LINKING SNOW COVER PROPERTIES AND AVALANCHE DYNAMICS

Walter Steinkogler[1,2*], Betty Sovilla[1] and Michael Lehning[1,2]

[1] WSL Institute for Snow and Avalanche Research SLF, Davos Dorf, Switzerland
[2] CRYOS, School of Architecture, Civil and Environmental Engineering, EPFL, Lausanne, Switzerland

ABSTRACT: Avalanches exhibit many different flow regimes from powder clouds to slush flows with fundamentally different flow dynamical characteristics, such as velocities and run-out distances. To explain these varying flow dynamics the snow cover properties must be taken into account. Recent investigations showed that the temperature of the flowing snow to be one of the most important factors controlling the avalanche typology and thus the flow dynamics. Our investigations allowed for the first time to quantify the relative contribution of the temperature in the released and entrained snow versus the temperature increase from frictional processes. Additionally, it was found in laboratory experiments that below a temperate threshold of -1°C a significant densification could be observed, yet the moving particles remained individual and cohesionless at the crystal scale. Such cold and dry snow is typically found in dry-dense flowing and powder avalanches. As soon as the snow was warmer than -1°C, distinct granules of varying sizes and properties formed and resulted in much more cohesive and larger particles, as found in moist and wet avalanches. These variations and transitions in granule structures as a function of temperature are at the basis for different flow regimes in avalanches. The results of this study are of significant interest for engineering problems, enhancements of avalanche dynamics models and forecasting. For example, snow safety personnel should be aware of snow cover property variations, e.g. altitude of 0°C line, since unexpected and atypical avalanche flow behavior, such as variations in expected run-out distance and flow direction, can occur.

KEYWORDS: Snow avalanche, snow temperature, mobility, flow dynamics.

1. INTRODUCTION

The increased demand, especially as caused by winter tourism and traffic routes across the Alps, to access mountainous regions all year long and independent of the snow and weather conditions has required the continuous investment of substantial financial efforts (SLF, 2000). Avalanche protection measures, both permanent and temporary, are an essential factor in the economic evolution of alpine regions. The most prominent avalanches paths have been mitigated with permanent structures, yet numerous avalanche paths remain and pose a danger for roads, railways and ski resorts. In the last decades, especially temporary protection measures such as artificial avalanche release and warning services experienced a rapid development (Stoffel, 2013; Rudolf-Miklau and Sauermoser, 2011). Systems for the artificial release of avalanches are increasingly applied to secure ski resorts, roads and railway tracks since they are cheaper than permanent measures (defensive structures, galleries, tunnels) and provide the possibility to release the avalanche at a defined time. This puts a lot of pressure on local authorities since it is already challenging to assess release location and time window for a snow avalanche threatening, for example, a road. Further, it is often impossible to predict the run-out distance. However, to decide on road closures, it is essential for local avalanche safety services to know whether the avalanche will reach the road or stop above. Such decisions are often very difficult as they demand the ability to correctly interpret weather forecasts, link the evolution of snowpack stability and its structure and finally evaluate the influence of the snow cover on avalanche dynamics and thus run-out distances (Blattenberger and Fowles, 1995).

Guidelines for hazard mapping (BFF, 1984; Rudolf-Miklau and Sauermoser, 2011) were originally created for extreme avalanches which are usually dry avalanches that release after extraordinary new snow events. Yet, especially for smaller and often more frequent avalanches it is essential to consider variations in snow cover properties of the flowing snow in order to accurately estimate run-out and flow behavior. Literature on the direct influence of snow characteristics on avalanche dynamics is sparse and mostly describes the link between new snow amounts and run-out for extreme avalanches (Eckert et al., 2010; Naaim and Durand, 2012).

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* *Corresponding author address:* W. Steinkogler
WSL Institute for Snow and Avalanche Research SLF,
Davos, Switzerland; tel: +41 81 417 03 75
email: steinkogler@slf.ch

Further, state of the art avalanche dynamics models, e.g. RAMMS (Christen et al., 2010), are calibrated for extreme dry avalanches and often produce unsatisfactory results for run-out distances of small- and mid-sized avalanches (defined as avalanches with a total mass of approximately 10^5 kg to 10^7 kg or size 2 to 4 according to Canadian Avalanche Association (2007)), which may still produce problems for infrastructure. New approaches and model modifications (Vera et al., 2012) seem to be very promising for the calculation of small-sized avalanches and in defining different flow regimes (Bartelt et al., 2011; Gauer et al., 2007). Bartelt et al. (2014) concluded that in future, avalanche dynamics models must reflect the variability of the natural snow conditions to improve the accuracy of model calculations. A better understanding of the influence of snow cover properties on avalanche dynamical parameters would be of great interest for further improvements of these models.

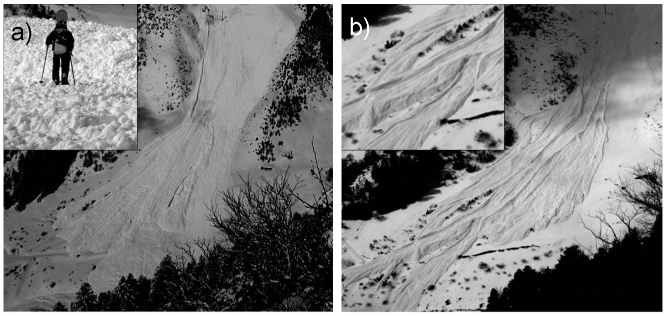

Fig. 1: Deposition area of avalanches including a closeup view of the deposited granules.

This would then, in combination with meteorological and snow cover models allow to account for varying weather conditions or climatic regions and facilitate a much more sophisticated now-casting tool for practitioners.

The intention of this study is to improve the understanding on the influence of snow cover properties on avalanche dynamics. Especially close to the melting point, rapid transitions in avalanche flow regimes are often observed (Fig. 1). This study therefore puts special focus on snow temperature effects on avalanche behavior. This requires the identification of typical features observed in real-scale avalanches under varying environmental conditions.

To improve the understanding of temperature influences, artificially released avalanches allowed a near real-time investigation of the temperature distribution and to identify potential thermal energy sources (Section 2). Finally, laboratory experiments on the granulation of snow allow to create a link between snow temperature and the associated granular structures that are typically observed in avalanche deposits (Section 3). The main findings and possible practical applications are discussed in Section 4. For additional technical information and more details on the individual subjects of this summary we refer the reader to the individual journal papers which are cited in here.

2. THERMAL ENERGY SOURCES

The properties of the alpine snow cover, e.g. snow depth or temperature, can drastically vary depending on the environmental conditions and altitudinal gradients. These variations can have drastic effects on the flow behavior of avalanches even if initial mass, release area and topography are similar. Steinkogler et al. (2013) showed with data on front velocities, run-out, flow regimes and powder clouds that different avalanches can form for similar initial conditions and on the same avalanche path. They concluded that especially the influence of snow temperature (Fig. 2) on granulation and consequently on the flow dynamics of an avalanche seems to play a crucial role.

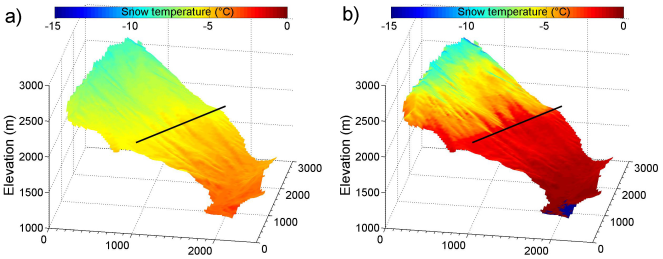

Fig. 2: Modeled snow temperature 40cm bellow snow surface for avalanches at the time of release.

Temperature was visualized in an illustrative way by applying an infrared radiation thermography (IRT) camera to assess the surface temperature before, during and just after the avalanche with a high spatial resolution. The acquired videos gave interesting qualitative, and partly quantitative, information on the flow dynamics of the investigated avalanches. For example a distinct acceleration and change in powder cloud temperature due to entrainment of warm snow by a secondary release (visible at the top of Fig. 3) could be observed. IRT images of the snow surface after the avalanche stopped, the powder cloud drifted aside due to moderate winds, revealed the warmest temperatures to be located in the center, i.e. close to the dense core, of the avalanche (Fig. 3).

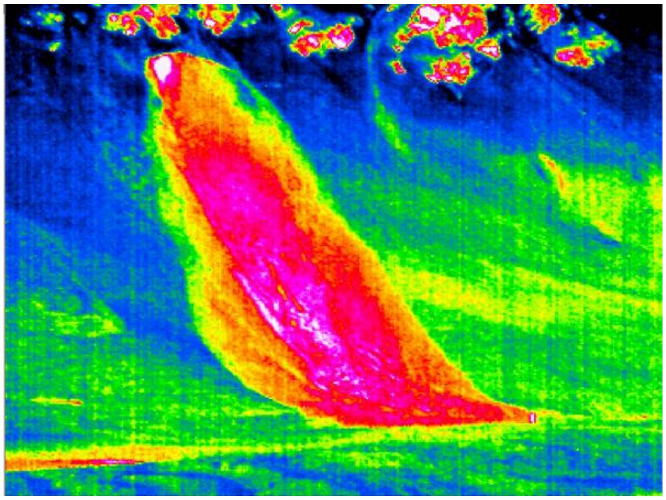

Fig. 3: Snow surface temperatures acquired with infrared radiation thermography just after the avalanche stopped.

The maximum temperatures in the area of the dense core of the avalanche were not only observed at the surface. Snow temperature measurements in a lateral trench in the deposition zone of the avalanche showed that the maximum snow temperature in the dense core also existed in vertical direction and gradually diminished towards the sides of the avalanche (Fig. 4).

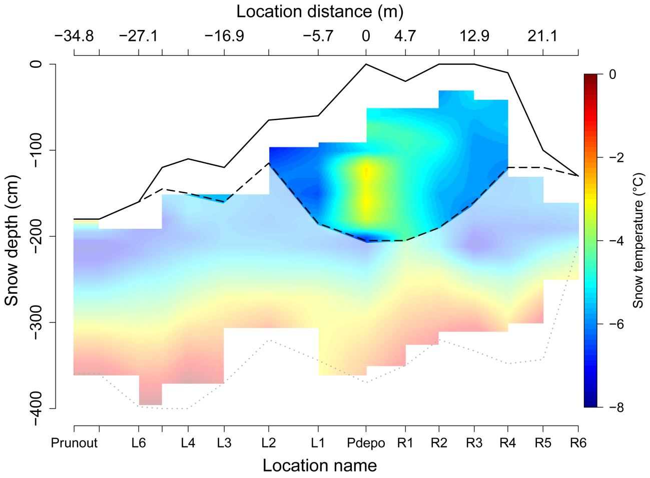

Fig. 4: Lateral snow temperature profiles in the avalanche deposits. P_{depo} and 0 m indicate the center of deposits and the index L and R represent left and right, looking uphill, measurement locations towards the lateral sides of the avalanches. Lines indicate the top of the avalanche deposit or snow cover (solid), bottom of avalanche deposit (dashed) and bottom of snow cover (pointed). Colors of undisturbed snow cover were softened for better distinction with avalanche deposits.

The temperature of flowing snow inside an avalanche is determined by the temperature of the released and entrained snow but also increases by frictional and collisional processes with time (Vera et al., 2012). To investigate the thermal balance of an avalanche in detail Steinkogler et al. (submitted) performed manually measured snow temperature profiles along the avalanche track and in the deposition area to quantify the temperature of the eroded snow layers. This data set allowed to calculate the thermal balance, from release to deposition, of an avalanche and to discuss the magnitudes of different sources of thermal energy in snow avalanches.

It was found that inside an avalanche the thermal energy increase due to friction is mainly depending on the elevation drop of the avalanche and thus a rather constant value (for a specific avalanche path and typology). Steinkogler et al. (submitted) calculated a temperature increase by friction of 0.5°C per 100 altitudinal meters for their investigated avalanches. Contrary, warming due to entrainment was very specific to the individual avalanche and depended on the temperature of the snow along the path and the erosion depth ranging from nearly no increase to 1°C. Especially in the cases of erosion all the way to the ground, and the consequent entrainment of warmer snow, the temperature increase due to entrainment can be large and significantly exceed the contribution by friction. Also altitudinal changes of snow temperature along the slope (Fig. 2) have been proven to be quite variable and directly influence flow dynamics (Steinkogler et al., 2013).

3. TEMPERATURE-DEPENDENT SNOW GRANULATION

Depending on the temperature of the snow inside the avalanche, different granular structures are typically observed in the depositions zone of avalanches which are consequently used to classify them into ‘cold’ (Fig. 1a) and ‘warm’ avalanches (Fig. 1b). It is well known that snow avalanches exhibit granulation phenomena, i.e. the formation of large and apparently stable snow agglomerates during the flow. This change of agglomerate sizes has an influence on flow behavior which, in turn, affects runout distances and avalanche velocities. The underlying mechanisms of granule formation are notoriously difficult to investigate within large scale field experiments, due to limited insight into temperatures, velocities and size distributions.

To address this issue Steinkogler et al. (Submitted) performed experiments with an ordinary concrete tumbler, which provided an appropriate means to investigate granule formation of snow on intermediate but relevant length scales. In a set of experiments at constant rotation velocity with varying temperatures and water content, they demonstrated that temperature has a major impact on the formation of granules. The experiments showed that granules only formed when the snow temperature exceeded -1°C. Depending on the conditions, different granulation regimes were obtained, which could qualitatively be classified according to their persistency and size distribution (Fig. 5).

Fig. 5: Snow inside tumbler for different experiments where (a) no persistent granules formed, (b) persistent-moist granules formed and (c) persistent-wet granules formed.

The potential of intermediate scale granulation of snow in a tumbler was further demonstrated by showing that experiments could be reproduced by cohesive discrete element simulations using appropriate dimensional analysis and dynamical similarity. The proposed discrete element (DE) model mimicked the competition between cohesive forces, which promote aggregation, and impact forces, which induce fragmentation, and supports the interpretation of the granule regime classification obtained from the tumbler experiments. Furthermore, the DE simulations reproduced the grain size distribution and general behavior observed in the different granule regimes.

4. DISCUSSION

Laboratory experiments and field measurements indicated a snow temperature close to -1°C as critical threshold for the transition between granular structures and consequently flow dynamics. For avalanches consisting of cold snow, i.e. $<$-1°C, a fine-grained structure with non-persistent granules can be expected. Even though granular structures are often observed in the deposit of avalanches in this temperature range (Bartelt and McArdell, 2009) these granules are likely to be fragments of the released or eroded snow cover. On the contrary, we expect that avalanches consisting of warm snow, i.e. $>$-1°C and possibly containing liquid water, to consist entirely of persistent granules. The properties of the granules also significantly influence flow dynamics and define the flow regime of avalanches, e.g. whether a plug or a sheared flow forms.

The results indicate that the thermal energy increase due to friction is mainly depending on the elevation drop of the avalanche and thus a rather constant value (for a specific avalanche path). Contrary, the warming due to entrainment is very specific to the individual avalanche and can significantly exceed the warming due to friction. As shown in the profiles along the avalanche track and the IRT pictures the snow temperature of the released and entrained snow can vary significantly depending on the erosion depth. Also altitudinal changes of snow temperature along the slope have been proven to be quite variable and directly influence flow dynamics (Steinkogler et al., 2013).

4.1 *Practical applications*

Snow cover simulations as shown in Fig. 2 can provide valuable information for forecasters and snow safety personnel. Based on data from automatic weather station it allows them to differentiate between ‘warm’ or ‘cold’ situations and to identify the altitude of the 0°C line in transitional cases. These calculations can be done for large areas and future developments will allow to couple the snow cover models to numerical weather prediction models, thus facilitating a forecast for the next hours.

Consideration of temperature effects in avalanche dynamics models will significantly improve their performance and practical application for different environmental and climatic conditions. An initial and practitioner friendly approach would be to have a binary switch between warm, i.e. snow temperature close to 0°C, and cold, i.e. $<$-1°C, situations. More sophisticated model developments could allow for gradual transitions between the regimes by considering the granule properties. To do so it has to be taken into account that granules can influence flow dynamics in two possible ways: by changing the size distribution of the flowing particles (Pouliquen, 1999) and by a change of their properties (Rognon et al., 2008; Alexander et al., 2006). The presented results from experimental and discrete element model simulations (Steinkogler et al, Submitted) provide a first step towards that approach.

5. CONCLUSIONS

For the conducted laboratory experiments and investigated avalanches the following conclusions can be made:

- Snow temperature has a major impact on the formation of granules and thus on avalanche flow dynamics.
- Consequently, different avalanches can occur on the same avalanche path even though the conditions in the release zone are similar.

- Granulation of snow is highly temperature dependent with a snow temperature threshold at -1°C. Below this temperature no persistent granules were observed.
- For the investigated dry avalanches, the thermal energy increase due to friction is mainly depending on the elevation drop of the avalanche with a warming of approximately 0.5°C per 100 height meters.
- Contrary, warming due to entrainment was very specific to the individual avalanche and depended on the temperature of the snow along the path and the erosion depth ranging from nearly no increase to 1°C.
- The warmest part of an avalanche is concentrated in the dense core.
- Especially close to the melting point rapid transitions in flow dynamics need to be expected.

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REFERENCES

Alexander, A.W., B. Chaudhuri, A. Faqih, F.J. Muzzio, C. Davies, and M.S. Tomassone, 2006: Avalanching flow of cohesive powders. *Powder Technology*, **164**, 13 – 21.

Bartelt, P., O. Buser, Y. Bühler, L. Dreier, and M. Christen, 2014: Numerical simulation of snow avalanches: Modelling dilatative processes with cohesion in rapid granular shear flows. *Fundamentals of Ground Engineering*, 327.

Bartelt, P., and B.W. McArdell, 2009: Granulometric investigations of snow avalanches. *Journal of Glaciology*, **55**, 829–833.

Bartelt, P., L. Meier, and O. Buser, 2011: Snow avalanche flow-regime transitions induced by mass and random kinetic energy fluxes. *Annals of Glaciology*, **52**, 159–164.

BFF, E., 1984: Richtlinien zur berücksichtigung der lawinengefahr bei raumwirksamen tätigkeiten. *Bundesamt für Forstwesen (BFF), Eidgenössisches Institut für Schnee-und Lawinenforschung (EISLF)*.

Blattenberger, G., and R. Fowles, 1995: Road closure to mitigate avalanche danger: a case study for little cottonwood canyon. *International Journal of Forecasting*, **11**, 159 – 174. Probability Forecasting.

Canadian Avalanche Association, 2007: *Observational Guidelines and Recording Standards for Weather, Snowpack and Avalanches*. Revelstoke, British Columbia: Canadian Avalanche Association.

Christen, M., J. Kowalski, and P. Bartelt, 2010: Ramms: Numerical simulation of dense snow avalanches in three-dimensional terrain. *Cold Regions Science and Technology*, **63**, 1 – 14.

Eckert, N., H. Baya, and M. Deschatres, 2010: Assessing the response of snow avalanche runout altitudes to climate fluctuations using hierarchical modeling: Application to 61 winters of data in france. *Journal of Climate*, **23**, 3157–3180.

Gauer, P., D. Issler, K. Lied, K. Kristensen, H. Iwe, E. Lied, L. Rammer, and H. Schreiber, 2007: On full-scale avalanche measurements at the ryggfonn test site, norway. *Cold Regions Science and Technology*, **49**, 39 – 53. Selected Papers from the General Assembly of the European Geosciences Union (EGU), Vienna, Austria, 25 April 2005.

Naaim, M., and Y. Durand, 2012: Dense avalanche friction coefficients influence of nivological parameters. In: *Proceedings, International Snow Science Workshop ISSW 2012, Anchorage, Alaska*.

Pouliquen, O., 1999: Scaling laws in granular flows down rough inclined planes. *Physics of Fluids*, **11**, 542–548.

Rognon, P., J.N. Roux, M. Naaim, and F. Chevoir, 2008: Dense flows of cohesive granular materials. *Journal of Fluid Mechanics*, **596**, 21–47.

Rudolf-Miklau, F., and S. Sauermoser, 2011: *Handbuch Technischer Lawinenschutz*. John Wiley & Sons.

SLF, 2000: Der lawinenwinter 1999. *Ereignisanalyse (588 p)*.

Steinkogler, W., B. Sovilla, and M. Lehning, 2013: Influence of snow cover properties on avalanche dynamics. *Cold Regions Science and Technology*, **97**, 121–131.

Stoffel, L., 2013: *Vergleich der Sprengmethoden: Gazex, Lawinenwächter / -mast Inauen-Schätti, Wyssen Sprengmast, Avalancheur*. WSL-Institut für Schnee- und Lawinenforschung SLF.

Vera, C., T. Feistl, W. Steinkogler, O. Buser, and P. Bartelt, 2012: Thermal temperature in avalanche flow. *Proceedings, International Snow Science Workshop ISSW 2012, Anchorage, Alaska*.