WHEN DO AVALANCHES RELEASE: INVESTIGATING TIME SCALES IN AVALANCHE FORMATION

Alec van Herwijnen*, Matthias Heck, Bettina Richter, Betty Sovilla, and Frank Techel

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

ABSTRACT: Forecasting snow avalanches requires a detailed understanding of the influence of meteorological boundary conditions on avalanche formation. For instance, while it is widely known that avalanche activity generally increases during snow storms, much less is known about typical time scales involved in avalanche formation. In other words, we generally do not know how quickly avalanche activity rises or when peak activity has been reached. Whereas meteorological data are nowadays readily available with high temporal resolution, the corresponding avalanche occurrence data are lacking. This is mainly because data on avalanche activity obtained through conventional visual observations are incomplete and inaccurate, especially regarding the release time. To identify characteristic time scales and dominant meteorological drivers associated with avalanche activity, we therefore used unique avalanche activity catalogues obtained through seismic and radar monitoring in combination with local meteorological measurements and snow cover simulations. Results show that different meteorological drivers related to avalanche activity throughout a season: energy input into the snow cover was a dominant driver late in the season, while modeled precipitation correlated best with avalanche activity earlier in the season. While these findings are not surprising, having more accurate release times for the avalanche events allowed us to cross-correlate meteorological drivers with avalanche activity to identify time scales. For precipitation, time scales were on the order of several days, while for energy input later in the season, time scales were on the order of several hours to one day. Finally, by using a moving windowed cross-correlation approach, we clearly identified regime changes throughout the season. Overall, our findings show that accurate avalanche activity data can provide novel insight into avalanche formation processes and ultimately can help improve avalanche forecasting using readily available meteorological data and snow cover simulations.

KEYWORDS: Avalanche forecasting, remote avalanche detection, detrended cross-correlation, avalanche formation, meteorological drivers.

1. INTRODUCTION

Since there is no comprehensive theory of avalanche formation, assessing the avalanche danger mainly involves evaluating data on weather, snow stratigraphy and avalanche activity (McClung and Schaerer, 2006). However, during snow storms, when the avalanche hazard generally increases, this becomes an increasingly difficult task as due to poor visibility it is generally not possible to obtain much needed avalanche occurrence data with conventional visual observations. Avalanche forecasters therefore have to predict how quickly the danger level rises and when the peak has been reached based on incomplete information and knowledge of the current situation.

Numerous attempts have been made to develop statistical avalanche forecasting techniques by relating local meteorological observations with avalanche occurrence data or estimated avalanche danger (e.g. Buser, 1983; Pozdnoukhov et al., 2011; Schweizer and Föhn, 1996). However, the main bottleneck in these approaches is often the poor temporal and spatial resolution of avalanche observations, typically obtained through incomplete and inaccurate visual observations. This usually results in poor correlations with metrological data due to uncertainties in the number and exact timing of avalanches (e.g. van Herwijnen et al., 2016). Meteorological measurements or forecasts at high spatial and temporal resolution, which nowadays are widely available, can therefore not be exploited to their fullest extent.

The obvious shortcomings of conventional avalanche observations have long been recognized, and since the 1970s various alternative methods for the remote detection of avalanches have been developed. Broadly speaking, there are three remote avalanche detection systems: radar, infrasound and seismic monitoring. While with the introduction of long-range, wide-angle radar systems, the maximum detection range of radar systems has greatly improved (Meier et al., 2016), a direct line of sight is required as the avalanche movement must be towards the radar. For avalanche detection over larger areas and multiple paths, seismic and infrasound monitoring systems are better suited (e.g.

* *Corresponding author address:*
Alec van Herwijnen, WSL Institute for Snow and Avalanche Research SLF, Davos, Swithzerland;
tel: +41-81-4170-161;
email: vanherwijnen@slf.ch

Heck et al., 2018b; Marchetti et al., 2015). These systems consist of one or several sensors which record the energy radiated by the avalanche, respectively in the ground and in the air. Avalanches that occur up to several kilometers away from the sensors can be detected, depending on the size of the event (e.g. Heck et al., 2018a; Mayer et al., 2018).

Thanks to recent technological and signal processing advances, the reliability of remote avalanche detection systems has greatly improved. With such systems avalanche activity can continuously be monitored, independent of weather and visibility, with the potential to increase the accuracy of avalanche danger level assessments and to advance our understanding of meteorological drivers responsible for avalanche release (e.g.Lacroix et al., 2012; van Herwijnen et al., 2016). Our aim is therefore to exploit avalanche catalogues obtained through seismic and radar monitoring in combination with local meteorological measurements and snow cover simulations to identify characteristic time scales and dominant meteorological drivers associated with avalanche activity.

2. DATA AND METHODS

2.1 *Field sites and instrumentation*

We compiled avalanche occurrence data at two sites in the Swiss Alps: above Davos in the Grisons and close to Arbaz, at the Vallée de la Sionne (VdIS) test site (Figure 1).

Above Davos two seismic arrays consisting of 7 seismic sensors (4.5 Hz vertical component geophones) were deployed approximately 14 km apart. Commercial data acquisition systems were used (Seismic Instruments Inc.) and data were continuously sampled at a rate of 500 Hz (for more details, see van Herwijnen and Schweizer, 2011). To improve the signal-to-noise-ratio, the sensors were either attached to rocks on the ground or buried 30 to 50 cm into the ground and deployed at relatively flat sites with a homogeneous snow cover at an elevation of 2000 and 2500 meters, respectively. At each seismic array we also installed several automatic cameras to provide ground truth data.

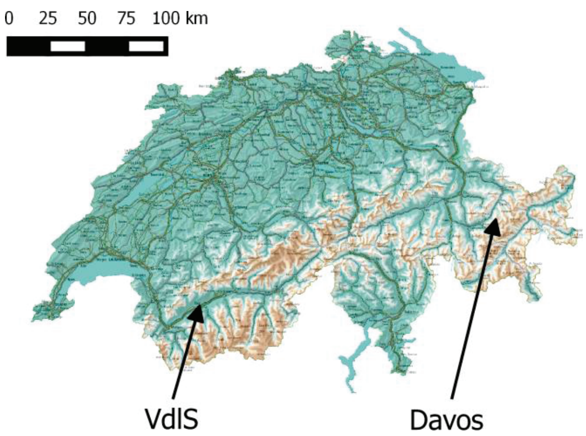

Figure 1: Location of the test sites (red dots). Map reproduced by permission of swisstopo (JA100118)

At VdIS, seismic sensors positioned in the avalanche track served as triggers to turn on the data acquisition system of various instruments, including the radar. The radar system (GEODAR) was installed on the opposite side of the valley on a concrete bunker. It is based on frequency modulated continuous wave technology, and was used to identify and classify avalanches with high spatial and temporal resolution (Köhler et al., 2018).

2.2 *Avalanche catalogues*

To identify seismic signals generated by avalanches at the field sites above Davos, we relied on images from the automatic cameras to correctly distinguish signals generated by avalanches from environmental noise (e.g. van Herwijnen and Schweizer, 2011). This allowed us to learn typical characteristics associated with signals generated by avalanches. Since environmental noise levels depend on site specific topography, geology and snow conditions (Heck, 2018), this learning step was repeated for each field site and each winter.

Despite these site specific differences, seismic signals generated by avalanches consistently had distinct temporal and spectral characteristics, allowing us to identify avalanches in the seismic data through visual inspection of the waveform and the spectrogram, i.e. the evolution of the frequency content of the signal with time (e.g. van Herwijnen et al., 2014). While it is clear that visual inspection of seismic data is time consuming and prone to observer bias, given the overall similarities between the seismic signals generated by avalanches, we are relatively confident in the accuracy of our visual inspection of the data. For both sites above Davos, we inspected three winter seasons from 2015-2016

Table 1: Number of avalanches observed each winter at each site

Site	Winter	Avalanches
VdIS	2013	9
VdIS	2014	12
VdIS	2015	28
VdIS	2016	36
VdIS	2017	36
Davos	2016	72
Davos	2017	54
Davos	2018	51

to 2017-2018, referred to as 2016, 2017 and 2018, respectively (Table 1). Avalanches occurrences from both sites were pooled to create three seismic avalanche catalogues consisting of the release time t_i of each avalanche found in the seismic data.

For VdlS, we visually inspected the GEODAR data of 5 winter seasons, from 2012-2013 to 2016-2017 referred to as 2013, 2014, 2015, 2016 and 2017, respectively (Table 1). This allowed us to create 5 avalanches catalogue consisting of the release time t_i of each avalanche found in the GEODAR .

2.3 Meteorological data

Meteorological data were obtained from automatic weather stations (AWS) in the vicinity of the field sites. For Davos, we used data from the Weissfluhjoch AWS located at an elevation of 2536 meters. For VdlS, we used data from the Donin du Jour AWS located at an elevation of 2385 meters. Meteorological data were recorded at 30 minute intervals and served as input for the numerical snow cover model SNOWPACK (operational version v1528; Lehning et al., 1999) to obtain estimates for the amount of new snow *HN* and the energy input *E* at the snow surface.

2.4 Statistical analysis

To investigate typical time scales involved in avalanche formation processes, one has to correlate avalanche activity data with meteorological parameters. Due to the presence of strong non-stationary fluctuations in meteorological data, including diurnal fluctuations and seasonal trends, it is essential to properly deterend the time series prior to performing the correlation analysis. We therefore performed a so-called detrended cross-correlation analysis (DCCA). The DCCA is designed to investigate cross-correlations between different simultaneously recorded time-series in the presence of non-stationarities (for more details see Zebende, 2011). The method is used to determine a dimensionless correlation coefficient for different time scales. The correlation coefficient ranges between -1 (perfect anti-correlation) and 1 (perfect correlation), similar to the more well-known Pearson linear correlation coefficient.

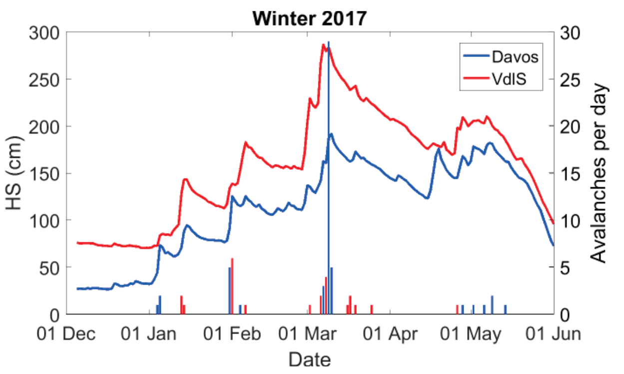

Figure 2: Snow height (lines) and avalanche activity (bars) during the winter of 2017 at VdlS (red) and Davos (blue).

3. RESULTS AND DISCUSSION

Overall, 298 avalanches were identified in the seismic and radar data during the investigation period (Table 1). The number of observed avalanches at VdlS was lower than in Davos. Nevertheless, the differences were surprisingly small considering that only one mountain flank was monitored at VdlS, while in Davos two seismic systems were used which can typically detect avalanches within a radius of about 3 km (Heck et al., 2018a). While this data set contains avalanche activity data from two sites over several winters, below we only focus on the 2014 and 2017 winters.

Despite being over 200 km apart, avalanche activity patterns at both sites during the 2017 winter were surprisingly similar. The two main avalanche cycles at both sites were in early February and around 10 March (Figure 3). While the similarities are obvious, there were also some differences. Indeed, avalanche activity in Davos preceded that in VdlS for the cycle in February, the opposite was true for the cycle in March. Finally, avalanche activity was clearly associated with new snow (increases in HS), even for the activity later in the season (after 1 May).

Looking at modeled hourly new snow and avalanche activity during the avalanche cycle in March in greater detail highlights the different avalanche patterns at both sites more clearly (Figure 3). In VdlS, most of the snow had fallen by noon on 8 March, by which time all avalanches had also released, either during the intense snowfall period or during a lull between two snowfall periods. In Davos, on the other hand, the second half of the snow

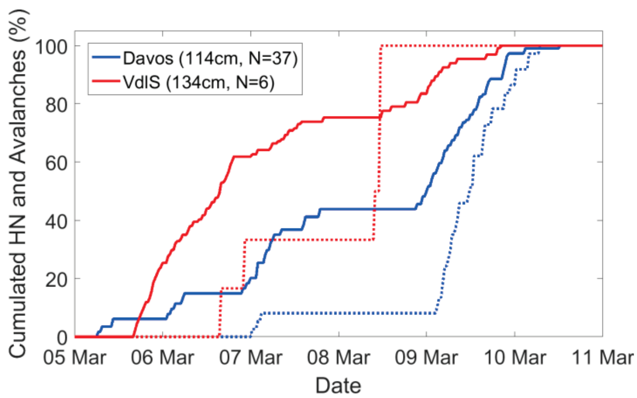

Figure 3: Cumulated new snow (HN, solid lines) and number of avalanches (dashed lines) between 5 and 11 March 2017 at VdlS (red) and Davos (blue), standardized to the respective sum shown in the legend during this period (= 100%).

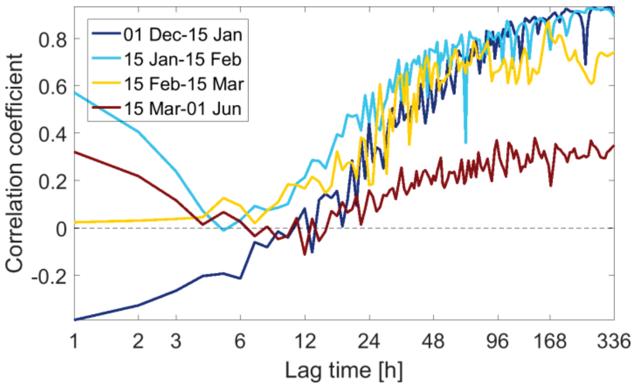

Figure 4: Detrended cross correlation coefficient with time scale between avalanche activity in Davos during the winter 2017 and modeled hourly new snow height (HN). The correlation analysis was performed for four separate periods corresponding to the main avalanche cycles (see Figure 2).

storm was most intense, from 9 March on, which was also the period when the vast majority of avalanches released.

While only for one particular snow storm, these results show that natural avalanche activity is closely linked to precipitation. However, when using avalanche activity data from Davos for the entire 2017 winter season (Figure 4), these results are confirmed. Indeed, although the detrended cross-correlation between avalanche activity and hourly new snow was somewhat erratic at very short time scales (< 6 hours), it clearly increased for larger time scales and there was an obvious difference between early season and late season (Figure 4). For the first part of the season (blue and yellow lines) the correlation rapidly increased up to about 48 hours (2 days), while later in the season (dark red line) the correlation increased more slowly and was much weaker.

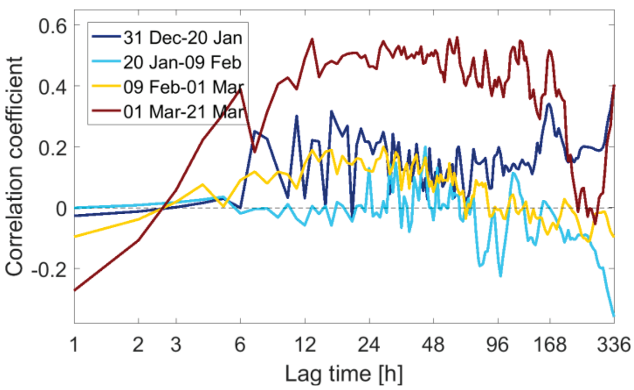

Figure 5: Detrended cross correlation coefficient with time scale between avalanche activity at VdlS during the winter 2014 and modeled hourly energy input (E). The correlation analysis was performed for four separate periods over the entire season.

Energy input into the snow cover is generally considered a good predictor for avalanches in spring (Helbig et al., 2015; Mitterer and Schweizer, 2013). This is also confirmed by our data. Indeed, avalanche activity late in the season of 2014 at VdlS correlated with hourly modeled energy input, when the correlation rapidly increased up to time scales of about 24 hours (dark red line in Figure 5). Earlier in the season, the correlation was much weaker (blue and yellow lines in Figure 5). Note that the cross-correlation with energy input was weaker than with precipitation (compare Figures 4 and 5).

4. CONCLUSIONS AND OUTLOOK

We highlighted the usefulness of accurate avalanche activity data obtained through seismic and radar avalanche detection systems for improving our understanding of avalanche activity patterns. Although a more in-depth analysis is required to confirm the results presented here, they highlight the potential to improve our knowledge on the complex interaction between meteorological drivers and natural avalanche release. Our results suggest that different drivers are related to avalanching throughout a season (i.e. winter or spring) and that the involved time scales are inherently different. Indeed, hourly new snow correlated best with avalanche activity early in the season at time scales of two or more days, while later in the season the energy input at the snow surface correlated best at shorter time scales (around 1 day).

Remote avalanche detection systems are becoming increasingly reliable, and in recent years operational systems based on radar or infrasound have emerged (e.g. Mayer et al., 2018; Meier et al., 2016). The development of seismic monitoring systems has somewhat lagged behind that of radar and infrasound systems. Nevertheless, with recent advances in signal processing, operational use of seismic monitoring systems is becoming a looming reality (Heck et al., 2018a). As remote avalanche detections systems become more common, these will undoubtedly provide reliable and accurate avalanche activity data useful for operational avalanche forecasting. Combined with meteorological measurements, these data will also provide new insight into avalanche formation processes and likely lead to the development of new models for avalanche forecasting.

ACKNOWLEDGEMENT

We would like to thank all the people that helped us with maintaining the field equipment during the winter.

REFERENCES

Buser, O., 1983. Avalanche forecast with the method of nearest neighbours: an interactive approach. Cold Regions Science and Technology, 8(2): 155-163.

Heck, M., 2018. Automatic detection and localization of snow avalanches using seismic monitoring. Ph.D. Thesis, ETH Zurich, Zurich, Switzerland.

Heck, M., Hammer, C., Hobiger, M., van Herwijnen, A., Schweizer, J. and Fäh, D., 2018a. Operational classification of seismic data for avalanche monitoring purposes, Proceedings ISSW 2018. International Snow Science Workshop, Innsbruck, Austria, 7-12 October 2018.

Heck, M., van Herwijnen, A., Hammer, C., Hobiger, M., Schweizer, J. and Fäh, D., 2018b. Automatic detection of avalanches using a combined array classification and localization. Earth Surface Dynamics Discussions: submitted.

Helbig, N., van Herwijnen, A. and Jonas, T., 2015. Forecasting wet-snow avalanche probability in mountainous terrain. Cold Regions Science and Technology, 120: 219-226.

Lacroix, P., Grasso, J.R., Roulle, J., Giraud, G., Goetz, D., Morin, S. and Helmstetter, A., 2012. Monitoring of snow avalanches using a seismic array: Location, speed estimation, and relationships to meteorological variables. Journal of Geophysical Research-Earth Surface, 117: F01034, doi: 10.1029/2011jf002106.

Lehning, M., Bartelt, P., Brown, R.L., Russi, T., Stöckli, U. and Zimmerli, M., 1999. Snowpack model calculations for avalanche warning based upon a new network of weather and snow stations. Cold Regions Science and Technology, 30(1-3): 145-157.

Marchetti, E., Ripepe, M., Ulivieri, G. and Kogelnig, A., 2015. Infrasound array criteria for automatic detection and front velocity estimation of snow avalanches: towards a real-time early-warning system. Natural Hazards and Earth System Sciences, 15(11): 2545-2555.

Mayer, S., van Herwijnen, A., Ulivieri, G. and Schweizer, J., 2018. Evaluating the performance of operational infrasound avalanche detection systems at three locations in the Swiss Alps during two winter seasons, Proceedings ISSW 2018. International Snow Science Workshop, Innsbruck, Austria, 7-12 October 2018.

Meier, L., Jacquemart, M., Blattmann, B. and Arnold, B., 2016. Real-time avalanche detection with long-range, wide-angle radars for road safety in Zermatt, Switzerland, Proceedings ISSW 2016. International Snow Science Workshop, Breckenridge, Colorado, USA, 3-7 October 2016, pp. 304-308.

Mitterer, C. and Schweizer, J., 2013. Analysis of the snow-atmosphere energy balance during wet-snow instabilities and implications for avalanche prediction. The Cryosphere, 7(1): 205-216.

Pozdnoukhov, A., Matasci, G., Kanevski, M. and Purves, R.S., 2011. Spatio-temporal avalanche forecasting with Support Vector Machines. Natural Hazards and Earth System Sciences, 11(2): 367-382.

Schweizer, J. and Föhn, P.M.B., 1996. Avalanche forecasting - an expert system approach. J. Glaciol., 42(141): 318-332.

van Herwijnen, A., Heck, M. and Schweizer, J., 2014. Detecting avalanches using seismic monitoring systems. In: P. Haegeli (Editor), Proceedings ISSW 2014. International Snow Science Workshop, Banff, Alberta, Canada, 29 September - 3 October 2014, pp. 116-121.

van Herwijnen, A., Heck, M. and Schweizer, J., 2016. Forecasting snow avalanches by using avalanche activity data obtained through seismic monitoring. Cold Regions Science and Technology, 132: 68-80.

van Herwijnen, A. and Schweizer, J., 2011. Seismic sensor array for monitoring an avalanche start zone: design, deployment and preliminary results. Journal of Glaciology, 57(202): 267-276.