Leveraging Novel Remote Sensing Technologies for Snow Avalanche Susceptability : A Comprehensive Review

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Abstract : Avalanches, the cataclysmic descending progressions of snow and debris propelled by gravitational forces on steep alpine terrain, pose substantial mortality risk globally, claiming numerous lives annually in regions prone to significant snowpack accumulation. Contemporaneous research endeavors aim to augment prognostic capabilities and mitigative measures by employing remote sensing techniques for data acquisition and machine learning models for detection. This comprehensive review, following the rigorous PRISMA method, meticulously examines recent literature, assessing various remote sensing modalities, including optical, radar, and LiDAR sensors, and machine learning algorithms encompassing supervised, unsupervised, and deep learning approaches utilized for avalanche detection and prediction. The integration of these cutting-edge technologies shall facilitate sophisticated avalanche forecasting systems, enhancing mitigation of these natural disasters' devastating consequences.

Keywords: Remote Sensing, Machine Learning, Snow Avalanche Detection

Introduction :

Snow avalanches are rapid, destructive flows of snow and debris cascading down mountainous slopes, often entraining and incorporating additional material such as rocks, trees, and other debris in their path. These cataclysmic events occur when the forces acting upon the snowpack exceed its structural integrity and cohesive strength, causing fractures to propagate and the snow to slide downslope [1]. Avalanches can manifest suddenly and without warning, rendering them extremely perilous and posing grave risks to human life and safety.

Several key factors contribute to the occurrence of avalanches:

Factor	Contributes to Avalanche Risk	General Ranges
Terrain Slope	Steeper slopes increase gravitational forces on snowpack [18].	>30 degrees considered avalanche terrain [19].
Snow Depth	Greater accumulation adds weight and stress to snowpack [20].	>1 meter new snow increases risk [21].
Snow Density	Denser snow more likely to fracture and slide as slab [22].	200-400 kg/m³ typical avalanche densities [23].
Snowpack Structure	Weak layers act as failure planes for upper layers [24].	Depth hoar, crusts, facets increase risk [25].
Weather Conditions	Rapid temperature changes, heavy precipitation, wind loading destabilize snowpack [26].	Risk highest during/after heavy snowfall, rain-on-snow, rapid warming [27].
Elevation	Higher elevations receive more accumulation and steeper terrain [28].	Most avalanches above treeline, typically >2,500-3,000m [29].
Aspect/ Solar Radiation	Slopes with more direct sunlight prone to warming and weakening [30].	South, west-facing slopes more avalanche-prone [31].

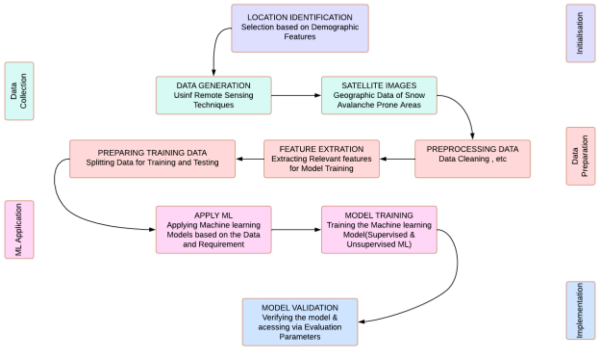
Table 1: Demographic Features for Snow Avalanche Occurence

Snow avalanches are most prevalent in mountainous regions that experience substantial snowfall. On average, avalanches claim numerous lives annually across various regions, with an estimated global death toll ranging from 150 to 300 per year [7]. In the United States and Canada alone, avalanches claim an average of 25-35 lives annually [8]. Many avalanche fatalities involve recreational activities such as skiing, snowmobiling, and climbing, where individuals venture into avalanche-prone areas [9].
Mitigating avalanche risk is a crucial endeavor, necessitating proper education, training, and the use of appropriate safety equipment and precautions.

Avalanche forecasting and warning systems, which incorporate meteorological data, snowpack observations, and advanced modeling techniques, play a vital role in helping individuals and communities avoid dangerous areas during high-risk periods [10]. Additionally, ongoing research efforts aim to improve our understanding of avalanche dynamics and develop more effective prevention and mitigation strategies [11].

Genreal Procedure for Snow Avalanche detection :

In a Conventional sense Remote Sensing is used for data aquisition and then the aquired Geographic Images or Data is used to Train ML models for Detecting the Possible Snow Avalanches .
Following is the Detailed flow of Operations for the Process:



Figur 1.1-Procedural Flow for Snow Avalanche Susceptability

Previous Work

Litrature Selection

We followed the PRISMA guidelines and accesses the research papers from the Google Scholar, Sematic Scholar and the Scopus Index Databases using the Litmaps tool for Creating Seed Maps for the litrature review purpose.
Segregating the papers on the basis of the Screening process mentioned as follows:

1. Excluding repititive Content
2. Keyword Search : Machine Learning, Snow Avalanche Detection, Remote Sensing, etc
3. Inadequate Data
4. Output Relevance Selection
5. Timeline Relevance

Out of Total 578 Articles a total of 35 full text articles were included for the final review , adhering to the criteria defined above.

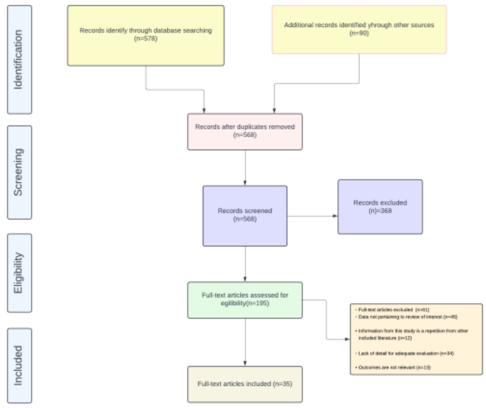


Figure 1.2 : Litrature Selection Using prisma guidelines

Presently sensing Tech for delineation of snow avalanches:

Remote sensing techniques, including LiDAR, and Radar sensors, have been explored for avalanche detection and mapping. Optical sensors measure fundamentally radiated or deliberate radiation, where as current LiDAR and Radar sensors discharge and calculate reflected energy [12]. A key challenge is that avalanche debris and surrounding snow often have similar electromagnetic properties. However, the physical properties of snow, such as grain size, liquid water content, and density, influence electromagnetic spectrum, reflectance and backscatter as well as providing opportunities for remote sensing-based avalanche monitoring [13,14].

Optical remote sensing can leverage contrast differences caused by changes in snow depth, density, and surface roughness to detect avalanche extent [15]. LiDAR can measure changes in snow cover mass balance to quantify avalanche volume and extent [16]. Radar can detect avalanche debris due to increased surface roughness [17]. Each technology has its strengths and limitations, and understanding the underlying physics of snow-electromagnetic interactions is crucial for effectively utilizing these remote sensing techniques for avalanche visualization and mapping.

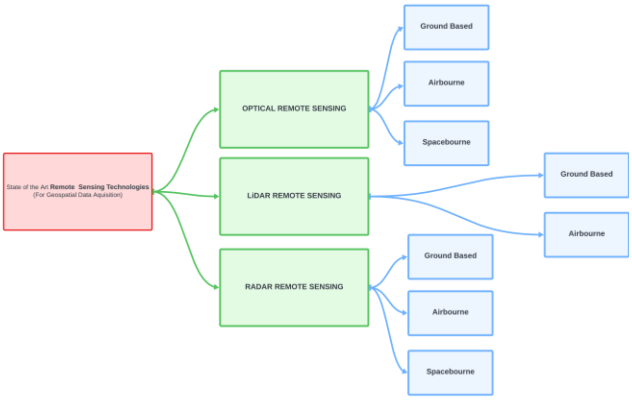


Figure 1.3 - Remote Sensing Techniques

Ground-based Optical Remote

Sensing for Avalanches :

Examining the literature and current research

Optical remote sensing techniques, particularly time-lapse photography, have been extensively utilized to study the behavior of cornices, glide cracks, and wet snow avalanches. Numerous studies have demonstrated the ability to monitor cornice fall activity and dynamics, as well as the potential to link meteoric data with high-frequency time-lapse photography to enhance comprehension of the management of wet snow avalanches [1-6]. Additionally, the structure-from-motion (SfM) photogrammetry technique has been applied to map slab fracture lines and compute surface models of avalanche deposits, enabling the computation of deposition area and amount [7].

Innovation, upper hand, and lower hand

Accurate near-real-time data is obtained by using automated time-lapse photography to monitor avalanche activity., allowing for the continuous observation of avalanche dynamics and associated processes. However, this approach is limited by bad weather conditions, such as low visibility and precipitation, which can obscure the field of view and compromise data quality. Additionally, ground-based techniques have a restricted spatial coverage compared to airborne or satellite-based methods, limiting their applicability to smaller study areas. Structure-from-motion (SfM) photogrammetry offers the ability to create detailed 3D models of avalanche deposits and fracture lines, providing valuable quantitative information for avalanche analysis. However, this technique requires post-georeferencing and can be challenging in areas with low contrast, such as snow-covered surfaces, where feature detection andmatching can be problematic.

Teleoperated Optical Remote Sensing of Avalanches from Above

assessment of the literature and current

Optical aerial imagery has been extensively utilized for various natural hazard applications, including avalanche detection and mapping. Bühler et al. [8] employed an airborne digital pushbroom scanner to map avalanche debris, achieving an accurate detection rate of 94% for medium to large avalanche deposits. [9] further expanded on this work by applying image analysis methods based on objects to orthorectified imagery, successfully identifying avalanche debris in two case studies with success rates of 95% and 97%. More recently, Eckerstorfer et al. [10] demonstrated the potential of using remotely piloted aircraft systems (RPAS) equipped with optical sensors to create high- resolution orthophotos and 3D models of avalanchedebris.

The pros and cons of Innovations

optical remote sensing techniques, such asthe use of digital pushbroom scanners, can provide high spatial and radiometric resolution data foravalanche detection and mapping. These platformsoffer flexibility in data acquisition, enablingtargeted surveys and timely responses to avalancheevents. However, airborne campaigns are highlycost and resource intensive, often requiringspecialized equipment and personnel. Furthermore,their sensitivity to weather conditions remains alimitation, as cloud cover, precipitation, and lowvisibility can significantly impact data quality andacquisition.

The use of RPAS offers a more cost-effective and flexible alternative for localized avalanche studies. These systems can acquire high-resolution imagery and generate detailed 3D models of avalanche deposits, providing valuable information for hazard assessment and mitigation efforts. However, the application of RPAS is often restricted by regulations in many countries, limiting their widespread use in avalanche research. Additionally, RPAS operations are subject to environmental factors such as wind and battery life, which can affect flight duration and data acquisition capabilities.

Spaceborne Optical Remote Sensing of Avalanches

assessment of the literature and current

The use of spaceborne optical remote sensing for avalanche studies has been relatively limited compared to ground-based and airborne techniques,but promising results have been reported. Larsen et al. [11] and Lato et al. [9] applied avalanche detection algorithms to spaceborne imagery from the Quick Bird satellite, with the algorithms demonstrating the ability to compensate for challenges such as over-illumination and shadedareas. Eckerstorfer et al. [12, 13] have also explored the use of Landsat-8 panchromatic images for the manual detection of medium to large avalanche debris.

Innovation, Pros, Cons

Spaceborne optical remote sensing platforms, such as QuickBird, Ikonos, and WorldView, can provide very high-resolution imagery for avalanche detection and mapping. These satellites offer global coverage and the ability to acquire data over remote and inaccessible areas, making them valuable tools for large-scale avalanche monitoring and hazard assessment. However, the high cost of commercial satellite data has limited its widespread use in avalanche research, particularly for small-scale or localized studies.

The recent availability of high-resolution, freely available data from Landsat-8 and the upcoming Sentinel-2 constellation offers new opportunities for spaceborne avalanche studies. These satellites provide global coverage and frequent revisit times, enabling the potential for near-real-time monitoring of avalanche events. Nonetheless, challenges remain, such as sensitivity to weather conditions, limitations in spatial coverage, and the need for further development and validation of automated detection algorithms. Additionally, the spatial resolution of these freely available datasets may not be sufficient for detailed avalanche analysis, particularly for smaller events or in complex terrain.

LiDAR Remote Sensing

LiDAR Remote Sensing of Avalanches from the Ground

assessment of the literature and current

Measurements of the snow depth in space are made using terrestrial LiDAR scanners (TLS). and avalanche detection was pioneered by Prokop (2008)[1]. This knowledge demonstrated the ability of TLS to obtain, within 500 meters of the scanner, snow depth readings with an inaccuracy of less than 10 centimeters. A pioneer in showcasing the capabilities of TLS for avalanche detection, Prokop (2008)[1] identified mass increases in debris areas and mass losses in beginning zones and slide pathways. After then, Prokop et al. (2013) used this strategy.In [2] and Deems et al. (2014)[3], who utilized TLS to measure avalanche debris volumes by quantifying changes in the snow cover mass balance. Furthermore, Sovilla et al. (2010)[4] demonstrated the capability of TLS to retrieve high-resolution snow depth measurements of avalanche debris, with a height resolution of 100 mm and a horizontal resolution of 500 mm.

Technology, advantages and disadvantages

Recent technological advancements in TLS systems, such as the development of the Riegl VZ-4000, VZ-6000, and Optech Ilris LR scanners, have provided increased range capabilities, higher resolution, and faster acquisition times[3]. These ground-based LiDAR systems are highly portable and not limited by changing weather conditions during surveys, making them well-suited for avalanche monitoring applications. However, the high cost of TLS systems, including the scanner, camera, GPS, and software, remains a significant limitation, potentially hindering their widespread adoption. Additionally, the range of the LiDAR system restricts the measurement area to individual slopes, which may be a constraint in certain research or operational contexts.

Airborne LiDAR Remote Sensing of Avalanches

assessment of the literature and current

There aren't many case studies that have been published in the literature about the use of aerial LiDAR for avalanche monitoring. With an accuracy of 20–30 cm, Vallet et al. (2000)[5] used an Optech ALTM 1020 laser scanner installed atop a helicopter to estimate the amount of avalanche debris. The use of digital elevation models (DEMs) generated from aerial LiDAR data to predict possible avalanche release zones was also investigated by Chrustek and Wezyk (2009)[6]. They discovered that the accuracy of their calculations in steep and complicated terrain enhanced by the use of higher-resolution DEMs.

Technology, advantages and disadvantages

While the available literature on the use of airborne LiDAR for avalanche detection provides limited information on the specific systems and their performance, the current market leaders in airborne LiDAR technology, such as Riegl with their VQ-580 system, Leica, and Optech, offer systems that could potentially be utilized for avalanche monitoring applications. The ability to cover large areas is a significant advantage of airborne LiDAR systems, enabling the assessment of avalanche hazards and impacts over extensive regions. However, the use of airborne LiDAR for avalanche studies comes with significant logistical and budgetary challenges, as these campaigns often require specialized equipment, personnel, and operational resources. Spaceborne LiDAR systems are currently not available for avalanche applications due to technological limitations and constraints.

Radar Remote Sensing of Avalanches

Ground-based Radar Remote Sensing of Avalanches

looking through the literature and recent studiesMartinez-Vacezez and Fortuny-Guasch were the first to employ ground-based synthetic aperture radar (SAR) systems for avalanche detection, thereby paving the way for the use of radar remote sensing for avalanche monitoring. They discovered that substantial avalanches altered the backscatter arrangement, resulting in temporal decorrelation that could be measured with coherence metrics. It was difficult to discern avalanches from other physical changes in the snowpack, though. The possibility of extracting avalanche volume from the ground-based radar data through the use of differential interferometric SAR (DInSAR) was also investigated by Martinez-Vazquez and Fortuny-Guasch.

In more recent times, a GAMMA Portable Radar Interferometer (GPRI) was used by Wiesmann et al. and Caduff et al. for continuous monitoring, taking pictures at intervals of two to three minutes. A few little avalanches were discernible to them. and within fifteen minutes saw how adding more liquid water affected coherence.

Innovation, Pros, Cons

High temporal (30 seconds) and spatial (meter-scale) resolution are available from ground-based radar systems like the GPRI, LISAlab, or Ibis-FL. with the ability to operate independently of weather and light conditions. The sensitivity to small (millimeter-scale) surface changes is a keyadvantage. However, the limited measurement range and high cost of these systems remain significant limitations. Accurate coregistration, filtering, and classification of the radar images are crucial.

Airborne Radar Remote Sensing of Avalanches

To date, no studies have reported on the use ofairborne radar remote sensing for avalanche monitoring. However, potential platforms include the E-SAR system developed by the German Aerospace Center (DLR), which operates in multiple frequency bands, and the UAVSAR radar developed by NASA, which is a L-band SAR system designed for installation on unmanned aerial vehicles (UAVs). The use of UAV-borne SAR sensors are a new technology that has a lot of promise for monitoring avalanches.

Spaceborne Radar Remote Sensing of Avalanches

*Analysis of the literature and current*The potential of spaceborne synthetic aperture radar (SAR) for avalanche detection was first demonstrated by Wiesmann et al., who used ERS-1/2 C-band SAR data to identify avalanche debris based on increased backscatter. Bühler et al. later used TerraSAR-X X-band SAR data for avalanche detection through backscatter change detection.

More recently, studies have explored the use of the freely available Sentinel-1A C-band SAR data for avalanche monitoring. Researchers were able to manually detect medium-sized avalanche debris in Radarsat-2 Ultrafine Mode and Sentinel-1A Interferometric Wide Swath Mode data. Additionally, automated avalanche detection algorithms applied to Sentinel-1A data achieved detection rates around 57% with omission and commission errors.

Technology, advantages and disadvantages Spaceborne SAR systems offer the advantage ofall-weather, all-light condition monitoring, with therecent availability of freely accessible data from theSentinel-1A satellite providing improved temporalcoverage. However, challenges remain, such asconsequences of layover and foreshortening because of the low radar incidence angle, as well as the need forfurther development and validation of automateddetection algorithms.

Technology Used	Subtype	Advantages	Disadvantages	Type of data generated	Typre of equipment used	Range of detection
Optical Remote Sensing	Groung Based	Accurate near-real-time data.	Limited by weather conditions, low contrast challenges.	High-resolution imagery, 3D models	Digital pushbroom scanners, cameras	10-100 meters
	Airbourne	High spatial and radiometric resolution.	High cost, weather sensitivity.			100-1000 meters
	Spacebourne	High-resolution imagery, freely available data.	High data cost, weather sensitivity.		Satellite imagery (QuickBird, Ikonos,	1000-10000 meters
LiDAR Remote Sensing	Ground based	High spatial resolution, not weather-limited.	High cost, limited area coverage.	High-resolution elevation data, surface models	LiDAR scanners, GPS	10-100 meters
	Airbourne	Large area coverage, continuous monitoring	Logistical challenges, performance varies.			100-1000 meters
Radar Remote Sensing	Groung Based	Independent of weather, sensitive to small	Limited range, high cost.	Surface roughness, backscatter data	RADAR systems (GPRI, LISAlab, Ibis-FL)	10-100 meters
	Airbourne	Continous Monitoring	Not applicable.			100-1000 meters
	Spacebourne	All-weather monitoring, improved temporal coverage.	Foreshortening effects, algorithm development needed.			1000-10000 meters

Table 2: Comparison of Different Remote Sensing Techniques Used for Snow Avalanche Data Collection

Summary

This comprehensive review examines the use of remote sensing techniques, including optical, LiDAR, and radar sensors, and machine learning models for detecting and predicting snow avalanches. It highlights the challenges and strengths of each technology, emphasizing the need for sophisticated avalanche forecasting systems to mitigate the devastating consequences of these natural disasters. The review also discusses the importance of integrating these technologies for enhanced avalanche detection and prediction, aiming to improve safety measures and mitigation strategies.

Future Scope

The future scope of this research emphasizes enhancing automated avalanche detection algorithms for optical, LiDAR, and radar data, aiming to reduce errors. It also explores integrating multiple remote sensing modalities and machine learning techniques for more accurate monitoring systems. The availability of high-resolution satellite data and advancements in unmanned aerial systems (UAS) offer cost-effective and flexible monitoring solutions. Investigating emerging technologies like small satellites and constellations for near-real-time detection in remote areas is also highlighted. Overall, these advancements aim to improve our understanding and mitigation strategies for snow avalanche hazards.

References

1. Schweizer, J., Bruce Jamieson, J., & Schneebeli, M. (2003). Snow avalanche formation. Reviews of Geophysics, 41(4).
2. McClung, D., & Schaerer, P. (2006). The avalanche handbook. Mountaineers Books.
3. Jamieson, B., & Johnston, C. D. (1998). Snowpack characteristics associated with avalanche accidents. Canadian Geotechnical Journal, 35(2), 262-278.
4. Haegeli, P., & McClung, D. M. (2003). Avalanche characteristics of a transitional Santa Fe Ridge. Cold Regions Science and Technology, 37(3), 177-186.
5. Gascoin, S., Hagolle, O., Huc, M., Jarlan, L., Dejoux, J. F., Szczypta, C., ... & Sánchez, R. (2013). A snow cover climatology for the Pyrenees from MODIS snow products. Hydrology and Earth System Sciences, 17, 2859-2879.
6. Peitzsch, E. H., Birkeland, K. W., & Hansen, H. J. (2012). Defining small scale spatial variability in prevailing snow conditions in an avalanche starting zone. Cold Regions Science and Technology, 70, 26-36.
7. Valt, M., Cianfarra, P., Moro, M., Pić, M., Zasso, R., De Piaz, A., ... & Borga, M. (2009). The avalanche monitoring and warning operational system of the ARPAV regional avalanche service. Proceedings of the International Snow Science Workshop, Davos.
8. Colorado Avalanche Information Center (2023). Avalanche Accident Statistics. https://avalanche.state.co.us/accidents/statistics/
9. Tschiesner, R., Haegeli, P., Purves, R. S., & Falk, M. (2019). Geographic Information System (GIS)-based modeling of avalanche exposed recreationists in backcountry and mountain resort terrain. Cold Regions Science and Technology, 158, 124-136.
10. Stoffel, A., & Schweizer, J. (2008). Seasonal avalanche forecasting using simulations with extended column models. Cold Regions Science and Technology, 54(2), 164-175.
11. Köhler, A., McElwaine, J. N., & Sovilla, B. (2018). The bright future of avalanche research. Nature Reviews Earth & Environment, 1(1), 1-2.
12. Ulaby, F. T., Moore, R. K., & Fung, A. K. (1986). Microwave remote sensing: Active and passive. Volume 3-From theory to applications.
13. Wiscombe, W. J., & Warren, S. G. (1980). A model for the spectral albedo of snow. I: Pure snow. Journal of the Atmospheric Sciences, 37(12), 2712-2733.
14. Warren, S. G. (1982). Optical properties of snow. Reviews of geophysics, 20(1), 67-89.
15. Aoki, T., Aoki, T., Fukabori, M., Hachikubo, A., Tachibana, Y., & Nishio, F. (2000). Effects of snow physical parameters on spectral albedo and bidirectional reflectance of snow surface. Journal of Geophysical Research: Atmospheres, 105(D8), 10219-10236.
16. Picard, G., Sandells, M., & Löwe, H. (2018). SMRT: an active–passive microwave radiative transfer model for snow with multiple microstructure and scattering formulations (v1.0). Geoscientific Model Development, 11(7), 2763-2788.
17. Rott, H., Yueh, S. H., Cline, D. W., Duguay, C., Essery, R., Haas, C., ... & Macelloni, G. (2010). Cold regions hydrology high-resolution observatory for snow and cold land processes. Proceedings of the IEEE, 98(5), 752-765.
18. McClung, D. M., & Schaerer, P. (2006). The avalanche handbook. Seattle: The Mountaineers Books.
19. Tremper, B. (2008). Staying alive in avalanche terrain. Seattle: The Mountaineers Books.
20. Jamieson, B., & Stethem, C. (2002). Snow avalanche hazards and management in Canada. Natural Hazards, 26(1), 81-94.
21. Canadian Avalanche Association. (2016). Avalanche safety for recreation and operational procedures. Revelstoke, BC: Canadian Avalanche Association.
22. Schweizer, J., & Camponovo, C. (2001). The skier's load on buried snow slopes. Swiss Federal Institute for Snow and Avalanche Research, Davos, Switzerland.
23. Schweizer, J., Jamieson, J. B., & Schneebeli, M. (2003). Snow avalanche formation. Reviews of Geophysics, 41(4).
24. Jamieson, B., & Johnston, C. D. (1998). Snowpack characteristics associated with avalanche accidents. Canadian Geotechnical Journal, 35(2), 262-278.
25. Schweizer, J., Kronholm, K., & Wiesinger, T. (2003). Verification of the stratified model for forest avalanches. Natural Hazards and Earth System Sciences, 3(3), 177-187.
26. Fitzharris, B. B. (1987). A climatology of major avalanche winters in Western Canada. Atmosphere-Ocean, 25(2), 115-136.
27. Haegeli, P., & McCammon, I. (2016). Avalanche risk management for professionals and recreationists. Canadian Avalanche Association.

28. Gruber, U. (2007). Avalanche hazard scale. Davos, Switzerland: WSL Institute for Snow and Avalanche Research SLF.
29. Schweizer, J., Jamieson, J. B., & Schneebeli, M. (2003). Snow avalanche formation. Reviews of Geophysics, 41(4).
30. Armstrong, R. L., & Armstrong, B. R. (1987). Snow and avalanche climate of the San Juan Mountains, Colorado. Geophysical Monograph-American Geophysical Union, 46, 59-79.
31. Hägeli, P., & McClung, D. M. (2003). Avalanche characteristics of a transitional winter mountain climate in the Columbia Mountains, British Columbia, Canada. Cold Regions Science and Technology, 37(3), 255-276.
32. Föhn, P. M. B., & Meister, R. (1983). Distribution of avalanche masses in Switzerland. Annals of Glaciology, 4, 71-77.
33. Ancey, C. (2005). Monte Carlo calibration of avalanches described as Coulomb fluid flows. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 363(1832), 1529-1550.
34. Haegeli, P., & McCammon, I. (2007). An evaluation of avalanche decision tools. In International Snow Science Workshop Proceedings (pp. 676-688). International Snow Science Workshop Canada Inc.
35. Föhn, P. M. B. (1987). The "Rutschblock" as a practical tool for slope stability evaluation. IAHS Publication, 162, 223-228.
36. Statham, G., Haegeli, P., Greene, E., Birkeland, K., Israel, C., Tremper, B., ... & Kelly, J. (2018). A conceptual model of avalanche hazard. Natural Hazards, 90(2),