VARIATIONS OF SNOW INSTABILITY SEEN FROM A BIRD'S EYE

Benjamin Reuter* and Jürg Schweizer

WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland

ABSTRACT: The layering of the seasonal snowpack resembles an archive of the season's meteorological history. Whereas at the mountain range scale mainly meteorological processes drive the variations, at the basin scale and below interactions with terrain become more influential and complex. With recent developments in measurement and analysis techniques, the previous difficulties in measuring, mapping and interpreting the observed variations can be overcome. We analyzed five campaigns in a small basin above Davos (eastern Swiss Alps) from the seasons between 2011 and 2013. The data cover five different avalanche situations and contain snow pit data plus about 750 spatially distributed snow micro-penetrometer profiles. From those profiles observer-independent measures of snow instability were derived, which agreed well with in-situ stability observations. We then analyzed the spatial variability seen among these measures of snow instability within our sampling area (≈0.2 km^2) and produced the first maps of basin scale instability variations. Whereas, on these maps some variability was apparently due to terrain and snow depth variations, the more complex couplings of micro-meteorological processes with terrain could only be identified with distributed snowpack simulations using Alpine3D. Causes of snow instability varied between the five avalanche situations, but still, slope aspect was the most prominent driver. According to the snowpack simulations, for one selected day, the micro-meteorological forcing was due to the preferential deposition of precipitation and the surface energy input. The obtained auto-correlation ranges suggest that in our sampling area small scale variations were rather due to micro-meteorological forcing than to terrain parameters or snow depth. We show how meteorological forcing causes variations of snow instability, and suggest a way to validate spatial snowpack simulations before operational use.

KEYWORDS: snow micro-penetrometer, spatial variability, snow instability, geostatistical modeling, snow cover modeling.

1. INTRODUCTION

Whereas warning services can estimate the degree of danger in a region, they can at best provide some information on the locations (slope aspects, elevation bands) where the danger is most prominent (Schweizer et al. 2003). Detailed variations of snow instability are currently not reported in danger forecasts, as many measurements or detailed simulations would be required to do so. Providing information on variations of snow instability would require knowing the causes of spatial variations as well as their temporal evolution (Logan et al. 2007). In other words, a link between the observed variations of snowpack properties and the meteorological drivers, such as precipitation, wind and radiation, and terrain needs to be established.

In order to address this issue, we performed about 150 penetration resistance measurements per day with the snow micro-penetrometer (SMP; Schneebeli and Johnson 1998) within a small basin and derived two quantitative criteria of snow instability, one for failure initiation and one for crack propagation (Reuter et al. 2015). By means of geostatistical modelling we determined the spatial distribution of both parameters for in total five field campaigns. Finally, we modeled for one season the snow cover with high spatial resolution for the entire basin to investigate the driving processes behind the mapped distribution of snow instability.

2. METHODS

2.1 *Field data*

Throughout the winter seasons between 2010 and 2013 we sampled the Steintälli basin above Davos (eastern Swiss Alps; 46.808° N, 9.788° E) five times. During the field campaigns we acquired a complete dataset with snow micro-penetrometer measurements at 150 locations including GPS positions, manual measurements of aspect, snow

* *Corresponding author address:*
Benjamin Reuter, WSL Institute for Snow and Avalanche Research SLF, Flüelastrasse 11, CH-7260 Davos Dorf, Switzerland.
tel: +41 81 4170 347; email: reuter@slf.ch

depth and slope angle. Also a terrestrial laser scan covering the catchment, nine manual snow profiles and concurrent snow instability observations completed the data set. The sampling design is presented in Figure 1 and consists of 25 partly randomized cell arrays, i.e. measurement locations were always along the legs of an “L”, but the “L” was randomly oriented in the cell.

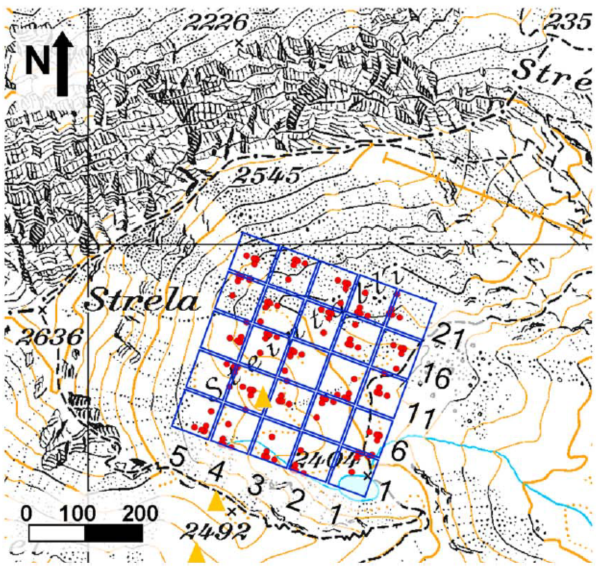

Fig 1: Map of field site showing all 25 cells (blues boxes with numbering along the sides) each with L-shaped sampling array (red points) including six SMP measurements and measurements of terrain parameters and snow depth. Manual snow profiles were conducted at corner points of the “L” in cells 1, 5, 7, 9, 13, 17, 19, 21, and 25.

2.2 SMP analysis

The snow micro-penetrometer (SMP) is a constant speed penetrometer which records microstructural and mechanical snow profile information, namely: rupture force, deflection at rupture, and structural element size (Löwe and van Herwijnen 2012). We introduced layers and assigned mean values obtained from moving window (window size 2.5 mm) averaging. The layering was consistent at the field site, and hence, we selected the same slab layers and the same weak layer, according to the most prominent weakness found in stability tests and manual snow profiles. The layer properties included snow density derived following Proksch et al. (2015), the weak layer fracture energy calculated according to Reuter et al. (2015), and the effective modulus and the strength as described by Johnson and Schneebeli (1999).

2.3 Snow instability criteria

For each SMP profile a failure initiation criterion *S* and the critical crack r_c as it would be measured in a propagation saw test were derived (Reuter et al. 2015).

2.4 Geostatistical Modelling

For the prediction of the two instability metrics over our study area we used a geostatistical modelling approach that divides the instability variations into a background field and residual patterns. The background field was modeled as a linear regression of the covariates, i.e. parameters which may have an influence on snow instability. Covariate data included coordinates, elevation, snow depth, slope angle, aspect; all data were available at single measurement locations, but also across the whole study site. Hence, processes varying smoothly with terrain are captured in the background field, whereas smaller scale variations are captured with the residual autocorrelation (Frei 2014).

The spatial interpolation was performed with external drift kriging, i.e. the background field provides a first estimation which is refined by the autocorrelation structure (Nussbaum et al. 2014); in other words, we added estimates from the analysis of the autocorrelation structure to the background field.

This technique has the advantage that the interpolation changes smoothly as terrain or snow depth, for instance, change and it considers the important driving factors which can vary between situations, such as snow depth or aspect.

2.5 Snow cover modelling

The model system Alpine3D (Lehning et al. 2006) was used to model the snow cover and its properties in the Steintälli basin based on the micrometeorological conditions. To this end, a digital elevation and a land cover model, both at a resolution of 4 m in the horizontal, were used. Therefore, the meteorological input data are interpolated on the digital elevation and land cover models yielding a 4 m resolution. Data records from four automatic weather stations around the Steintälli study site were used including the Weissfluhjoch data records.

The Alpine3D model system provides three modules which include the interaction of micrometeorological processes. The modules are related to preferential deposition and redistribution of snow (snow transport by wind), to the energy balance (radiation module), and to internal processes in the snow cover (SNOWPACK). The first two spatially interacting processes (snow transport and radiation) must be included, if spatial variations in snow properties are expected to be simulated.

3. RESULTS AND DISCUSSION

3.1 External driving agents

The most important terrain-related driving agent was slope aspect, which was included in the regression models in all cases. However, the regression models, in general, differed; they contained the coordinates, slope angle, and elevation as significant covariates in seven cases, whereas snow depth entered the regression model in six out of ten cases. In most cases a similar set of covariates described the background field of the two instability criteria on a single day. Hence, the agents varied depending on the situation.

3.2 Spatial autocorrelation

In all cases a spatial autocorrelation pattern was identified for both metrics of instability. The obtained autocorrelation ranges typically varied between 5 and 31 m (once 68 m) similar to the ranges found in previous slope scale studies (e.g. Bellaire and Schweizer 2011; Lutz et al. 2007) and clearly below the autocorrelation ranges of the terrain (between 47 and 100 m).

As snow instability variations due to terrain were modeled with the external drift model and autocorrelation ranges are shorter than the scale on which terrain varies, obtained autocorrelation ranges are suggested to be due to micrometeorological processes causing slope scale variations.

3.3 Maps of snow instability

For all sampling days external drift kriging predictions were performed based on multiple regressions based on terrain and snow depth data and the remaining residual autocorrelation. Figures 2 and 3 show the modeled failure initiation criterion and the critical crack length, respectively, for one sampling day, namely 3 March 2011.

The verified avalanche danger rating was "considerable" for the area of our field site. Signs of instability such as whumpfs were present. Both maps show rather critical values for both metrics (Reuter et al. 2015) indicating that failures could be initiated in most of the area and, in addition, cracks had the propensity to propagate.

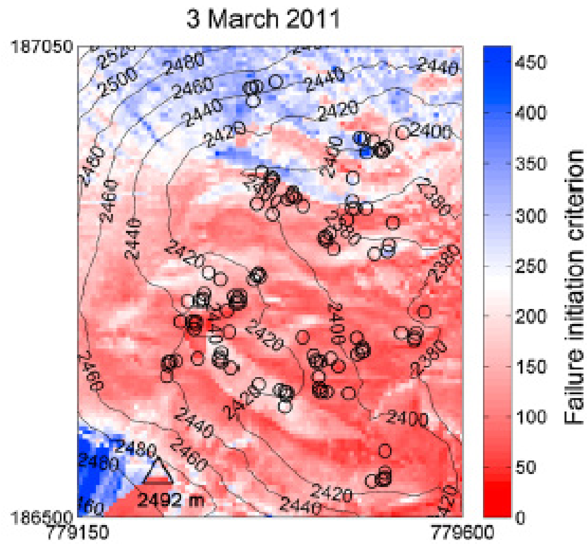

Fig. 2: Map of the failure initiation criterion predicted with external drift kriging for 3 March 2011 for the Steintälli field site. Axes are labeled with Swiss coordinates (in meters). Average modeled value S = 194.

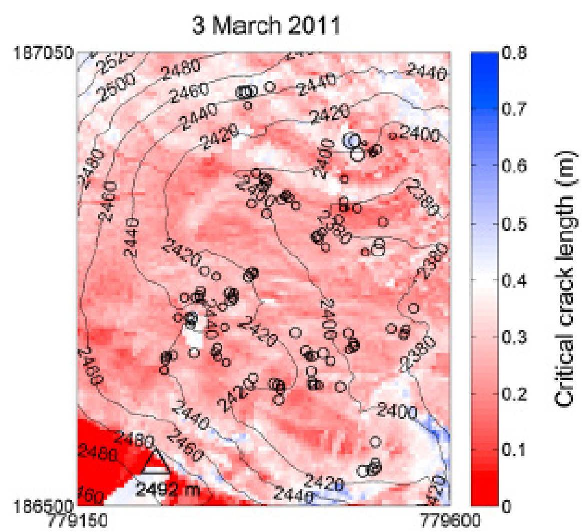

Fig. 3: Map of the critical cut length predicted with external drift kriging for 3 March 2011 for the Steintälli field site. Axes are labeled with Swiss coordinates (in meters). Average modeled value r_c = 38 cm.

As the metrics are process-based we may interpret the maps in the sense that if failure initiation is possible, the crack propagation propensity has to be considered – since propagation follows initiation in our present understanding of dry-snow slab avalanche release (Schweizer et al. 2016); on 3 March 2011 both criteria indicated rather unstable conditions.

In line with earlier studies based on snow stability observations on spatial variations above the slope scale (e.g., Birkeland 2001; Schweizer et al. 2003), our maps showed that variations of snow instability followed terrain features.

4. CONCLUSIONS

We derived two snow instability criteria from stratified snow micro-penetrometer measurements within a small basin and performed robust geostatistical analyses for five sampling days with the aim to describe spatial patterns and identify their causes. Using external drift kriging, we interpolated the snow instability measures at the basin scale and provide first exemplary maps of snow instability over terrain.

Significant covariates, among which slope aspect was the most prominent, varied depending on the situation. In other words, there is no single generally valid relation between terrain parameters and snow instability.

The resulting maps clearly showed how the propensity for failure initiation and crack propagation varied in our study site depending on terrain. Only when both snow instability criteria yielded below threshold values in most of the sampling area, the avalanche danger rating was as well “considerable” indicating rather critical conditions.

For one situation we identified the meteorological forcing responsible for the observed snow instability variations at the basin scale. Repeating the geostatistical analysis with modeled snow cover data as covariates, we obtained the same autocorrelation ranges and similar prediction errors for both instability criteria. This approach allowed us for the first time to track back potential causes for the variations of snow instability. The observed variations were mainly due to variations in slab layer properties which in the case of 3 March 2011 were caused by preferential deposition of precipitation and energy input at the snow surface during the formation period of the slab layers.

ACKNOWLEDGEMENTS

We would like to thank Andreas Papritz for the advice on the geostatistical analyses, Jochen Veitinger for the support with TLS data processing, Mathias Bavay and Bettina Richter for the help with the Alpine3D simulations. Moreover, we are grateful to all colleagues involved in the field campaigns, in particular Alec van Herwijnen, Thomas Grünewald, Anna Haberkorn, Christoph Mitterer, Lino Schmid, Stephan Simioni, and Walter Steinkogler.

REFERENCES

Bellaire, S., and J. Schweizer, 2011: Measuring spatial variations of weak layer and slab properties with regard to snow slope stability. *Cold Reg. Sci. Technol.*, **65,** 234-241.

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

Frei, C., 2014: Interpolation of temperature in a mountainous region using nonlinear profiles and non-Euclidean distances. *Int. J. Climatol.*, **34,** 1585-1605.

Johnson, J. B., and M. Schneebeli, 1999: Characterizing the microstructural and micromechanical properties of snow. *Cold Reg. Sci. Technol.*, **30,** 91-100.

Lehning, M., I. Völksch, D. Gustafsson, T. A. Nguyen, M. Stähli, and M. Zappa, 2006: ALPINE3D: a detailed model of mountain surface processes and its application to snow hydrology. *Hydrol. Process.*, **20,** 2111-2128.

Logan, S., K. W. Birkeland, K. Kronholm, and K. J. Hansen, 2007: Temporal changes in the slope-scale spatial variability of the shear strength of buried surface hoar layers. *Cold Reg. Sci. Technol.*, **47,** 148-158.

Löwe, H., and A. van Herwijnen, 2012: A Poisson shot noise model for micro-penetration of snow. *Cold Reg. Sci. Technol.*, **70,** 62-70.

Lutz, E. R., K. W. Birkeland, K. Kronholm, K. J. Hansen, and R. Aspinall, 2007: Surface hoar characteristics derived from a snow micropenetrometer using moving window statistical operations. *Cold Reg. Sci. Technol.*, **47,** 118-133.

Nussbaum, M., A. Papritz, A. Baltensweiler, and L. Walthert, 2014: Estimating soil organic carbon stocks of Swiss forest soils by robust external-drift kriging. *Geosci. Model Dev.*, **7,** 1197-1210.

Proksch, M., H. Löwe, and M. Schneebeli, 2015: Density, specific surface area and correlation length of snow measured by high-resolution penetrometry. *J. Geophys. Res.*, **120,** 346-362.

Reuter, B., J. Schweizer, and A. van Herwijnen, 2015: A process-based approach to estimate point snow instability. *Cryosphere*, **9,** 837-847.

Schneebeli, M., and J. B. Johnson, 1998: A constant-speed penetrometer for high-resolution snow stratigraphy. *Ann. Glaciol.*, **26,** 107-111.

Schweizer, J., K. Kronholm, and T. Wiesinger, 2003: Verification of regional snowpack stability and avalanche danger. *Cold Reg. Sci. Technol.*, **37,** 277-288.

Schweizer, J., B. Reuter, A. van Herwijnen, and J. Gaume, 2016: Avalanche release 101. *Proceedings ISSW 2016. International Snow Science Workshop, Breckenridge CO, U.S.A., 3-7 October 2016 (this issue)*.