

ON THE INFLUENCE OF SNOW DEPTH ON SURFACE SHAPE AND ROUGHNESS IN THE RELEASE AREAS OF OBSERVED SKIER-TRIGGERED AVALANCHES

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ABSTRACT: The snow-covered winter surface differs significantly from its snow-free equivalent due to the smoothing caused by progressive snow accumulation and erosion. This smoothing effect becomes more pronounced as the absolute snow depth increases. However, variations in accumulation, settling and redistribution occur in complex mountain terrain. The spatial variability of snow depth plays a crucial role in the formation and dynamics of snow avalanches. Surface shape and roughness serve as established metrics to assess the effect of snow on terrain. In this study, we investigate snow surface smoothing within the release areas of typical skier-triggered avalanches observed in the vicinity of Davos, Switzerland. We analyze the release areas of nearly 2000 avalanches of class size 2 to 3, using high spatial resolution (0.5 m) annual snow depth maps recorded during the peak of winter over 6 years and covering an area of 275 km². These avalanche release areas are grouped according to their main terrain shape. Within each group, the influence of snow depth on surface shape and roughness is assessed. Finally, we investigate the effect of different DEM resolutions on the terrain smoothing factor and analyze the intra-annual consistency of the terrain smoothing. For the first time, we assess the role of snow depth on surface shape and surface roughness in avalanche release areas over a large sample size and a large area. We find strong agreement in the intra-annual terrain smoothing behavior despite significant differences in mean snow depths observed over the study period, ranging from 0.73 m in 2023 to 2.2 m in 2019.

KEYWORDS: Snow depth, surface shape, surface roughness, snow avalanches, remote sensing.

1. INTRODUCTION

Surface smoothing in alpine terrain due to increasing snow depth has a significant impact on several natural processes. As snow accumulates, it gradually fills in small depressions and covers rough features, resulting in a smoother surface. This phenomenon changes the physical characteristics of the terrain and affects the dynamics of snow movement and stability. In particular, the smoothed surface can decrease variability in the snowpack layering and promote crack propagation in the avalanche formation process. In addition, surface smoothing alters the energy balance by changing albedo and insulating properties (Warren, 1982), thereby affecting the local microclimate and ecological processes in alpine environments.

The importance of surface smoothing for avalanche formation is widely recognized in the literature. For shallow snowpacks, a rough surface can have a stabilizing function and prevent the

formation of weak layers (Schweizer and Jamieson, 2003). Van Herwijnen and Heierli (2009) point out that in the case of a weak layer collapse, the roughness of the underlying surface plays an important role in whether or not a crack can propagate. McClung and Schaerer (2006) found, that with increasing snow depth, the stabilizing effects of terrain roughness disappear, and the formation of a widespread weak layer and slab is facilitated.

Airborne laser scanning (Wehr and Lohr, 1999), terrestrial laser scanning (Prokop, 2008) as well as photogrammetry (Bühler et al., 2015) have become increasingly reliable and effective techniques to obtain high-resolution terrain and snow surface data even in alpine terrain. Based on these data, the focus of research so far has been the analysis of snow depth and snow distribution at different scales. There are only a few studies on the influence of snow depth on roughness. Schweizer et al. (2003) found that a snow depth of 0.3 to 1 m is required to eliminate terrain roughness. Veitinger et al. (2014) used terrestrial and airborne laser scanning in three basins to evaluate the effect of snow depth on surface smoothing based on a multi-scale roughness approach. They found that the relation between terrain smoothing, and snow depth parameters follows a

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power law, suggesting that snowfall at the beginning of the winter season is more efficient at removing terrain roughness than snowfall later in the season.

The existing studies in this field are limited to a few areas. Recent advances in remote sensing and data processing (Eberhard et al., 2021) allow us to analyze the influence of snow depth on surface shape and roughness in the release areas of nearly 2000 avalanches of size 2 to 3, which are considered typical for human-triggered avalanches. High spatial resolution (0.5 m) annual snow surface and snow depth maps are recorded during the peak winter season since 2017 over the study area, located near Davos, Switzerland, covering an area of 275 km² (Bührlé et al., 2023, Figure 1). Based on these annual snow data and the underlying terrain data, we evaluate the snow surface and terrain type (Dikau, 1989) as well as the surface roughness (Veitinger et al., 2014) for each release area and snow map acquisition. Furthermore, we analyze the correlation between snow depth and terrain smoothing at 0.5, 2, and 5 m grid resolution and check for the intra-annual consistency of the results.

2. METHODS AND DATA

2.1 Study area, snow depth and release areas

The study area is defined by the airplane-based snow depth acquisitions recorded with the large-frame Vexcel UltraCam sensor in the years 2017 to 2023 over the broader extent of the Dischma valley near Davos, Switzerland (Figure 1). Details on the snow surface and snow depth processing can be found in Eberhard et al. (2021) and Bührlé et al. (2023). The 2018 data acquisition was obstructed by cloudy conditions and is therefore excluded from this study. The original 0.5 m cell size snow depth and snow surface grids are generalized to 2 and 5 m, respectively, to improve comparability with existing studies and to assess scaling effects caused by the spatial grid resolution. The summer terrain data are provided by swisstopo's swissALTI3D LiDAR DTM in 0.5 and 2 m grid resolution. The 5 m DTM is resampled from the 2 m grid resolution.

Within the extent of these snow depth maps, the avalanche database established at SLF recorded more than 3000 observed avalanches of class size 2 to 3, the size of avalanches considered to be typical for skier-triggered avalanches. The release areas of these avalanches were automatically defined by Harvey et al. (2018).

In this study, we removed release areas by applying a vegetation and buildings mask, and further checked the release areas for snow coverage on the snow map acquisition dates. The remaining dataset contains 1937 release areas. Their elevations range from 1550 to 3050 m a.s.l. with a mean elevation of 2350 m a.s.l. The aspect distribution is dominated by NE (29 %) and E (19 %), followed by W (12 %), SE (11 %), N (9 %), SW (8 %), NW (6 %), and S (6 %).

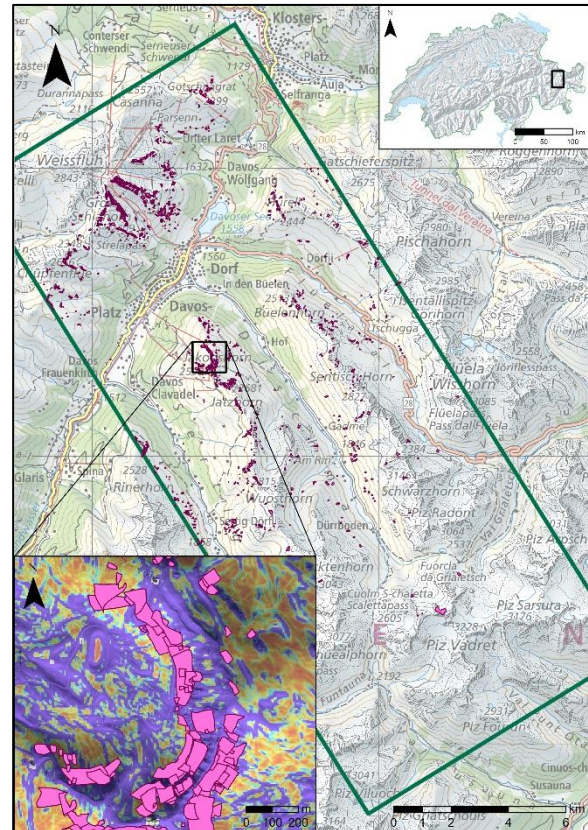


Figure 1: Main map: Study area based on the common extent of the snow maps (green outline), overlaid by the 1937 release areas (purple polygons). Detailed map: Release areas and snow surface roughness on 11.04.2019 at 5 m grid resolution (orange = smooth, purple = rough).

For each of the selected release areas, we calculate the mean snow depth ($\overline{HS}$) based on the annual snow depth maps. Over the 6-year study period, the mean snow depth within these release areas differs significantly, with the winter of 2022/23 having the lowest mean snow depth and the winter of 2018/19 having the highest mean snow depth (Table 1).

Date	$\overline{HS}$ [m] (Percentage of $\overline{HS}$ at 6- year max.)	Max $\overline{HS}$ [m]	$\sigma(HS)$ [m]
16.03.2017	1.15 (52)	3.91	0.56
11.04.2019	2.20 (100)	7.90	1.02
06.04.2020	1.37 (62)	5.48	0.76
16.04.2021	1.39 (63)	5.40	0.76
23.03.2022	1.02 (46)	3.92	0.52
22.03.2023	0.73 (33)	2.35	0.41

Table 1: Snow map acquisition dates, mean snow depth ($\overline{HS}$), percentage of $\overline{HS}$ compared to the measured maximum $\overline{HS}$ (11.04.2019), maximum $\overline{HS}$, and standard deviation $\sigma(HS)$ over the 1937 release areas.

2.2 Terrain type

Dikau's (1989) approach, also used by Maggioni and Gruber (2003), Vontobel (2011), and Vontobel et al. (2013), is implemented to evaluate the terrain and snow surface shape of the release areas. The profile and plane curvature are used to differentiate nine shape elements that occur on slopes.

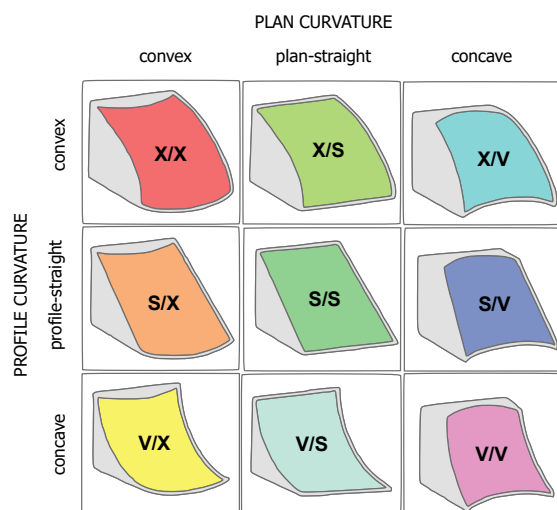


Figure 2: Classified terrain types (adapted from Dikau, 1989)

The average value of the plan and profile curvature within the release areas is assigned to one of the three characteristics: convex (X), straight (S),

and concave (V), based on a threshold of -0.2 and 0.2. The curvatures classified in this way, ultimately determine the shape of the terrain (Figure 2).

2.3 Surface roughness and terrain smoothing

The quantification of surface roughness and the terrain smoothing caused by the winter snowpack (Figure 3) is implemented according to Veitinger et al. (2014). They introduced a method to quantify terrain smoothing based on roughness and snow depth, where roughness is estimated based on geomorphological parameters of summer and winter terrain. First, the release area terrain and snow surface roughness are derived as a vector ruggedness measure by Sappington et al. (2007). The vector ruggedness is then computed for all winter surfaces and the corresponding summer terrain in all spatial resolutions. The neighborhood size is kept constant at 5 m. To quantify terrain smoothing, a linear regression analysis is performed between all pixels of a winter and the corresponding summer surface intersected by a release area (Veitinger et al., 2014). The resulting smoothing factor F ranges from 0, where surface roughness is equal to terrain roughness to 1, for complete surface smoothing.

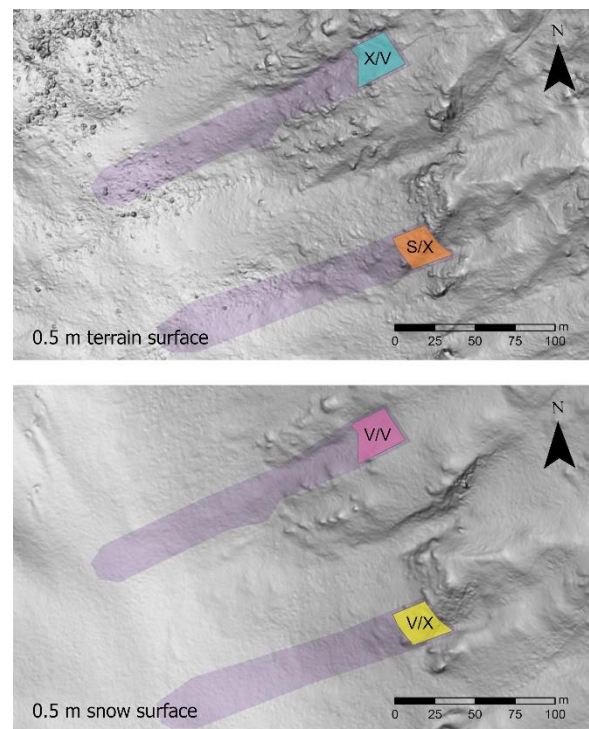


Figure 3: Relief shading of the terrain surface (top) and the corresponding snow surface measured on April 11, 2019 at 0.5 m grid resolution (bottom). The terrain smoothing caused by the snowpack leads to diverting terrain shapes in the release areas (labeled polygons). The extent of the avalanches is shown in light purple.

3. RESULTS AND DISCUSSION

3.1 *Terrain surface shape analysis*

The terrain surface type analysis of the 1937 selected avalanches shows that most release areas are characterized by concave profile curvatures, with V/V (28 %), V/S (13 %), and V/X (12 %), as shown in Figure 4.

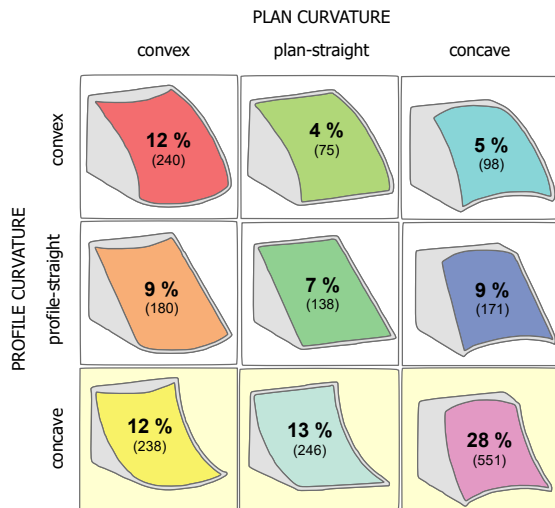


Figure 4: Distribution of terrain surface types over the selected 1937 release areas in percent (absolute numbers). Concave profile curvatures dominate (highlighted background).

3.2 *Snow surface shape analysis*

The snow surface shape may differ from the underlying terrain surface shape due to snow accumulation, settling and redistribution processes. Based on the selected 1937 release areas, we analyze the snow surface at the 6 snow map acquisition dates, i.e. we assess the snow surface shape for a total of 11622 snow surfaces. Comparing the terrain surface shapes with these snow surface shapes; the terrain type differs for 4309 release areas (37 %). In absolute numbers the largest deviations occur for the concave profile curvature types V/V (20 %), V/S (14 %), and V/X (14 %). Comparing the deviation over all 6 years with the annual deviations, we find that the intra-annual distribution of deviating profile types is largely consistent, differing only within a range of 0 to 3 % (Table 2).

Terrain type	All 6 years [%]	2017 [%]	2019 [%]	2020 [%]	2021 [%]	2022 [%]	2023 [%]
X/X	10	10	11	10	10	10	10
X/S	5	5	5	5	5	6	6
X/V	5	6	5	5	4	5	5
S/X	13	14	13	14	13	13	14
S/S	9	9	9	10	10	9	9
S/V	10	10	9	10	10	10	10
V/X	14	13	14	13	14	14	13
V/S	14	15	12	13	15	12	15
V/V	20	19	22	21	20	21	19

Table 2: Percentage of release areas with a different type of snow-free terrain compared to the type of snow surface, summarized over all 6 years and on an annual basis.

Normalized by occurrence the straight profile and plan curvatures deviate most often, with S/X (14 %), S/S (13 %), S/V (11 %), X/S (14 %), V/S (11 %), followed by the more convex and concave terrain shapes (Figure 5).

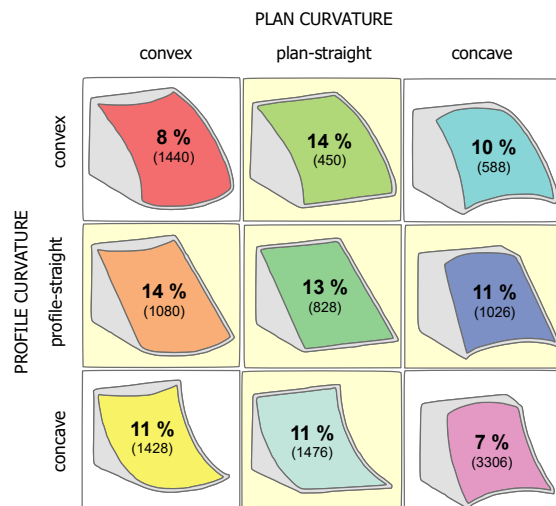


Figure 5: Total percentage of release areas with deviating terrain to snow surface type normalized by occurrence. Straight profile types dominate (highlighted background).

This result supports the findings of Deems et al. (2008) that the characteristics of a given site are relatively insensitive to variations in snow accumulation. Similarly, Schirmer et al. (2011) found a very high interannual consistency of snow distributions in alpine terrain.

3.3 *Terrain smoothing assessment*

Understanding the effect of snow depth on surface smoothing in avalanche release areas is of great importance. To better understand this relationship, we apply the methodology of Veitinger et al. (2024). Therefore, we analyze the correlation between mean snow depth ($\overline{HS}$) and terrain smoothing (F) within 1937 release areas for 6 years at 0.5, 2, and 5 m grid resolution.

Figure 5 shows that, in general, terrain smoothing increases with increasing snow depth. At 2 and 5 m grid resolution a power function can be fitted, but with a low coefficient of determination ($R^2 = 0.17$ at 2 m; $R^2 = 0.2$ at 5 m, Figure 6). Veitinger et al. (2024) obtained a similar or higher coefficient of determination at 5 m grid resolution using basin-scale data. At 0.5 m grid resolution, we are unable to establish a general relationship between the two variables (not shown). Similarly, Veitinger et al. (2014) did not find a relationship at 1 m resolution.

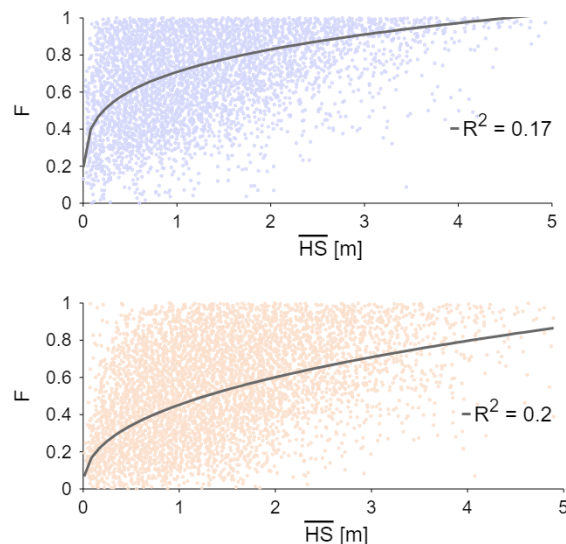


Figure 6: Terrain smoothing (F) as a function of mean snow depth ($\overline{HS}$) at 2 m grid resolution (top) and at 5 m grid resolution (bottom).

Next, we divide these data into terrain types to check for terrain dependent patterns in the coefficients of correlation. At 2 m grid resolution, the planar curvature groups (convex, plan-straight,

concave) best discriminate the snow depth dependence of terrain smoothing. Where convex terrain shapes (spur, ridge) show the lowest correlation while the concave curvature terrain shapes (depression) show the highest correlation. Interestingly, at 5 m grid resolution, the profile curvature is a better discriminator than the plan curvature. The convex profile curvatures show the lowest correlation between snow depth and surface smoothing, while the concave curvature terrain shapes show the highest correlation (Figure 7).

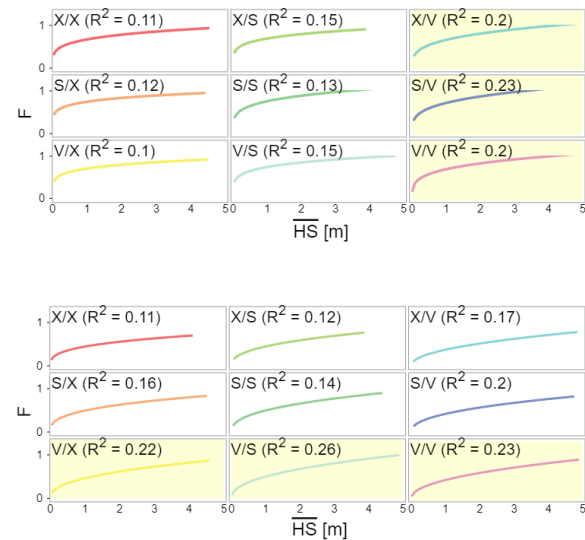


Figure 7: Terrain smoothing (F) as a function of mean snow depth ($\overline{HS}$) at 2 m grid size (top) and at 5 m grid size (bottom) divided by terrain type. The best correlations are shown with highlighted background.

Finally, we evaluate the intra-annual relationship between HS and F for the selected release areas over the 6 recorded dates. We find a power function that is nearly identical for each snow depth acquisition, despite the substantial differences in absolute snow height between the years studied (Figure 8). This finding is independent of the grid resolution, while the base and exponent of the power function differ with changing grid resolution due to the scale dependence. This is consistent with previous studies by Lehning et al. (2011), Deems et al. (2008), Deems et al. (2006), and Veitinger et al. (2014).

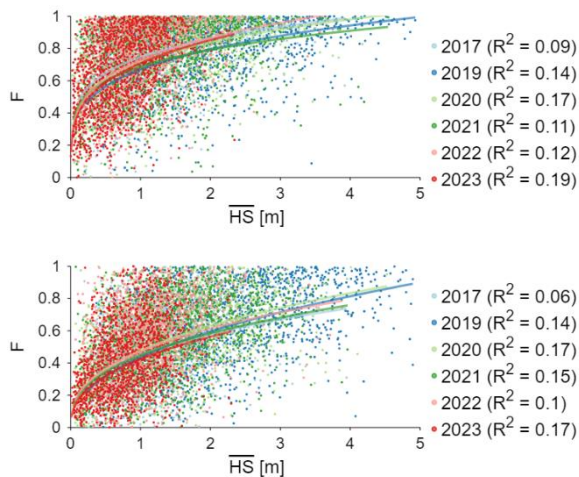


Figure 8: Terrain smoothing (F) as a function of mean snow depth ($\overline{HS}$) at 2 m grid resolution (top) and at 5 m grid resolution (bottom) segmented by snow depth dates (6 years).

4. CONCLUSIONS

In this study we investigate the influence of snow depth on surface shape and surface smoothing in avalanche release areas in the region of Davos, Switzerland. We analyze the release areas of nearly 2000 avalanches of class size 2 to 3, the size of avalanches considered to be typical for skier-triggered avalanches. The study is based on 6 years of snow depth and snow surface data collected by airborne photography near to the peak of winter snow depth (Bührlé et al. 2023).

The terrain type analysis shows that due to snow accumulation, settling and redistribution, the snow surface type differs significantly from the underlying terrain surface type in 37 % of the release areas. Normalized by occurrence, the straight profile and plan curvatures deviate the most, while the highly concave or convex terrain shapes require large redistribution efforts to change the terrain surface type.

Furthermore, we analyzed the correlation between snow depth and terrain smoothing within the release areas at 0.5, 2, and 5 m grid resolution using the methodology introduced by Veitinger et al. (2014). This method derives a power function between snow depth and surface smoothing, which can only be fitted to our data with low coefficients of determination. We observe that the method used is less suitable for terrain data captured at high spatial resolution than at lower resolution. The analysis of the multi-winter relationship between snow depth and surface smoothing shows that the power function is comparable between years, despite the considerable absolute differences in snow accumulation.

This analysis is the first to investigate the smoothing effect of snow depth on surface roughness for a large sample size in avalanche release areas. Despite the low coefficient of determination observed, we show that the smoothing effect of snow depth on surface roughness can be modeled with a power function at grid resolutions of 2 and 5 m, which are commonly used in avalanche dynamics simulations, thus simplifying the input assumptions of avalanche simulations.

In the future, a re-analysis of the potential release areas of larger avalanches, which were not included in this study, could improve the understanding of the terrain characteristics of observed skier-triggered and potential natural avalanches.

REFERENCES

- Bühler, Y., Marty, M., Egli, L., Veitinger, J., Jonas, T., Thee, P., and Ginzler, C.: Snow depth mapping in high-alpine catchments using digital photogrammetry, *The Cryosphere*, 9, 229-243, 10.5194/tc-9-229-2015, 2015.
- Bührlé, L. J., Marty, M., Eberhard, L. A., Stoffel, A., Hafner, E. D., and Bühler, Y.: Spatially continuous snow depth mapping by aeroplane photogrammetry for annual peak of winter from 2017 to 2021 in open areas, *The Cryosphere*, 17, 3383-3408, 10.5194/tc-17-3383-2023, 2023.
- Deems, J., Fassnacht, S., and Elder, K.: Fractal distribution of snow depth from lidar data, *JOURNAL OF HYDROMETEOROLOGY*, 7, 285-297, 2006.
- Deems, J. S., Fassnacht, S. R., and Elder, K. J.: Interannual Consistency in Fractal Snow Depth Patterns at Two Colorado Mountain Sites, *Journal of Hydrometeorology*, 9, 977-988, 10.1175/2008jhm901.1, 2008.
- Dikau, R.: The application of a digital relief model to landform analysis in geomorphology, *Three-dimensional Applications in Geographical Information Systems*, edited by: Raper, J., Taylor & Francis, London, 1989.
- Eberhard, L. A., Sirguey, P., Miller, A., Marty, M., Schindler, K., Stoffel, A., and Bühler, Y.: Intercomparison of photogrammetric platforms for spatially continuous snow depth mapping, *The Cryosphere*, 15, 69-94, 10.5194/tc-15-69-2021, 2021.
- Harvey, S., Schmudlach, G., Bühler, Y., Dürr, L., Stoffel, A., and Christen, C.: Avalanche terrain maps for backcountry skiing in Switzerland, *International Snow Science Workshop ISSW*, Innsbruck, Austria, 2018.
- Lehning, M., Grünwald, T., and Schirmer, M.: Mountain snow distribution governed by an altitudinal gradient and terrain roughness, *Geophysical Research Letters*, 38, 2011.
- Maggioni, M., and Gruber, U.: The influence of topographic parameters on avalanche release dimension and frequency, *Cold Regions Science and Technology*, 37, 407-419, 10.1016/S0165-232X(03)00080-6, 2003.
- McClung, D. M., and Schaerer, P.: *The Avalanche Handbook*, 3 ed., The Mountaineers Books, Seattle, 2006.
- Prokop, A.: Assessing the applicability of terrestrial laser scanning for spatial snow depth measurements, *Cold Regions Science and Technology*, 54, 155-163, 2008.

- Sappington, J. M., Longshore, K. M., and Thompson, D. B.: Quantifying landscape ruggedness for animal habitat analysis: A case study using bighorn sheep in the Mojave Desert, *Journal of Wildlife Management*, 71, 1419-1426, 10.2193/2005-723, 2007.
- Schweizer, J., and Jamieson, J. B.: Snowpack properties for snow profile analysis, *Cold Regions Science and Technology*, 37, 233-241, 2003.
- Schweizer, J., Jamieson, J. B., and Schneebeli, M.: Snow avalanche formation, *Reviews of Geophysics*, 41, -, 2003.
- van Herwijnen, A., and Heierli, J.: Measurement of crack-face friction in collapsed weak snow layers, *Geophysical Research Letters*, 36, 1-5, 10.1029/2009GL040389, 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, 10.5194/tc-8-547-2014, 2014.
- Vontobel, I.: Geländeanalysen von Unfalllawinen, MSc, Department of Geography, University of Zurich, 89 pp., 2011.
- Vontobel, I., Harvey, S. and Purves, R.S., 2013. Terrain analysis of skier-triggered avalanche starting zones. In: F. Naaim-Bouvet, Y. Durand and R. Lambert (Editors), *Proceedings ISSW 2013. Inter-national Snow Science Workshop*, Grenoble, France, 7-11 October 2013. ANENA, IRSTEA, Météo-France, Grenoble, France, pp. 371-375.
- Warren, S.: Optical Properties of Snow, *Reviews of Geophysics and Space Physics*, 20, 67 - 89, 1982.
- Wehr, A., and Lohr, U.: Airborne laser scanning--an introduction and overview, *ISPRS Journal of Photogrammetry and Remote Sensing*, 54, 68-82, 1999.