Cold Regions Science and Technology 120 (2015) 168–178

Contents lists available at ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

Relating simple drivers to snow instability

Benjamin Reuter *, Alec van Herwijnen, Jochen Veitinger, Jürg Schweizer

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

ARTICLE INFO

Article history:
Received 30 December 2014
Received in revised form 6 May 2015
Accepted 29 June 2015
Available online 4 July 2015

Keywords:
Snow stability
Spatial variability
Terrain
Avalanche forecasting

ABSTRACT

Snow layers form during and after accumulation due to the interaction of meteorological and physical processes. It is known that the vertical structure and also the lateral continuity of layers depend on these processes and the boundaries set by the terrain. This study addresses the variations seen among vertical penetration resistance profiles and investigates possible forcings at the basin scale. In the past years we acquired a unique dataset with 613 snow micro-penetrometer (SMP) resistance measurements covering a variety of dry-snow conditions. With recent advances in signal processing all snow layer properties required for snow instability modeling are extracted from a SMP signal so that quantitative metrics of the propensity to failure initiation and crack propagation can be calculated. The modeled values of instability corresponded well with field test results obtained during the measurement campaigns and the verified, local danger. We then analyzed whether snow instability was related to simple drivers such as slope aspect, snow depth, and slope angle. In general, aspect was the most prominent driver as on all field days we found associations of our measures of snow instability with aspect. For 'old' slab layers the relation between aspect and snow instability was more pronounced than for recently deposited slab layers. However, the relationships between drivers and our measures of snow instability varied depending on whether we analyzed the single field days separately or jointly. Considering all field days jointly, which reflects mean trends over varying snowpack conditions, slope angle was weakly related to the failure initiation propensity and snow depth to the crack propagation propensity. Our findings suggest that with SMP field measurements differences in snow conditions can be resolved which relate to the failure initiation and crack propagation propensity relevant for snow instability assessment. Our analysis of terrain and snow depth data showed that readily and widely available simple drivers have the potential to enhance snow instability predictions from point measurements at the basin scale.

1. Introduction

Classical snow instability observations require an in-depth knowledge on site selection (e.g., Landry et al., 2004; Schweizer and Jamieson, 2010), snow profiling technique and above all interpretation (e.g., Schweizer and Jamieson, 2007). As we often already know the general avalanche conditions within a region, but are interested in local differences, we may look at the drivers responsible for snow instability patterns. The causes (or drivers) of spatial variations in snow instability, and in general of snowpack properties, can be divided into external and internal agents acting during and/or after deposition (Sturm and Benson, 2004). These process drivers include precipitation, wind, radiation, temperature and snow metamorphism; they all cause spatial variations mainly by interacting with terrain (Schweizer et al., 2008b). Whereas at the slope scale, the causes of spatial variations are difficult to explain since typical drivers such as radiation do hardly vary, the problem is perceived to be somewhat less complex at the basin scale (for a definition of scales used in spatial variability studies see Schweizer and Kronholm, 2007). In fact, at the scale of a basin, covering several slopes within a subregion of a valley, it has been shown that, for example, differences in snow depth can be explained to a large extent by the average wind speed, altered by terrain (Schirmer et al., 2011). Just by applying a simple terrain parameter based model (Winstral et al., 2002) they were able to reproduce general snow accumulation patterns at the basin scale. Therefore, we hypothesize that at the basin scale variations of snowpack properties relating to instability may be mainly due to varying topography so that simple drivers such as terrain parameters can be considered instead of the process drivers to explain observed spatial patterns. In contrast, this assumption does not hold at the slope scale, where these variations of topography simply do not exist.

Exploiting simple drivers such as terrain parameters or snow depth for snow instability estimation may be useful when making decisions in the field or interpolating snow instability information. Snow instability assessment is basically based on weighing meteorological conditions such as new snow accumulation, snow temperature and wind with snowpack stratigraphy and terrain (Schweizer et al., 2003a). Accounting for detailed terrain characteristics is key for accurately modeling

* Corresponding author. Tel.: +41 81 417 0347; fax: +41 81 417 0110.
E-mail address: reuter@slf.ch (B. Reuter).

http://dx.doi.org/10.1016/j.coldregions.2015.06.016

incoming global radiation (Helbig et al., 2010) and thus snow temperatures, but also for assessing snow accumulation which is forced by local, terrain induced winds (Dadic et al., 2010). As both, the radiation balance and snow accumulation are closely tied to terrain parameters, the terrain parameters aspect and slope angle are believed to shape snow instability patterns (Schweizer et al., 2008b). Moreover, slope angle is not only an important parameter of incoming short wave radiation, but also directly determines the stress state within the snowpack. Snow depth is suspected to be an indicator of snow instability, just as recurring snow depth patterns are shaped by terrain and average weather conditions (Grünewald et al., 2010). Above all, simple drivers have the great advantage that they are readily and widely available.

Various studies have investigated associations between snow instability and simple drivers such as slope aspect, snow depth and slope angle. At the slope scale, Campbell and Jamieson (2007) performed Rutschblock (RB) tests on rather uniform slopes with small differences in either aspect, snow depth or slope angle. Their results were mostly inconclusive, as on most slopes they could not find a clear relation between RB score and snow depth, aspect or slope angle. Furthermore, when correlations were present, e.g. for snow depth and slope angle, they were either positive or negative. Birkeland et al. (1995) measured snow strength with a digital resistograph as an indicator of snow instability on two different slopes. Whereas they found no relation between snow depth and snow strength at one site, they suspected less complex terrain characteristics at a second site to cause a significant relation between snow depth and snow strength.

At the regional scale, however, some studies identified relations between snow stability test results or specific snow instability related properties and terrain parameters. Birkeland (2001) was among the first to investigate the dependence of snow instability on terrain and found lower stability results in high elevation north-facing slopes. His results also indicate that differences evolve with time, i.e. variable weather conditions shape the snowpack and introduce terrain driven differences. Schweizer et al. (2003b) analyzed snow instability observations from five periods during a winter season covering a mountain region as well. Among the simple drivers specified above they found that snow depth was the best indicator of snow instability. Assessing the predictive power of meteorological and snowpack properties for observed snow instability, Zeidler and Jamieson (2004) also found snow depth to be a significant driver for instability, which they described with a skier stability index.

At the basin scale, Schweizer et al. (2008a) performed manual observations of snow surface properties and measurements of penetration resistance with the snow micro-penetrometer (SMP) (Schneebeli and Johnson, 1998). With the penetration resistance measurements (four per manual observation) they found a larger amount of variation in snow surface properties than with manual observations indicating that variation depends on measurement support, the area represented by each sample. They also explored the causes of the snow surface hardness variations based on measurements of a nearby automatic weather station. Whereas their analysis of the causes of variability at the slope scale was mainly inconclusive, they observed a general trend to lower penetration resistance in the topmost 2 cm and lower slope-scale variation after a snowfall event and higher resistance and variability during a subsequent period of fair weather.

Buried surface hoear layers can cause widespread avalanching and periods of poor snow stability. Hence, a couple of studies focused on how terrain parameters drive the distribution of surface hoar. Lutz and Birkeland (2011) modeled the radiation budget in forest openings including the sky visibility and found that spatial differences of measured surface hoar size depended thereof. Feick et al. (2007) and Borish et al. (2012) identified a correlation between elevation and surface hoar crystal size and snow instability estimates, which both attributed to local wind regimes. Schweizer and Kronholm (2007), on the other hand, found aspect and slope angle to be more indicative for the presence of surface hoar at the regional scale. Slope angle and aspect were also rated as important drivers of surface hoar formation and persistence by Helbig and van Herwijnen (2012) who modeled surface hoar size in complex terrain based on simple terrain characteristics. Horton et al. (2015) observed surface hoar sizes at a regional scale; they suggested air humidity, wind speed and surface temperature to be responsible for surface hoar formation along elevation bands. Their model results obtained from snow cover modeling coupled to numerical weather prediction output, however, were less conclusive.

In summary, the above mentioned spatial variability studies investigated if simple terrain characteristics or snow depth were associated with either snow instability observations or weak layer properties. In particular cases, such as the formation of surface hoar, drivers were identified. With regard to snow instability, however, weak layer and slab layer properties interact together which complicates the influences of drivers. Currently, it is not clear whether and when differences in snow instability can be explained by simple drivers.

Snow depth distributions in catchments or basins have successfully been modeled, but with a focus on estimating snow water equivalent or ablation rather than on snow instability prediction. Winstral et al. (2009) obtained realistic snow depth distributions from terrain, vegetation and wind data in catchments of 0.26 km^2 to 14 km^2 by including the upwind topography and employing a sheltering index. Mott and Lehning (2010) even included micro-meteorological processes such as preferential deposition and true redistribution and were able to model small-scale deposition patterns, such as dunes and cornices. Terrestrial laser scanning (TLS) is widely used to measure the spatial distribution of snow depositions (Prokop, 2008) and study ablation rates (Grünewald et al., 2010). Modeled snow distributions have been validated with this technique and exhibited recurring patterns with elevation, slope and aspect being the most important predictors (Grünewald et al., 2013). Grünewald et al. (2010) compared terrestrial and airborne laser scans from the same area and found a deviation of around 10 cm depending on the incident angle of the beam and footprint size. Using LIDAR methods spatial distributions of snow depth can be measured with high spatial resolution. A link between spatial distributions of snow depth and snow instability that could support snow instability mapping in data sparse areas, however, is pending. Also, a detailed comparison between snow instability and terrain parameters seems interesting since digital elevation models are widely available and may enhance spatial snow instability mapping. Both ideas, however, require a method for closely spaced snow instability measurements or spatially distributed snow instability modeling for comparison with LIDAR snow depth measurements or terrain parameters from digital elevation models.

The snow micro-penetrometer offers an objective way to measure snow mechanical properties relevant for slab avalanche release at high spatial resolution (Reuter et al., 2013) and to derive measures of instability (Schweizer and Reuter, 2015). In particular, a recently developed approach to determine the propensity of failure initiation and crack propagation now allows evaluating field measurements of snow stratigraphy in view of snow instability (Reuter et al., 2015). With this approach we are now able to obtain observer independent metrics of snow instability in a rapid way allowing spatial sampling with more than 100 measurements per day—exceeding former frequencies of manual stability observations.

To investigate whether snow instability is tied to simple drivers, we present snowpack and terrain data from five situations in a small basin. For every situation snow instability was derived from more than 100 SMP profiles with the approach described by Reuter et al. (2015) which allows assessing the influence of potential drivers on the propensity of failure initiation and crack propagation separately. The drivers include slope aspect, snow depth and slope angle. Driver data were available at high-resolution for the entire basin from an elevation model with 1 m horizontal resolution and repeated laser scans of the snow surface resulting in snow surface elevation models with the same resolution. Results showed associations between simple drivers and snow instability with potential to support snow instability mapping in data sparse areas.