Nat. Hazards Earth Syst. Sci. Discuss., doi:10.5194/nhess-2016-7, 2016
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Published: 29 January 2016

Natural Hazards and Earth System Sciences
Open Access
Discussions

Linking snow depth to avalanche release area size: Measurements from the Vallée de la Sionne fieldsite

J. Veitinger and B. Sovilla

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

Correspondence to: J. Veitinger
(veitinger@slf.ch)

Abstract. One of the major challenges in avalanche hazard assessment is the correct estimation of avalanche release area size which is of crucial importance to evaluate the potential danger that avalanches pose to roads, railways or infrastructure. The assessment of potential release area size is nowadays mainly based on terrain analysis; however, it is assumed that with increasing snow accumulation and the attenuation of terrain irregularities larger release areas may form. To investigate this hypothesis, the relation between avalanche release area size, snow depth and surface roughness was investigated using avalanche observations of artificially triggered slab avalanches over a period of 15 years in a high-alpine fieldsite. High resolution, continuous snow depth measurements at times of avalanche release showed a decrease of mean surface roughness with increasing release area size both for the bed surface and the snow surface before avalanche release. Further, surface roughness patterns in snow covered winter terrain appeared to be well suited to demarcate release areas, suggesting an increase of potential release area size with greater snow depth. In this context, snow depth around terrain features that serve as potential delineation borders, such as ridges or trenches, appeared to be particularly relevant for release area size. Furthermore, snow depth measured at a nearby weather station was to a considerable extent related to potential release area size, as it was often representative for snow depth around those critical features where snow can accumulate over a long period before becoming susceptible for avalanche release. Snow depth - due to its link to surface roughness - could therefore serve as a highly useful variable with regard to potential release area definition for varying snow cover scenarios, as for example, the avalanche hazard assessment for transport ways or ski resorts.

1 Introduction

Avalanche release is the result of a series of mechanical actions involving terrain, snow cover and meteorological conditions and the understanding of avalanche release at the level of the single mechanical processes is unbelievably complex (Schweizer et al., 2003). Terrain is the only constant and therefore often serves as basis for release area delimitation in avalanche hazard management and mitigation (Veitinger et al., 2015; Bühler et al., 2013; Maggioni and Gruber, 2003). While basing release area estimation on terrain analysis may be valid for extreme avalanches where only coarse - scale terrain features such as major ridges are relevant to delimit potential release areas, it reaches its limit when smaller, more frequent avalanches have to be assessed, as for example the optimisation temporal mitigation measures for road and ski resort protection.

The potential release area size of such avalanches are often influenced by smaller terrain features, which may hinder a fracture to propagate and delimit the release area. However, during and after snowfall events, wind (Gauer, 2001), snow gliding and avalanches (Sovilla et al., 2010; Gruber, 2007) redistribute snow and accordingly smooth the fine-scale morphology of the terrain by filling irregularities. These processes can have a significant impact on size and location of avalanche release areas.

To understand the formation of avalanches, one has to recognise that the winter snowpack consists of layers of different density or cohesion as a result of intermittent snowfall periods and changing meteorological conditions. Slab avalanches form due to the failure of a cohesive layer (slab) overlaying a less cohesive layer (a so-called weak layer). Accordingly, the bed surface, defined as the sliding plane of the slab (just below the weak layer) may either be the ground or, most often, an underlying snow layer. In a shallow snowpack, terrain roughness present at bed surface can have a stabilising function, hindering the formation of continuous weak layers (Schweizer et al., 2003) as well as providing mechanical support to the slab (McClung, 2001; van Herwijnen and Heierli, 2009). As a result predominately small and localized release areas form. With increasing snow accumulation, surface roughness is progressively smoothed out (Veitinger et al., 2014), and terrain features buried in the snow cover below the bed surface reduce the mechanical support of a slab (McClung and Schaerer, 2002). At the same time, variability in the surface layers is reduced (Mott et al., 2010) and the formation of continuous weak layers and slabs is facilitated (Simenhois and Birkeland, 2008). Under these conditions, wider release areas may form.

These observations raise the question if snow depth is related to avalanche release area size. As surface roughness generally decreases with increasing snow accumulation, snow depth could serve as a useful parameter to define avalanche release area scenarios as a function of snow distribution. This could be an important step forward towards a more snow cover dependent avalanche hazard assessment, as for example, for transport ways or ski resorts.

Therefore, in this study, the relation between release area size and surface roughness of artificial triggered avalanches at the Vallée de la Sionne fieldsite is evaluated. Further, snow depth at a nearby weather station and – when available – snow depth measured by laser scanning and photogrammetry in the release area before and after avalanche release is compared to potential release area size. We investigate in particular how the local snow distribution affects location and extent of observed avalanche release areas.

2 Methods and study site

2.1 Measurements of avalanche release areas

The site of Vallée de la Sionne (VdlS) is located in the south-western part of Switzerland in the canton of Valais, near Sion (Fig. 1).

The area upon which we focus in this study corresponds to typical locations of avalanche release areas, and is characterised by elevations between 2460 m a.s.l. and 2679 m a.s.l., whilst orientation ranges from E to SE. The VdlS field site can be divided into three different basins characterized by distinct topography: Crêta Besse 1 (CB1) is steepest and roughest with a mean slope of 42.4°, whereas Crêta Besse 2 (CB2) is less steep with amean slope of 36.2° and a ratzher homogeneous terrain

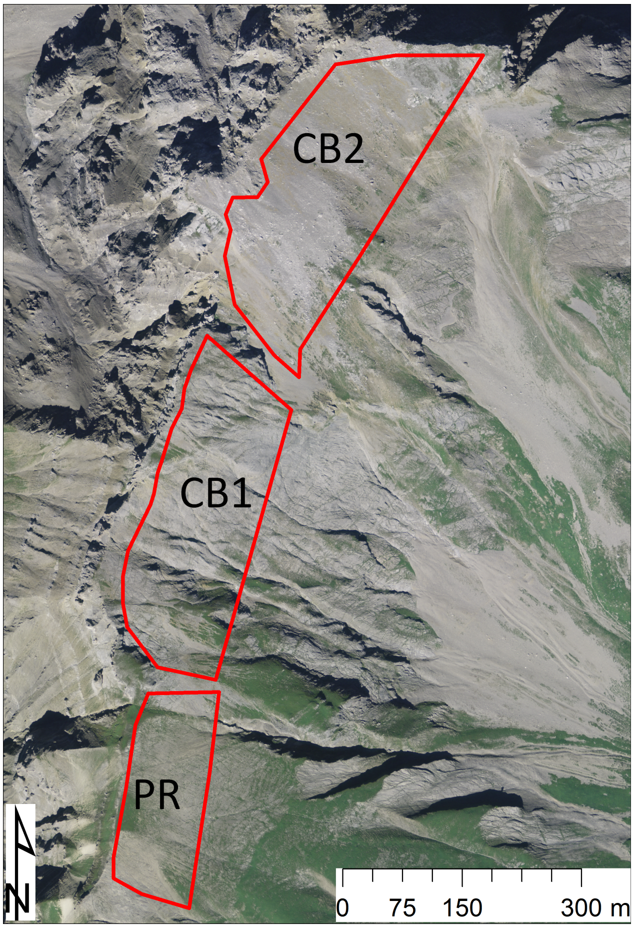


Figure 1. Field site Vallée de la Sionne near Sion. In red are marked the locations of the analysed basins, PR, CB1 and CB2. Pixmaps© 2016 swisstopo (5704 000 000).

surface without major ridges or cliffs. CB1 is separated of CB2 by a prominent rocky ridge. The Pra Roua (PR) basin has the smoothest terrain surface with an average steepness between the one of CB1 and CB2 and mean slope of 37.7°.

Since the winter season 1998/1999, avalanches are artificially released by explosives from a helicopter. Generally, experiments were only performed after a significant snowfall (> 80 cm) where large avalanches can be expected. Snow depth data is obtained from a near-by weather station providing half -hour data about snow depth (HS) and other meteorological parameters such as wind and temperature. Artificial avalanche release is generally performed at several locations ranging from Pra Roua to CB2. Until the winter season 2004/2005, snow depth distribution before and after avalanche release was recorded by photogrammetry (Vallet et al., 2001). Measurements were mostly restricted to the area around the crown fracture, with an average point spacing of 5 m. The accuracy (RMS) of the measurements is around 25 cm when compared to manual measurements of fracture depth.

Nat. Hazards Earth Syst. Sci. Discuss., doi:10.5194/nhess-2016-7, 2016
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Published: 29 January 2016

Natural Hazards and Earth System Sciences
Open Access
Discussions

Since the year 2005/2006, photogrammetry was replaced by a helicopter - based, airborne laser scanning (ALS) system, providing continuous, high resolution (0.5 m) snow depth data. The vertical accuracy of the data is 10 cm. A detailed description of the method and the precision of the measurements can be found in Sovilla et al. (2010).

2.2 Surface roughness

In this study, a surface roughness measure is used to describe the irregularity of the terrain. It is based on the vector ruggedness measure developed by Sappington et al. (2007), which quantifies changes of slope and aspect in a given neighbourhood around a center pixel of a DTM. Biquadratic polynomials of the form

$$z = ax^2 + by^2 + cxy + dx + ey + f, \tag{1}$$

where z corresponds to the elevation estimate at a point (x, y) and $a - -f$ are the coefficients that define the quadratic surface (Evans, 1980) are used as a basis for the computation of slope and aspect.

Direction (aspect) and magnitude (slope) of the steepest gradient at the central grid cell of the fitted surface is determined by calculating the rate of change in x and y direction:

$$\frac{\mathrm{d}z}{\mathrm{d}xy} = \left(\sqrt{\left(\frac{\mathrm{d}z}{\mathrm{d}x}\right)^2 + \left(\frac{\mathrm{d}z}{\mathrm{d}y}\right)^2}\right). \tag{2}$$

The partial derivatives for x and y are noted as:

$$\frac{\mathrm{d}z}{\mathrm{d}x} = 2ax + cy + d, \tag{3}$$

and

$$\frac{\mathrm{d}z}{\mathrm{d}y} = 2by + cx + e. \tag{4}$$

In order to obtain the parameter at the central point of the surface ($x = y = 0$), equations 3 and 4 are integrated into equation 2, and note:

$$\frac{\mathrm{d}z}{\mathrm{d}xy} = \sqrt{d^2 + e^2}. \tag{5}$$

Slope (α) is thus given as:

$$\alpha = \arctan\sqrt{d^2 + e^2}. \tag{6}$$

Nat. Hazards Earth Syst. Sci. Discuss., doi:10.5194/nhess-2016-7, 2016
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Published: 29 January 2016

Natural Hazards and Earth System Sciences
Open Access
Discussions

Likewise aspect is defined as

$$\beta = \arctan \frac{e}{d}. \tag{7}$$

Wood (1996), instead of taking into account only grid values within a 3x3 window, showed that one can fit the trend surface over any arbitrarily sized window. By this means, multi-scale slope and aspect calculations can be obtained. We use these new definitions of slope and aspect to derive multi-scale roughness. In contrast to the method of Sappington et al. (2007), we preserve a constant 3x3 kernel window to calculate roughness. Scale is accounted for by the size of the neighbourhood window used to compute slope and aspect. Scale is defined as the width of the kernel window.

Thus, the new roughness definition reads as follows:

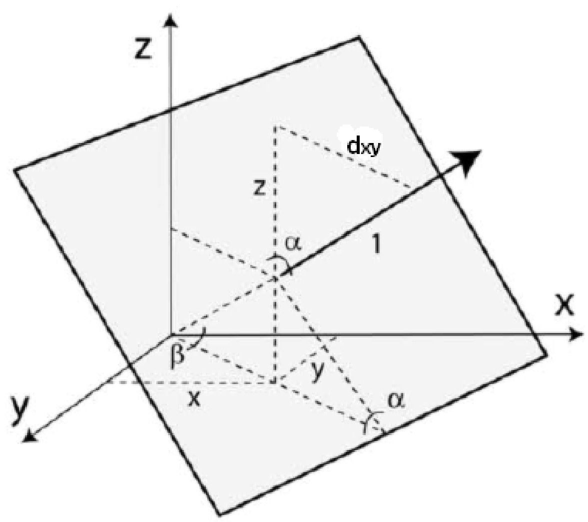


Figure 2. Decomposition of normal unit vectors of a DTM grid cell into x, y, z components using slope α and aspect β. Graphic from Sappington et al. (2007).

Nat. Hazards Earth Syst. Sci. Discuss., doi:10.5194/nhess-2016-7, 2016
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Published: 29 January 2016

Natural Hazards and Earth System Sciences
Open Access
Discussions

Normal unit vectors of every grid cell of a digital elevation model (DEM) are decomposed into x, y and z components (Fig. 2):

$$z = 1 \cdot \cos(\alpha), \tag{8}$$

$$d_{xy} = 1 \cdot \sin(\alpha), \tag{9}$$

$$x = d_{xy} \cdot \cos(\beta), \tag{10}$$

$$y = d_{xy} \cdot \sin(\beta). \tag{11}$$

A resultant vector $|r|$ is then obtained for every pixel by summing up the single components of the centre pixel and its 8 neighbours using a moving window technique.

$$|r| = \sqrt{(\sum x)^2 + (\sum y)^2 + (\sum z)^2}, \tag{12}$$

as shown in Fig. 3b. The magnitude of the resultant vector is then normalised by the number of grid cells and subtracted from 1:

$$R = 1 - \frac{|r|}{9}, \tag{13}$$

where R is the vector ruggedness measure.

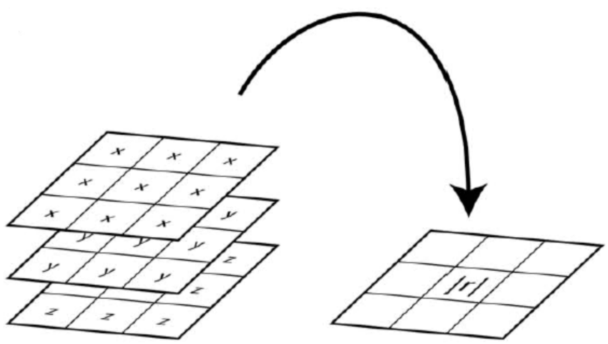
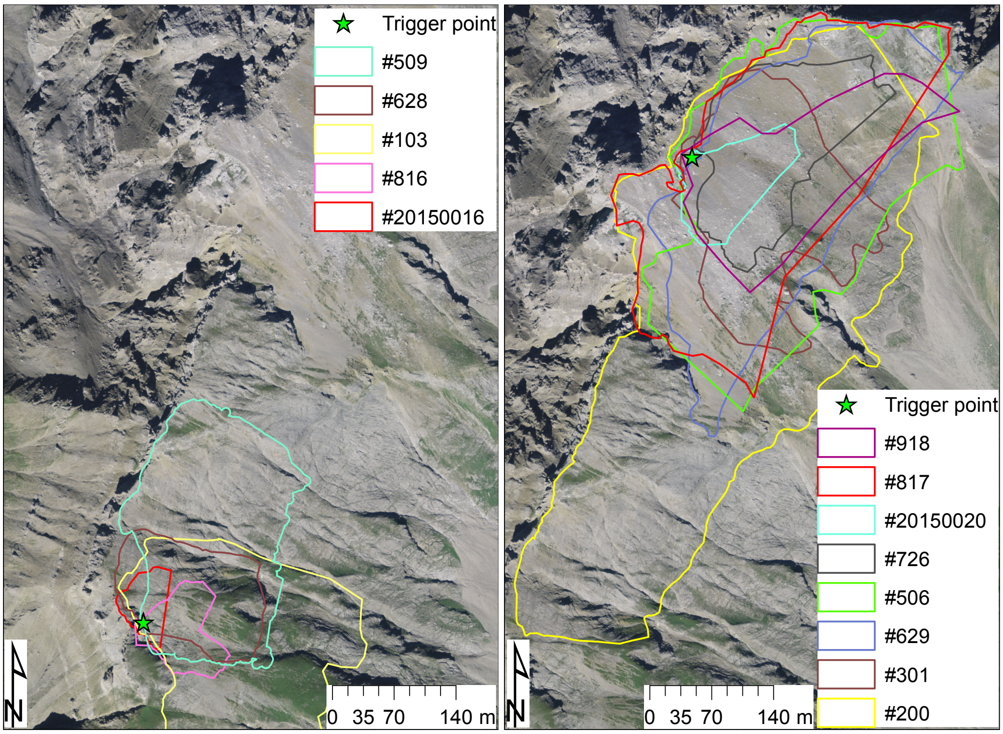


Figure 3. Resultant vector r is obtained by summing up the x, y, z components of all pixels n within the neighbourhood window. Graphics from Sappington et al. (2007).

Nat. Hazards Earth Syst. Sci. Discuss., doi:10.5194/nhess-2016-7, 2016
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Published: 29 January 2016

Natural Hazards and Earth System Sciences
Discussions



(a) (b)

Figure 4. Extent of all artificially triggered avalanches in (a) the southwestern part of CB1 and (b) CB2.

3 Data

In this paper, we focus our study on avalanches that were triggered at two different locations. One is the rather smooth area of CB2 and the second is the south- western part of CB1, consisting of a steeper, more irregular surface than CB2. Figure 4 shows the release areas of all avalanches between the years 1998 and 2015 and the approximate locations of the trigger points. Frequently, spontaneous releases occurred in the PR basin prior to artificial avalanche release in CB1, which prevented most release areas to extend into the PR basin. Therefore, for release area #103, only the part that is located in the CB1 basin is considered. All avalanches are dry slab avalanches. Experiments, where only very small avalanches due to the direct effect of the explosion occurred, were neglected.

Until the winter season 2005/2006 photogrammetry was used to determine snow distribution before and after avalanche release. Table 1 shows an overview over all released avalanches measured with photogrammetry. Snow depth measurements before and after avalanche release were either performed in the entire release area or along the avalanche crown; however, it has to be noted that snow distribution at the crown is often not representative for the entire release area.

Nat. Hazards Earth Syst. Sci. Discuss., doi:10.5194/nhess-2016-7, 2016
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Published: 29 January 2016

Natural Hazards and Earth System Sciences
Open Access
Discussions

Table 1. Number, date, release area width (W), snow depth (HS) and new snow depth (dHS) measured at the weather station of Donin du Jour, mean snow depth before ($\overline{\mathrm{HS}_1}$), after avalanche release ($\overline{\mathrm{HS}_2}$) and mean fracture depth ($\overline{\mathrm{d}}$) for avalanche release areas occurring before the winter season 2005/2006. Further, the spatial measurement extent is provided.

Aval Nr.	Date	W $[m]$	HS [cm]	dHS [cm]	$\overline{\mathrm{HS}_1}[cm]$	$\overline{\mathrm{HS}_2}[cm]$	$\overline{\mathrm{d}}[cm]$	Extent
CB1								
#103	10 Feb 1999	165	350	140	200	98	102	Crown
#509	07 Feb 2003	285	360	90	291	146	145	Area
#628	19 Jan 2004	120	300	110	314	195	119	Area
CB2								
#301	30 Jan 1999	220	260	120	304	141	163	Crown
#200	24 Feb 1999	760	440	100	295	100	195	Crown
#506	31 Jan 2003	470	290	60	x	x	60	Crown
#629	19 Jan 2004	500	300	110	330	153	176	Area

From the winter season 2005/2006 onwards, ALS measurements were used to determine snow distribution. An overview over all released avalanches measured with ALS can be observed in Tab. 2. Using ALS, continuous snow depth measurements were performed over the entire release area.

Table 2. Number, date, release area width W, snow depth (HS) and new snow depth (dHS) measured at the weather station of Donin du Jour, mean snow depth before ($\overline{\mathrm{HS}_1}$), after avalanche release ($\overline{\mathrm{HS}_2}$) and mean fracture depth ($\overline{\mathrm{d}}$) for avalanche release areas occurring from the winter season 2005/2006 onwards.

Aval Nr.	Date	W $[m]$	HS [cm]	dHS [cm]	$\overline{\mathrm{HS}_1}[cm]$	$\overline{\mathrm{HS}_2}[cm]$	$\overline{\mathrm{d}}[cm]$
CB1							
#816	08 Mar 2006	105	290	120	334	190	144
#917	26 Mar 2008	110	350	80	-	-	-
#20150016	03 Feb 2015	90	210	110	221	104	118
CB2							
#726	17 Feb 2005	280	220	70	-	-	170
#817	08 Mar 2006	480	290	120	366	229	137
#918	26 Mar 2008	310	350	80	-	-	-
#20150020	03 Feb 2015	170	210	110	236	56	180

Avalanche release areas in the CB2 basin are typically large, covering large areas of the basin surface. Normally, the release area does not extend into the CB1 basin and is confined by the clear topographical break between CB1 and CB2. In one

Nat. Hazards Earth Syst. Sci. Discuss., doi:10.5194/nhess-2016-7, 2016
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Published: 29 January 2016

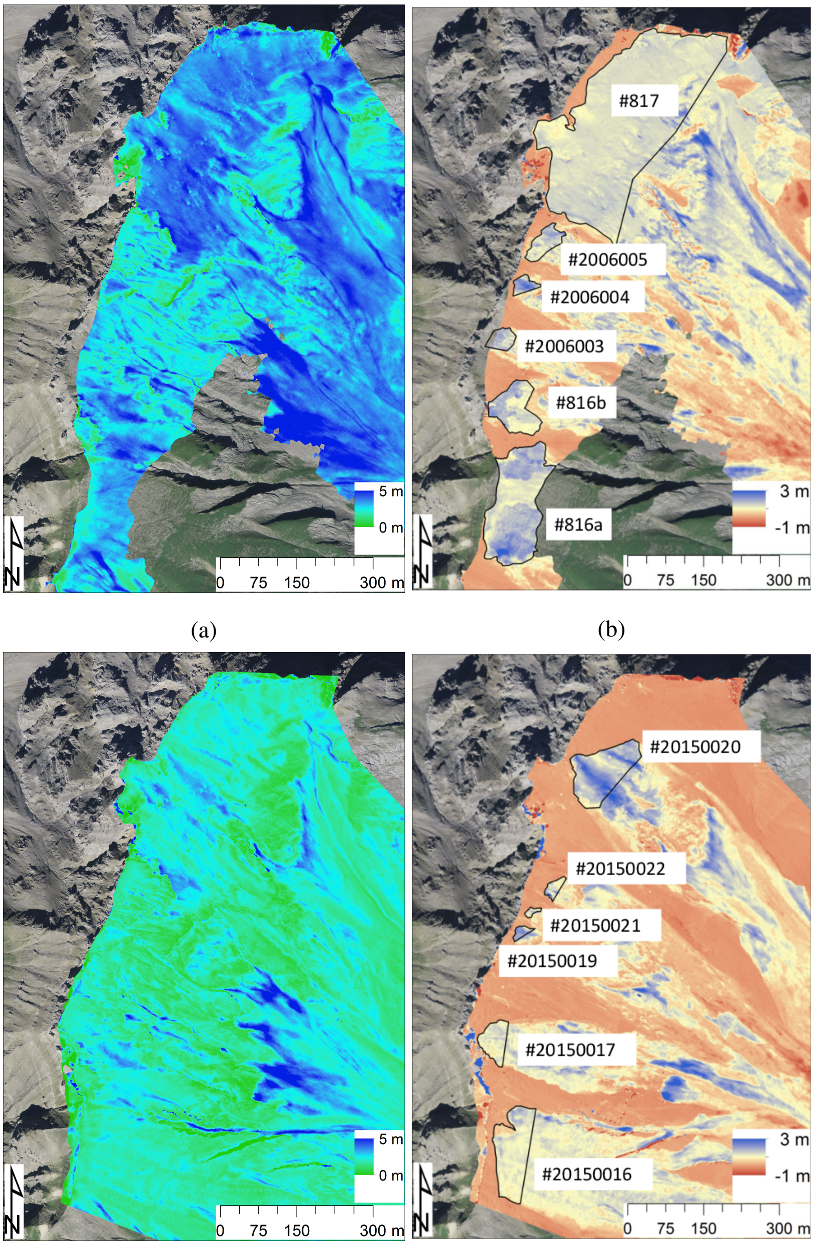
case, during the catastrophic winter of 1998/1999 (Gruber and Margreth, 2001), an avalanche released simultaneously over the entire CB2 and CB1 basin. In contrast, release areas in the CB1 basin are smaller and occur in sub-areas of the basin, which is subdivided by many gullies and ridges.

Further, to take full advantage of the high resolution snow depth measurements since the season 2005/2006, we prepared another dataset that covers all avalanches retrieved with ALS measurements independent of their location. This includes, beside the avalanches shown in Tab. 2, also avalanches releasing in the PR basin as well as avalanches releasing all over CB1. The dataset consists of two sets of 6 dry slab avalanches that were artificially triggered on 8 March 2006, and on 3 February 2015. Four large slabs ($> 10000\,m^2$) were observed where the fracture propagated over a larger distance within the very smooth basins of CB2 and PR (#816a and #817, #20150016 and #20150020). Four medium sized slabs ($1500\,m^2 - 10000\,m^2$) were observed on the southern end of CB1 (#816b and #20150017) and on CB1 (#2006004, #2006005). The other slabs within CB1 were rather small ($< 1500\,m^2$) with only very little fracture propagation (#2006003, #20150019, #20150021, #20150022). Avalanche #816a and #816b also triggered deeper layers of the snowpack. Interestingly, avalanche #816b released due to the detonation, whereas avalanche #816a was triggered remotely by avalanche #816b.

For these avalanches, a more in-depth analysis was performed. Release area size A, mean slab thickness ($\overline{\mathrm{d}}$), mean snow depth before ($\overline{\mathrm{HS}_1}$) and after avalanche release at the bed surface ($\overline{\mathrm{HS}_2}$) and mean roughness of the snow free terrain ($\overline{\mathrm{R_T}}$), the snow surface before avalanche release ($\overline{\mathrm{R}_1}$) and the bed surface after avalanche release ($\overline{\mathrm{R}_2}$) was calculated for all triggered avalanches (Table 3, Fig. 5).

Table 3. Number, date, release area size (A), mean snow depth before ($\overline{\mathrm{HS}_1}$) and after avalanche release ($\overline{\mathrm{HS}_2}$), mean fracture depth ($\overline{\mathrm{d}}$), mean roughness of the snow free terrain ($\overline{\mathrm{R_T}}$), the snow surface before avalanche release ($\overline{\mathrm{R}_1}$) and the bed surface after avalanche release ($\overline{\mathrm{R}_2}$) for all avalanche release areas with ALS measurements in VdlS.

Aval Nr.	Date	Size A $[m^2]$	$\overline{\mathrm{HS}_1}[m]$	$\overline{\mathrm{HS}_2}[m]$	$\overline{\mathrm{d}}[m]$	$\overline{\mathrm{R_T}}$	$\overline{\mathrm{R}_1}$	$\overline{\mathrm{R}_2}$
#816a	08 Mar 2006	21874	319	154	165	0.0014	0.0004	0.0009
#816b	08 Mar 2006	6944	334	190	144	0.0024	0.0005	0.0015
#2006003	08 Mar 2006	1906	296	142	162	0.0019	0.0013	0.0027
#2006004	08 Mar 2006	1265	343	148	195	0.0018	0.0006	0.0016
#2006005	08 Mar 2006	2885	261	112	149	0.0024	0.0009	0.0023
#817	08 Mar 2006	78390	366	229	137	0.0019	0.0003	0.0007
#20150016	03 Feb 2015	10816	190	74	116	0.0012	0.0003	0.0005
#20150017	03 Feb 2015	3508	221	104	118	0.0035	0.0009	0.0015
#20150019	03 Feb 2015	622	234	47	187	0.0016	0.0003	0.0018
#20150021	03 Feb 2015	341	156	31	125	0.0036	0.0010	0.0035
#20150022	03 Feb 2015	974	185	49	136	0.0032	0.0025	0.0035
#20150020	03 Feb 2015	10909	236	56	180	0.0016	0.0002	0.0010



(a) (b) (c) (d)

Figure 5. Snow depth before avalanche release on (**a**) 08 March 2006 and (**c**) 03 February 2015. Difference of snow depth before and after artificial avalanche release obtained from the scans of (**b**) 08 March 2006 and (**d**) 03 February 2015. The release zones and their avalanche tracks are clearly visible. Further, release area numbers according to Tab. 3 are also shown.

Nat. Hazards Earth Syst. Sci. Discuss., doi:10.5194/nhess-2016-7, 2016
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Published: 29 January 2016

4 Results and interpretation

4.1 Release area size and roughness

In this section, release area size of all avalanches shown in Fig. 5 and Tab. 3 was analysed as a function of mean roughness of summer terrain, $\overline{\mathrm{R_T}}$, bed surface, $\overline{\mathrm{R_2}}$ and snow surface prior to avalanche release, $\overline{\mathrm{R_1}}$ (Fig. 6). We restricted our analysis to medium and large sized release areas where clear fracture propagation occurred, assuming that the small release areas are rather a result of the direct effect of the explosives than due to fracture propagation.

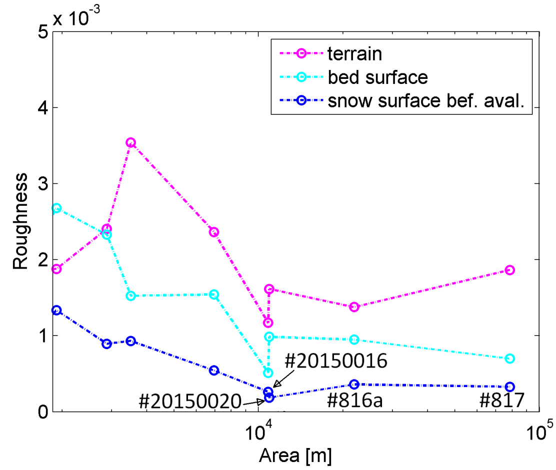


Figure 6. Release area size as a function of its surface roughness at the level of the snow-free terrain (red), the bed surface (light-blue) and the snow surface prior to avalanche release (dark-blue). Roughness shown corresponds to a scale of 1.5 m.

Figure 6 shows that the avalanche bed surface is generally less rough when compared with the underlying terrain. At the same time, the snow surface prior to avalanche release is always smoother than the underlying bed surface (and the terrain). This nicely illustrates the progressive terrain smoothing within avalanche release areas. The results further show a clear trend of decreasing surface roughness with increasing release area size. This trend is more pronounced for the bed surface and the snow surface before avalanche release; to a lesser extent for terrain roughness. This suggests that the winter terrain appears to be more explanatory to potential release area size than the summer terrain.

However, the decrease of average snow surface roughness is limited to a certain avalanche size. Release areas exceeding this critical size show similar surface roughness as for example release areas #816, #817, #20150016 and #20150020 (Fig. 6).

As an example, Figure 7 shows images the of release areas #817 and #20150020. Surface roughness inside the release area was similar for both avalanches (Fig.

This is supported by Fig. 8, which shows surface roughness at a scale of 1.5 m for the summer terrain and the three winter terrain surfaces of 8 December 2010, 3 February 2015 and 8 March 2006. The winter surfaces are characterized by snow depths

(a) (b)

Figure 7. Images of the artificially triggered avalanches at the CB2 basin on (**a**) 08 March 2006 (avalanche #817) and (**b**) 03 February 2015 (avalanche #20150020).

ranging from 1.2 m in 2010 over 2.4 m in 2015 to 3.7 m in 2006. It can be observed that increasingly large and connected areas of low surface roughness are formed with increasing snow depth. Moreover, the roughness patterns caused by different snow cover scenarios appear to be well suited to demarcate the observed release areas. Release area #20150020 can be associated with the roughness pattern in between the summer terrain and the one with little snow depth in the year 2010, whereas release area #817 corresponds rather to the snow scenarios of 2006 and 2015. This suggests that surface roughness corresponding to a snow cover similar to the one at avalanche release my be suited to delimit the potential size of avalanche release areas.

Interestingly, there is only little difference in surface roughness in CB2 for 2006 and 2015, despite a significant deeper snowpack in 2006. The difference in snow depth only has effects on the border of the basin, such as the ridge linking CB1 to CB2 and several features within the CB1 basin (red circles in Fig. 8). These features are more attenuated in 2006 with additional snow depth. It can be assumed that in a further increasing snowpack, they would also be cancelled out, enlarging the continuous areas of low surface roughness. This highlights the important role of snow depth for potential release area size, which will be explored in the following section.

4.2 Release area size and snow distribution

4.2.1 Release area size and snow cover parameters

In this section, the relation between snow cover parameters and avalanche release area size is analysed. In a first step, snow depth at bed surface for the two sets of avalanches in 2006 and 2015 (Tab. 3) was compared to their respective avalanche sizes (Fig. 9).

Nat. Hazards Earth Syst. Sci. Discuss., doi:10.5194/nhess-2016-7, 2016
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Published: 29 January 2016

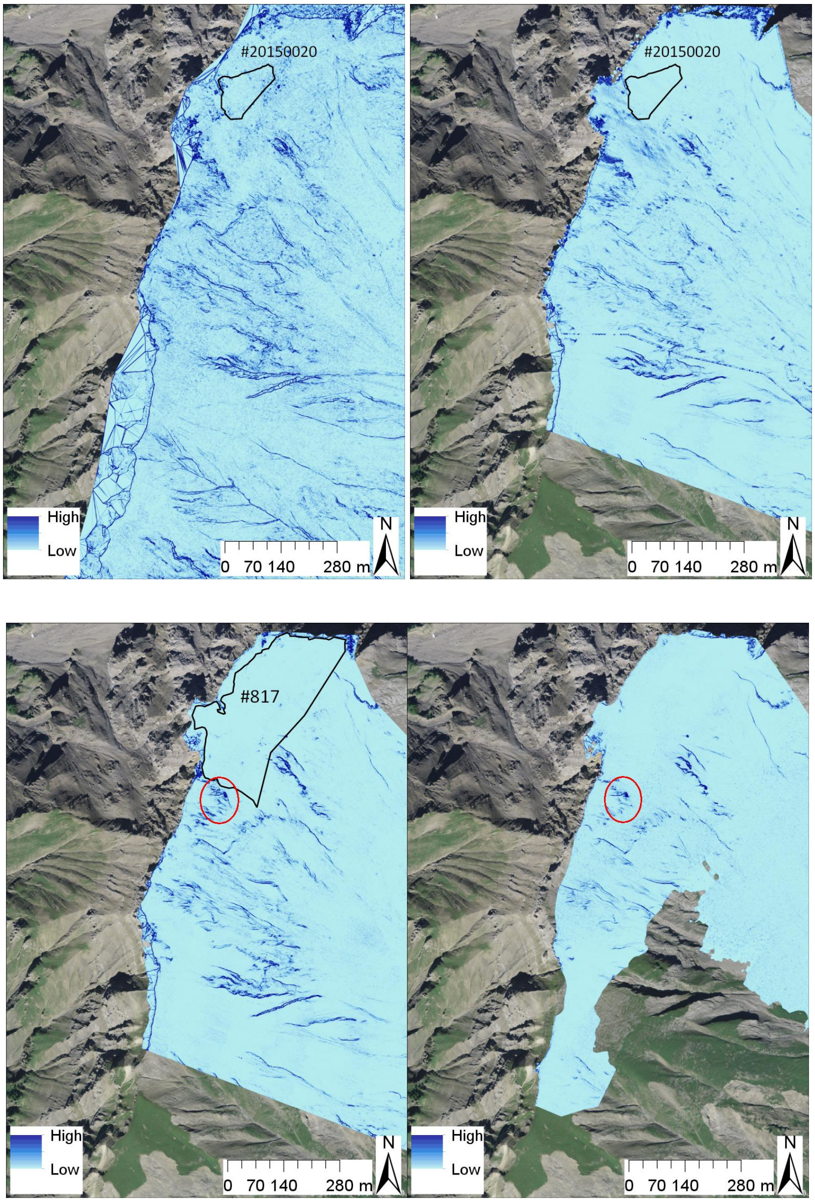


Figure 8. Surface roughness at a scale of 1.5 m of (**a**) the summer terrain, (**b**) the winter terrain for the snow distribution of 8 December 2010, (**c**) the winter terrain for the snow distribution of 3 February 2015 and (**d**) the winter terrain for the snow distribution of 8 March 2006. In black the outlines of avalanche release areas at CB2 are shown. The red circles show critical terrain features with different degrees of smoothing due to a varying snow depth.

Nat. Hazards Earth Syst. Sci. Discuss., doi:10.5194/nhess-2016-7, 2016
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Published: 29 January 2016

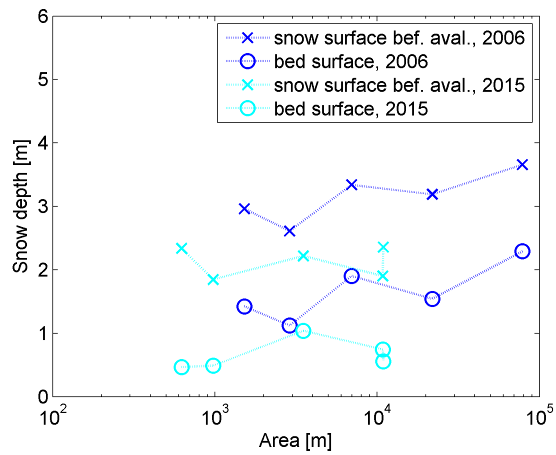


Figure 9. Release area size as a function of snow depth at the bed surfaces for the avalanches released in 2006 and in 2015.

It is observed that avalanche release areas triggered in the deeper snowpack of 2006 are always larger compared to their similarly located avalanches of 2015. Both snow depth at bed surface and before avalanche release is consistently deeper for every single avalanche released in 2006 when compared to its counterpart in 2015. These observations support our hypothesis that a deepening snow cover forms increasing areas of low surface roughness, which could have resulted in larger release areas in 2006.

To support this finding, release area size of all avalanches was compared to the snow conditions at times of avalanche release. However, as continuous snow depth measurements were not available for many of the avalanches, release area width was compared to snow depth measured at the weather station (Fig. 10).

A significant correlation between snow depth and release area width is observed (R^2 = 0.78, p = 0.023) in CB2 – to a lesser extent also in CB1 (R^2 = 0.70, p = 0.120) which again supports the hypothesis that larger avalanche releases can form in a thicker snow cover. Moreover, smaller avalanches are observed in CB1 compared to CB2, supporting the hypothesis that rough terrain such as CB1, requires more snow to form sufficiently smooth winter terrain conditions to produce large release areas. However, smaller avalanches in CB1 could also be explained by the steeper terrain of CB1 compared to CB2, generally leading to increased avalanche and sloughing activity, preventing the formation of a thick continuous snow cover.

At the same time, no correlation is observed between new snow depth and release area width (Fig. 11a) as well as between mean slab depth and release area width (Fig. 11b), suggesting that these variables alone cannot explain the differences in release area size.

Nat. Hazards Earth Syst. Sci. Discuss., doi:10.5194/nhess-2016-7, 2016
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Published: 29 January 2016

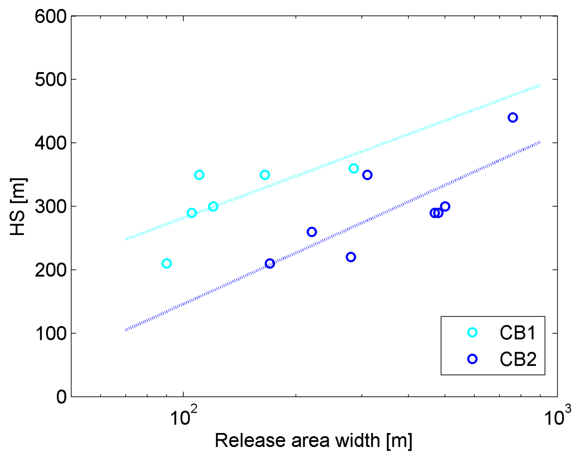
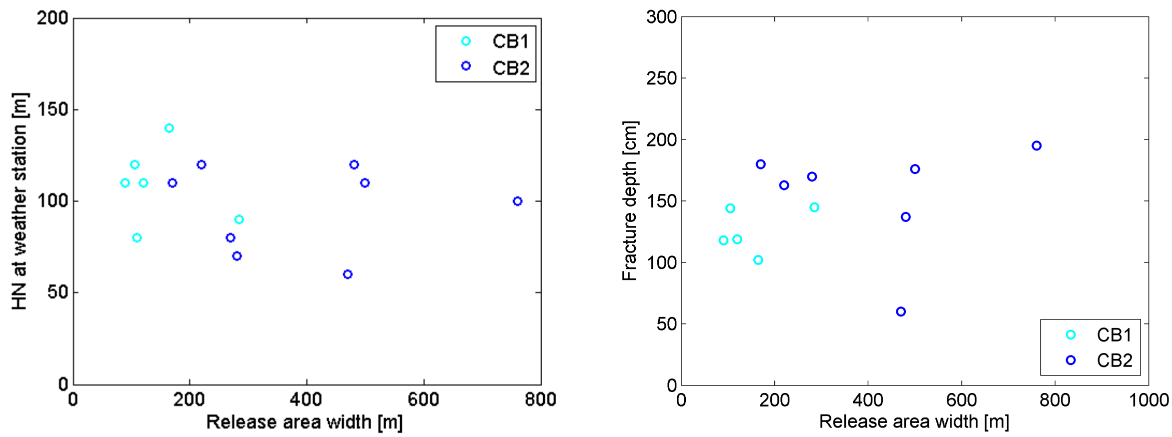


Figure 10. Release area width in the basins CB1 and CB2 as a function of snow depth measured at the weather station.



(a) (b)

Figure 11. Release area width in the basins CB1 and CB2 as a function of (a) new snow depth of the snowfall period previous to avalanche release and (b) mean fracture depth.

4.2.2 Release area size and local snow distribution

The results in the previous section showed a clear relation between snow depth at the weather station and observed release area size. Further, section 4.1 suggests that snow depth at critical terrain features is particularly relevant for potential release area size. Therefore, an in-depth analysis of the local snow distribution around terrain features that are critical for release areas size

Nat. Hazards Earth Syst. Sci. Discuss., doi:10.5194/nhess-2016-7, 2016
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Published: 29 January 2016

was performed and compared to snow depth measured at the weather station. To this purpose, we analysed several snow depth profiles at several locations in the release area (Fig. 12).

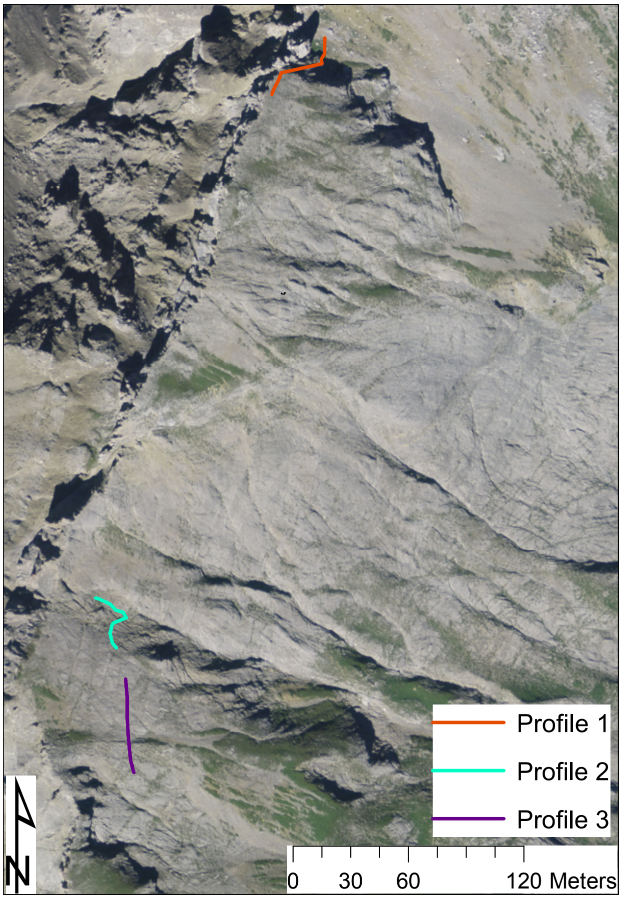


Figure 12. Locations of snow depth profiles in the CB1 basin (profiles 2 and 3) and at border between CB1 and CB2 (profile 1).

Figure 13 shows snow depth at time of avalanche release for the release areas #200, #817 and #20150020 along profile 1 following the crown fracture of release area #200 at the border between CB1 and CB2.

We observe that the snowpack of release area #200 is in most locations deeper compared to #817, which is itself significantly deeper than for #20150020. In particular at the ridge separating CB1 from CB2, the snowpack of avalanche #200 appears to be significantly deeper. This shows that snow depth of release area #200 was not affected by the previous release of avalanche #301, triggered about a month earlier. Avalanche #301 released below the crown fracture of avalanche #200 and did not fully propagate through CB2. As a result, the thick snow cover at the borders of the basin remained, possibly facilitating full fracture propagation through CB1 in the case of avalanche #200, whereas the fracture of #817 was arrested at the prominent ridge separating CB1 from CB2. The lower snowpack for #20150020 resulted in an even smaller release area and did not even

Nat. Hazards Earth Syst. Sci. Discuss., doi:10.5194/nhess-2016-7, 2016
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Published: 29 January 2016

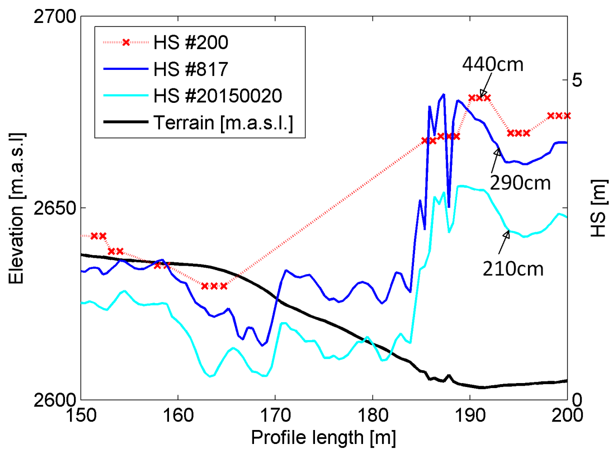


Figure 13. Snow depth profile 1 along the crown fracture of avalanche #200 for snow distributions of avalanches #200, #817 and #20150020 at the area separating CB1 from CB2. The numbers indicate the corresponding snow depth measured at the weather station.

fully propagate through CB2. These snowpack differences are clearly shown by the weather station, which can be considered representative, at least for the border between CB1 and CB2, where previous avalanches did not occur.

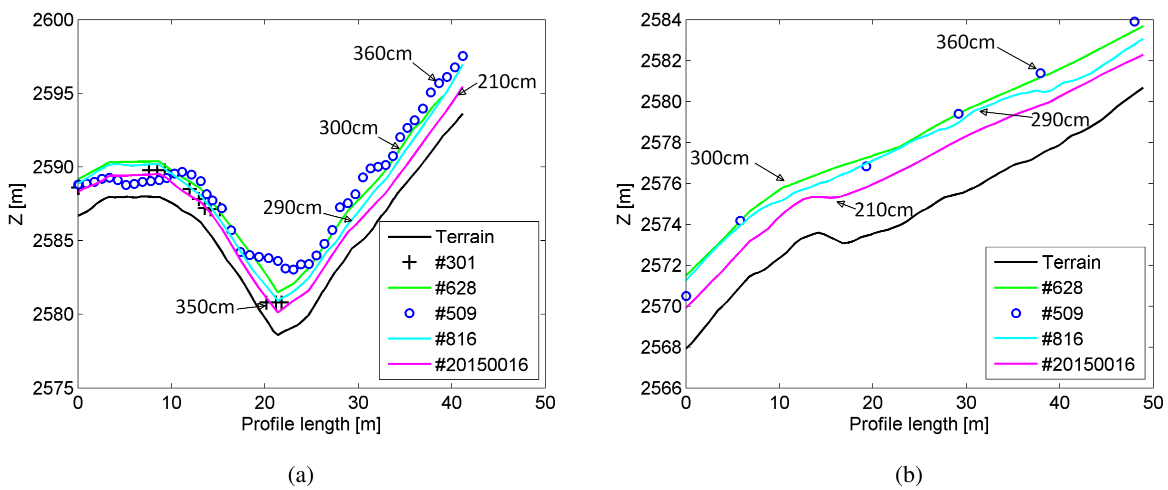


Figure 14. Elevation profiles (a) 2 and (b) 3 (Fig. 12) in snow covered terrain before avalanche release. The numbers indicate the corresponding snow depth measured at the weather station.

This is confirmed in CB1. Two representative snow depth profiles (profiles 2 and 3, Fig. 14) show a generally good agreement between snow depth measured at the weather station and snow depth in the release area. Further, profile 2, located across the prominent gully where the avalanches #628 and #103 stopped, whereas #509 propagated through, shows a significantly larger snow depth in the gully for #509 than for #628 and #103. At the same time, snow depth outside the gully was similar or even lower. Again, this confirms our observations in section 4.1. that snow depth at specific terrain features, which serve as delimiting borders for avalanche release, may be decisive for potential release areas size. However, in contrast to the snow covers of avalanches #628, #816b and #20150016, snow depth in the gully for avalanches #103 and #509 deviates significantly from the weather station measurements. Snow depth was significantly larger for release area #509 and significantly lower for release area #103 compared to the weather station measurements. Snow was probably locally removed from the gully (e.g. avalanching)in the case of #103, whereas it was rather accumulated for avalanche #509 (Fig. 14).

These observations suggest that the weather station is in many cases indicative for potential release area size, as it is representative for snow conditions in the release area, in particular around critical features such as ridges and rocky outcrops, which are often less affected by frequent avalanches as they require a very thick snow cover before avalanches may form. However, exceptions are possible, in particular when important snow redistribution processes occur which de- or increase fracture propagation propensity relative to snow depth measured at a nearby weather station.

5 Discussion

The results revealed the connexion between release area size and decreasing surface roughness with snow accumulation. This is in line with the current understanding of terrain smoothing processes, which reduce the mechanical support of a slab (McClung and Schaerer, 2002), favour the formation of continuous slabs and weak layers (Schweizer et al., 2003), which can subsequently lead to potentially larger release areas. Moreover, in our dataset, wide release areas occurred for bed surfaces near the ground and thick slab thickness (e.g. #726) and vice-versa (e.g.#506), suggesting that terrain smoothing is relevant for release area size regardless of the height of the bed surface above ground. This is supported by field observations, where large release areas are not only observed for avalanches running on upper layers of the snowpack, but also for slab avalanches running on weak layers near the ground (so called deep slabs (Tracz and Jamieson, 2010)). They are known to reach important sizes, even propagating across terrain features that generally arrest fractures. These observations suggest that a slab is to some extent capable to way out irregularities at the bed surface which is consistent with recent simulations of the slab weak layer system (Gaume et al., 2014). The models show that slab thickness and stiffness increase fracture propagation propensity, due to their smoothing effect on weak layer heterogeneity such as topographical irregularities. Therefore, it is accepted nowadays that properties of the weak layer and the slab are important for crack propagation and – as a result – the width of the release area (Reuter et al., 2013).

Further, it is obvious that snowpack stability and the spatial variability of snowpack properties (Schweizer et al., 2008) affect release area size in a given situation. As an example, observed release area sizes in our dataset could have been affected by previous avalanches, significantly disturbing the layering of the snowpack, especially in very steep areas where frequent avalanches are regularly observed. Nevertheless, as we only selected avalanches that occurred under clearly unstable conditions and considering the fact that in homogeneous terrain rather homogeneous stability patterns prevail (Harvey et al., 2012), terrain and its alteration with snow accumulation can be considered with good reason as the main constraint for potential release area

Nat. Hazards Earth Syst. Sci. Discuss., doi:10.5194/nhess-2016-7, 2016
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Published: 29 January 2016

size in our dataset. This is further supported by recent mechanically based statistical modelling of the slab–weak-layer system, which emphasises the importance of changes in terrain or snow cover distribution rather than snow properties, for potential release area size (Gaume, 2012).

6 Conclusions

In this study, the relation between surface roughness, snow depth and release area size in a high-alpine fieldsite was evaluated. Lidar and photogrammetry measurements before and after avalanche release were used to characterize snow distribution and surface roughness of artificially triggered avalanches. The comparison between mean surface roughness of the release area and its size showed a decrease of surface roughness with increasing release area both for the bed surface and the snow surface before avalanche release. The trend was less pronounced on the snow-free terrain, suggesting that the snow covered winter terrain is more relevant for potential release area size than the underlying snow-free terrain.

However, the results also showed that the relation of release area size and mean surface roughness is restricted towards a minimum value of surface roughness. Reaching this value, release area size increased without significant change of mean surface roughness. This suggests that fracture propagation over large distances is facilitated once mean roughness reaches a certain minimum. At this point, a fracture will most likely self-propagate until it is arrested by major changes in the snow cover or terrain such as terrain breaks, ridges or major boulders. This is supported by surface roughness patterns in snow covered winter terrain that appear well suited to demarcate release areas. The patterns evolved as a function of the snow distribution suggesting an increase of potential release area size with larger snow depth.

Snow depth - due to its link to surface roughness - could therefore serve as important parameter to define potential release area size. Snow depth profiles in the release area showed that snow depth, in particular around terrain features that are critical for fracture propagation, such as ridges or trenches, control potential release area size. In this vein, an increase of snow depth only leads to an increase of potential release area size if it is large enough to attenuate terrain features that currently delimit the release area. Furthermore, snow depth measured at a nearby weather station was to a considerable extent related to potential release area size, as it was often representative to snow depth around critical terrain features that are able to accumulate important quantities of snow before they become susceptible for avalanche release. This highlights the potential of a representative weather station in the process of snow cover - avalanche scenario definition. However, it has also been shown that important local snow depth differences can form for similar snow accumulation at the weather station, mainly due to avalanching and sloughing, which can both increase and decrease potential release area size in a given situation. This limits the explanatory power of snow depth for potential release area definition, in particular in real-time hazard assessment.

Acknowledgements. Funding for this research has been provided through the Interreg projects STRADA and STRADA 2.0 by the following partners: Amt für Wald Graubünden, Canton du Valais – Service de forêts et paysage, Regione Lombardia, ARPA Lombardia, ARPA Piemonte, and Regione Autonoma Valle d'Aosta.

References

Bühler, Y., Kumar, S., Veitinger, J., Christen, M., Stoffel, A., and Snehmani: Automated identification of potential snow avalanche release areas based on digital elevation models, Natural Hazards and Earth System Science, 13, 1321–1335, 2013.

Evans, I. S.: An integrated system of terrain analysis and slope mapping, Zeitschrift für Geomorphologie, Suppl. Bd. 36, 274–295, 1980.

Gauer, P.: Numerical modeling of blowing and drifting snow in Alpine terrain, Journal of Glaciology, 47, 97–110, 2001.

Gaume, J.: Evaluation of avalanche release depths. Combined statistical mechanical modeling, Ph.D. thesis, Universit é de Grenoble, 2012.

Gaume, J., Schweizer, J., van Herwijnen, A., Chambon, G., Reuter, B., Eckert, N., and Naaim, M.: Evaluation of slope stability with respect to snowpack spatial variability, Journal of Geophysical Research: Earth Surface, doi:10.1002/2014JF003193, http://dx.doi.org/10.1002/2014JF003193, 2014.

Gruber, S.: A mass-conserving fast algorithm to parameterize gravitational transport and deposition using digital elevation models, Water Resources Research, 43, doi:10.1029/2006WR004868, http://dx.doi.org/10.1029/2006WR004868, 2007.

Gruber, U. and Margreth, S.: Winter 1999: a valuable test of the avalanche-hazard mapping procedure in Switzerland, Annals of Glaciology, 32, 328–332, doi:10.3189/172756401781819238, 2001.

Harvey, S., Rhyner, H., and Schweizer, J.: Lawinenkunde, Bruckmann Verlag GmbH, 2012.

Maggioni, M. and Gruber, U.: The influence of topographic parameters on avalanche release dimension and frequency, Cold Regions Science and Technology, 37, 407 – 419, 2003.

McClung, D.: Characteristics of terrain, snow supply and forest cover for avalanche initiation caused by logging, Annals of Glaciology, 32, 223–229, 2001.

McClung, D. M. and Schaerer, P. A.: The Avalanche Handbook, The Mountaineers Books, Seattle, WA, 2002.

Mott, R., Schirmer, M., Bavay, M., Grünewald, T., and Lehning, M.: Understanding snow-transport processes shaping the mountain snow-cover, The Cryosphere Discussions, 4, 865–900, 2010.

Reuter, B., Proksch, M., Loewe, H., van Herwijnen, A., and Schweizer, J.: On how to measure snow mechanical properties relevant to slab avalanche release, Naaim-Bouvet, F.; Durand, Y. ; Lambert, R. (eds) International Snow Science Workshop 2013, October, 2013 7th-11th. Proceedings. ISSW 2013. Grenoble - Chamonix Mont Blanc. Grenoble, ANENA., pp. 7–11, 2013.

Sappington, J., Longshore, K., and Thomson, D.: Quantifiying Landscape Ruggedness for Animal Habitat Anaysis: A case Study Using Bighorn Sheep in the Mojave Desert, J. Wildl. Manage., 71, 1419 –1426, 2007.

Schweizer, J., Bruce Jamieson, J., and Schneebeli, M.: Snow avalanche formation, Reviews of Geophysics, 41, doi:10.1029/2002RG000123, 1016, 2003.

Schweizer, J., Kronholm, K., Jamieson, J. B., and Birkeland, K. W.: Review of spatial variability of snowpack properties and its importance for avalanche formation, Cold Regions Science and Technology, 51, 253–272, 2008.

Simenhois, R. and Birkeland, K. W.: The effect of changing slab thickness on fracture propagation, Proceedings of the 2008 International Snow Science Workshop, Whistler, B.C., pp. 755–760., 2008.

Sovilla, B., McElwaine, J. N., Schaer, M., and Vallet, J.: Variation of deposition depth with slope angle in snow avalanches: Measurements from Vallée de la Sionne, J. Geophys. Res., 115, 2010.

Tracz, D. and Jamieson, J.: Characteristics of old-deep-slab avalanches., Proceedings of the 2010 International Snow Science Workshop, Squaw Valley, CA, USA, pp. 148–154, 2010.

Vallet, J., Gruber, U., and Dufour, F.: Photogrammetric avalanche volume measurements at Vallée de la Sionne, Switzerland, Ann. Glaciol., 32, 141–146, 2001.

van Herwijnen, A. and Heierli, J.: Measurement of crack-face friction in collapsed weak snow layers, Geophysical Research Letters, 36, doi:10.1029/2009GL040389, l23502, 2009.

Veitinger, J., Sovilla, B., and Purves, R. S.: Influence of snow depth distribution on surface roughness in alpine terrain: a multi-scale approach, The Cryosphere, 8, 547–569, 2014.

Veitinger, J., Sovilla, B., and Purves, R. S.: Potential slab avalanche release area identification from estimated winter terrain: a multi-scale, fuzzy logic approach, Nat. Hazards Earth Syst. Sci. Discuss., 3, 6569–6614, doi:10.5194/nhessd-3-6569-2015, 2015.

Wood, J.: The Geomorphological Characterisation of Digital Elevation Models, Ph.D. thesis, University of Leicester, Leicester, 1996.