SNOW DEPTH VARIABILITY IN AN AVALANCHE RELEASE ZONE: ONE SEASON OF MEASUREMENTS AND TOPOGRAPHIC RELATIONS

Pia Ruttner-Jansen[1,2,3,*], Annelies Voordendag[3], Julia Glaus[1,2,4], Andreas Wieser[3], Yves Bühler[1,2]

[1] *WSL Institute for Snow and Avalanche Research SLF, Davos Dorf, Switzerland*
[2] *Climate Change, Extremes, and Natural Hazards in Alpine Regions Research Center CERC, Davos Dorf, Switzerland*
[3] *Institute of Geodesy and Photogrammetry ETH Zurich, Zürich, Switzerland*
[4] *Institute for Geotechnical Engineering ETH Zurich, Zürich, Switzerland*

ABSTRACT: Wind- and gravity-induced redistribution of snow leads to a high variability in snow depth across a slope, which is one of the major drivers to be taken into account for the assessment of avalanche danger. However, data on snow depth distribution in avalanche release zones at high spatial and temporal resolution are rarely available. We applied a newly developed monitoring system using low cost lidar and optical data that measured the snow depth distribution once per hour over the winter season 2023/24 at the release zone of the Wildi avalanche in Davos, Switzerland. The dataset consists of more than 3'000 epochs, each including an RGB image and lidar scans. In this contribution we present our experiences after one winter season of measurements, focusing on the station stability. By investigating apparent position changes of stable targets in the scan area we can quantify the stability of our measurement system. Additionally, we take first steps towards basic snow depth distribution modeling, by correlating the measured snow depths to terrain parameters. With the topographic position index (TPI) we test the common assumption that the mean snow depth is lower at ridges and hilltops, and higher at gullies and valleys than the mean overall snow depth. Up-to-date information on the snow depth variability in avalanche release zones is valuable for the refinement of avalanche simulation approaches, as well as for practitioners who decide on avalanche safety measures.

Keywords: lidar, snow depth, wind-drifted snow, modeling

1. INTRODUCTION

One of the major drivers of snow avalanches is snow that is redistributed by the wind (Schweizer et al., 2003). A wind slab problem arises with snowdrift during a snowfall event or when the wind redistributes the snow from near-surface layers (EAWS, 2024). Wind-blown snow forms a denser, more packed layer on top of soft and not well-bound old snow serving as weak layer. Alternatively, the weak layer can form within the wind slab layers due to variations in wind speed. Consequently, the wind can create perfect avalanche conditions when putting a slab on top of a soft weak layer (EAWS, 2024). In addition to snowpack stability and the distribution of weak layers, the snow depth has a major influence on the potential size of avalanches. However, detailed and up-to-date information about the variation of snow depth across a slope, especially in an avalanche release zone, is rarely available. Traditionally, the snow depth variability was derived by interpolating values from manual measurements or weather stations, but this approach cannot represent the spatial variability on a small scale. Today, the state-of-the-art methods to measure snow depth at high spatial resolution are using photogrammetry (Bühler et al., 2015; Vander Jagt et al., 2015; Bührle et al., 2023; Filhol et al., 2019; Deschamps-Berger et al., 2020) or lidar (Light Detection and Ranging; Prokop, 2008; Deems et al., 2013; Painter et al., 2016; Voordendag et al., 2024), either ground based, or mounted on drones, airplanes, or satellites. Recent developments explore the potential of using low-cost versions of those systems (Goelles et al., 2022; Ruttner-Jansen et al., 2024) or autonomously operating drones (Dryer et al., 2023).

Nevertheless, measuring snow depth distribution is usually associated with great effort and high investments and cannot be carried out at every location. In order to obtain comprehensive information, the known values are often extended by modeling. Consequently, the goal is to find approaches to accurately model the snow depth distribution using only few or easily accessible measurements. Many existing attempts involve the derivation of snow depth distribution from terrain parameters, ranging from basic statistic correlations (Marchand and Killingtveit, 2001; Winstral et al., 2002; Plattner et al., 2004; Grünewald et al., 2010; Lehning et al., 2011; Grünewald et al., 2013), to more advanced methods of machine learning (Revuelto et al., 2020; Meloche et al., 2022; Daudt et al., 2023).

In this contribution we present the dataset over one winter season from a newly equipped test site next to Davos in Switzerland. We show preliminary results of the setup stability and first attempts to cor-

*Corresponding author address:
Pia Ruttner-Jansen, SLF
7260 Davos Dorf, Switzerland;
tel: +41 814170369
email: pia.ruttner@slf.ch

relate the snow depths with terrain parameters.

2. STUDY SITE

The study site is located in the Dischma valley, next to Davos in south-east Switzerland. The monitored area covers the release area of the Wildi avalanche, which is at a north-east facing slope at around 2250 m. Two monitoring stations are operational since November 2023. They host a low-cost automotive-grade lidar sensor, an RGB camera and meteorological sensors measuring the air and snow surface temperature, wind speed and direction, and relative humidity (Ruttner-Jansen et al., 2024). Figure 1 shows an overview of the study site.

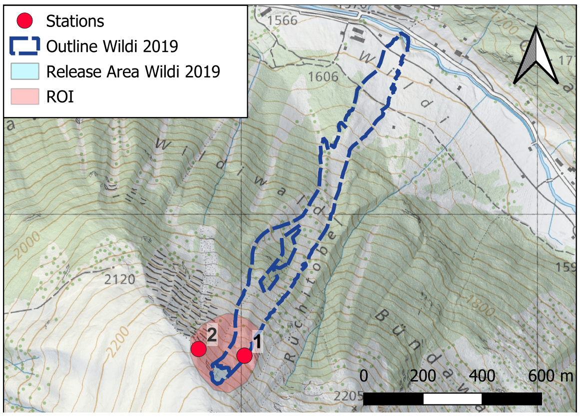

Figure 1: Map of the study site in the Dischma valley, showing the outline of the Wildi avalanche path, its release area, where the region of interest (ROI) is located and the positions of stations 1 and 2.

3. MEASUREMENTS

Both stations were set up on November 23, 2023. Station 1 recorded 3'443 epochs (hourly scans) until April 14, 2024 when a glide snow avalanche destroyed the station. Station 2 measured 4'335 epochs until the end of the season, around June 18, 2024. Due to technical issues, station 2 has a lower data availability in the beginning of the season, which improved after the replacement of the lidar sensor on February 6, 2024. Figure 2 illustrates the data availability for both stations, where 100% means that we could record a lidar scan each hour of the day (24 epochs).

3.1 Station stability

The stability of the measurement station needs to be assessed, as small changes in the lidar's position result in inconsistencies in the point cloud data. To assess the stability of the stations, we installed several mini-prisms in the monitored area, choosing stable rocks that remain free of snow. We estimated the prism centers using the method developed by Schmid et al. (2024). Then we calculated the transformation of the prism center coordinates of each

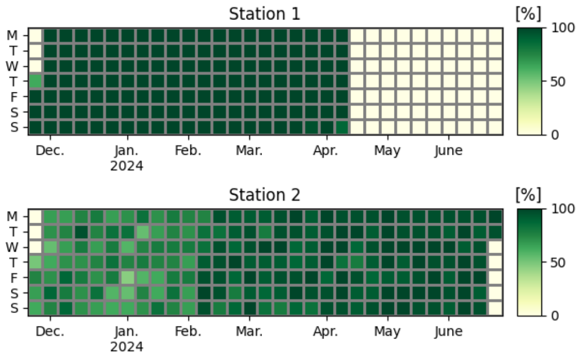

Figure 2: Data availability for the winter 2023/2024 for station 1 (top) and station 2 (bottom).

epoch to the mean coordinates of all epochs (Figure 4). Apparent movement of these prisms in the scan data reveals instabilities in the sensor's position. Analysing results, the rotation angles show little variation or drifts over most of the measurement season. In April 2024 there is some drift (up to 0.1 degrees) in the yaw-angle (Figure 3), which we could also identify when analysing the camera images. The roll-angle is subject to the biggest variation (from -0.2 to 0.25 degrees), the axis of which runs parallel to the line of sight of the sensor.

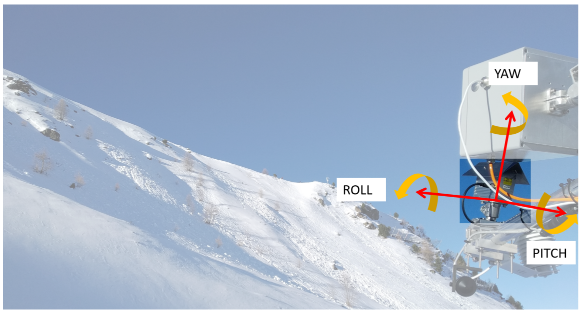

Figure 3: Visualisation of the rotation angles of the scanner, in it's own coordinate system.

Additionally, we checked for systematic deviations between the lidar measurements. We calculated the rotation of the scan when aligning each epoch to the previous epoch (time step of 1 hour), using the point-to-plane iterative closest point (ICP) algorithm (Besl and McKay, 1992; Chen and Medioni, 1992). The roll angle shows a systematic pattern, with a period of 2 measurements and an amplitude of around 0.6 degrees (Figure 5). An angular error in this magnitude causes a deviation of around 10 cm at 100 m distance. Due to the regularity of the pattern, we assume that its origin is in the sensor itself. An explanation could be a variation of the internal prism initialization, since the sensor is only supplied with power at the start of each measurement and turned off in between. However, further analysis is needed to verify the assumption and develop a possible correction function.

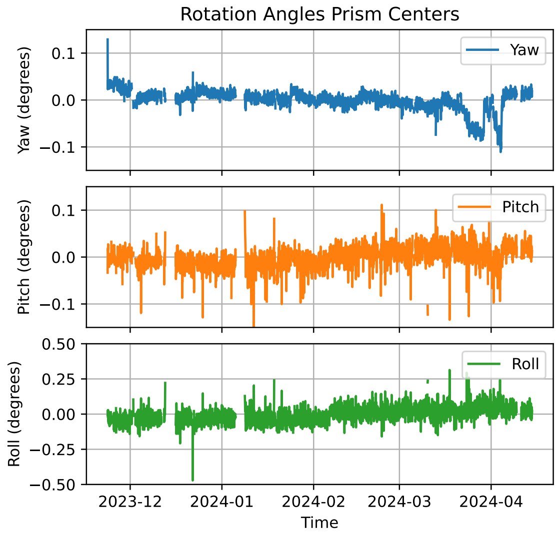

Figure 4: Rotation angles between the prism centers of each scan with respect to the mean prism center of all epochs.

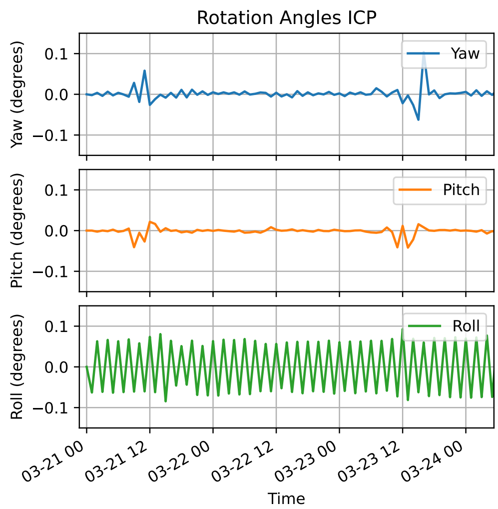

Figure 5: Rotation angles of the iterative closest point (ICP) transformations between consecutive scan epochs, for an example of a few days in March 2024.

4. TOPOGRAPHIC RELATION

For a first step in the direction of snow depth modeling, we correlate the measured snow depth with the topographic position index TPI (Weiss, 2001). The TPI compares the elevation of a point z_0 with the mean elevation $\overline{z}$ of its neighborhood within a radius R (Weiss, 2001; De Reu et al., 2013):

$$TPI = z_0 - \overline{z} \tag{1}$$

$$\overline{z} = \frac{1}{n_R} \sum_{i \in R} z_i \tag{2}$$

Depending on the search radius R, different scales of terrain structures become recognisable. In general, positive TPI values indicate landforms like ridges, hilltops, cliff edges or upper slopes (close to top). A TPI value around zero occurs at flat and constant slopes, or saddles. Negative TPI values relate to valleys, gullies, and lower slopes (close to bottom; Weiss, 2001).

Slope position	TPI threshold	Slope
Ridge/hilltop	TPI > 1	
Upper slope	0.5 < TPI <= 1	
Middle slope	-0.5 <= TPI <= 0.5	> 30°
Flat slope	-0.5 <= TPI <= 0.5	<= 30°
Lower slope	-1 <= TPI < -0.5	
Valley/gully	TPI < -1	

Table 1: TPI classification into slope positions (Weiss, 2001; Deumlich et al., 2010).

We calculated the TPI based on the (snow off) DEM derived from a photogrammetric drone acquisition of October 18, 2022, using an empirically chosen radius of R=10 m. We compare the resulting TPI with the snow depth (HS), derived from our lidar measurements on December 19, 2023.
Figure 6 illustrates the snow depth variation and the TPI at the test site of the Wildi avalanche. The mean snow depth is 1.3 m with a standard deviation of 0.3 m. At the test site (masked by available HS data), about 13% of the area has a TPI < -0.5, which indicate lower slopes, valleys, or gullies, 79 % are flat or constant slopes and 8 % has a TPI > 0.5, indicating upper slopes, ridges or hilltops. It is generally assumed that the highest snow depths are found in gullies, whereas ridges and hilltops contain less snow.

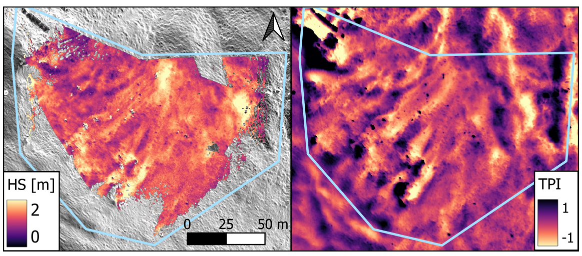

Figure 6: Left: Map of snow depths (HS) on December 19, 2023, derived from the lidar acquisitions. Right: TPI, derived from a photogrammetric drone acquisition on October 18, 2022. Both maps show the same area, the bright blue polygon is for orientation.

To confirm this statement and show the statistical differences between different topographical features, we calculated the distributions of HS as probability density functions (PDF) for different slope positions (see Table 1) and compared them to the respective mean values (Figure 7).
The mean HS in areas with a TPI < -0.5 (lower slope, valley, gully) is clearly higher, compared to the overall mean HS in the monitored area. At the lowest slope position class (TPI < -1) the mean snow depth is 150 % higher than the mean over

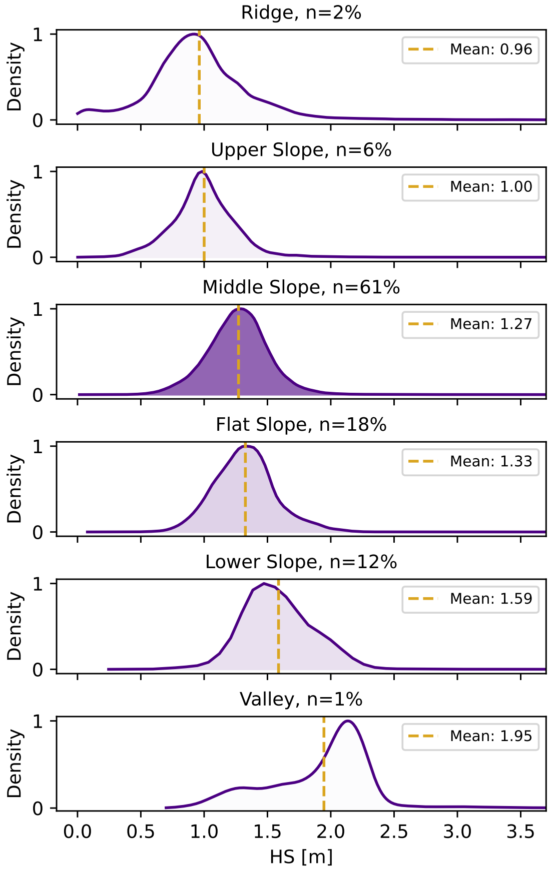

Figure 7: Probability density functions (PDFs) of snow depths (HS), filtered by slope positions. Mean HS overall: 1.3 m. Darker shading of the PDF indicates a higher percentage of samples (n) in the bin.

the area. Areas with TPI between -0.5 and 0.5 (flat, constant slope) have a mean HS of 1.27 m - 1.33 m, which is around the overall mean HS. Where TPI > 1 (ridge, hilltop), the mean HS is 0.96 m, which is 26 % lower than the overall mean, and thus shows, that less snow has accumulated or that snow has been blown away on the ridges and hilltops.

Even though the distribution of HS over the different TPI bins is not Gaussian, the analysis of the relation between the TPI and HS enables us to estimate the effect of topographical features on snow depth. Knowing the distribution relative to the mean snow depth is a valuable input for snow distribution models. However, to more comprehensively investigate the variability in snow depth, we will relate the snow depth over the different TPI bins also to other parameters, such as mean wind direction and aspect.

5. CONCLUSION AND OUTLOOK

Information of snow depth distribution at high spatial and temporal resolution are rarely available. To fill this gap, we present our specially developed low-cost monitoring system including a lidar and an optical camera. We share our experiences after one season of measurements. More than 3'000 measurement epochs show the potential, but also the challenges of the setup of this system. The analysis of apparent motion of fixed points in the area (installed prisms) demonstrates the importance of inter-epoch registration. We also found a systematic error, most likely originating in the lidar sensor itself, that causes up 10-15 cm deviations in the scan. We plan to overcome this with an appropriate registration method in further data processing steps.

As a first step towards snow depth modeling we look into the relationship of the snow depth to the topographic position index (TPI). With this basic comparison, we can quantify the correlation of low TPI values (gullies) with higher snow depths, and high TPI values at ridges and hilltops with lower snow depths (compared to the mean snow depth of the area). This relation is obvious, but quantifying snow depth distribution over terrain at high spatial, and especially high temporal resolution is a big step forward towards including snow depth models in avalanche simulations. In the future we aim to include other parameters, like wind direction and speed in our snow depth modeling.

In the upcoming winter seasons we will expand our dataset, monitoring at additional locations and aspects. These improved and extended snow depth measurements, and further analysis of topographic parameters and meteorological data, will help us to better understand the dynamics of snow depth variations for avalanche modelling.

ACKNOWLEDGEMENT

This research is funded by the Swiss National Science Foundation SNSF with the project "Avalanche Safety for Roads" (Nr. 207519). We thank the electronic workshop of SLF for the technical realization and installation of the measurement system.

References

Besl, P. J. and McKay, N. D.: Method for Registration of 3-D Shapes, in: Robotics - DL Tentative, edited by Schenker, P. S., pp. 586–606, Boston, MA, doi:10.1117/12.57955, 1992.

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, doi:10.5194/tc-9-229-2015, 2015.

Bührle, 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, doi:10.5194/tc-17-3383-2023, 2023.

Chen, Y. and Medioni, G.: Object Modelling by Registration of Multiple Range Images, Image and Vision Computing, 10, 145–155, doi:10.1016/0262-8856(92)90066-C, 1992.

Daudt, R. C., Wulf, H., Hafner, E. D., Bühler, Y., Schindler, K., and Wegner, J. D.: Snow Depth Estimation at Country-Scale with High Spatial and Temporal Resolution, ISPRS Journal of Photogrammetry and Remote Sensing, 197, 105–121, doi:10.1016/j.isprsjprs.2023.01.017, 2023.

De Reu, J., Bourgeois, J., Bats, M., Zwertvaegher, A., Gelorini, V., De Smedt, P., Chu, W., Antrop, M., De Maeyer, P., Finke, P., Van Meirvenne, M., Verniers, J., and Crombé, P.: Application of the Topographic Position Index to Heterogeneous Landscapes, Geomorphology, 186, 39–49, doi:10.1016/j.geomorph.2012.12.015, 2013.

Deems, J. S., Painter, T. H., and Finnegan, D. C.: Lidar Measurement of Snow Depth: A Review, Journal of Glaciology, 59, 467–479, doi:10.3189/2013JoG12J154, 2013.

Deschamps-Berger, C., Gascoin, S., Berthier, E., Deems, J., Gutmann, E., Dehecq, A., Shean, D., and Dumont, M.: Snow Depth Mapping from Stereo Satellite Imagery in Mountainous Terrain: Evaluation Using Airborne Laser-Scanning Data, The Cryosphere, 14, 2925–2940, doi:10.5194/tc-14-2925-2020, 2020.

Deumlich, D., Schmidt, R., and Sommer, M.: A Multiscale Soil–Landform Relationship in the Glacial-Drift Area Based on Digital Terrain Analysis and Soil Attributes, Journal of Plant Nutrition and Soil Science, 173, 843–851, doi:10.1002/jpln.200900094, 2010.

Dryer, P., Glassett, T., Marlow, R., and McKee, M.: UNMANNED AERIAL SYSTEMS FOR AVALANCHE MONITORING AND MITIGA- TION: A COLLABORATIVE APPROACH BY ALASKA DOT&PF AND ALASKA RAILROAD, 2023.

EAWS: Standards: Avalanche Problems, https://www.avalanches.org/standards/avalanche-problems/, 2024.

Filhol, S., Perret, A., Girod, L., Sutter, G., Schuler, T. V., and Burkhart, J. F.: Time-Lapse Photogrammetry of Distributed Snow Depth During Snowmelt, Water Resources Research, 55, 7916–7926, doi:10.1029/2018WR024530, 2019.

Goelles, T., Hammer, T., Muckenhuber, S., Schlager, B., Abermann, J., Bauer, C., Expósito Jiménez, V. J., Schöner, W., Schratter, M., Schrei, B., and Senger, K.: MOLISENS: MObile LIdar SENsor System to Exploit the Potential of Small Industrial Lidar Devices for Geoscientific Applications, Geoscientific Instrumentation, Methods and Data Systems, 11, 247–261, doi:10.5194/gi-11-247-2022, 2022.

Grünewald, T., Schirmer, M., Mott, R., and Lehning, M.: Spatial and Temporal Variability of Snow Depth and Ablation Rates in a Small Mountain Catchment, The Cryosphere, 4, 215–225, doi:10.5194/tc-4-215-2010, 2010.

Grünewald, T., Stötter, J., Pomeroy, J. W., Dadic, R., Moreno Baños, I., Marturià, J., Spross, M., Hopkinson, C., Burlando, P., and Lehning, M.: Statistical Modelling of the Snow Depth Distribution in Open Alpine Terrain, Hydrology and Earth System Sciences, 17, 3005–3021, doi:10.5194/hess-17-3005-2013, 2013.

Lehning, M., Grünewald, T., and Schirmer, M.: Mountain Snow Distribution Governed by an Altitudinal Gradient and Terrain Roughness, Geophysical Research Letters, 38, doi:10.1029/2011GL048927, 2011.

Marchand, W.-D. and Killingtveit, Å.: Analyses of the Relation Between Spatial Snow Distribution and Terrain Characteristics, in: 58th EASTERN SNOW CONFERENCE, Ottawa, Ontario, Canada, 2001.

Meloche, J., Langlois, A., Rutter, N., McLennan, D., Royer, A., Billecocq, P., and Ponomarenko, S.: High-Resolution Snow Depth Prediction Using Random Forest Algorithm with Topographic Parameters: A Case Study in the Greiner Watershed, Nunavut, Hydrological Processes, 36, e14 546, doi:10.1002/hyp.14546, 2022.

Painter, T. H., Berisford, D. F., Boardman, J. W., Bormann, K. J., Deems, J. S., Gehrke, F., Hedrick, A., Joyce, M., Laidlaw, R., Marks, D., Mattmann, C., McGurk, B., Ramirez, P., Richardson, M., Skiles, S. M., Seidel, F. C., and Winstral, A.: The Airborne Snow Observatory: Fusion of Scanning Lidar, Imaging Spectrometer, and Physically-Based Modeling for Mapping Snow Water Equivalent and Snow Albedo, Remote Sensing of Environment, 184, 139–152, doi:10.1016/j.rse.2016.06.018, 2016.

Plattner, C., Braun, L. N., and Brenning, A.: SPATIAL VARIABILITY OF SNOW ACCUMULATION ON VERNAGTFERNER, AUSTRIAN ALPS, IN WINTER 2003/ 2004, Zeitschrift für Gletscherkunde und Glazialgeologie, 39.1, 2004.

Prokop, A.: Assessing the Applicability of Terrestrial Laser Scanning for Spatial Snow Depth Measurements, Cold Regions Science and Technology, 54, 155–163, doi:10.1016/j.coldregions.2008.07.002, 2008.

Revuelto, J., Billecocq, P., Tuzet, F., Cluzet, B., Lamare, M., Larue, F., and Dumont, M.: Random Forests as a Tool to Understand the Snow Depth Distribution and Its Evolution in Mountain Areas, Hydrological Processes, 34, 5384–5401, doi:10.1002/hyp.13951, 2020.

Ruttner-Jansen, P., Voordendag, A., Hartmann, T., Glaus, J., Wieser, A., and Bühler, Y.: Monitoring Snow Depth Variations in an Avalanche Release Area Using Low Cost LiDAR and Optical Sensors, doi:10.5194/egusphere-2024-744, 2024.

Schmid, L., Medic, T., Frey, O., and Wieser, A.: Target-Based Georeferencing of Terrestrial Radar Images Using TLS Point Clouds and Multi-Modal Corner Reflectors in Geomonitoring Applications [Under Review], 2024.

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

Vander Jagt, B., Lucieer, A., Wallace, L., Turner, D., and Durand, M.: Snow Depth Retrieval with UAS Using Photogrammetric Techniques, Geosciences, 5, 264–285, doi:10.3390/geosciences5030264, 2015.

Voordendag, A., Goger, B., Prinz, R., Sauter, T., Mölg, T., Saigger, M., and Kaser, G.: A Novel Framework to Investigate Wind-Driven Snow Redistribution over an Alpine Glacier: Combination of High-Resolution Terrestrial Laser Scans and Large-Eddy Simulations, The Cryosphere, 18, 849–868, doi:10.5194/tc-18-849-2024, 2024.

Weiss, A.: Topographic Position and Landforms Analysis., 2001.

Winstral, A., Elder, K., and Davis, R. E.: Spatial Snow Modeling of Wind-Redistributed Snow Using Terrain-Based Parameters, Journal of Hydrometeorology, 3, 524–538, doi:10.1175/1525-7541(2002)003⟨0524:SSMOWR⟩2.0.CO;2, 2002.