters. Layer properties proved to be more continuous than stability scores and often layers existed throughout a slope of given aspect and elevation (Kronholm, 2004). Also, rutschblock release type proved to be more repeatable than rutschblock scores, especially for low median scores (Campbell and Jamieson, 2006b).

4. REGIONAL AND MOUNTAIN SCALE STUDIES

Table 2 summarizes spatial variability studies at scales larger than the slope scale. These studies mainly focused on weak layer formation at the snow surface (“Today’s snow surface is tomorrow’s failure layer”), on regional stability or avalanche danger patterns and on avalanche observations. Observations of weak layer formation showed that initially these layers were continuously present across whole mountain ranges even over hundreds of kilometers. Accordingly, stability indices derived from study plot measurements (as well as stability scores from index slopes) were found to clearly correlate with skier triggered avalanche activity in the surrounding terrain. At a smaller scale, patterns in weak layer formation were described depending on the local wind regime, valley clouds and the freezing level during storms. Of course, aspect and elevation were found to affect snow stability and avalanche danger at the regional scale, as well as snow climate at larger scale. Typical stability variations were derived for a given danger rating clearly indicating that a single snowpack observation will be insufficient to verify the local danger, in particular at the lower end of the danger scale.

Table 1: Selection of slope scale studies with summary of major results

Study	Property	Results
Conway and Abrahamson (1984)	Stability index	- Large changes in stability over 0.5 m, "outliers" not discarded - CV, stable slopes: 65%; CV, unstable slopes: 82% - Critical length of "deficit zone": < 1 m
Conway and Abrahamson (1988)	Stability index	- Critical length of "deficit zone": > 2.9 m - Measurements should be spaced less than 0.5 m apart to capture variability and should span at least 3 m - The pattern of point stability on a slope is important for slope stability - Concluded that small deficit zones were not enough to make slopes unstable
Föhn (1989)	Stability index	- CV, stable slopes: < 30% with "outliers" excluded - CV, stable slopes: < 38% with "outliers" included
Jamieson and Johnston (1993), Jamieson (1995)	Rutschblock score	- With 97% probability, a rutschblock score on the uniform part of a slope is within ± 1 score of the slope median score - One of nine slopes investigated included a small area of very weak surface hoar, possibly a "deficit zone"; the slope did not fail during measurements
Birkeland et al., (1995)	Penetration resistance	- CV of average penetration resistance was 28% to 58% on two slopes over two seasons - Average penetration resistance was positively correlated with snow depth variations caused by wind drifting - Weaker average penetration resistance was statistically correlated with sites overlying rocks
Chernouss (1995)	Snow depth, density, strength	- Spatial autocorrelation functions were calculated for four different snow properties
Takeuchi et al., (1998)	Penetration resistance	- No quantification of horizontal variability - A dry snowpack showed more spatial continuity in layer hardness than a wet snowpack
Jamieson and Johnston (2001)	Shear strength	- CV of 7-12 shear strength measurements within 2 m ranged from 3% to 66% with a mean of 15% - Larger variation in avalanche release areas than level study plots
Stewart (2002), Stewart and Jamieson (2002)	Point stability	- Patches of below and above average stability were found in most of the 39 investigated slopes - No spatial autocorrelation length was found - CV max: 82%, min: 10%, mean: 50%
Landry (2002), Landry et al. (2004)	Shear strength, point stability	- CV of weak layer shear strength between 10% and 50% with a mean of 24% on 11 slopes - Stability variation was in the same range - Maximum and minimum values on one slope were found in adjacent tests - 25- 39% of pits dug on relatively "uniform" slopes were found to not be statistically representative of that slope - Layering throughout a mountain range was relatively consistent at the same time shear strength and point stability across a small slope was quite variable

Kronholm and Schweizer (2003)	Point stability	- All the sixteen weak layers on eight slopes analyzed were spatially continuous - The spatial variation of point stability consisted of a strong trend which explained a large part of the variation - Variation expressed as quartile coefficient of variation was around 40% but dropped to around 20% when the trend was removed - A stability scheme including information on (a)weak layer continuity, (b) average and (c) variation of point stability was suggested, with continuous weak layers with low average point stability and small variation in point stability being the most critical
Harper and Bradford (2003)	Stratigraphy	- Investigated the snow layering on a flat glacier using translucent and manual profiles - Thick (5-10 cm) layers were continuous over tens of meters whereas thin features (1-10 mm) within those layers were not - No quantification of horizontal variability
Birkeland et al. (2004a)	Penetration resistance	- No spatial trend in penetration resistance of a buried surface hoar layer on two slopes - CV of weak layer thickness varied from 24% to 34% - CV of the median weak layer penetration resistance varied from 43% to 48%
Birkeland et al., (2004b)	Penetration resistance	- Analyzed the spatial structure of the penetration resistance for slabs and weak layers on three slopes - Of the eight layers analyzed, three had quantifiable spatial structure and five did not - The sampling method on a slope can significantly affect the interpretation of the spatial structure
Kronholm et al. (2004a)	Penetration resistance	- Seven layers on a single slope were investigated - All layers were spatially continuous and had slope scale trends in penetration resistance - The range of autocorrelation varied from 3.9 m to more than the extent of the measurement setup
Campbell and Jamieson (2006a)	Point stability	- Twelve of 36 arrays had significant clusters of either high scores, low scores or both, ranging in length from 1 m to 4 m. - Nineteen arrays had significant spatial clusters in slab thickness. In 2 cases clusters of high slab thickness corresponded with clusters of high point stability.
Campbell and Jamieson (2006b)	Point stability	- 84% of RB scores were within ±1 of the median on slopes with variability typical of release zones. - Within some arrays no significant correlations with snowpack and terrain predictors found. - In others, RB score increased with slab thickness and decreased with slope angle. - In some arrays with weak layers of surface hoar, the point stability decreased with increasing weak layer thickness and increased with increasing weak layer depth.
Logan (2005), Logan et al. (2006)	Shear strength, point stability	- 90% of pits were statistically representative of their particular “uniform” slope (using smaller slopes and a different test than Landry (2002)) - Spatial structure of shear strength difficult to quantify, though some autocorrelation observed at distances < 1 m

		- Quartile CV of shear strength ranged from 9% to 13% on the two slopes over 10 sampling days
Lutz et al. (2006)	Penetration resistance	- Looked at different parts of the weak layer using the SMP on two different slopes - The spatial structure of the penetration resistance of the different parts of the weak layer were difficult to quantify on one slope, but could be quantified on the other slope

Table 2: Selection of regional and mountain scale studies with summary of major results

Study	Property	Results
Bradley (1970)	Hardness	- Studied two slopes - Correlated depth hoar strength to the timing of large avalanches on different aspects
Dexter (1986)	Penetration resistance	- Collected data from 39 points over an area of about 10 km^2 - Penetration resistance increased with elevation on northerly facing slopes and decreased with elevation on southerly facing slopes
Birkeland (2001)	Point stability, penetration resistance	- On two days field teams investigated snow stability in a mountain range - Stability was correlated with terrain using various statistical methods - On both days elevation and aspect were significant predictors of stability, but the strength of those relationships varied between the two days - Average penetration resistance increased at higher elevations and on more northerly aspects
Stoffel et al. (1998)	Avalanche observations	- Analyzed and visualized a 14 year long period of avalanche observations in the region around a village - South-facing release areas produced less avalanches than their proportion of release areas predicted
Kozak et al. (2003)	Snow slab hardness	- Related spatial variability of snow slab hardness to terrain and meteorological variables - Hardness increased over time and the rates of hardness increase were related to temperature and incoming shortwave energy on different aspects
Hägeli and McClung (2003)	Avalanche observations	- Analyzed avalanche observation data from the Columbia Mountains in Canada - Most persistent weak layers with considerable avalanche activity were observed and active across the entire mountain range
Schweizer et al. (2003)	Point stability, danger ratings	- On ten days avalanche danger forecasts were verified by numerous point stability observations. - Point stability measurements were coordinated on the slope, regional and mountain range scale. - Regional stability (avalanche danger) depended on aspect and elevation, and snow climate. - Typical stability distributions were derived for the danger levels Low, Moderate and Considerable. - Verification of avalanche forecasts not possible by single point stability observations

McCollister et al. (2003)	Avalanche observations	- Explored the relationship between specific meteorological conditions and the spatial pattern of avalanche activity - Avalanche activity relates to actual location more closely than simple aspect because of the importance of wind patterns around specific topographic features. - Specific sets of avalanche paths had higher proportions of different types of avalanches.
Feick et al. (2004)	Weak layer formation	- Related the spatial variations of surface hoar growth and decay in a basin to terrain and meteorology (drainage winds) - Small-scale terrain variables best explained the observed differences
Zeidler and Jamieson (2004)	Stability index, avalanche observations	- In a sheltered mountain range, study plot stability index correlated with skier-triggered avalanches within kilometers of the study plot
Heilig (2004)	Penetration resistance, surface properties	- Four slopes of northerly aspect within a drainage were investigated simultaneously to cover the point, the slope and the drainage scale. - Three slopes were fairly sheltered and surface properties were continuous across scales, whereas penetration resistance of the surface layer was found to show more variation. - The fourth slope was wind exposed and its properties were typically different from the ones of the more sheltered slopes.
Schweizer and Kronholm (2005)	Penetration resistance, point stability	- Snow stability and weak layer presence was investigated by coordinating field sampling over the slope, regional and mountain range scales. - Before burial the weak layer (surface hoar) was present everywhere but at the mountain range scale the initial surface hoar size differed due to different growth conditions. - After burial surface hoar presence depended on aspect due to influence by wind immediately before burial and due to faster metamorphic processes on the south-facing slopes after burial. - Initial surface hoar size was related to surface hoar presence after burial such that regions of large initial grains were more likely to have surface hoar for longer periods. - At the slope scale the surface hoar layer was continuous. - Presence of surface hoar strongly influenced stability test results. - Geostatistical analysis revealed different lengths of autocorrelation depending on the extent chosen to calculate the variogram. This indicates that the observed variability was the result of several physical processes with different typical scales.
Jamieson (2006)	Weak layer formation	- Related spatial variations in the presence and vertical location of faceted weak layers to meteorology and terrain
Jamieson et al., (2006b)	Stability index	- Stability index for natural avalanches varies less than overburden or weak layer strength because weak layer strength increases with overburden.
Colbeck and Jamieson (2006)	Weak layer formation	- Elevation bands of buried surface hoar related to antecedent valley cloud.
Jamieson et al., (2006a)	Danger ratings	- Agreement of local scale (10 km^2) danger rating with rating from regional bulletins increased as scale of region decreased from 40,000 km^2 to 100 km^2. - Large scale danger ratings are averages over areas with variable avalanche danger.

5. OTHER STUDIES

Here, we will briefly mention a few studies that were not directly related to snow stability evaluation at the scales of interest, but are of interest for other reasons.

Besides radiation and wind, the terrain roughness, most prominently if trees are present modifies the snow cover stratigraphy. The large spatial variations in snow layering found in forest stands (Gubler and Rychetnik, 1991) and the fact that avalanche hardly ever release in forests exemplifies that spatial variability affects avalanche formation.

At the scale of the snowpack layer pinching was observed (Pielmeier, 2003) and dye tracer experiments revealed the large heterogeneity caused by water infiltration (Schneebeli, 1995). With improved FMCW radar technology (Marshall et al., 2005), the radar signal was related to snow stratigraphy as measured with the SnowMicroPen (Schneebeli and Johnson, 1998) and near-infrared photography (NIR) (Matzl, 2006). All these methods should improve the quantitative description of snow stratigraphy which is needed for spatial variability studies.

Sturm and Benson (2004) investigated variations in snow stratigraphy in the arctic at various scales.

Besides observations, numerical modeling of avalanche release using cellular automata models suggest that spatial variations of weak layer strength have a substantial effect on slope stability (e.g., Fyffe and Zaiser, 2004; Kronholm and Birkeland, 2005).

6. METHODS USED

One reason for the diverse and seemingly contradictory estimates of spatial variability may be the large number of methods used to measure and describe the variability. First, and most importantly, different studies have described the variability of different properties as diverse as point stability and penetration resistance (Tables 1 and 2). Clearly, only studies which have investigated the same property are comparable.

Secondly, a number of methods have been used to measure similar properties. Variation in point stability, for example, has been described using at least 6 different test methods: rutschblock tests (Jamieson, 1995); drop hammer tests (Stewart, 2002); rammrutsch tests (Kronholm, 2004); stuffblock tests (Kronholm et al., 2004b); two types of quantified loaded column tests (Landry, 2002). In addition to these methods of measuring point stability using vertical loading, some studies test the shear strength of the critical weak layer and infer point stability by relating shear strength to shear stress due to the snow above the weak layer (Conway and Abrahamson, 1984; Logan, 2005). Not only do these tests have different supports, but they also use different ways of loading the sample to failure (in case of the vertical load tests) and apply the shear force differently (for weak layer shear strength measurements). While comparisons between the most similar of these test methods may be possible, they must be treated cautiously. In addition, each measurement method is associated with a specific error, which for most methods is unknown. Observed variations in test results are therefore due to a combination of natural (true, deterministic) variability of the snow cover and test specific errors. This must be kept in mind when analyzing variability results to avoid associating variability due to test errors with true variability, which in some studies may be smaller than test errors.

Thirdly, when comparing studies which have investigated the same property with the same methods, it is apparent that differences in the scale triplets' spacing and extent may cause different conclusions about the scale of the observed variability (Blöschl and Sivapalan, 1995). For example, the sampling design may affect the results by controlling the extent and spacing of the study (Birkeland et al., 2004b; Kronholm and Birkeland, submitted) and designs covering multiple scales may show larger variability at certain scales although variability is present at all scales investigated (Schweizer and Kronholm, 2005).

Fourthly, the methods used to describe the variability of the measurement results differ. Some studies describe the variations of a layer property by non-spatial statistics such as the mean and spread of the value (Jamieson, 1995). Other studies analyze the data in a spatial sense either implicitly by comparing results from different locations without respect to the absolute locations (Landry, 2002) or explicitly using methods that include the absolute measurement locations (Kronholm, 2004). For studies of spatial variability is seems best to explicitly include measurement locations using for example geostatistical techniques. The drawback of such analyses is that they generally require a large number of measurements to produce reliable results (Webster and Oliver, 1992).

Finally, the interpretation of the outcome of a statistical analysis seems to depend on preconceived ideas of the investigators.

7. EFFECT OF SPATIAL VARIABILITY ON AVALANCHE FORMATION

Spatial variability affects avalanche formation. Spatial variations of the weak layer and slab properties (strength and stress) were postulated as prerequisites for failure initiation as well as for fracture arrest (Schweizer, 1999). In other words, disorder is considered as fundamental for the fracture process (Herrmann and Roux, 1990). Interpreting spatial variability in terms of fracture localization and propagation, Kronholm and Schweizer (2003) suggested that slope stability is controlled by the variation of stability, the length-scale of the variation and the mean stability. A key factor in this view is the relation between the critical length l of the initial failure to the spatial scale of the variability ξ (or the range from the semi-variogram). If, for example, $\xi/l < 1$ then the variability has a stabilizing effect (Kronholm et al., 2004c).

Best estimates from slab avalanche release models (McClung, 1979; 1981; Bader and Salm, 1990) for the critical length l are 0.1 - 10 m (Schweizer, 1999). Field and laboratory measurements as well as theoretical considerations suggest that the size is on the order of the slab thickness, i.e. 0.1 - 1 m.

A single point stability observation inherently includes two sources of uncertainty: spatial variation and test errors. Accordingly, reliable slope stability prediction requires additional information. One option is to consider several predictors (related to the fracture process) that will result in a more robust estimation (Schweizer et al., 2006). Doing side-by-side stability tests does usually not provide insight into the spatial variation. Any variation in stability scores is more likely to be due to test errors than natural spatial variability. If at all more than one test is done on the same slope, the tests should rather be spaced out on the order of at least 10 m. They should be further apart than the autocorrelation length – which however is typically unknown – in order to give information about the natural variability.

8. SUMMARY AND CONCLUSIONS

After the landmark papers of Conway and Abrahamson (1994; 1988) spatial variability became synonymous with any unexpected avalanche release and a subject of much heated debate, in particular on the value of snowpack observations. Many field studies have shown a wide range of spatial variation and demonstrated that spatial continuity exists besides spatial heterogeneity. Today, it is accepted that spatial variation exists and the question is rather how to accommodate it in stability evaluation and avalanche forecasting – other than with a disclaimer in view of the uncertainty. While doing local observations, patterns (in particular at the snow surface) and their scale provide the key to assess the effect of spatial variations on stability. Multi-scale studies on the causes of variability will be needed to include spatial variability information into avalanche forecasting. Nevertheless, uncertainty due to spatial variation will remain.

Instead of conclusions, a few points are mentioned in the following (not in order, not exhaustive) that we think are relevant in the context of spatial variability.

- Spatial variation of snowpack properties exists. Widely varying conditions have been observed, in particular in avalanche starting zones above tree line where wind causes most of the random spatial variation.
- In general, layer properties, as well as fracture character (or rutschblock release type), are more continuous than stability scores. Accordingly, also structural instability indices (lemons, yellow flags etc.) are expected to be less subject to spatial variability.
- Stability tests are useful (as one important piece of information in combination with other observations), and their interpretation has been improved to counterbalance their drawbacks. Frequently, in particular when seeking instability (targeted sampling) a single rutschblock score can expected to be within ±1 degree of the slope median.
- Extrapolation from study plot measurements (or more generally from point observations) is possible to a certain degree.
- Scale and scale issues are crucial for studying and understanding spatial variability.
- The scale of spatial variation is crucial for avalanche formation. Small scale patterns (less than about 1 m) rather prevent avalanche initiation.
- The main causes of spatial variability are meteorological conditions and topography, predominately radiation and wind, the climate in general at larger scale. Other sources of variability, in particular in shallow snowpacks, may be due to variable properties of the underlying ground.

- The observed spatial variation can often be described with a deterministic and a stochastic component. However, the amount of variation in each component and the process drivers that contribute to variation in each component is determined by the scale of the study.
- For stability evaluation spatial variability is a burden, but it is not so much something to primarily worry about, but the point is to seek patterns and relate them to the avalanche formation processes. Examples for specific patterns in weak layer formation are surface hoar growth due to valley clouds, and faceting near crusts in the elevation band of the freezing level during the last storm.
- Spatial variability measurements are useful as input data for models to study the triggering of instabilities in geosystems.
- Numerical models suggest that spatial variation of strength properties has a substantial knockdown effect on slope stability and that the effect increases with increasing spatial correlation.
- Doubtless, variability brings uncertainty in the decision making process (Jamieson, 1993). Partly this can be counteracted by modern risk management approaches, i.e. primarily by clever terrain usage and by paying attention to human factors (another source of uncertainty). Greater uncertainty, e.g. in case of a patchy surface hoar layer deep in the snowpack, requires a greater margin of safety.

REFERENCES

Bader, H., Haefeli, R., Bucher, E., Neher, J., Eckel, O. and Thams, C., 1939. Der Schnee und seine Metamorphose. Beiträge zur Geologie der Schweiz - Geotechnische Serie - Hydrologie, Lieferung 3. Kümmerly and Frey, Berne, Switzerland, 340 pp. (Snow and its metamorphism, SIPRE Translation, 14, 1954)

Bader, H. and Salm, B., 1990. On the mechanics of snow slab release. Cold Reg. Sci. Technol., 17: 287-299.

Birkeland, K., Kronholm, K., Schneebeli, M. and Pielmeier, C., 2004a. Changes in shear strength and micropenetration hardness of a buried surface-hoar layer. Ann. Glaciol., 38: 223-228.

Birkeland, K., Logan, S. and Kronholm, K., 2004b. A comparison of the spatial structure of the penetration resistance of snow layers in two different snow climates, Proceedings ISSMA-2004, International Symposium on Snow Monitoring and Avalanches. Snow and Avalanche Study Establishment, India, Manali, India, 12-16 April 2004, pp. 3-11.

Birkeland, K.W., 2001. Spatial patterns of snow stability throughout a small mountain range. J. Glaciol., 47(157): 176-186.

Birkeland, K.W., Hansen, H.J. and Brown, R.L., 1995. The spatial variability of snow resistance on potential avalanche slopes. J. Glaciol., 41(137): 183-189.

Blöschl, G. and Sivapalan, M., 1995. Scale issues in hydrological modelling - a review. Hydrol. Process., 9: 251-290.

Bradley, C.C., 1970. The location and timing of deep slab avalanches. J. Glaciol., 9(56): 253-261.

Campbell, C. and Jamieson, J.B., 2006a. Spatial patterns in slab stability and snowpack properties within avalanche start zones, Proceedings ISSW 2006. International Snow Science Workshop, Telluride CO, U.S.A., 1-6 October 2006, in press (this volume).

Campbell, C. and Jamieson, J.B., 2006b. Spatial variability of slab stability and fracture characteristics within avalanche start zones. Cold Reg. Sci. Technol.: in press.

Chernouss, P., 1995. Spatial and time variability of avalanche predictors and accuracy of their estimations. In: F. Sivardière (Editor), Les apports de la recherche scientifique à la sécurite neige, glace et avalanche. Actes de Colloque, Chamonix, France, 30 mai-3 juin 1995. ANENA, Grenoble, France, pp. 123-127.

Chernouss, P.A. and Fedorenko, Y.V., 1998. Probabilistic evaluation of snow-slab stability on mountain slopes. Ann. Glaciol., 26: 303-306.

Colbeck, S.C., 1991. The layered character of snow covers. Rev. Geophys., 29(1): 81-96.

Colbeck, S.C., Akitaya, E., Armstrong, R., Gubler, H., Lafeuille, J., Lied, K., McClung, D. and Morris, E., 1990. The international classification of seasonal snow on the ground. International Commission on Snow and Ice (ICSI), International Association of Scientific Hydrology, Wallingford, Oxon, U.K., 23 pp.

Colbeck, S.C. and Jamieson, J.B., 2006. Surface hoar growth from valley cloud, Proceedings ISSW 2006. International Snow Science Workshop, Telluride CO, U.S.A., 1-6 October 2006, in press (this volume).

Conway, H. and Abrahamson, J., 1984. Snow stability index. J. Glaciol., 30(116): 321-327.

Conway, H. and Abrahamson, J., 1988. Snow-slope stability - a probabilistic approach. J. Glaciol., 34(117): 170-177.

Dexter, L.R., 1986. Aspect and elevation effects on the structure of the seasonal snow cover in Colorado. Ph.D. Thesis, University of Colorado, 228 pp.

Feick, S., Kronholm, K. and Schweizer, J., 2004. Spatial variability of surface hoar layers at the basin scale. Geophysical Research Abstracts, 6: 06265.

Föhn, P.M.B., 1989. Snow cover stability tests and the areal variability of snow strength, Proceedings International Snow Science Workshop, Whistler, British Columbia, Canada, 12-15 October 1988. Canadian Avalanche Association, Revelstoke BC, Canada, pp. 262-273.

Fyffe, B. and Zaiser, M., 2004. The effects of snow variability on slab avalanche release. Cold Reg. Sci. Technol., 40(3): 229-242.

Gubler, H. and Rychetnik, J., 1991. Effects of forests near the timberline on avalanche formation. In: H. Bergmann, H. Lang, W. Frey, D. Issler and B. Salm (Editors), Symposium at Vienna 1991 - Snow, Hydrology and Forests in High Alpine Areas, IAHS Publ., 205. Int. Assoc. Hydrol. Sci., Wallingford, U.K., pp. 19-37.

Hägeli, P. and McClung, D.M., 2003. Avalanche characteristics of a transitional snow climate - Columbia Mountains, British Columbia, Canada. Cold Reg. Sci. Technol., 37(3): 255-276.

Harper, J.T. and Bradford, J.H., 2003. Snow stratigraphy over a uniform depositional surface: spatial variability and measurement tools. Cold Reg. Sci. Technol., 37(3): 289-298.

Heilig, A., 2004. Die flächige Variabilität der Oberflächeneigenschaften der Schneedecke in Hinsicht auf die Lawinenbildung. Diploma Thesis, Ludwig-Maximilian University, Munich, Germany, 130 pp.

Herrmann, H.J. and Roux, S., 1990. Statistical models for the fracture of disordered media. Random materials and processes. North-Holland, Elsevier Science Publishers, Amsterdam, 353 pp.

Jamieson, J.B., 1995. Avalanche prediction for persistent snow slabs. Ph.D. Thesis, University of Calgary, Calgary AB, Canada, 258 pp.

Jamieson, J.B., 2003. Risk management for the spatial variable snowpack. Avalanche News, 66: 30-31.

Jamieson, J.B., 2006. Formation of refrozen snowpack layers and their role in slab avalanche release. Rev. Geophys., 44(2): RG2001, doi:10.1029/2005RG000176.

Jamieson, J.B., Campbell, C. and Jones, A.S.T., 2006a. Spatial and time scale effects in Canadian avalanche bulletins, Proceedings ISSW 2006. International Snow Science Workshop, Telluride CO, U.S.A., 1-6 October 2006, in press (this volume).

Jamieson, J.B. and Johnston, C.D., 1993. Rutschblock precision, technique variations and limitations. J. Glaciol., 39(133): 666-674.

Jamieson, J.B. and Johnston, C.D., 2001. Evaluation of the shear frame test for weak snowpack layers. Ann. Glaciol., 32: 59-68.

Jamieson, J.B., Zeidler, A. and Brown, C., 2006b. Spatial extrapolation of slab stability indices for snow avalanche forecasting. Geophysical Research Abstracts, 8: 09663.

Kozak, M.C., Elder, K., Birkeland, K. and Chapman, P., 2003. Variability of snow layer hardness by aspect and prediction using meteorological factors. Cold Reg. Sci. Technol., 37(3): 357-371.

Kronholm, K., 2004. Spatial variability of snow mechanical properties with regard to avalanche formation. Ph.D. Thesis, University of Zurich, Zurich, Switzerland, 192 pp.

Kronholm, K. and Birkeland, K.W., 2005. Integrating spatial patterns into a snow avalanche cellular automata model. Geophysical Research Letters, 32(19).

Kronholm, K., Schneebeli, M. and Schweizer, J., 2004a. Spatial variability of micropenetration resistance in snow layers on a small slope. Ann. Glaciol., 38: 202-208.

Kronholm, K. and Schweizer, J., 2003. Snow stability variation on small slopes. Cold Reg. Sci. Technol., 37(3): 453-465.

Kronholm, K., Schweizer, J., Pielmeier, C. and Schneebeli, M., 2004b. Spatial variability of snowpack stability on small slopes studied with the stuffblock test. Data of Glaciological Studies, 97: 180-188.

Kronholm, K., Schweizer, J. and Schneebeli, M., 2004c. The effect of spatial variability on snow avalanche formation. Geophysical Research Abstracts, 6: 06272.

Landry, C., Birkeland, K., Hansen, K., Borkowski, J., Brown, R. and Aspinall, R., 2004. Variations in snow strength and stability on uniform slopes. Cold Reg. Sci. Technol., 39(2-3): 205-218.

Landry, C.C., 2002. Spatial variations in snow stability on uniform slopes: Implications for extrapolation to surrounding terrain. M.Sc.

Thesis, Montana State University, Bozeman MT, U.S.A., 194 pp.
Logan, S., 2005. Temporal changes in the spatial patterns of weak layer shear strength and stability on uniform slopes. M.S. Thesis, Montana State University, Bozeman MT, U.S.A., 157 pp.
Logan, S., Birkeland, K.W., Kronholm, K. and Hansen, K.J., 2006. Temporal changes in the slope-scale spatial variability of the shear strength of buried surface hoar layers. Cold Reg. Sci. Technol.: in press.
Lutz, E.R., Birkeland, K.W., Kronholm, K., Hansen, K.J. and Aspinall, R., 2006. Surface hoar characteristics derived from a snow micro-penetrometer using moving window statistical operations. Cold Reg. Sci. Technol.: in press.
Marshall, H.P., Schneebeli, M., Koh, G., Matzl, M. and Pielmeier, C., 2005. Measurements of snow stratigraphy with FMCW radar: comparison with other snow science instruments. In: K. Elder (Editor), Proceedings ISSW 2004. International Snow Science Workshop, Jackson Hole WY, U.S.A., 19-24 September 2004, pp. 57-63.
Matzl, M., 2006. Quantifying the stratigraphy of snow profiles. Ph.D. Thesis, ETH Zurich, Zurich, Switzerland, 78 pp.
McClung, D.M., 1979. Shear fracture precipitated by strain softening as a mechanism of dry slab avalanche release. J. Geophys. Res., 84(87): 3519-3526.
McClung, D.M., 1981. Failure characteristics of alpine snow in slow deformation. Proceedings, International Symposium on the mechanical behaviour of structured media, Ottawa, Canada, 18-21 May 1981: 409-418.
McCollister, C., Birkeland, K., Hansen, K., Aspinall, R. and Comey, R., 2003. Exploring multi-scale spatial patterns in historical avalanche data, Jackson Hole Mountain Resort, Wyoming. Cold Reg. Sci. Technol., 37(3): 299-313.
Pielmeier, C., 2003. Textural and mechanical variability of mountain snowpacks. Ph.D. Thesis, University of Berne, Berne, 127 pp.
Pielmeier, C. and Schneebeli, M., 2003. Developments in snow stratigraphy. Surveys in Geophysics, 24(5-6): 389-416.
Schneebeli, M., 1995. Development and stability of preferential flow paths in a layered snowpack. In: K.A. Tonnessen, M.W. Williams and M. Tranter (Editors), Biogeochemistry of seasonally snow-covered catchments (Proceedings of Symposium at Boulder CO, U.S.A., July 1995). IAHS Publ., 228, Int. Assoc. Hydrol. Sci., Wallingford, U.K., pp. 89-95.
Schneebeli, M. and Johnson, J.B., 1998. A constant-speed penetrometer for high-resolution snow stratigraphy. Ann. Glaciol., 26: 107-111.
Schweizer, J., 1999. Review of dry snow slab avalanche release. Cold Reg. Sci. Technol., 30(1-3): 43-57.
Schweizer, J. and Kronholm, K., 2005. Multi-scale spatial variability of a layer of buried surface hoar. In: K. Elder (Editor), Proceedings ISSW 2004. International Snow Science Workshop, Jackson Hole WY, U.S.A., 19-24 September 2004, pp. 335-342.
Schweizer, J., Kronholm, K. and Wiesinger, T., 2003. Verification of regional snowpack stability and avalanche danger. Cold Reg. Sci. Technol., 37(3): 277-288.
Schweizer, J., McCammon, I. and Jamieson, J.B., 2006. Snow slope stability evaluation using concepts of fracture mechanics, Proceedings ISSW 2006. International Snow Science Workshop, Telluride CO, U.S.A., 1-6 October 2006, in press (this volume).
Seligman, G., 1936. Snow structure and ski fields. International Glaciological Society, Cambridge, UK, 555 pp.
Stewart, K., 2002. Spatial variability of slab stability within avalanche start zones. M.Sc. Thesis, University of Calgary, Calgary AB, Canada.
Stewart, K. and Jamieson, J.B., 2002. Spatial variability of slab stability in avalanche start zones. In: J.R. Stevens (Editor), Proceedings ISSW 2002, International Snow Science Workshop, Penticton BC, Canada, 29 September-4 October 2002, pp. 544-548.
Stoffel, A., Meister, R. and Schweizer, J., 1998. Spatial characteristics of avalanche activity in an alpine valley - a GIS approach. Ann. Glaciol., 26: 329-336.
Sturm, M. and Benson, C.S., 2004. Scales of spatial heterogeneity for perennial and seasonal snow layers. Ann. Glaciol., 38: 253-260.
Takeuchi, Y., Nohguchi, Y., Kawashima, K. and Izumi, K., 1998. Measurement of snow-hardness distribution. Ann. Glaciol., 26: 27-30.
Webster, R. and Oliver, M.A., 1992. Sample adequately to estimate variograms of soil properties. Journal of Soil Science, 43(1): 177-192.