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Editorial

# Some recent advances in snow and avalanche science

## 1. Introduction

The 2010 International Snow Science Workshop (ISSW), was held in Squaw Valley, California, USA on 17–22 October. This biannual meeting of snow avalanche practitioners and scientists was the largest gathering to date, with over 920 participants, including 60 oral talks and 90 poster presentations, as compared to only 250 participants and 34 presentations when the meeting was last held in the Lake Tahoe area in 1986. The ISSW meeting has become the premier snow avalanche meeting in North America, drawing participants from around the globe; this year 98 registrants came from a different continent. The meeting brings together scientists and practitioners with the theme of “A Merging of Theory and Practice.”

The 9 papers in this Special Issue cover a wide range of topics in current avalanche science, including advances in modeling thermal and mechanical processes in snow, new instrumentation and techniques for monitoring and measuring snow properties and conditions, a statistical analysis of avalanches in the high Arctic, and forecasting of ice avalanches.

## 2. Snow cover properties

New tools such as micro-computed tomography using X-rays, operated in climate controlled laboratories at subfreezing temperatures, have given snow scientists a new view into snow metamorphism (e.g. Schneebeli and Sokratov, 2004). These techniques provide 3D measurements of snow microstructure, and can be used to monitor changes in snow structure when different thermal conditions are applied. Large temperature gradients within the snowpack lead to highly anisotropic snow crystals, which cause important anisotropic thermal properties, as shown by Shertzer et al. (2011-this issue). The ice lattice is much more effective at transmitting heat in the direction parallel to the long-term temperature gradient, and this causes thermal effects that cannot be represented in models that use bulk isotropic properties. This work will improve the capability of modeling the flow of heat near layers with anisotropic crystals, critical for understanding the evolution of weak layers which are important for slab avalanches.

Radar continues to develop as a tool for non-destructively measuring bulk as well as internal snow properties (Marshall and Koh, 2008). In particular, if the radar system is buried in the ground beneath the snowpack the evolution of snow stratigraphy during the winter season can be followed (e.g. Heilig et al., 2010). Mitterer et al. (2011-this issue) continuously operated an upward-looking impulse radar system (upGPR) to track the advance of a wetting front as it progressed during the melt season. Although it was not possible to distinguish between a uniform wetting front and percolation channels, an estimate of the bulk liquid water content could be made using radar travel-time and an independent measurement of snow depth. Strong multiple reflections appear to be caused by layers with high liquid water content, which adds information about the heterogeneity of the liquid water within the snowpack.

## 3. Snow stability and avalanche release

The release of a dry-snow slab avalanche can be envisaged as a fracture process (e.g. Schweizer et al., 2003). The specific fracture energy and the stiffness of the overlying slab are therefore among the most relevant properties of snow to be measured for avalanche release prediction. The propagation saw test (PST) (Gauthier and Jamieson, 2006) is the field test best suited to determine the fracture properties of snow. Schweizer et al. (2011-this issue) performed over 150 PSTs combined with snow micro-penetrometer (SMP) measurements (Schneebeli and Johnson, 1998) to estimate weak layer fracture energy. They used a finite element model to evaluate the results from the propagation saw tests with associated SMP measurements. Their values were mostly in the range of 0.5 to 2 J $m^{-2}$, which is larger than previously reported values (Sigrist and Schweizer, 2007). Comparison with independent estimates using a video sequence of one fracture test shows promising results (van Herwijnen and Heierli, 2010).

Avalanche initiation typically occurs when a basal weakness parallel to the slope fails, followed by failure in tension at the crown wall. The basal weakness fails in mixed-mode (compression and shear) loading, and models proposing either mode as the dominant mechanism have been presented in the recent literature (e.g. Heierli et al., 2008; McClung, 2007). Linear elastic fracture mechanics has been used to model snow as a brittle material, which is a useful first assumption. However, snow is also known to show strain-softening behavior under many conditions in both tension and shear and is therefore considered a quasi-brittle material. Borstad and McClung (2011-this issue) performed beam bending tests in a cold laboratory using natural snow samples. They then applied a nonlocal isotropic damage model to replicate the tensile failure of the dry snow slab specimens, which were both notched and unnotched. Their simulations reproduced the significant decrease in strength observed with the notched samples and produced both initiation and propagation of a crack, for unnotched and notched samples, respectively.

Whereas explosives are routinely used to trigger avalanches in ski resorts and along transportation corridors, our understanding of the dynamic response of the snowpack to avalanche control explosives is rather limited. Little progress has been made since the pioneering work by Gubler (1977). Miller et al. (2011-this issue) developed an explicit non-linear model which simulates an explosive air blast above the snowpack. Their modeling results show that a shear stress

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wave develops, which is concentrated just above the weak layer. Due to the acoustic insulating properties of snow, their model shows an increased air pressure impulse and resulting response for explosives suspended above the snow surface when compared to explosions on the snow surface. Results show that stresses in the slab are approximately 50% greater for an air blast at a distance of about 4 m from the blast axis when compared to a surface detonation. This greater effectiveness of air blasts was shown over 30 years ago by Gubler (1977) and has been used by practitioners for decades, but has not been confirmed by explicit modeling of explosions over snow until now.

## 4. Avalanche monitoring and characteristics

Seismic sensors were first shown to be useful tools for monitoring avalanche activity by St. Lawrence and Williams (1976). Studies on seismic signals generated by avalanches have essentially two main goals: improving our understanding of avalanche dynamics (e.g. Vilajosana et al., 2007) and monitoring avalanche activity (e.g. Navarre et al., 2009). Unlike previous studies, van Herwijnen and Schweizer (2011-this issue) inserted the geophones directly in an avalanche start zone, allowing for the detection of substantially smaller avalanches, including loose snow avalanches. They confirm previous work that avalanches generate unique seismic signals and recorded a unique dataset of basin scale avalanche activity over one winter season, which included over 380 seismic signals likely generated by avalanches. They relate these events to local meteorological conditions, confirming previous relationships between local weather conditions and avalanche occurrence.

Avalanches not only generate characteristic seismic signals, but also infrasonic, low frequency (<20 Hz) acoustic waves propagating through the air at the speed of sound. Therefore, infrasound can also be used to monitor avalanche activity. Recently, the use of infrasound arrays has improved the identification of signals generated by avalanches (Scott et al., 2007), and such arrays are currently used by avalanche forecasters to identify avalanche activity during low-visibility conditions along at least two road corridors in the United States. Ulivieri et al. (2011-this issue) installed a 4-element small aperture, infrasound array in the northwestern Italian Alps. During the winter of 2009–2010 they detected and characterized 343 infrasonic events. Many of these events were sharp infrasonic transients caused by explosions during avalanche control work. The long lasting signals are possibly caused by avalanches, but only few of these were validated by direct avalanche observation. Whereas Ulivieri et al. (2011-this issue) consider their results as promising, they also point out that adequate treatment of environmental noise and careful data processing are still needed to successfully monitor avalanches on an operational basis.

While avalanches are not commonly problematic in the High Arctic, near Longyearbyen, Svalbard, they significantly affect the unusually large snowmobile traffic. Eckerstorfer and Christiansen (2011-this issue) present a new 4 year record of 156 avalanche events and meteorological data from nearby automatic weather stations in the Arctic, for which avalanche studies have so far been absent from the literature. While their dataset is not large enough to produce a robust statistical forecasting tool, they were able to show that precipitation and a snowdrift index (based on Hendrikx et al., 2005) from the previous 24, 48, and 72 h, had the highest correlation with avalanche events.

## 5. Hazard mitigation

Ice masses breaking off from hanging glaciers can trigger large snow avalanches. For local authorities responsible for safety it is therefore essential when planning preventive measures to take into account both the avalanche danger and the risk of falling ice. Margreth et al. (2011-this issue) present an operational safety concept for a hanging glacier near Mont Blanc (Italian Alps). The Whymper glacier endangers the village of Planpincieux and its surroundings in the Val Ferret. They show that ice avalanches in that area can be modeled with a snow and rock avalanche model, and develop safety measures based on the forecasted avalanche danger and estimated volume of ice. They describe their detailed observation system, which includes total stations, GPS measurements, and seismometers. They calibrated their modeling approach using the catastrophic June 1998 event, and use their model to evaluate 14 different scenarios. The monitoring and modeling approach worked reasonably well on a small event in 2010 and is promising, however the model used was not developed specifically for ice avalanches and more data are still needed.

## 6. Concluding remarks

New innovative instrumentation continues to enhance our ability to monitor snow conditions and measure properties important to the avalanche formation, initiation, and propagation processes. Models continue to improve, and with the use of new data from modern instrumentation, more fundamental physics have been incorporated, improving our understanding of the snowpack's response to external conditions. Snow properties at the micro-scale have a strong influence on snow failure and the avalanche process (e.g. Reiweger and Schweizer, 2010; van Herwijnen et al., 2009), and spatial variability in snow properties at various scales (e.g. Schweizer et al., 2008) continues to make operational application even with innovative techniques difficult. Future work combining remote sensing, modeling, and high resolution ground-based snow measurements may provide tools for improving understanding of spatial variability of snow properties and may lead to better spatial estimates of snow stability for operational avalanche forecasting.

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