Characteristics and Hazards of Different Snow Avalanche Types in a Continental Snow Climate Region in the Central Tianshan Mountains (Postprint)

Authors: HAO Jiansheng, Richard MIND' JE, LIU Yang, HUANG Farong, ZHOU Hao, Lanhai Li, LI Lanhai

Date: 2021-04-30T00:00:00+00:00

Abstract

Snow avalanches are a common natural hazard in many countries with seasonally snow-covered mountains. The avalanche hazard varies with snow avalanche type in different snow climate regions and at different times. The ability to understand the characteristics of avalanche activity and hazards of different snow avalanche types is a prerequisite for improving avalanche disaster management in the mid-altitude region of the Central Tianshan Mountains. In this study, we collected data related to avalanche, snowpack, and meteorology during four snow seasons (from 2015 to 2019), and analysed the characteristics and hazards of different types of avalanches. The snow climate of the mid-altitude region of the Central Tianshan Mountains was examined using a snow climate classification scheme, and the results showed that the mountain range has a continental snow climate. To quantify the hazards of different types of avalanches and describe their situation over time in the continental snow climate region, this study used the avalanche hazard degree to assess the hazards of four types of avalanches, i.e., full-depth dry snow avalanches, full-depth wet snow avalanches, surface-layer dry snow avalanches, and surface-layer wet snow avalanches. The results indicated that surface-layer dry snow avalanches were characterized by large sizes and high release frequencies, which made them having the highest avalanche hazard degree in the Central Tianshan Mountains with a continental snow climate. The overall avalanche hazard showed a single peak pattern over time during the snow season, and the greatest hazard occurred in the second half of February when the snowpack was deep and the temperature increased. This study can help the disaster and emergency management departments rationally arrange avalanche relief resources and develop avalanche prevention strategies.

Full Text

1 Introduction

Avalanches pose serious threats to communities, transportation corridors, transmission and communication lines, and pipelines, significantly impeding sustainable development in mountainous regions (Wastl et al., 2011; Schweizer et al., 2021). Asian alpine countries experience catastrophic avalanche events annually. For instance, a regional snow avalanche in Kashmir on 14–16 January 2020 claimed over 160 lives; a snow avalanche in southern Kazakhstan on 17 February 2017 killed more than seven people; and a regional snow avalanche in Bishkek, Kyrgyzstan, on 29 March 2017 paralyzed transport networks and caused four fatalities. Consequently, avalanche disaster prevention and management are critically important in these countries due to substantial economic losses and numerous deaths (Ganju and Dimri, 2004; Hao et al., 2018). As Central Asia' s largest mountain system, the Tianshan Mountains experience abundant snowfall during the cold season due to westerly circulation and distinctive topography, leading to active avalanche activity with frequent disasters (Ma and Hu, 1990; Hu et al., 1992; Zhang et al., 2019). Snow avalanches are well-documented and have been studied extensively in the Central Tianshan Mountains, particularly in the mid-altitude Kunes Valley, where decades of observations have revealed the conditions governing avalanche release (Ma and Hu, 1990; Hu et al., 1992; Hao et al., 2018).

Along the Kunes River Valley, numerous avalanches are reported each winter by local transport authorities because they disrupt traffic on major transportation corridors crossing the Tianshan Mountains (Hao et al., 2018). Although several studies have investigated snow avalanche activity distribution in the central Tianshan Mountains (Hu et al., 1992; Hao et al., 2018; Yang et al., 2020), avalanche prevention strategies remain underdeveloped due to insufficient hazard assessments. Avalanche hazard assessments are essential for effective disaster prevention and management (Wastl et al., 2011; Schweizer et al., 2020). Implementing appropriate measures based on hazard severity is the primary objective in critical situations, and understanding avalanche activity characteristics under specific snow climate conditions is a prerequisite for developing and improving hazard assessments and evaluating potential climate change impacts on avalanche activity and types (Shandro and Haegeli, 2018).

Avalanche formation and release depend on multiple factors, including climate, topography, and snow cover characteristics (Schweizer et al., 2003; Guy and Birkeland, 2013; Mitterer and Schweizer, 2013; Valero et al., 2018). Avalanche release mechanisms vary considerably, and different avalanche types have distinct formation mechanisms due to variations in snowpack stratigraphy, soil temperature and moisture, and regional weather patterns (van Herwijnen and Jamieson, 2007; Ceaglio et al., 2017; Köhler et al., 2018; Shandro and Haegeli, 2018). Previous research has investigated the formation of different snow avalanche types (Clarke and McClung, 1999; Ancey and Bain, 2015;

Schweizer et al., 2021). Studies classify avalanches as full-depth or surface-layer based on failure layer position (Clarke and McClung, 1999; Bartelt et al., 2012; Schweizer et al., 2021). Full-depth avalanches originate from failure at the snow-soil interface when wet conditions reduce basal friction (Höller, 2014; Ancey and Bain, 2015). The snow-soil interface becomes wet due to three primary mechanisms: warm ground temperatures stored before the snow season melt the lowermost snow layer (Höller, 2014; Ceaglio et al., 2017); strong hydraulic pressure gradients move free water from soil into the bottom snow layer (Ceaglio et al., 2017; Maggioni et al., 2019); and meltwater or rain percolates from the snow surface to the snow-soil interface (Conway and Raymond, 1993; Peitzsch et al., 2012; Höller, 2014).

Surface-layer avalanche formation and influencing factors have been examined by McClung (1981) and reviewed by Schweizer et al. (2003), who concluded that surface-layer avalanches typically release due to weak layer failure within the snowpack and crack propagation within that weak layer. Extra loading from snowfall, earthquakes, explosions, and skiing can trigger weak layer failure and crack propagation (McClung, 2013; McClung and Borstad, 2019; Parshad et al., 2019). An avalanche can be described as a falling mass of snow that may contain ice, rock, and/or soil (Ancey and Bain, 2015; Schweizer et al., 2021). Based on snow characteristics at release, avalanches are divided into wet and dry avalanches, which have significantly different formation mechanisms (Schweizer et al., 2021). Dry avalanche release mechanisms have been summarized in previous reviews (Schweizer et al., 2003; Birkeland et al., 2019; McClung and Borstad, 2019), concluding that dry snow slab avalanches release due to overloading of existing snowpack weaknesses, naturally initiating during or shortly after snowstorms. Wet snow avalanche formation originates from liquid water percolation within the snow cover (Ancey and Bain, 2015; Valero et al., 2018; Abermann et al., 2019), with volumetric liquid water content, air temperature, and shortwave radiation serving as critical predictive parameters (Mitterer and Schweizer, 2013; Ancey and Bain, 2015).

Avalanche characteristics vary significantly due to snowpack, soil, and weather conditions (Schweizer et al., 2021). Avalanche hazard is defined by frequency, release mechanism, type, and size (Schweizer et al., 2020). Consequently, spatial and temporal avalanche hazards differ substantially across snow climate regions and evolve over time. Regional avalanche hazard assessments inform land-use planning and disaster management. Spatial hazard assessment considers formation factors such as terrain, elevation, and snow depth (Choubin et al., 2019; Schweizer et al., 2020). Wastl et al. (2011) assessed avalanche hazards and identified high-risk areas based on historical data, prioritizing them for detailed investigation and protective measure planning. Avalanches can recur along the same paths, with types varying throughout a snow season due to evolving snowpack, soil, and meteorological properties (Laute and Beylich, 2014; Ceaglio et al., 2017; Statham et al., 2018), causing different avalanche types to prevail at different times. Spatial avalanche hazard represents the superposition of hazards from different types, making avalanche hazard dynamic over time in specific areas. Limited understanding of temporal variability in avalanche type and hazard level complicates timely implementation of appropriate management measures. Climate change alters avalanche type and frequency in some regions, increasing hazard uncertainty (Castebrunet et al., 2014). Understanding temporal variation in regional avalanche hazards and influencing factors is essential for improving management and assessing climate change impacts. Although literature provides good spatial hazard assessment overviews, temporal distribution characteristics and the changing climate, snowpack, and soil properties affecting hazards in specific snow climate regions are not fully understood due to lack of quantitative temporal assessment methods.

To address these gaps, this study demonstrates an approach for assessing avalanche hazards and understanding their temporal distribution and influencing factors during a snow season. We collected avalanche, meteorological, and snowpack data during four snow seasons (2015–2016, 2016–2017, 2017–2018, and 2018–2019) in the Central Tianshan Mountains to ensure appropriate data sources. We analyzed characteristics of different snow avalanche types, identified hazards during snow seasons, and presented, interpreted, and discussed factors favoring different avalanche type formation and their hazard impacts.

2.1 Study Area

We investigated avalanches along National Road 218 (G218) in the Kunes River Valley of the Central Tianshan Mountains. The G218 is a critical national traffic route connecting eastern and western Xinjiang Uygur Autonomous Region and passes through the Tianshan Mountains, experiencing avalanche events in winter and spring. Most road sections are exposed to snow avalanche hazards. Although protective infrastructure (ditches, small retaining walls) exists, it is insufficient to stop avalanches. These structures rapidly fill with snow, allowing avalanches to reach the road at many locations. Severe avalanche hazards cause annual traffic accidents and casualties in this region. South-facing slopes consist mainly of steep meadows interrupted by open and closed forests, shrubs, and rocky areas—terrain favorable for avalanche development. The average slope angle in avalanche starting zones is 37.2°, with two-thirds of avalanches occurring on slopes between 36.0° and 42.0° (Hao et al., 2018). Avalanche paths in the Kunes River Valley were identified and described in detail by Yang et al. (2020). The Tianshan Station for Snow Cover and Avalanche Research, Chinese Academy of Sciences (TSSAR; 43°16 N, 84°24 E) was established to monitor avalanches and snow cover in this area. The TSSAR is located in the Central Tianshan Mountains at 1776 m a.s.l., adjacent to the G218 [Figure 1: see original paper].

Based on TSSAR observations, annual precipitation totals approximately 870 mm, with 30%–40% falling as snow during the snow season (November to March). Snowpack temperature approaches 0°C during March, and snowmelt often begins in early March, creating moist or wet snowpack. Average snow depth at the station is 78 cm, with a maximum of approximately 160 cm in the cold season, based on 2000–2001 data. Snowpack is characterized by low density, high temperature gradients, and high proportions of depth hoar (Wei et al., 2001; Hao et al., 2018). Persistent weak layers composed of depth hoar are considered the primary cause of frequent avalanche releases during the winter season (December to February) (Ma and Hu, 1990; Hu et al., 1992; Hao et al., 2018).

2.2 Meteorological and Snowpack Data

Meteorological data were collected automatically and hourly by an automatic weather station at TSSAR [Figure 1: see original paper], including precipitation, snow depth, air temperature, humidity, wind speed, and shortwave radiation (upward and downward). The station was established near an avalanche zone [Figure 1: see original paper]. Due to mechanical equipment failures and other factors causing incomplete snow depth and air temperature data, manual recordings were used to correct and fill gaps. Manual weather stations were set up in a safe zone with low avalanche danger, 20 m from the automatic weather station [Figure 1: see original paper]. Snow pit observations were conducted according to Fierz et al. (2009) at a snowpack observation field near the weather stations to determine physical properties representative of the study area. A 100 cm^3 box-cutter sampler (6.0 cm $\times$ 5.5 cm $\times$ 3.0 cm) with a weighing scale (http://snowmetrics.com/shop/prosnow-kit-i/) measured snow density, while a snow fork measured liquid water content (Techel and Pielmeier, 2011).

2.3 Record of Snow Avalanches

Avalanche data were collected by field teams from the Narat Highway Administration, Transport Department of Xinjiang Uygur Autonomous Region, China, and TSSAR. Teams sampled avalanches at the worst-affected G218 sections during four snow seasons (2015–2016, 2016–2017, 2017–2018, and 2018–2019). Approximately 20 avalanche-prone sites accounted for 6 km of road length [Figure 1: see original paper]. During daily patrols, observers recorded avalanche date, location, type, scale, destruction caused, and deposit characteristics including density, liquid water content, and composition .

Snow was classified as wet or dry based on avalanche deposit liquid water content measured by snow fork and estimated using quantitative empirical criteria from Fierz et al. (2009). Wet snow is defined as having volumetric liquid water content greater than 3%, characterized by recognizable water menisci between grains at 10$\times$ magnification (Fierz et al., 2009; Techel and Pielmeier, 2011). Considering snow characteristics and failure layer position, avalanches were classified into four categories: full-depth dry snow avalanche (FDA), full-depth wet snow avalanche (FWA), surface-layer dry snow avalanche (SDA), and surface-layer wet snow avalanche (SWA). Observers were trained to discriminate these types based on failure layer position and snow/deposit characteristics.

Because avalanche deposits block roads and entering release zones is difficult and dangerous, this study focused on measuring deposit parameters on roads to assess hazards. The deposit accumulation body on roads is typically semi-elliptical, with volume (V, m^3) calculated by:

$$V = \frac{\pi}{6} \times W \times H \times L \tag{1}$$

where W (m), H (m), and L (m) are width, height, and length of the deposit body, respectively. A 3-m snow ruler and laser rangefinder measured these dimensions [Figure 1: see original paper]. A 100 cm^3 sampler estimated deposit density at different depths, which were then averaged. Avalanche deposit mass was obtained by multiplying volume by average density. A total of 138 avalanches were recorded during the four snow seasons. Because deposits must be cleared quickly to maintain road access, all parameters were measured for 54 avalanches; for others, only time, location, and type were recorded.

2.4 Methods

Snow climate classification extensively describes general snowpack conditions in mountain ranges, providing useful background for expected avalanche activities (Mock and Birkeland, 2000; Haegeli and McClung, 2007; Shandro and Haegeli, 2018). Snow climate is divided into three categories: maritime, transitional, and continental. The classification scheme uses mean air temperature, total rainfall, total snowfall, total snow water equivalent, and average December snowpack temperature gradient during the snow season (1 December to 31 March) to define local snow climate (Mock and Birkeland, 2000).

Avalanches with large-volume and high-mass deposits cause greater damage to infrastructure and vehicles than those with small volumes. Different avalanches exhibit significantly different destructive power due to volume and mass differences. To quantitatively describe damage potential, we defined the Avalanche Damage Index (ADI), where higher values indicate greater damage to infrastructure and vehicles. The ADI for individual avalanches and for specific avalanche types is calculated using:

$$\mathrm{ADI}_k = \frac{M_k - M_{\min}}{M_{\max} - M_{\min}} \quad (k = 1, 2, \dots, n) \tag{2}$$

$$\mathrm{ADI}_i = \frac{\sum_{k=1}^{n_1} \mathrm{ADI}_k}{n_1} \quad (i = 1, 2, \dots, m) \tag{3}$$

where ADI_k is the damage index of the kth avalanche in a dataset of n avalanches; M_k is the mass of deposits from the kth avalanche; ADI_i is the damage index of the ith avalanche type among m types; and n_1 is the sample number of the ith avalanche type.

Different avalanche types occur at different times with varying frequencies. The Avalanche Activity Index (AAI) quantitatively describes frequency of different avalanche types in specific time intervals:

$$\mathrm{AAI}_{ij} = \frac{N_{ij}}{\sum_{j=1}^{p} N_{ij}} \quad (i = 1, 2, \dots, m;\ j = 1, 2, \dots, p) \tag{4}$$

where AAI_{ij} is the activity index of the ith avalanche type in the jth time interval (with the snow season divided into p intervals), and N_{ij} is the total number of the ith avalanche type in the jth interval. This study used half-month intervals.

Avalanche hazard degree is a numeric expression of avalanche damage in a given time, determined by multiplying the activity index and damage index:

$$\mathrm{AHD}_{ij} = \mathrm{AAI}_{ij} \times \mathrm{ADI}_{i} \tag{5}$$

$$\mathrm{AHD}_{j} = \sum_{i=1}^{m} \mathrm{AHD}_{ij} \tag{6}$$

where AHD_{ij} is the hazard degree of the ith avalanche type in the jth interval, and AHD_j is the overall avalanche hazard degree in the jth interval.

3.1 Characteristics of Different Types of Avalanche Deposits

Snow climate analysis using the classification scheme revealed that the study area has a typical continental snow climate across the four snow seasons (2015-2019). Deposit characteristics are shown in [Figure 2: see original paper]. FDA deposits on roads averaged 300–380 kg/m^3 density [Figure 2a: see original paper]. Based on measurements of 10 FDA deposits during 2015-2019, average volume was 137 m^3 and average weight was 46.2 t (sample size = 9). FDA deposits had the smallest volume and mass among all types, with a significantly lower damage index than other avalanches in this mid-altitude continental snow climate region [Figure 2d: see original paper].

SDAs release through failure within the snowpack and crack propagation in snow layers. SDA deposits were powdery snow with 280-340 kg/m^3 density and 0.5-3.0 mm grain size. SDA deposit volumes varied greatly, but averaged 335 m^3 (sample size = 20), the largest among all avalanche types [Figure 2b: see original paper]. Despite having the lowest density, SDA deposits' large volume yielded the greatest average mass (approximately 113.0 t), resulting in the highest damage index. During SDA release, snow particles collided and became airborne, creating powder clouds and powerful airwaves that severely damaged trees, houses, and road infrastructure.

SWAs consist of snow with liquid water content exceeding 3%. SWA deposit density was 410–490 kg/m^3 (sample size = 13), second only to FWAs [Figure 2a: see original paper]. SWA deposit volume and mass were lower than SDA and FWA deposits [FIGURE:2b,c]. FWA deposits appeared as lumpy soil-snow mixtures with 560-690 kg/m^3 density and >3% liquid water content. Numerous snowballs were observed on hillsides before FWA release. Avalanche volume increased during descent, carrying melted soil and creating multi-layered deposits with tan outer soil layers and white inner snow layers averaging 20–30 cm diameter, with 5–10 cm snow cores. FWA deposits had relatively small volume (167 m^3 average) but the highest density, yielding relatively large mass (104.0 t, sample size = 12). High water content, large density, and entrainment of soil, sand, and stone made FWAs highly destructive to vehicles and pedestrians. Due to significant differences in deposit density and volume, avalanche mass and damage ranked as: SDA > FWA > SWA > FDA [Figure 2d: see original paper].

3.2 Occurrence Time of Different Types of Avalanches

Snow seasons were defined as November to March due to consistent snowfall patterns [Figure 3: see original paper]. Temperatures continuously declined below 0°C and snow depth increased sharply in early season (November–December) [Figure 4: see original paper]. Mid-season (January–February) brought the lowest temperatures, slow snow depth increases, and minimal snowpack water content. Late season (March) saw temperatures transition above 0°C, snowmelt causing rapid depth reduction, and peak snow density and water content.

A total of 138 avalanches were recorded during the four snow seasons (2015–2019), comprising 34 FDAs, 50 SDAs, 26 SWAs, and 28 FWAs. Avalanches occurred throughout the snow season, with 48% in late February and early March. FDAs predominated in early season, peaking in early December [Figure 5a: see original paper]. FWAs occurred mainly in late season, most active in early March. SDAs dominated mid-season, with February being most active. SWAs occurred during the transition from mid to late season (late February and early March) [Figure 5a: see original paper]. February and March were the most active avalanche months, with type activity sequence: FDA > SDA > SWA > FWA [Figure 5b: see original paper].

3.3 Hazard of Different Snow Avalanche Types

Avalanche hazard degree ranked from highest to lowest as SDA, FWA, SWA, and FDA [Figure 6a: see original paper]. FDAs were relatively active in early season but had low hazard degree [Figure 6a: see original paper]. Maximum FDA hazard occurred in early December (approximately 0.14). FWA hazards concentrated in March, peaking at approximately 0.35. SDA hazard increased gradually in mid-season, reaching highest values in late February—approximately four times the FDA maximum. SDAs posed the highest hazard among all types

[Figure 6a: see original paper]. Overall avalanche hazard showed a single-peak temporal pattern, increasing significantly from late January, peaking in late February, then decreasing [Figure 6b: see original paper].

4.1 Comparison of Different Types of Avalanches

Previous studies divided avalanches into full-depth or surface-layer types based on failure layer position (Clarke and McClung, 1999; Bartelt et al., 2012; Schweizer et al., 2021). Full-depth avalanches (FDAs and FWAs), which mobilize the entire snowpack to ground level, occurred primarily at season beginnings and ends [Figure 5: see original paper], consistent with Northern Hemisphere observations (Ma and Hu, 1990; Clarke and McClung, 1999; Dreier et al., 2016; Maggioni et al., 2019). Surface-layer avalanches (SDAs and SWAs) dominated mid-season and the mid-to-late season transition [Figure 5: see original paper]. Full-depth avalanches originate from snow-soil interface failure (Clarke and McClung, 1999; Bartelt et al., 2012; Ancey and Bain, 2015). Höller (2014), Dreier et al. (2016), and Ceaglio et al. (2017) confirmed that wetting reduces snow-soil interface friction, causing failure. From early to mid-season, declining temperatures gradually froze soil and the snow-soil interface, increasing friction and reducing FDAs [Figure 5: see original paper]. From mid to late season, rising temperatures melted surface snow, with water percolation reducing snow-soil friction and increasing FWAs. Surface-layer avalanches originate from weak layer failure and rapid crack expansion (Schweizer et al., 2003; Gauthier et al., 2010; Reiweger and Schweizer, 2013; Gaume et al., 2018). Weak layer failure beneath cohesive slabs is necessary for surface-layer release. Depth hoar weak layers persist in mid-season in this region (Ma and Hu, 1990; Hu et al., 1992; Hao et al., 2018), causing surface-layer avalanches during this period [Figure 4: see original paper]. Thus, full-depth avalanches dominate early and late season, while surface-layer avalanches prevail in mid-season due to evolving snowpack, soil, and weather conditions.

Full-depth avalanches with different snow characteristics showed distinct timing and mechanisms. Pressure differences between snow and soil allow bottom snow layers to absorb soil water, increasing water content and reducing snow-soil interface friction (Dreier et al., 2016; Ceaglio et al., 2017; Maggioni et al., 2019). Increased bottom snow water content from geothermal heat and soil water transport decreased interface friction, triggering FDAs in early season. With average temperatures below 0°C and low snowpack water content [Figure 4: see original paper], FDAs were common in early season. Due to minimal snow development and compression, early-season snow density was lowest, resulting in low FDA deposit mass and relatively low damage. FDAs typically occurred 1–3 days after snowfall during periods of intense solar radiation.

At season end, water infiltration from melting surface snow under high temperature and radiation reduced snow-soil friction, causing full-depth avalanches (Mitterer and Schweizer, 2013; Dreier et al., 2016; Ceaglio et al., 2017). Snow cover density and water content reached seasonal maxima due to melting, producing FWAs in late season [Figure 5b: see original paper]. FWAs coincided with sharp temperature increases, as observed elsewhere (Peitzsch et al., 2012; Dreier et al., 2016; Wever et al., 2016). Compared to FDAs, FWAs occurred after significant snow settlement, depth reduction, and temperature increases. High late-season snow density and water content, combined with soil entrainment, gave FWAs relatively high hazard and difficult-to-clear deposits.

Mid-season temperatures below 0°C [Figure 4: see original paper] and snowpack water content below 3% produced SDAs. SDAs were typically triggered by heavy snowfall, with strong winds increasing weak layer shear stress and destabilizing slopes (Schweizer et al., 2003). Although SDA deposits consisted of low-density new and surface snow, most occurred during or immediately after storms when slope snow storage was maximal, creating the largest deposit volumes and masses and highest hazards. When maximum air temperature exceeded 0°C during the mid-to-late season transition, surface melting increased snow water content and density. Weak layer shear strength decreased due to meltwater infiltration, destabilizing slope snow and triggering SWAs (Mitterer and Schweizer, 2013). SWAs were often triggered by sharp temperature rises and intense solar radiation. Some SWAs stopped near their origin as starving avalanches rather than reaching valley bottoms (Bartelt et al., 2012), with deposits causing shear failure in surrounding weak layers (Bartelt et al., 2012; Ancey and Bain, 2015). As temperatures continued rising, more free water seeped through shear cracks, reducing slope stability and potentially causing more damaging avalanches. The period from crack opening to SWA release varied from hours to days, making SWAs dangerous and difficult to predict.

4.2 Hazards of Snow Avalanches and Influencing Factors

Avalanche hazard is determined by damage degree and activity degree, with high values in both creating high hazard levels (Barbolini et al., 2002; Schweizer et al., 2020). Snowpack, soil characteristics, and weather conditions determine avalanche damage and activity (Dreier et al., 2016; Ceaglio et al., 2017). Different avalanche types exhibited significant differences in these conditions, causing substantial hazard variations. As snowpack, soil, and air temperature evolved throughout the snow season, hazards of different avalanche types fluctuated temporally with distinct patterns [Figure 6a: see original paper].

FDAs were relatively active in early season but had low hazard due to low density and shallow snowpack. As depth hoar developed and the snow-soil interface froze, FDAs diminished and SDA hazards increased in mid-season. Snow depth peaked in late February [Figure 3: see original paper], when SDA hazard was highest—approximately four times the FDA maximum. Rising temperatures after late February increased FWA hazard through snowmelt infiltration. After March, weak layer disappearance and reduced snow-soil interface friction made FWAs dominant. Despite March having the highest snowpack density and water content, FWA hazard was slightly lower than SDA hazard due to reduced snow depth during FWA release. Overall avalanche hazard showed a single-peak temporal pattern, peaking in late February. Deep snowpack in late February created large avalanche volumes and masses, while low slope stability during heavy snowfall, earthquakes, and strong winds triggered high release frequency [Figure 5: see original paper], making late February the most hazardous period requiring enhanced prevention efforts.

Snowpack, soil, and climate characteristics vary temporally under different snow climate conditions (Mock and Birkeland, 2000; Wei et al., 2001; Shandro and Haegeli, 2018), creating different temporal hazard patterns across regions. The Coast Mountains in Canada (Haegeli and McClung, 2007), Cascades and Sierra Nevada in the USA (Mock and Birkeland, 2000), and Japanese seaside mountains (Ikeda et al., 2009) have maritime snow climates with warmer temperatures, higher snowpack density and water content, and few persistent weak layers. The Columbia Mountains in Canada (Haegeli and McClung, 2007) and most European Alps (Rudolf-Miklau et al., 2015) have transitional snow climates with persistent weak layers lasting several weeks. The Central Tianshan Mountains have a continental snow climate with colder temperatures and thinner snowpack conducive to persistent weak layers lasting several months. Lower total snowfall, density, and water content in continental snow climate regions result in lower avalanche damage degrees compared to maritime and transitional regions. Consequently, Central Tianshan avalanche damage is lower than in the Coast and Columbia Mountains (Canada), Japanese seaside mountains, and European Alps. However, persistent weak layer duration is longer in continental snow climate regions (Mock and Birkeland, 2000; Shandro and Haegeli, 2018), yielding higher surface-layer avalanche activity. Therefore, surface avalanches pose greater relative hazards in the Central Tianshan's continental snow climate than in maritime or transitional climate mountains.

5 Conclusions

Understanding temporal characteristics and hazards of different avalanche types during snow seasons helps disaster management agencies allocate resources rationally and develop prevention strategies. This study presented a new approach to quantify avalanche frequency and damage degree for describing overall seasonal hazard. We analyzed a unique dataset of visually observed avalanche records from four snow seasons (2015–2019) near TSSAR, comparing characteristics and hazards across avalanche types. Results showed SDAs occurred in mid-season when persistent weak layers existed, primarily triggered by heavy snowfall and strong winds. SDA deposits had the largest volume and mass, creating the highest hazard—approximately four times greater than the lowest-hazard FDAs. FWAs occurred in late season due to rapid temperature increases, with deposits having the highest density and liquid water content, making their hazard second only to SDAs. Snowpack, soil, and weather conditions favorable for different avalanche formations created hazard ranking: SDA > FWA > SWA > FDA.

As snowpack, soil, and air temperature evolved during snow seasons, hazards of different avalanche types fluctuated, causing temporal variation in overall hazard. Avalanche hazard showed single-peak temporal fluctuation, peaking in late February when snow depth was greatest and temperatures rose. Prevention efforts should be strengthened during this period. Climate variation alters regional snowpack and climate characteristics, affecting temporal activity of different avalanche types and changing hazard patterns. This will complicate avalanche risk control. Assessing climate change impacts on regional avalanche risks over time will be our next research step.

Acknowledgements

This work was supported by the Open Project of the Xinjiang Uygur Autonomous Region Key Laboratory (2017D04010). The authors thank Dr. LI Linxi from Ontario Veterinary Medical Association for linguistic assistance. We are grateful to TSSAR for field and laboratory support and to the Narat Highway Administration, Transport Department of Xinjiang Uygur Autonomous Region, China for data collection assistance.

References

Abermann J, Eckerstorfer M, Malnes E, et al. 2019. A large wet snow avalanche cycle in West Greenland quantified using remote sensing and in situ observations. Natural Hazards, 97(3): 517-534.

Ancey C, Bain V. 2015. Dynamics of glide avalanches and snow gliding. Reviews of Geophysics, 53(3): 745-784.

Barbolini M, Natale L, Savi F. 2002. Effects of release conditions uncertainty on avalanche hazard mapping. Natural Hazards, 25(3): 225-244.

Bartelt P, Feistl T, Bühler Y, et al. 2012. Overcoming the stauchwall: Viscoelastic stress redistribution and the start of full-depth gliding snow avalanches. Geophysical Research Letters, 39(16): L16501, doi: 10.1029/2012GL052479.

Birkeland K W, van Herwijnen A, Reuter B, et al. 2019. Temporal changes in the mechanical properties of snow related to crack propagation after loading. Cold Regions Science and Technology, 159: 142-152.

Castebrunet H, Eckert N, Giraud G, et al. 2014. Projected changes of snow conditions and avalanche activity in a warming climate: The French Alps over the 2020-2050 and 2070-2100 periods. The Cryosphere, 8(5): 1673-1697.

Ceaglio E, Mitterer C, Maggioni M, et al. 2017. The role of soil volumetric liquid water content during snow gliding processes. Cold Regions Science and Technology, 136: 17-29.

Choubin B, Borji M, Mosavi A, et al. 2019. Snow avalanche hazard prediction using machine learning methods. Journal of Hydrology, 577: 123929, doi: 10.1016/j.jhydrol.2019.123929.

Clarke J, McClung D. 1999. Full-depth avalanche occurrences caused by snow gliding, Coquihalla, British Columbia, Canada. Journal of Glaciology, 45: 539-546.

Conway H, Raymond C F. 1993. Snow stability during rain. Journal of Glaciology, 39: 635-642.

Dreier L, Harvey S, van Herwijnen A, et al. 2016. Relating meteorological parameters to glide-snow avalanche activity. Cold Regions Science and Technology, 128: 57-68.

Fierz C, Armstrong R, Durand Y, et al. 2009. The international classification for seasonal snow on the ground. (UNESCO, IHP (International Hydrological Programme)-VII, Technical Documents in Hydrology, No. 83, IACS (International Association of Cryospheric Sciences) contribution No. 1. Paris: UNESCO-IHP.

Ganju A, Dimri A P. 2004. Prevention and mitigation of avalanche disasters in western Himalayan region. Natural Hazards, 31(2): 299-308.

Gaume J, Chambon G, van Herwijnen A, et al. 2018. Stress concentrations in weak snowpack layers and conditions for slab avalanche release. Geophysical Research Letters, 45(16): 8363-8369.

Gauthier D, Brown C, Jamieson B. 2010. Modeling strength and stability in storm snow for slab avalanche forecasting. Cold Regions Science and Technology, 62: 107-118.

Guy Z M, Birkeland K W. 2013. Relating complex terrain to potential avalanche trigger locations. Cold Regions Science and Technology, 86: 1-13.

Haegeli P, McClung D M. 2007. Expanding the snow-climate classification with avalanche-relevant information: initial description of avalanche winter regimes for southwestern Canada. Journal of Glaciology, 53: 266-276.

Hao J S, Huang F R, Liu Y, et al. 2018. Avalanche activity and characteristics of its triggering factors in the western Tianshan Mountains, China. Journal of Mountain Science, 15(7): 1397-1411.

Höller P. 2014. Snow gliding and glide avalanches: A review. Natural Hazards, 71(3): 1259-1288.

Hu R J, Ma H, Wang G. 1992. An outline of avalanches in the Tien Shan Mountains. Annals of Glaciology, 16: 7-10.

Ikeda S, Wakabayashi R, Izumi K, et al. 2009. Study of snow climate in the Japanese Alps: Comparison to snow climate in North America. Journal of Mountain Science, 59(2-3): 119-125.

Köhler A, Fischer J T, Scandroglio R, et al. 2018. Cold-to-warm flow regime transition in snow avalanches. The Cryosphere, 12(12): 3759-3774.

Laute K, Beylich A A. 2014. Geomorphology Morphometric and meteorological controls on recent snow avalanche distribution and activity at hillslopes in steep mountain valleys in western Norway. Geomorphology, 218: 16–34.

Ma W L, Hu R J. 1990. Relationship between the development of depth hoar and avalanche release in the Tian Shan Mountain. Journal of Glaciology, 36: 37–40.

Maggioni M, Godone D, Frigo B, et al. 2019. Snow gliding and glide snow avalanches: recent outcomes from two experimental test sites in Aosta Valley (NW Italian Alps). Natural Hazards and Earth System Science, 19: 2667–2676.

McClung D M. 1981. Fracture mechanical models of dry slab avalanche release. Journal of Geophysical Research, 86(B11): 10783–10790.

McClung D M. 2013. Effects of triggering mechanism on snow avalanche slope angles and slab depths from field data. Natural Hazards, 69(3): 1721–1731.

McClung D M, Borstad C P. 2019. Probabilistic size effect law for mode II fracture from critical lengths in snow slab avalanche weak layers. Journal of Glaciology, 65: 1–11.

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

Mock C J, Birkeland K W. 2000. Snow avalanche climatology of the western United States mountain ranges. Bulletin of the American Meteorological Society, 81(10): 2367–2392.

Parshad R, Kumar P, Snehmani, et al. 2019. Seismically induced snow avalanches at Nubra–Shyok region of Western Himalaya, India. Natural Hazards, 99(5): 843–855.

Peitzsch E H, Hendrikx J, Fagre D B, et al. 2012. Examining spring wet slab and glide avalanche occurrence along the Going-to-the-Sun Road corridor, Glacier National Park, Montana, USA. Cold Regions Science and Technology, 78: 73–81.

Reiweger I, Schweizer J. 2013. Weak layer fracture: Facets and depth. The Cryosphere, 7(5): 1447–1453.

Rudolf-Miklau F, Sauermoser S, Mears A, et al. 2015. The Technical Avalanche Protection Handbook. New York: Wiley, 1–430.

Schweizer J, Jamieson B, Schneebeli M. 2003. Snow avalanche formation. Reviews of Geophysics, 41(4): 1016.

Schweizer J, Mitterer C, Techel F, et al. 2020. On the relation between avalanche occurrence and avalanche danger level. The Cryosphere, 14(2): 737–750.

Schweizer J, Bartelt P, van Herwijnen A. 2021. Snow and Ice-Related Hazards, Risks, and Disasters. Amsterdam: Elsevier, 377–398.

Shandro B, Haegeli P. 2018. Characterizing the nature and variability of avalanche hazard in western Canada. Natural Hazards and Earth System Sciences, 18(4): 1141-1158.

Statham G, Haegeli P, Greene E, et al. 2018. A conceptual model of avalanche hazard. Natural Hazards, 90(2): 663-691.

Techel F, Pielmeier C. 2011. Point observations of liquid water content in wet snow and ndash; investigating methodical, spatial and temporal aspects. The Cryosphere, 5(2): 405-418.

Valero C V, Wever N, Christen M, et al. 2018. Modeling the influence of snow cover temperature and water content on wet-snow avalanche run out. Natural Hazards and Earth System Sciences, 18(3): 869-887.

van Herwijnen A, Jamieson B. 2007. Snowpack properties associated with fracture initiation and propagation resulting in skier-triggered dry snow slab avalanches. Cold Regions Science and Technology, 50: 13-22.

Wastl M, Stötter J, Kleindienst H. 2011. Avalanche risk assessment for mountain roads: A case study from Iceland. Natural Hazards, 56(2): 465-480.

Wei W S, Qing D H, Liu M Z. 2001. Properties and structure of the seasonal snow cover in the continental regions of China. Annals of Glaciology, 32(1): 93-96.

Wever N, Valero C V, Fierz C. 2016. Assessing wet snow avalanche activity using detailed physics based snowpack simulations. Geophysical Research Letters, 43(11): 5732-5740.

Yang J M, Li C Z, Li L H, et al. 2020. Automatic detection of regional snow avalanches with scattering and interference of C-band SAR Data. Remote Sensing, 12(17): 2781.

Zhang X T, Li X M, Li L H, et al. 2019. Environmental factors influencing snowfall and snowfall prediction in the Tianshan Mountains, Northwest China. Journal of Arid Land, 11(1): 15-28.

Note: Figure translations are in progress. See original paper for figures.