

## Linking weather conditions to snow property variations

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**ABSTRACT:** One of the challenges to modern avalanche forecasting is to enhance the forecasts' content with information on how snow instability varies in time and space at the sub-regional scale. Slope instability estimates for different aspects within a region rely on sparse field data, such as avalanche activity or snow profiles combined with the forecasters' experience. Snow instability modelling is in the early stages, not least because our knowledge of the inherently variable nature of the mountain snowpack and its causes is limited. In the past two winters we measured snowpack properties with the snow micro-penetrometer at the basin scale. With meteorological input from AWS located near the field sites we reconstructed the evolution of the weather prior to the time of our field campaigns. In a first analysis we looked at the general synopsis which describes recurring weather situations over central Europe. Then, we characterized the local weather in the region by the meteorological conditions at the weather station in the basin. Finally, we zoomed in further and modelled the meteorological conditions in the slopes where we had performed the field measurements. Differences in basin scale stability were not resolved with categorized synoptic scale weather information. Local weather conditions as captured by the AWS accounted for some of the observed differences in snow properties on the three different days. Considering the local slope conditions showed that in one case surface warming (energy input) caused the differences in slab density. Our preliminary analyses suggest that modelling the snow cover and the meteorological conditions over time might well indicate spatial instability patterns at the basin scale.

**KEYWORDS:** snow microstructure, snow properties, fracture, snow stability, spatial variability, weather

### 1 INTRODUCTION

Avalanche forecasting is complicated by variations of snow properties not only in time but as well in space. Spatial variations are the result of the complex interaction of mountain weather with terrain (e.g. Schweizer et al., 2008). Today, avalanche forecasts do include indications of where in the terrain the danger is most prominent. This information at the regional scale is provided as elevation bands and aspects. To predict slope instability for different aspects is often challenging due to sparse field data such as avalanche activity or snow profiles.

However, before more detailed information on spatial variations of instability can be provided, a link between observed variations of snowpack properties and meteorological drivers such as precipitation, wind and radiation, and terrain needs to be established. Once the link is established, i.e. we know how meteorological drivers cause variations in snowpack properties and thereby control stability, it may well become possible to anticipate stability variations based on the type of meteorological conditions.

Several studies have shown that snow

properties can readily be measured with the snow micro-penetrometer (SMP) (Schneebeli and Johnson, 1998) and have revealed spatial patterns of various snow properties (e.g. Kronholm et al., 2004). Recently, Reuter et al. (2013) have found post-processing of SMP data to provide realistic values of key snow properties through comparisons with two independent, established measurement techniques. By now, meteorological data are available on many scales, spanning from the synoptic to the slope scale where conditions can be modelled with the help of snow cover models such as SNOWPACK (Lehning and Fierz, 2008).

Our aim is to explore how measured variations of snowpack properties relevant to avalanche release can be explained with meteorological data by zooming from the largest (synoptic) to the finest available (slope) scale.

### 2 METHODS

#### 2.1 Snow properties

Snow properties were derived from snow micro-penetrometer measurements performed on a semi-random grid covering 120'000 m<sup>2</sup> in the Steintälli basin above Davos, Switzerland. Density and elastic properties of the snow slab as well as the weak layer toughness are relevant parameters for snow instability estimation. Density was derived from the penetration resistance measured with the SMP based on the

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work by Pielmeier (2003). The effective modulus (not claiming to be a truly linear elastic property) of the snowpack, was estimated from the results of quasi-static uniaxial compression experiments performed by Scapozza (2004). The specific fracture energy, the key property of the weak layer, was derived from the penetration resistance in the weak layer measured with the SMP. The critical cut length, as would be obtained with a propagation saw test experiment (Gauthier and Jamieson, 2008) was modelled (Heierli, 2008); it reflects the crack propagation propensity and is regarded a measure of instability.

## 2.2 General synopsis

We used a classification scheme of the general synopsis provided by MeteoSwiss that describes ten different average atmospheric conditions over the Alps. The data basis for the classification included air temperature anomalies and precipitation from interpolated ground observations across the Alps as well as the 500hPa geopotential height from the ERA-40 re-analysis of collected meteorological observations. For each day the prevailing flow direction and a simple characteristic of the air mass (wet or dry) is provided. As the information are limited (basically giving the origin of the air mass), the classification may at best reproduce the average appearance of a particular scenario.

## 2.3 Local meteorological conditions

At an automatic weather station (AWS) the current weather conditions in the Steintälli basin were recorded. Here, we examine true wind speed and direction at the summit station above the particular site where the field measurements had been performed.

## 2.4 Conditions on the slope

From the AWS located in the Steintälli basin measured air temperature, relative humidity, wind speed and direction, precipitation, incoming and outgoing shortwave radiation and incoming and outgoing longwave radiation were used to drive the snow cover model SNOWPACK in order to predict the specific meteorological conditions on the slopes in the Steintälli basin above Davos.

Table 1: Mean values of slab density ( $\rho$ ), slab effective modulus ( $E_{\text{bulk}}$ ), weak layer specific fracture energy ( $w_f$ ) and critical cut length ( $r_c$ ).

Date	$\rho$ ( $\text{kg/m}^3$ )	$E_{\text{bulk}}$ (MPa)	$w_f$ ( $\text{J/m}^2$ )	$r_c$ (m)
3 Mar 11	200	1.1	0.24	0.14
13 Feb 12	157	0.8	0.31	0.22
9 Mar 12	180	1.1	0.46	0.26

For every single SMP measurement location terrain parameters (coordinates, slope angle, aspect) were known enabling us to look up the corresponding meteorological conditions in a set of performed slope simulations.

## 3 RESULTS AND DISCUSSION

### 3.1 Snow properties

Table 1 compiles three snow properties (measured) and a measure of instability (modelled) for three field campaigns. The average modelled critical cut lengths correlated well with the verified avalanche danger level (3 March 2011: ‘considerable’ danger, 13 February 2012: ‘moderate’ danger with whumpfs, 9 March 2012: ‘moderate’ danger without whumpfs).

### 3.2 General synopsis

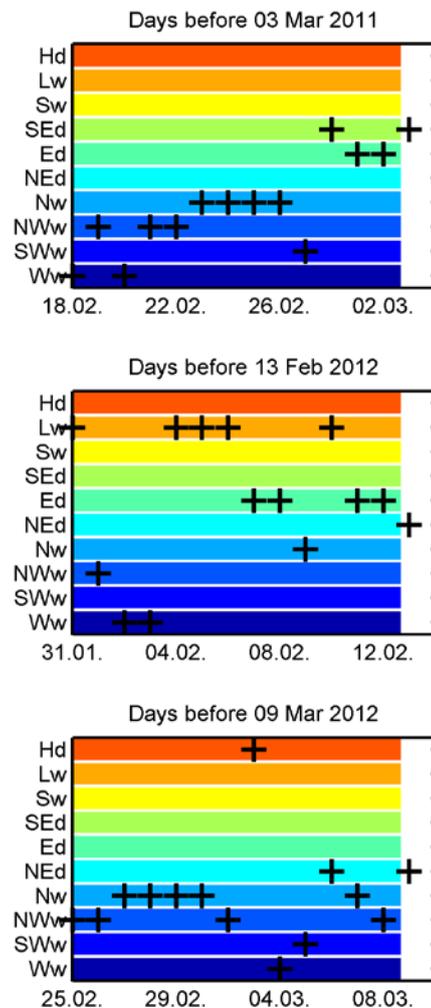


Figure 1: General synopsis over the Swiss Alps 13 days prior to the field campaigns. Coloured bands highlighting the classification categories. Abbreviations are composed of flow direction at 500 hPa or local high (H) or low (L) pressure and wet (w) or rather dry (d) air mass.

In the case of 3 March 2011 northerly and westerly flows brought wet air to the Eastern Swiss Alps before dry air masses driven by easterly flows became dominant three days before the field campaign. Characteristic: Calm conditions after storm period.

The nine days before 13 February 2012 can be characterized by a stationary low pressure system or by easterly flows, both bringing rather dry air masses to the Eastern Swiss Alps with one interruption. Characteristic: Changeable with little precipitation and one short storm.

The situation presented in the bottom panel looks quite similar to the one in the top panel; however, the flow did not change significantly before 9 March 2012 but remained north and north-westerly with wet air masses bringing precipitation. Characteristic: Storms with one high pressure interruption.

From the characteristics of the general synopsis we might assume that the avalanche danger on (or prior to) 3 March 2011 was higher than on 13 February 2012 due to more storms with more expected precipitation. But without additional information it is not obvious why on the third day modelled critical cut lengths were longer on average than at the other two days.

### 3.2 Local meteorological conditions

Zooming in one more step to the local weather in the Steintälli area helps understand the differences of snow properties between the three situations.

Figures 2 to 4 show the distribution of wind speeds and directions measured at the AWS located at the summit above the Steintälli basin 14 days before the field campaigns. The basin is open to the SE, but shaded from the other sides. Whereas even strong winds came into the basin from south-easterly directions before 3 March 2011 and 9 March 2012 (Fig. 2 and 4), it remained calm in the basin before 13 February 2012 as the area is surrounded by ridges to all other sides (Fig. 3). The high wind speeds having entered the basin before 3 March 2011 and 9 March 2012 led to snow drift accumulations and explain the high values of density and effective modulus shown in Table 1.

In the cases of 13 February and 9 March 2012 one of two depth hoar layers, which had developed after 16 January and 23 January, respectively, was prone to fail. From Table 1 we see that the specific fracture energy increased with time as the weak layers aged.

### 3.3 Conditions on the slope

The reasons for local differences of slab density within the Steintälli basin came to light when the meteorological conditions in the par-

ticular slopes were simulated. Figure 5 shows the modelled energy input on the snow surface for the terrain parameters at the measurement locations against SMP-derived slab density. High values of slab density were found on slopes which received high energy input within the 72 hours prior to the field campaign of 9 March 2012. The trend was significant.

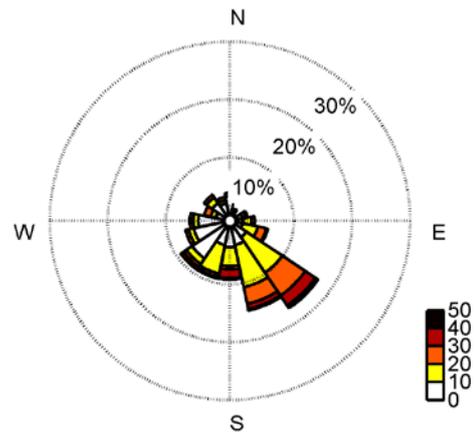


Figure 2: Wind rose presenting distribution of maximum wind speed (km/h) and direction 14 days prior to 3 March 2011.

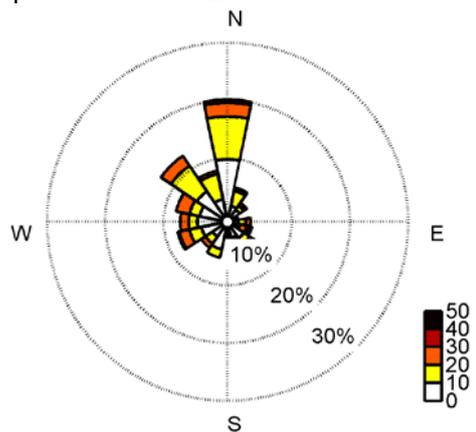


Figure 3: Wind rose presenting distribution of maximum wind speed (km/h) and direction 14 days prior to 13 February 2012.

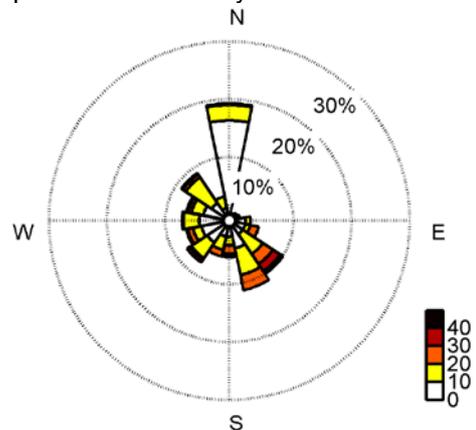


Figure 4: Wind rose presenting distribution of maximum wind speed (km/h) and direction 14 days prior to 9 March 2012.

Hence, on 9 March a meteorological driver, here surface warming, was responsible for the measured spatial differences of slab density. On 13 February 2012 no significant trend was observed between energy input and slab density. Along with the wind patterns discussed in section 3.2 above, this resulted in relatively low values of average density (Table 1).

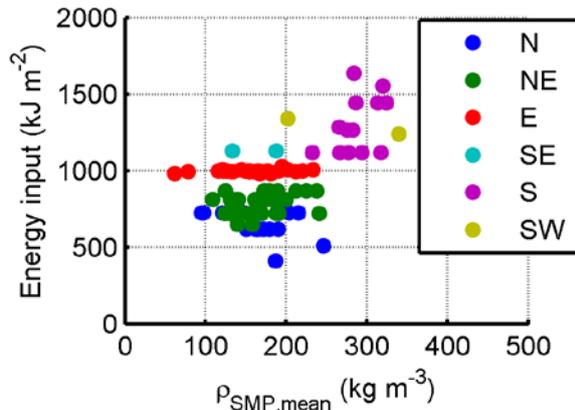


Figure 5: Energy input at the snow surface within 72 h before 9 Mar 2012 and SMP-derived slab density, colours indicating aspect ( $r=0.54$ ,  $p<0.01$ ).

#### 4 CONCLUSIONS

We related measured snow properties and a modelled measure of instability to weather data from three scales.

Results showed that basin scale stability variations were not resolved with categorized synoptic scale weather information. Local weather conditions as captured by the AWS accounted for some of the observed differences in snow properties on the three different days. Considering the local slope conditions showed that in one case surface warming (energy input) caused the differences in slab density.

Our preliminary analyses suggest that it may well become possible to anticipate stability variations based on the type of meteorological conditions provided snow and weather conditions are modelled at the slope scale.

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