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Editorial

Recent developments in applied snow and avalanche research

1. Introduction

The International Snow Science Workshop (ISSW) is a biennial, international conference that brings together avalanche safety specialists of all types – public avalanche forecasters, avalanche safety consultants, ski patrollers, mountain guides, search and rescue technicians, highway avalanche forecasters, avalanche educators, manufacturers of safety equipment and academic researchers – from across the world to share their experiences, present research results, demonstrate new products and brainstorm about solutions for existing challenges. This close exchange between practitioners has been a hallmark of the avalanche community and many innovative solutions to avalanche safety challenges have been born at one of the many ISSWs.

The 2014 ISSW, which was held in Banff, Canada from 29 September to 3 October 2014, attracted over 800 participants from 16 countries. During the oral and poster sessions of the conference, a total of 215 papers were presented covering a wide range of topics including properties of snow; snowpack structure, variability and metamorphism; instrumentation and measurement; avalanche formation, failure and dynamics; avalanche forecasting; avalanche terrain; avalanche hazard assessment, human factors; risk management; avalanche accidents and rescue; avalanche education; and data management. Together with the proceedings from previous ISSWs, all of the contributions presented at the 2014 ISSW are available online at http://arc.lib.montana.edu/snow-science. This special issue compiles ten extended research papers from the 2014 ISSW that address some of today's most challenging topics in avalanche risk control.

2. Snowpack properties

Weak layer formation within the snow cover is rare — most weak layers develop at the snow surface and get subsequently buried. Among the few scenarios is the growth of faceted crystals adjacent to buried melt-freeze crusts. Whereas this formation process has long been known (e.g., Colbeck and Jamieson, 2001; Jamieson, 2006), its quantification was so far lacking. Using laboratory experiments, Hammonds et al. (2015 - in this issue) examine the microstructural evolution of buried ice crusts and in particular of the snow layer above and below. Using micro-thermocouple arrays, X-ray micro-computed tomography and scanning electron microscopy, the authors document the temporal evolution of temperature gradients and microstructure at sub-millimeter resolution around a 4 mm ice crust in an artificial snow sample over a range of large-scale temperature gradients. The study finds that the local temperature gradients within 1 mm of the snow-ice interface can be nearly 40 times larger than the imposed macroscopic (or bulk) temperature gradient. Furthermore, the temperature gradient at the bottom interface was found to be approximately two-times larger than at the top interface. Supported by their observations of crystal growth via deposition at the bottom and sublimation at the top of the ice crust, the authors provide a detailed explanation of the observed temperature gradients using theoretical considerations on conduction and latent heat flux. The results of this study clearly highlight that the processes leading to weak layer formation near ice crusts occur under temperature gradients that are much larger and scales much smaller than detectable with observational techniques typically used in the field. This paper represents an important step in improving our understanding of faceting near ice or melt-freeze crusts and its effect on avalanche formation.

Over the last decade, the variable nature of the mountain snowpack has attracted a lot of research interest. This variability is present at a large range of scales (e.g., Grünewald et al., 2013) and important for many processes such as run-off related to melt of snow (e.g., Pomeroy et al., 1998) and avalanche formation (Schweizer et al., 2008). Spatial variations in slab and weak layer properties are believed to control the avalanche release process by either promoting or hindering failure initiation as well as crack propagation and fracture arrest. Several field studies have characterized the variations in snow properties by analyzing point measurements with geostatistical methods (e.g., Kronholm et al., 2004; Lutz and Birkeland, 2011) and occasionally also addressed stability variations (e.g., Schweizer and Reuter, 2015). Whereas it seems clear that the heterogeneity of the mountain snowpack is related to variations in terrain and micro-meteorological conditions – and their interaction – few studies have addressed the causes of heterogeneity (e.g., Birkeland, 2001). The study of Reuter et al. (2015 - in this issue) builds on this body of research and pursues the question whether simple drivers like slope aspect, slope angle and snow depth are associated with variations of snow stability at the basin scale. Combining a dataset of 613 snow micro-penetrometer (SMP) (Schneebeli and Johnson, 1998) measurements collected in five field campaigns under different snow conditions with a 1 m-resolution digital elevation model of the study sites and high resolution terrestrial laser scans for determining snow depth distributions at the study sites, the authors examined the relationships between the mentioned simple drivers and two recently developed quantitative metrics of snow instability describing the propensity of failure initiation and crack propagation extracted from the SMP signal (Reuter et al., 2015). The analyses presented in this paper reveal that slope aspect is the most prominent simple driver. Furthermore, snow depth was found to be associated with crack propagation propensity and slope angle was related with failure initiation propensity. These results clearly highlight that easily obtainable terrain and snowpack observations can provide important clues for assessing the variability of snow stability within individual basins.

Even though explosives are used extensively for temporary mitigation of avalanche risk (e.g., in ski areas to protect ski runs or

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along transportation routes to proactively release small avalanches), relatively little research has been conducted to better understand the interaction between the shock wave produced by the explosive and the snowpack (e.g., Gubler, 1977; Miller et al., 2011). Simioni et al. (2015 - in this issue) aim to address this knowledge gap by developing an experimental setup for measuring the effect of an explosion on the snowpack using microphones, accelerometers and high-speed cameras in snow pits for subsequent analysis of the displacement field. The goal of this study was to measure acoustic wave propagation in the snowpack and to derive empirical relationships for the decay of near-surface air pressure, acceleration, displacement velocity and displacement with respect to distance from explosion and depth within the snowpack. Based on 37 experiments, the authors found that waves within the snowpack arrived earlier than the corresponding air pressure waves and that the waves at the lower sensors in the snowpack did not arrive significantly later than at the top sensors. They conclude that this likely indicates surface waves propagating through the snowpack. Accelerations decayed strongly with depth at any distance in dry and wet snowpacks. By evaluating the wave arrival times at the microphones, the air pressure wave speeds were determined; this allows estimating the distance where the transition of shock to elastic wave occurs. Even though the experimental setup did not support a quantitative analysis of the displacement field, a visual inspection of video stills allowed identifying two types of weak layer failures: one caused by the air pressure wave close to the observation point, and the other caused by the air pressure wave closer to the explosion and subsequent crack propagation. This work shows that many issues with regard to explosive induced failures are still unknown – despite the fact that avalanche control by explosives is widely applied – indicating that explosive use may still be optimized.

3. Snowpack tests

Stability tests are a key tool for assessing the likelihood of avalanches and the Extended Column Test (ECT) introduced by Simenhois and Birkeland (2009) has been shown to provide insights into failure initiation and crack propagation (see, e.g., Schweizer and Jamieson, 2010). As a consequence, the ECT has gained considerable popularity among practitioners. The study of Bair et al. (2015 - in this issue) examines the effect of beam length for assessing stability with ECTs. They collected a data set of 220 ECTs including 136 tests of 2-m long ECTs that were performed next to standard ECTs (90 cm column length) where a fracture had propagated across the entire column. The results of the study show that including a 2-m ECT after a fully propagated standard ECT was effective at detecting stable conditions, thereby reducing the likelihood of false unstable results of the standard ECT. However, the 2-m ECT exhibited a high likelihood to false stable results — even at "poor" and "very poor" stability, almost half of 2-m ECTs did not propagate. The authors therefore conclude that the standard ECT is superior for binary stability assessments (stable versus unstable) and do not recommend the 2-m ECT for this purpose.

4. Remote sensing

Using terrestrial or airborne laser scanners has greatly advanced our understanding of snow distribution from the slope to the mountain range scale (e.g., Deems et al., 2013; Prokop, 2008; Schirmer et al., 2011). Detailed knowledge of overall snow depth and snow accumulations from individual storm periods can offer valuable insights for the local assessment of avalanche hazard and the planning of avalanche control missions. While technical limitations of early terrestrial laser scan (TLS) systems prevented their operational application, recent improvements in data collection time, scan range and resolution offer new opportunities. Deems et al. (2015 - in this issue) present the results of a pilot study at Arapahoe Basin Ski Area in Colorado, where two Riegl laser mapping systems were examined for operational use in avalanche control planning and post-control assessment. The study shows that the high-resolution TLS maps of snow depth and accumulation can offer unprecedented characterization of the local conditions and have great potential to provide valuable information for operational avalanche control efforts. The authors conclude their paper by highlighting possibilities to further improve the operational application of this promising technology.

Having accurate and comprehensive avalanche occurrence records is critical for improving our understanding of the physical processes underlying avalanche release and advancing avalanche forecasting practices (e.g., Schweizer and van Herwijnen, 2013). Therefore, several monitoring systems for the automated remote detection of avalanches have been developed (e.g., Marchetti et al., 2015; Thüring et al., 2015; van Herwijnen and Schweizer, 2011). However, monitoring by either infrasonic sensors or geophones can only provide avalanche activity within a few kilometers. Obviously, a much higher spatial coverage can be obtained with airborne remote sensing techniques (e.g., Bühler et al., 2009), though so far the temporal resolution is limited and operational application for avalanche forecasting is not possible yet (Bühler et al., 2014). Eckerstorfer and Malnes (2015 - in this issue) describe a technique for manually detecting avalanche debris in high-resolution Radarsat-2 synthetic aperture radar (SAR) images. For an avalanche cycle in northern Norway (Troms region) in March 2014, they compare the results of their technique with other detection methods and show that their approach is able to reliably detect avalanche occurrences over large spatial areas that would otherwise not be accessible. Based on their results, the authors also present a qualitative model for electromagnetic backscatter on avalanche debris. Even though the authors highlight that the operational use of the described detection method is likely limited due to the high acquisition cost, small ground swath and uncertain repeat time of Radarsat-2 SAR images, their paper is an important contribution in the emerging research field of space-borne avalanche detection.

5. Avalanche forecasting

The mechanics of wet-snow avalanches are still not well understood and their prediction remains challenging (e.g., Baggi and Schweizer, 2009; Mitterer and Schweizer, 2013). Helbig et al. (2015 - in this issue) explore whether a combination of large-scale meteorological forecast data and terrain parameters can be used to predict large-scale wet-snow avalanche patterns over complex topography. Using wet-snow avalanche observations recorded by time-lapse photography at the Dorfberg in Davos, Switzerland, they derived probability density functions for wet-snow avalanching with respect to daily mean air temperature and incoming shortwave radiation. These reference probability density functions were then applied to predicted daily mean air temperature and subgrid terrain-corrected incoming shortwave radiation from the numerical weather prediction model COSMO of the Swiss meteorological service to produce joint probability maps of wet-snow avalanche probability for all of Switzerland on a 2.5 km grid. The algorithm also includes a probability density function for mean subgrid slopes of previously observed avalanche grid cells during the current avalanche cycle to account for the particular characteristics of the current cycle. The validation results show that the described approach produces maps that represent the observed spatial pattern of wet-snow avalanche activity reasonable well. Even though the presented approach is unable to predict the onset of a wet-snow avalanche cycle, this contribution is an important step for improving our ability to predict wet-snow avalanches.

Similarly to wet-snow avalanches, the prediction of deep slab avalanches on persistent weak layers is a challenging task (Jamieson et al., 2001). The study of Marienthal et al. (2015 - in this issue) examines the usefulness of meteorological variables for predicting seasons and days with deep slab avalanches. Using classification trees (Breiman et al., 1998) and random forests (Breiman, 2001), the authors explore a data set from the Bridger Bowl ski area in southwest Montana that covers 44 winter seasons. Their analysis confirms the results of previous work in this area, but also provides a few valuable additional insights. Consistent with previous work, days with deep slabs were found to be associated with greater cumulative precipitation and warmer air temperatures over the seven days prior to the event. Deep wet slabs were associated with sustained above freezing air temperatures during the preceding three days. The results clearly highlight the importance of temperature as a contributing factor for deep wet-snow slab avalanches. The analysis also showed that seasons with dry or wet deep slab avalanches at Bridger Bowl are typically associated with less early season precipitation than seasons without observed deep slab activity, but sufficient precipitation to form a continuous weak layer or bed surface above the local ground roughness. The authors therefore conclude that seasonal meteorological variables (monthly sums and averages) that describe the character of the current season can provide valuable insight for forecasting deep slab avalanches.

The objective of the study by Peitzsch et al. (2015 - in this issue) was to improve the understanding of the effect of terrain characteristics on glide snow avalanches, another type of avalanches that is difficult to predict (e.g., Höller, 2014; Mitterer and Schweizer, 2012). Using a data set from the Going-to-the-Sun road in Glacier National Park, Montana, the authors contrasted the terrain characteristics of 53 avalanche paths where 192 glide snow avalanches have been observed to 117 non-glide snow avalanche starting zones to gain a better understanding of terrain characteristics associated with the occurrence of glide snow avalanches. A classification tree analysis revealed four key terrain characteristics for distinguishing between glide and non-glide snow avalanche terrain: glide factor (a combination of surface roughness/ground class and aspect; Margreth, 2007), maximum slope angle, sum of solar radiation from 15 March to 1 June, and maximum slope curvature. Terrain with observed glide snow avalanches typically had a larger glide factor (>2.5), smaller maximum slope angle (≤65°), smaller sum of solar radiation (≤3.9 kWh/m^2) and more uniform slopes with less curvature (≤3.5). A 10-fold cross-validation of the classification tree indicates that while the model is able to reliably identify glide snow avalanche terrain, its ability to classify non-glide snow avalanche terrain is lower. While the implementation of the classification tree as a simple spatial model provides an interesting perspective on the distribution of glide snow avalanche terrain, it also highlights the overestimation of potential areas — a weakness thoroughly discussed by the authors.

Whereas weather forecasting largely relies on numerical weather prediction (NWP), its direct application in avalanche forecasting is still limited (Bellaire et al., 2011; Lehning et al., 2004; Schweizer et al., 2006) — with a few exceptions (Durand et al., 1999; Rousselot et al., 2010). Vernay et al. (2015 - in this issue) introduce the approach of ensemble forecasting, a method increasingly used in meteorological and hydrological models to explicitly incorporate uncertainty (e.g., Rossa et al., 2011), to avalanche hazard forecasting. In their paper, the authors describe how they expanded the existing functionality of the SAFRAN-SURFEX/ISBA-Crocus-MEPRA model chain (Durand et al., 1999; Lafaysse et al., 2013), which is used for operational avalanche hazard forecasting in France, by replacing the input for the model chain from the single deterministic output of the numerical weather prediction model used by Météo France to 35 members of the recently developed PEARP ensemble weather prediction system (Descamps et al., 2015). The resulting 35 different predictions of snowpack and avalanche hazard conditions illustrate the possible range of conditions to be expected during the forecast period much more explicitly. However, in one example of an ensemble forecast for a storm snow event in the Pyrenees during January 2013, the ensemble dispersion was very high so that the hazard index often ranged from low to very high hazard. Nevertheless, the validation and case studies suggest that ensemble forecasting systems can significantly improve the skill of the model chain and hence may offer valuable additional information to avalanche forecasters.

6. Concluding remarks

The papers included in this special issue clearly highlight the breadth and quality of work that is currently being conducted in the avalanche research community. Many of the recent developments are based on successfully exploiting modern technologies. In particular, at the micro-scale these new approaches have significantly advanced our understanding or at least allowed quantifying processes previously only understood in a qualitative sense. The latter is crucial for numerical modeling which certainly is the key to modern avalanche forecasting — even tough observational data will continue to be essential, in particular those related to snow instability. Remote sensing has contributed to a better understanding of the processes at the other end of the relevant scales and is not only indispensable for model validation, but eventually might also provide near-real time date for operational purposes. It remains to be seen how micro-scale processes can be up-scaled and incorporated into avalanche release models that predict snow instability in complex terrain — and are amenable to validation.

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