Linking avalanche hazard in Western Canada to climate oscillations

by

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Abstract

While the effect of large-scale climate patterns (e.g., El Niño-Southern Oscillation) on winter temperature and precipitation in Western Canada is relatively well understood, little is known regarding the link between climate and avalanche hazard. Previous studies have been hindered by the inconsistent or incomplete avalanche, weather, and snowfall observations. Using avalanche hazard assessments from Avalanche Canada and Parks Canada from the 2009/10 to 2016/17 winter seasons I examined the nature and variability of avalanche hazard and the relationship to large-scale climate patterns. I identify typical avalanche hazard situations and calculate their seasonal prevalence to develop a quantitative measure of the nature of local avalanche hazard conditions. I then use the prevalence values of typical hazard conditions to examine the relationship between climate oscillations and avalanche hazard. This study suggests a relationship between the climate patterns and avalanche hazard situations with a method that is more informative for avalanche risk management.

Keywords: Snow and avalanche climate, Avalanche forecasting, El Niño-Southern Oscillation, Pacific Decadal Oscillation, Pacific North America Pattern, Arctic Oscillation

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List of Acronyms

AHC	Agglomerative hierarchical clustering
AO	Arctic Oscillation
BC	British Columbia
CMAH	Conceptual model of avalanche hazard
ENSO	El Niño Southern Oscillation
IQR	Interquartile range
NOAA	National Oceanic and Atmospheric Administration
NS	Not significant
PDO	Pacific Decadal Oscillation
PNA	Pacific North American
SARP	SFU Avalanche Research Program
SOM	Self-organizing maps
SWE	Snow water equivalent
TG	Temperature gradient

Introduction

Snow avalanches are a deadly natural hazard that claim an average of 13 lives in Canada every year (Jamieson, Haegeli, & Gauthier, 2010). Most victims are backcountry recreationists, such as skiers, snowboarders, mountain snowmobilers and mountaineers, either making their own decisions about when and where to travel or being led by professionally trained guides. In addition, avalanches threaten communities, utility lines, resource operations and cause traffic hazards and economic loss by blocking highways and railways.

Avalanches that injure or kill people and damage property are typically slab avalanches, where a cohesive slab of snow releases from the rest of the snowpack along a weak layer and slides down the slope as a unit. The conditions for avalanches evolve throughout the winter as sequences of storms and clear weather periods to create a snowpack with a distinct layer structure. The strength of the bond between these layers depends on the crystal type and grain size of the snow grains within these layers. Slab avalanches happen when the stress on one of the existing layers in the snowpack overcomes its strength, and the overlying snowpack detaches from the deeper parts of the snowpack. These can either occur naturally during a storm, when the stress on a potential weak layer is increased by the addition of new snow, accidentally when a skier or snowmobile rider crossing a slope adds additional stress to the layer, or intentionally when explosives are used to trigger avalanche preventatively. Interested readers are referred to Schweizer et al. (2016) for an overview on avalanche release.

The physical risk from avalanches is managed by continuously monitoring the hazard conditions using a wide range of weather, snowpack and avalanche observations, and choosing risk mitigation measures to reduce the associated risk to an acceptable level. Depending on the application, different forms of avalanche risk mitigation approaches are applied (Canadian Avalanche Association, 2015). Avalanche hazard mapping is used to ensure that the exposure of residential and commercial developments to avalanche hazard is always below an acceptable threshold. Infrastructure or activities that are located in avalanche terrain (e.g., highways, ski areas, work sites, and commercial backcountry recreation operations) manage avalanche risk with local avalanche forecasting programs, which continuously monitor the conditions and apply mitigation measures when needed (e.g., artificially triggering avalanches with explosives, temporary closures or evacuations). Public avalanche bulletins provide information about regional avalanche hazard conditions to allow backcountry recreationists to make informed choices about when and where to travel in the backcountry.

Making informed mitigation choices begins with an in-depth understanding of connections between the evolution of the weather conditions during a winter and avalanche conditions. Numerous studies have shown a link between large-scale atmosphere-ocean oscillations and the winter surface weather conditions in Western Canada. Shabbar and Khandekar (1996) found the El Niño Southern Oscillation (ENSO) to affect the winter surface temperatures in Western Canada, with mean wintertime temperatures warmer than average in positive phase winters and the opposite effect in negative phase winters. Stahl et al. (2006) demonstrated how synoptic-scale circulation patterns in Western Canada are influenced by positive phases of the Pacific North American Pattern (PNA), Pacific Decadal Oscillation (PDO), and ENSO and in turn result in warmer winter time air temperature and decreased precipitation in British Columbia (BC). Considerable synoptic weather pattern variance was explained by index-phase anomalies, supported the warm and dry conditions in many regions for positive phases ENSO, PDO, and PNA indices. Fleming et al. (2006) inferred a connection between the sea level pressure and warmer seasonal temperatures in Northwest BC and the positive phase of the Arctic Oscillation (AO).

Given their influence on surface temperature and precipitation, one would expect that these large-scale atmosphere-ocean oscillations also have an effect on the seasonal avalanche hazard conditions in Western Canada. Fitzharris (1987) was the first who considered synoptic patterns and circulation indices to explain major avalanche winters in Rogers Pass, BC. His study found that large anomalies in atmospheric circulation are associated with changes in factors contributing to major avalanche winters. Bellaire et al. (2016) examined the relationship between avalanche activity patterns and climate change at Rogers Pass, BC, between 1965 to 2014, but were unable to conclusively identify any meaningful trends. They attributed the limited insight of their results to changes in mitigation practices during their study period. McClung (2013) found significant correlations between avalanche activity (overall as well as dry and wet avalanches separately) with positive phase ENSO winters having more wet avalanches at Bear Pass and Kootenay Pass, BC. Thumlert et al. (2014) confirmed these results in their study examining the correlation between large-scale climate oscillations and yearly avalanche activity of six highway passes in BC. In addition, they found a similar significant a relationship between avalanche activity and the PDO, more wet avalanches during positive PDO winters and more dry avalanches during negative phase winters.

However, studies relating avalanche activity to climate oscillations are fundamentally limited by the challenges of operational avalanche activity records. Backcountry avalanche datasets are inherently incomplete because it is impossible to comprehensively monitor large backcountry areas, and low visibility during storms further reduces observers' ability to record avalanches reliably. In areas that are more tightly controlled (e.g., transportation corridors), long-term avalanche datasets are hampered by changes in risk mitigation requirements, mitigation technology, and mitigation practices. (Sinickas, Jamieson, & Maes, 2016). Trends observed in these datasets can therefore not necessarily be interpreted as reliable signals of changing avalanche activity patterns due to climatological factors. Furthermore, avalanche activity alone also does not provide a comprehensive picture of avalanche hazard conditions, and the absence of avalanche activity does not necessarily indicate low avalanche hazard. For example, early season rain-on-snow events can result in a persistent weakness in the snowpack that dominates the approach to avalanche risk mitigation and backcountry travel for an entire season. The facet layer of November 1996 described by Jamieson and Johnston (1997) is an example of such a persistent weakness. While these types of weaknesses are often dormant throughout most of the season, they occasionally release large avalanches, which are difficult to predict. These weaknesses are also often associated with large avalanche cycles in the spring when the snowpack starts to melt. Such lingering avalanche problems can dominate the avalanche hazard character and influence the avalanche professional's selection of risk management mitigation measures during the entire winter.

This study aims to improve our understanding of the relationship between large-scale atmosphere-ocean oscillations and avalanche hazard conditions in Western Canada by providing a more comprehensive perspective. Instead of focusing on avalanche activity, this study uses archived public avalanche bulletins from Avalanche Canada (formerly Canadian Avalanche Centre) and Parks Canada, which provide daily expert assessments of region-specific avalanche hazard conditions in Western Canada. Both agencies use the conceptual model of avalanche hazard (CMAH) developed by Statham et al. (under review) as a framework for synthesizing the available observations, conceptualizing the existing hazard conditions, and describing them in an organized way. The structured approach of the CMAH and the quantitative nature of the resulting dataset opens new opportunities for characterizing the nature of avalanche conditions of entire winters and relating them to climate oscillations. A better understanding of this relationship will provide new avenues for producing seasonal avalanche hazard forecasts and examining the effect of climate change on avalanche hazard in Western Canada.

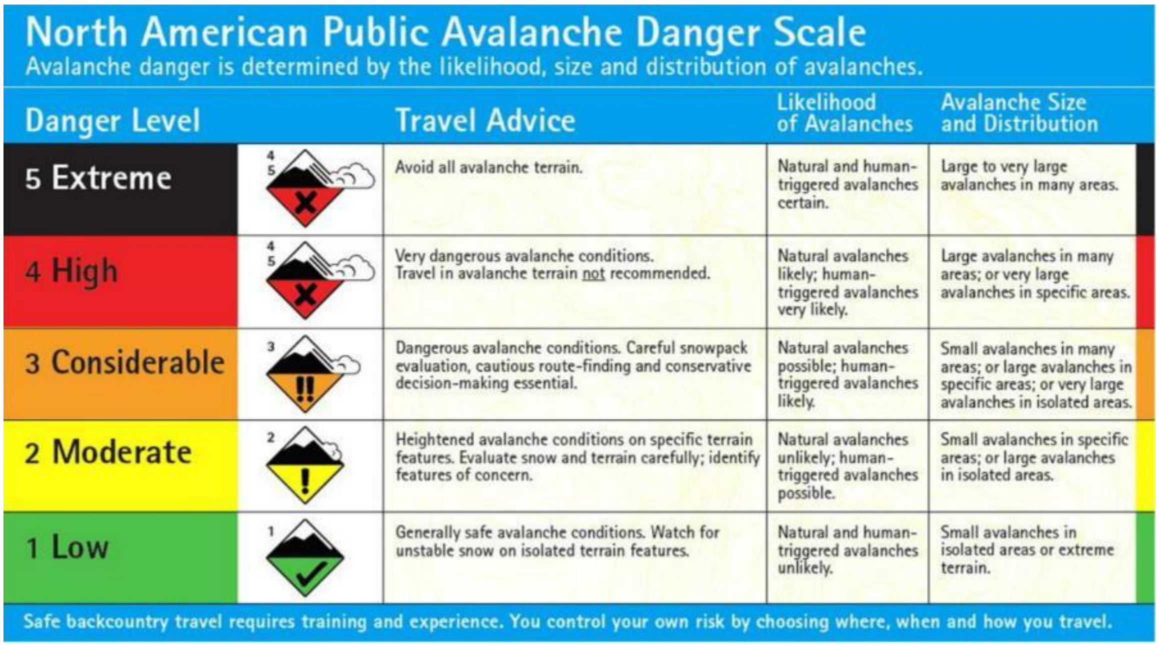
Background

Avalanche forecasting and conceptual model of avalanche hazard

Avalanche forecasting aims to predict the current and future avalanche hazard based on past, present, and expected conditions (McClung, 2002). Avalanche forecasters use a wide variety of weather, snowpack and avalanche observations to make subjective judgements about avalanche conditions. This synthesizing process, which uses some deductive methods (i.e., making conclusions based on scientific understanding of the principles of the physics of snow) but is primarily based on inductive logic (i.e., extrapolating from individual observations), relies on expert judgment and requires considerable field experience that LaChapelle (1980) described as holistic rather than analytical.

Avalanche forecasts are an important part of the risk management process, as they are the foundation for selecting mitigation measures (Canadian Avalanche Association, 2015). Professional ski guides use their own avalanche forecasts to choose terrain that limits the risk from avalanche to themselves and their guests to an acceptable level. Private recreationists making their own decisions use avalanche forecasts published in public avalanche bulletins to make choices when planning trips and their own observations and assessments once on their trips. In transportation corridors, avalanche forecasts are used to schedule closures and conduct avalanche control work.

The result of avalanche forecasts is most commonly communicated with hazard ratings. Public avalanche bulletins published in North America use the North American Avalanche Danger Scale (Statham et al., 2010), an ordinal, five-level scale that describes the overall nature of the avalanche conditions with a single keyword and color (Figure 1).



North American Public Avalanche Danger Scale

Avalanche danger is determined by the likelihood, size and distribution of avalanches.

Danger Level	Travel Advice	Likelihood of Avalanches	Avalanche Size and Distribution
5 Extreme	Avoid all avalanche terrain.	Natural and human-triggered avalanches certain.	Large to very large avalanches in many areas.
4 High	Very dangerous avalanche conditions. Travel in avalanche terrain not recommended.	Natural avalanches likely; human-triggered avalanches very likely.	Large avalanches in many areas; or very large avalanches in specific areas.
3 Considerable	Dangerous avalanche conditions. Careful snowpack evaluation, cautious route-finding and conservative decision-making essential.	Natural avalanches possible; human-triggered avalanches likely.	Small avalanches in many areas; or large avalanches in specific areas; or very large avalanches in isolated areas.
2 Moderate	Heightened avalanche conditions on specific terrain features. Evaluate snow and terrain carefully; identify features of concern.	Natural avalanches unlikely; human-triggered avalanches possible.	Small avalanches in specific areas; or large avalanches in isolated areas.
1 Low	Generally safe avalanche conditions. Watch for unstable snow on isolated terrain features.	Natural and human-triggered avalanches unlikely.	Small avalanches in isolated areas or extreme terrain.

Safe backcountry travel requires training and experience. You control your own risk by choosing where, when and how you travel.

Figure 1: North American public avalanche danger scale (Statham et al., 2010).

However, Atkins (2004) pointed out that the character of expected avalanches is more important for risk management than a hazard rating alone. In his seminal paper, Atkins presented a list of 35 avalanche hazard patterns or scenarios with unique characteristics that require different approaches to risk management when travelling in the backcountry. In 2010, a group of North American avalanche professionals expanded and generalized Atkins' idea of avalanche scenarios into a Conceptual Model of Avalanche Hazard (CMAH). The CMAH contributed to the assessment process in two main ways. First, it provided a structured pathway between raw field observations and avalanche hazard. Second, the CMAH offered a standardized language to describe avalanche hazard in a way that is relevant for risk mitigation decisions (Statham et al., under review). The CMAH essentially breaks avalanche hazard into four key questions that professional avalanche workers and recreationalists need to ask themselves when making decisions regarding backcountry travel:

1. What types of avalanche problem(s) exist?
2. Where are these problems located within the terrain?
3. How likely are avalanches associated with these problems (natural or artificially triggered)?
4. How big will these avalanches be?

The conceptual framework provides avalanche forecasters with standardized ordinal scales for expressing their assessment of these questions and a structured workflow for how these components are combined into an overall picture of the hazard conditions (Figure 2).

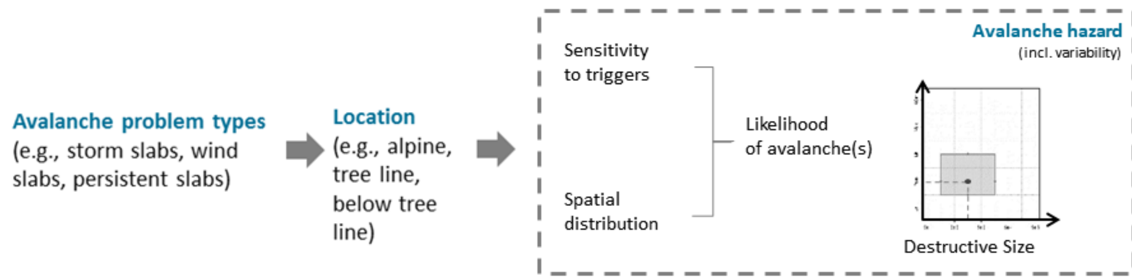


Figure 2: The workflow of the Conceptual Model of Avalanche Hazard (Statham et al., under review)

Avalanche problem types play a critical role in this process as they represent distinct avalanche hazard patterns that result from repeatable combinations of snowpack, weather, and terrain factors. The CMAH defines nine distinct avalanche problem types (Table 1). Identifying the types of one or more existing avalanche problems at the beginning of the assessment process considerably simplifies the process because these types differ in what types of observations are most relevant for their recognition and assessment, and they limit the possible range of likely assessment values. For example, when assessing storm slab avalanche problems, the primary observations include the amount of new snowfall and the previous snow surface conditions (Haegeli, Atkins, & Klassen, 2010). Furthermore, avalanche problem types have a direct link to risk mitigation because they were defined based on the distinct approaches required for managing the associated risks. For example, while wind slab avalanche problems are easily avoided because they stabilize relatively quickly and are associated with specific terrain features, persistent slab avalanche problems need to be given a much wider berth as the associated avalanches are larger, can propagate into mellow terrain, and are less predictable.

Table 1: Overview of avalanche problem types (after Statham et al. (under review) & Haegeli, Atkins & Klassen (2010))

Avalanche problems type	General description
Dry loose avalanche problem	Often small cohesion-less dry surface snow such as recent snowfall or faceted old surface snow, starting from a point and occurring in steep terrain (+40°) lasting from hours to days, longer with dry, cold, clear weather.
Wet loose avalanche problem	Cohesion-less wet snow starting from a point caused by melting or precipitation, require fairly a steep slope (+35°). Loose wet avalanches triggered by solar radiation mostly occur on solar aspect, and loose wet avalanches triggered by warm temperature or rain are widely distributed, and their duration is correlated with warm air temperature, precipitation, and/or solar radiation.
Storm slab avalanche problem	Problem size depends on storm intensity forming a cohesive slab of soft new snow that creates an instability within the new snow or at the interface of the old snow surface. Located in sufficiently steep and open terrain at any elevation and lasting from hours to days after the end of the storm.
Wind slab avalanche problem	Small to medium cohesive slabs of wind-deposited snow formed by broken snow crystals packed into a dense slab created on the downwind slope or around natural wind obstructions. Duration depends on wind loading intensity and slabs tend to stabilize within several days following formation.
Persistent slab avalanche problem	Medium to very large cohesive slabs of snow that is poorly bonded and slowly stabilizes to a persistent weak layer that may occur at various spatial distributions depending on the weather process responsible for the persistent weak layer. This problem can persist for weeks to months.
Deep persistent slab avalanche problem	Very large destructive potential involving the bond deterioration between a thick, hard cohesive slab of old snow and an early season persistent weak layer on or near the ground and can be widely distributed or limited to specific terrain features lasting months and usually to the end of the winter. Dormant instabilities often activate after storms or with warm spring weather.
Wet slab avalanche problem	Generally, a large wet cohesive slab that results in dense, slushy debris caused by rain or meltwater infiltrates and weakens bonding of the snow pack. Peaks during periods of rainfall or extended warm weather and persists until the snowpack refreezes or the snowpack turns to cohesion-less slush.
Cornice avalanche problem	A mass of dense, wind-deposited snow overhanging a sharp break in terrain, such as a ridge or cliff, formation occurs during warm storms with high winds located on downwind side of terrain breaks. Cornice formation persists all winter and tends to collapse spontaneously during periods of warming or following intense wind events.
Glide avalanche problems	Involving the entire snowpack, first cracks then glides slowly downslope until releasing a full depth avalanche which can form anytime during the winter. Occur on smooth ground such as grass or smooth rock slopes and avalanche activity is almost impossible to predict.

The CMAH uses a hazard chart to visualize the estimates of likelihood of triggering and destructive size of the identified avalanche problems, combined in a concise, but informative fashion (Figure 3). While the centre point of the squares for each avalanche problem represents their respective estimated typical value for likelihood of triggering and destructive size, the left/lower and right/upper limits represent the estimated minimum and maximum values to represent variability in space and time as well as forecaster uncertainty (Statham et al., under review).

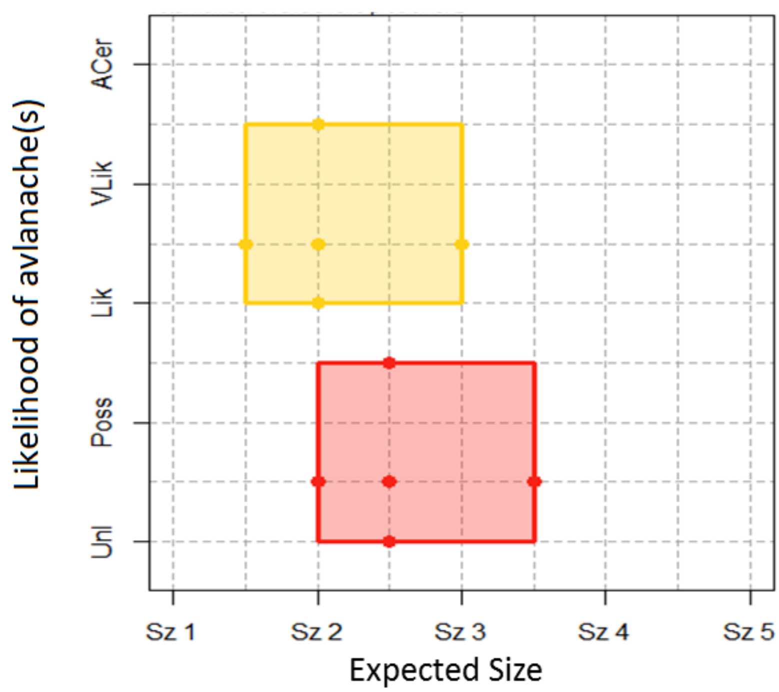


Figure 3: **Hazard chart defining the likelihood of avalanches and destructive size. The yellow and red rectangle represents a storm slab and a persistent slab avalanche problem respectively. The points in the middle explain the typical value of likelihood and destructive size, while the outer edges represent the maximum and minimum values.**

CMAH has been adopted broadly in the avalanche safety communities in North America and has now become an essential part of the daily risk management workflow of nearly all avalanche safety programs in Canada. To initially test the operational benefits of the CMAH, Haegeli (2008) developed an online wizard that guides avalanche safety operations through their assessment process according to the CMAH. The response was overwhelmingly positive and in 2011, Parks Canada integrated the CMAH into the newly developed public avalanche forecasting software AvalX (Statham, Campbell, & Klassen, 2012). Since then, all Canadian public avalanche bulletins are produced according to the CMAH. In 2013, the CMAH was further integrated into the InfoEx (Haegeli et al., 2014), the daily exchange of observations and assessments among more than a 120 professional avalanche safety programs in Canada. This means that the structure and language described in the CMAH have become an established best practice in avalanche hazard assessment in Canada.

Climate oscillations affecting Western Canada

My study is focusing on four large-scale climate oscillations that are known to affect weather conditions in Western Canada: ENSO, PNA, PDO, and AO. While the ENSO, PNA, and PDO are closely related, the AO is independent of these Pacific orientated teleconnections (Moore et al., 2009).

El Niño Southern Oscillation

ENSO is a large-scale climate oscillation originating in the Eastern South Pacific off the coast of Peru that has large effects on the weather in numerous regions around the world ranging from tropical to polar latitudes (Christensen et al., 2013) that can be predicted with a reasonable accuracy (Wu & Kirtman, 2006). Various indices are used to identify the phase and describe the strength of ENSO. In this study, I used the Multivariate El Niño Index (MEI), which considers six main parameters observed over the tropical Pacific, including: sea-level pressure, zonal and meridional components of surface wind, sea surface temperature, surface air temperature, and total cloudiness fraction of the sky (Wolter & Timlin, 2011).

Over Western Canada, El Niño (positive ENSO phase) winters are associated with a shift towards warmer than normal temperatures, while La Niña (negative ENSO phase) winters exhibit colder than normal temperatures (Shabbar and Khandekar, 1996). Furthermore, Shabbar and Bonsal (2004) showed that El Niño are also associated with increased frequencies of winter warm in Southwestern Canada and generally the opposite during La Niña winters. The signal in precipitation is less distinct. Shabbar, Bonsal, and Khandekar (1997) did not identify any precipitation anomalies during El Niño or La Niña winters, but found negative anomalies for the winters following the onset of an El Niño, and positive anomalies following a La Niña event. Stahl et al. (2006) found the response to differ spatially with the strongest temperature response in Coastal BC, while the interior BC had the strongest precipitation response.

McAfee and Wise (2016) provide a comprehensive summary of the existing research on the effect of ENSO on weather patterns in the Pacific Northwest of the continental United States (i.e., Washington, Oregon, Idaho and Montana). In this area, ENSO generally has the strongest effect on weather patterns in the late winter. Overall, winters are typically colder and wetter with greater snowfall during a La Niña events (negative anomalies), while El Niño events (positive anomalies) are generally warmer with less snowfall. (Lute & Abatzoglou, 2014) show that La Niña events are associated with more frequent as well as more intense snowfall events. However, the effect of ENSO has considerable regional differences. For example, the authors Jin et al. (2006) and Wise (2010) found that the winter precipitation response to ENSO is weakened in central Washington and Oregon or even reversed in the rain shadow of the Cascades.

Pacific Decadal Oscillation

The PDO refers to variabilities in surface air temperature and precipitation over the entire North American continent and extratropical North Pacific (Christensen et al., 2013). Generally, the PDO is dominated by warm or cold regimes lasting approximately two decades. However, a regime shift may have been underway during the period of the present study (Whitfield, Moore, Fleming, & Zawadzki, 2010). The intensity of this climate oscillations is described with the PDO index, which is calculated from monthly sea surface temperature anomalies and the monthly mean global average sea surface temperature anomaly (Mantua et al., 1997). The PDO pattern is known to have a modulating effect on ENSO related temperature anomalies. The effect of strong positive temperature anomalies is stronger and more widespread during positive ENSO phases and positive PDO winters (Bonsal, Shabbar, & Higuchi, 2001; Mantua & Hare, 2002). The negative phase ENSO and PDO have been clearly linked to negative temperature, increased precipitation anomalies in Western Canada (Bonsal et al., 2001; Stahl et al., 2006), as well as the weaker Aleutian low resulting in decreased winter precipitation (Mantua & Hare, 2002).

Pacific North American pattern

The PNA teleconnection pattern influences the jet stream and storm tracks over the Pacific and North American sectors, exerting notable influences on the temperature and precipitation in these regions on intraseasonal and interannual time scales (Christensen et al., 2013). The PNA is measured with the PNA index, which relates to anomalies in the 700 mb and 500 mb geopotential height fields observed over Western and Eastern North America (Zhao, Higuchi, Waller, Auld, & Mote, 2013), with mean flow characterized by a trough in the Eastern-Central Pacific, and a ridge over the Rocky Mountains (Whitfield et al., 2010). In Western Canada, positive anomalies are associated with warm and dry air and reduced snow cover, while negative anomalies have more zonal circulation and produce higher snow accumulation and colder than average temperatures (Brown & Goodison, 1996; Kluver & Leathers, 2015; Stahl et al., 2006).

Arctic Oscillation

The AO is a hemispheric scale climate oscillations that mostly affects higher latitudes and represents differences atmospheric mass between the Arctic and mid-latitudes on month-to-month timescales (Thompson & Wallace, 1998). It is described with the AO index, which incorporates non-seasonal sea-level pressure variations north of 20-degree latitude. Positive anomalies are characterized by lower pressure over the Arctic and higher pressure in mid latitudes accompanied by strong westerly flow and higher springtime temperatures in BC, while negative phase AO conditions are associated with lower midlatitude surface pressures and weaker westerly flow (Fleming et al., 2006).

Methods

Study area

The landscape of Western Canada is characterized by three main mountain ranges: the Coast Mountains along BC's coastline, the Columbia Mountains in the interior of BC, and the Rocky Mountains along the BC-Alberta border. Each of these mountain ranges exhibits distinct snow climate and related avalanche hazard characteristics (McClung & Schaerer, 2006) (Figure 4).

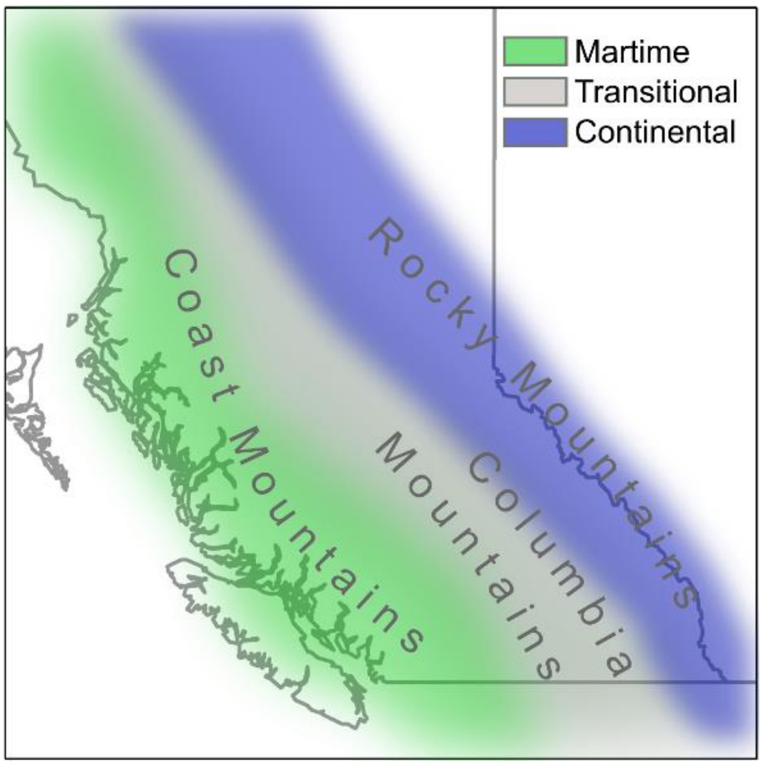


Figure 4: General mountain ranges and snow climate areas of Western Canada.

The maritime snow climate of the Coast Mountains is characterized by relatively warmer temperatures, cloudier skies, heavier snowfall resulting in fewer weak layers in the snowpack. Avalanches mostly occur during or immediately following a storm and the warmer temperature promotes rapid stabilization (McClung & Schaerer, 2006). The continental snow climate of the Rocky Mountains exhibits colder temperatures, more frequent periods of clear skies, less snowfall, and therefore a relatively thin snowpack, which is conducive to the formation of depth hoar and persistent weak layers. Avalanches in the Rocky Mountains are more frequently associated with persistent structural weaknesses within the snowpack (McClung & Schaerer, 2006). The Columbia Mountains experience weather effects that have both maritime and continental character, which results in a distinct transitional snow climate, which is characterized by large snowfalls and weaknesses in the snowpack that can persist for weeks and months (Haegeli & McClung, 2007). These weaknesses are typically facet-crust combinations resulting from rain-on-snow events primarily early in the winter, or surface hoar layers that develop during extended periods of clear weather in the main winter months.

While these snow climate descriptions provide some insight into the general character of the snowpack and associated avalanche activity in these mountain ranges, studies like Mock and Birkeland (2000) or Haegeli and McClung (2007) show substantial interseasonal variability in the nature of the local snow and avalanche conditions. For example, while surface hoar layers are rare in the Coast Mountains, they can be observed during winters that exhibit extended periods of clear weather. Similarly, the number of persistent weak layers in the Columbia varies from winter to winter depending on the relative strength of the maritime and continental influences. Haegeli and McClung (2007) therefore introduced the concept of avalanche winter regimes to describe the general nature of the local avalanche hazard conditions of individual winters.

Study period

My study covers the eight winter seasons from 2009/10 to 2016/17. These winters exhibited a wide variety of weather and avalanche conditions and therefore represent a meaningful sample of the possible winters experienced in Western Canada.

The 2009/10 winter season was characterized by multiple persistent slab avalanche problems. Extended periods of cold drought conditions followed by short periods of intense snowfall and sporadic rain to high elevations created long-lasting structural weaknesses in the snowpack. During the main winter months, the Columbia Mountains experienced the rather unusual situation of three simultaneously active surface hoar weaknesses in the snowpack. ENSO and PNA were in positive phases during this winter, while the AO index exhibited the most negative winter season average of the winters included in this study.

The early to-mid-season of the 2010/11 winter was relatively dry, which was followed by heavy snowfall in the late season. Many cold Arctic high-pressure systems during the early season kept snow accumulations near historical minimum and created a weak snowpack with many persistent weak layers. Starting in January, however, constant snowfall accumulated to snowpack depths near historical maxima by mid-February, overlying the weak snowpack formed in the early season. The weak foundation of the snowpack remained a deep persistent avalanche problem for the rest of the season. The average winter season ENSO and PDO patterns were recorded in a relatively strong negative phase, while the AO and PNA were close to neutral.

The 2011/12 winter exhibited warmer than average temperatures and widespread deep persistent slab avalanche problems. An early period of warm weather was followed by a cold drought, which formed a troublesome crust-facets combination that remained a concern for the entire winter season. An additional mid-season period of cold and dry weather formed another significant persistent weak layer in mid-February that created the potential for large destructive avalanches and results in extended periods of high avalanche danger. This winter exhibited the most negative PDO pattern of the study period.

The 2012/13 winter season experienced several periods of both warmer and colder than average temperatures. Despite several periods of clear weather ideal for weak layer formation, frequent warm tropical storms encouraged stabilization of the snowpack and caused many loose wet avalanche problems. During this winter, both the AO and PDO were in a negative phase.

The winter of 2013/14 was characterized by an extremely shallow early to mid-season snowpack that produced widespread deep persistent slab avalanche problems that persisted throughout the entire season. This resulted in the winter with the highest average danger rating for the study period. Additionally, significant layers of surface hoar or facets formed during a month-long drought, which ended in the first week of February and resulted in serious and long-lived persistent slab avalanche problems. Many destructive avalanches associated with these layers were recorded throughout Western

Canada during the second half of the season. During this winter, the winter average AO index was positive while the ENSO, PDO and PNA winter average indices were slightly negative.

The 2014/15 winter season saw several *Pineapple Express* events (also referred to as atmospheric rivers) alternating with cold arctic high-pressure systems, which created a shallow snowpack with many ice crust and facet layers. Periods of rising temperature, high avalanche danger with persistent slab avalanche and loose wet avalanche problems were interrupted by intense cold and dry periods with relatively low avalanche danger. During this winter, all four climate oscillations were in positive phases, but the PDO winter average was the most positive among the winters included in this study.

The 2015/16 winter season was characterized by strong *El Niño* conditions with above average temperatures especially in late winter to early spring. Below average snowpack depths were observed throughout the study area. Unseasonably warm spring temperatures created many loose wet and wet slab avalanche problems. However, on average, this was the winter with the most stable conditions and lower hazard ratings during the study period. For the second winter in a row, the average indices for all climate oscillations were positive, but the winter average ENSO index exhibited the highest positive value of the study period.

The 2016/17 winter season experienced consistently stormy conditions, above average seasonal snowfall, and below average seasonal temperatures, which resulted in wind slab avalanche problems being more prevalent than normal. An early November rain-on-snow event was responsible for the creation of a widespread deep persistent slab avalanche problem that was problematic for much of the season. While all climate indices remained positive for the third winter in a row, they were weaker and their average values for the main winter months were close to zero.

Dataset

I used three different datasets for exploring the relationship between large-scale climate oscillations and avalanche hazard conditions:

1. Weather observations from permanent high elevation weather sites to apply the existing snow climate classification algorithm of Mock and Birkeland (2000) as a reference.

2. Public avalanche bulletin data from Avalanche Canada and Parks Canada to characterize the seasonal avalanche hazard conditions

3. Indices describing the phases of the climate oscillations included in this study for the main winter months.

Weather data

High elevation automated weather sites with consistent daily weather and snowpack observations (including height of snowpack, 24 hr new snow, rain) from early December to late March are rare in Western Canada. Available weather records from Environment Canada, Parks Canada, the avalanche program of the British Columbia Ministry of Transportation and Infrastructure and the InfoEx (industrial information exchange among avalanche safety programs in Canada administered by the Canadian Avalanche Association) were scanned for suitable weather sites. For each of these sites, I included daily records of mean air temperature (°C), total rainfall (mm per 24 hours), total snowfall (cm per 24 hours), total snow water equivalent (SWE, mm per 24 hours) and height of snowpack (cm). For the present study, I used data from 13 weather stations (Table 1,Figure 5).

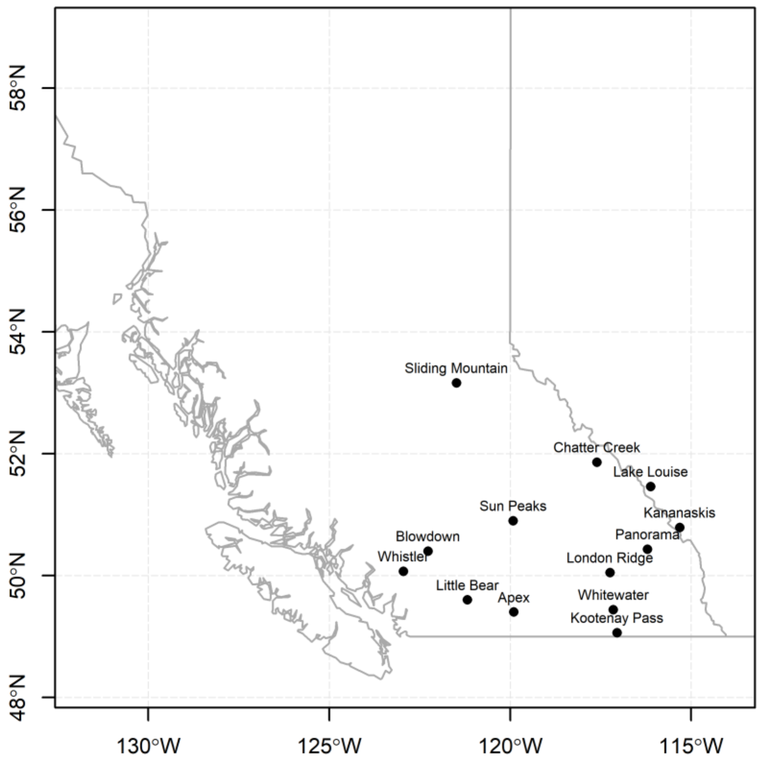


Figure 5: Weather station locations.

Table 2: Overview of weather data included in the present analysis.

Site name	Elevation	Latitude	Longitude	Source	Forecast region	2009 /10	2010 /11	2011 /12	2012 /13	2013 /14	2014 /15	2015 /16	2016 /17
Coast Mountains													
Whistler Roundhouse	1835 m	50.07	-122.95	EC	Sea-to-Sky				NA				
Blowdown	1890 m	50.40	-122.47	MOTI	South Coast Inland								
Little Bear	1660 m	49.60	-121.18	MOTI	South Coast Inland								NA
Columbia Ranges													
Sliding Mountain	1675 m	53.16	-121.48	MOTI	Cariboos								
Sun Peaks	2055 m	50.90	-119.92	EC	North Columbia	NA	NA						
Apex	1750 m	49.40	-119.90	MOTI	Kootenay Boundary								
London Ridge	2070 m	50.04	-117.24	MOTI	South Columbia				NA				
Whitewater	1950 m	49.44	-117.15	InfoEx	Kootenay Boundary		NA					NA	
Kootenay Pass	1780 m	49.06	-117.04	MOTI	Kootenay Boundary				NA				
Rocky Mountains													
Chatter Creek	1615 m	51.86	-117.60	InfoEx	-								
Panorama	2356 m	50.43	-116.20	InfoEx	Purcells								
Lake Louise	2200 m	51.46	-116.12	InfoEx	Banff, Kootenay Yoho			NA					
Kananaskis	1890 m	50.79	-115.31	InfoEx	Kananaskis Country	NA							

MOTI Ministry of Transportation and Infrastructure
EC Environment Canada
NA Forecast regions excluded from analysis because of inconsistent records
Grey shading indicates stations included in analysis.

Public avalanche bulletins

I used archived daily public avalanche bulletins from Avalanche Canada and Parks Canada to characterize the avalanche hazard conditions of Western Canada during the study period. The core information presented in avalanche bulletins in Canada consists of a characterization of the existing avalanche problems according to the CMAH and avalanche danger ratings for the three elevation bands alpine, treeline and below treeline for up to three days into the future (Figure 6). Some avalanche bulletins also include more detailed discussions of observed snowpack structure and avalanche activity, as well as current and future weather conditions.

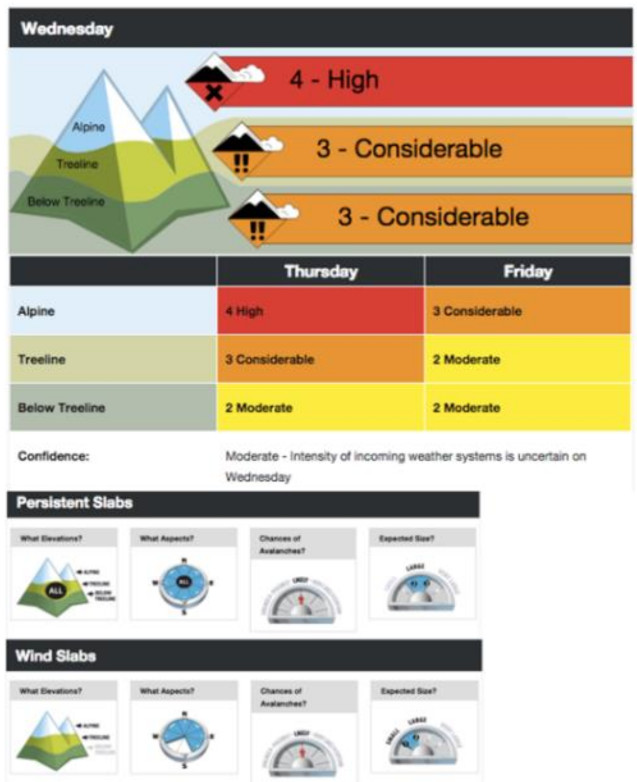


Figure 6: Example of a public avalanche bulletin for Avalanche Canada and Parks Canada containing two avalanche problems, a persistent slab avalanche problem and a wind slab avalanche problem.

All assessments are stored in Microsoft SQL Server databases, which are shared with the SFU Avalanche Research Program (SARP) at the end of every winter season.

The combined dataset from Avalanche Canada and Parks Canada consists of 14,892 avalanche hazard assessments for 24 different forecast regions over eight winter seasons (Table 3 & 4). Forecast regions that are only serviced with infrequent bulletins or bulletins of reduced content (North Shore, North Rockies, Bighorn Country, Little Yoho, Whistler Blackcomb, and the Yukon forecast regions) were excluded to ensure a consistent analysis dataset. The final dataset for statistical analysis consisted of 13,396 public avalanche bulletin records spanning eight winters from 20 forecast regions

Numerous adjustments were made to the boundaries of avalanche bulletin regions during the study period. During the winter seasons 2009/10 and 2010/11, Avalanche Canada produced public avalanche bulletins for six forecast regions (Figure 7): *Northwest*, *South Coast*, *North Columbia*, *South Columbia*, *Kootenay Boundary*, and *South Rockies*. In 2012, Avalanche Canada split some of their larger forecast regions to better represent the spatial variability of avalanche hazard in Western Canada (Figure 8). The *South Coast* forecast region was separated into *Sea-to-Sky* and *South Coast Inland*, and the *Northwest* region was separated similarly into *Northwest Coastal* and *Northwest Inland*. In the Columbia Mountains, the *Cariboo* forecast region was split from the *North Columbia* forecast region and the *South Columbia* region was reduced to accommodate the new *Purcell* forecast regions. In the Rocky Mountains, the *Lizard Range* was separated from the *South Rockies* forecast region. In 2015, Parks Canada separated the *Little Yoho* forecast region from the *Banff, Yoho, and Kootenay* region. The most recent change in the forecast regions occurred in 2017 when Avalanche Canada expanded the boundaries of the *North Shore* to include the mountains on the Sunshine Coast and along Howe Sound and renamed the region *South Coast*. This newly created South Coast forecast region was not included in my analysis because consistent bulletin data was only available for one season.

Table 3: Overview of the number of Avalanche Canada avalanche bulletin assessments included in the present analysis.

Region	Mountain Range	2009/10	2010/11	2011/12	2012/13	2013/14	2014/15	2015/16	2016/17	Total
*North Shore**	*Coast Mtn*	*71*	*120*	*122*	*122*	*122*	*60*	*121*	*0*	*738*
*South Coast**	*Coast Mtn*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*125* [A]	*125*
South Coast	Coast Mtn	90	119	0	0	0	0	0	0	209
Sea-to-Sky	Coast Mtn	0	0	123 [B]	122	122	122	123	127 [C]	739
South Coast – Inland	Coast Mtn	0	0	123 [B]	122	122	122	123	125	737
Northwest – BC	Coast Mtn	85	118	0	0	0	0	0	0	203
Northwest Inland	Coast Mtn	0	0	123 [D]	122	122	122	121	123	733
Northwest Coastal	Coast Mtn	0	0	122 [D]	122	122	122	123	123	734
*Whistler Blackcomb**	*Coast Mtn*	*0*	*0*	*2*	*0*	*0*	*0*	*121*	*0*	*123*
North Columbia	Columbia Mtn	98	116	122 [E]	122	122	122	123	130	955
Cariboos	Columbia Mtn	0	0	123 [E]	122	122	122	123	125	737
South Columbia	Columbia Mtn	87	116	123 [F]	122	122	122	122	125	939
Purcells	Columbia Mtn	0	0	122 [F]	121	122	122	123	127	737
Kootenay Boundary	Columbia Mtn	85	120	123	122	122	121	123	129	945
South Rockies	Rocky Mtn	92	118	123 [G]	122	122	121	122	125	945
Lizard Range	Rocky Mtn	0	0	123	122	122	121	123	127	738
*Bighorn Country – AB**	*Rocky Mtn*	*6*	*17*	*0*	*0*	*0*	*0*	*0*	*0*	*23*
*North Rockies – BC**	*Rocky Mtn*	*12*	*17*	*0*	*0*	*0*	*0*	*0*	*0*	*29*
Kananaskis Country**	Rocky Mtn	0	0	72	121	119	114	112	117	655
*Yukon**	*n/a*	*0*	*0*	*41*	*0*	*36*	*18*	*13*	*0*	*108*
	Total	626	861	1586	1584	1619	1531	1716	1628	11152

* Forecast regions excluded from analysis because of inconsistent records

** Bulletins produced by Kananaskis Country, but hosted by Avalanche Canada

A Boundaries of North Shore expanded and renamed to South Coast

B Boundaries of South Coast separated into Sea-to-Sky and South Coast Inland

C Boundaries of Sea-to-Sky reduced to accommodate North Shore expansion

D Boundaries of Northwest – BC separated into Northwest Coastal and Northwest Inland

E Boundaries of North Columbia separated into Cariboos and North Columbia

F Boundaries of South Columbia reduced to accommodate the Purcells

G Boundaries of the South Rockies reduced to accommodate the Lizard Range

Table 4: Overview of the number of Parks Canada public avalanche bulletin assessments included in the analysis.

Region	Mountain Range	2009/10	2010/11	2011/12	2012/13	2013/14	2014/15	2015/16	2016/17	Total
Glacier	Columbia	0	0	146	178	170	170	172	158	994
Banff, Yoho and Kootenay	Rocky	0	0	140	181	181	175 [A]	181	169	1027
*Little Yoho**	*Rocky*	*0*	*0*	*0*	*0*	*0*	*136*	*175*	*164*	*475*
Jasper	Rocky	0	0	144	173	156	151	155	159	938
*Waterton Lakes**	*Rocky*	*0*	*0*	*40*	*45*	*52*	*44*	*65*	*60*	*306*
	Total	0	0	470	577	559	676	748	710	3740

* Forecast regions excluded from analysis because of inconsistent records

** Bulletins produced by Kananaskis Country, but hosted by Avalanche Canada

A Boundaries of Banff, Yoho, and Kootenay reduced to accommodate Little Yoho

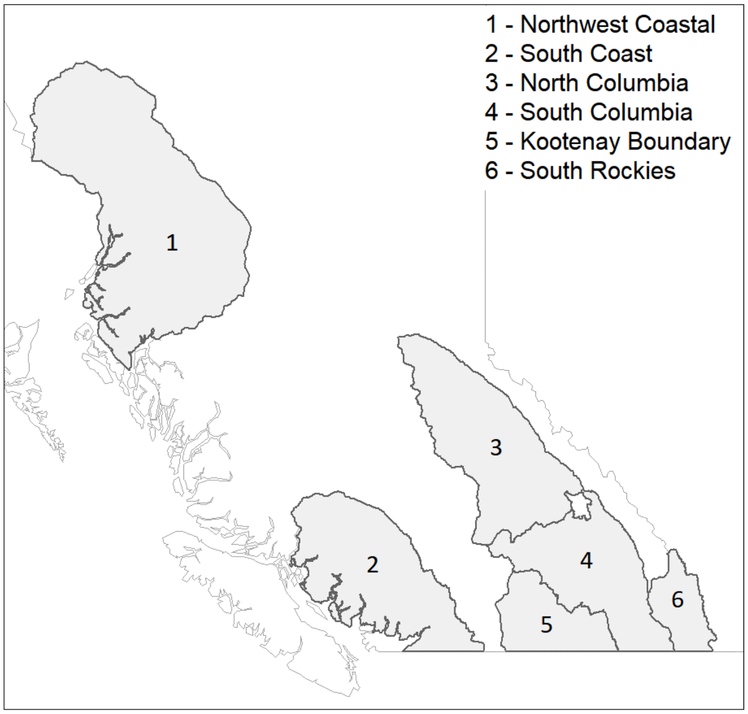


Figure 7: **Public avalanche bulletin regions for Western Canada from 2009/10 to 2010/11.**

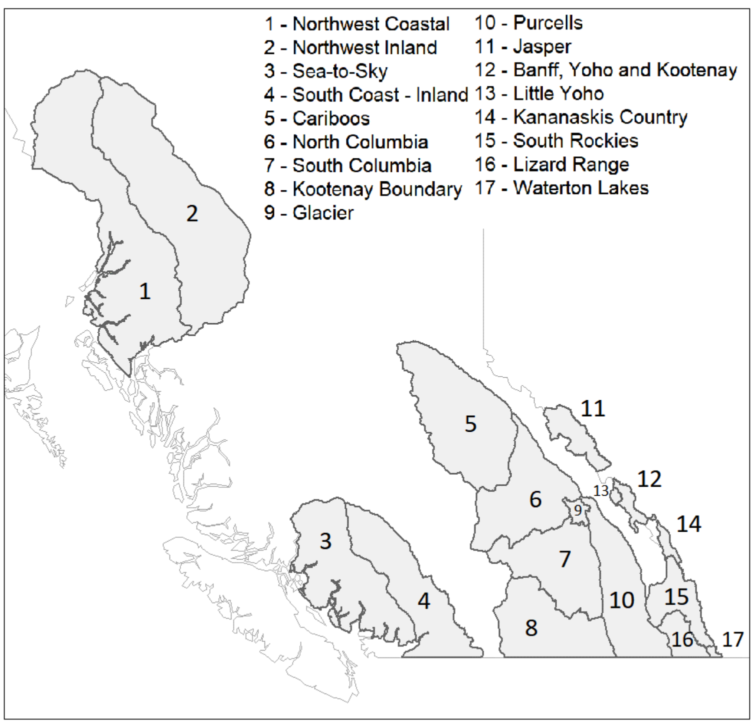


Figure 8: **Public avalanche bulletin regions for Western Canada from 2011/12 to 2015/16. North Shore and Yukon forecast regions are not shown.**

Climate oscillations data

I used publicly available data from the National Oceanic and Atmospheric Administration (NOAA) of the U.S. Department of Commerce for characterizing the various climate oscillations. I downloaded monthly values of the PDO, PNA, and AO indices for the winter months (November to April) of the 2009/10 to 2016/17 winter seasons from http://www.cpc.noaa.gov/data (NOAA, 2017). Wolter and Timlin (2011) provide monthly Multivariate ENSO Index (MEI) data.

Statistical analysis

My approach for quantitatively examining the relationship between climate oscillations and seasonal avalanche hazard conditions consisted of five distinct steps. Since avalanche hazard is composed of one of more avalanche problems, I first examined the typical characteristics of avalanche problems grouped according to the eight avalanche problem types described in the CMAH to better understand the fundamental components of avalanche hazard. In the second step, I identified typical daily avalanche hazard situations, which consist of combinations of avalanche problems, to effectively characterize the daily nature of avalanche hazard. These avalanche hazard situations are the foundation for the quantitative description of winter seasons I use in this study. In the third step, I characterized the nature of avalanche hazard during winter seasons for individual forecast regions in two different ways. First, I used the Mock and Birkeland (2000) approach to classify winter seasons based on high-elevation weather data. This allowed me to link the results of my study to existing research on snow and avalanche climates in Canada and the United States. Second, I calculated the seasonal prevalence of typical hazard situations to provide a numerical winter characterization that is more comprehensive and more insightful for avalanche risk management. In the fourth step, I clustered forecast regions that exhibit similar patterns in the time series of seasonal avalanche hazard situation prevalence over the study period to objectively identify larger climate zones that behave similarly. I then calculated average seasonal prevalence of typical hazard situations for the identified climate zones to produce a numerical expression of avalanche hazard at an objectively determined spatial scales. In the final step, I examined the relationship between climate oscillations and seasonal avalanche hazard conditions in identified homogenous forecast regions by exploring correlations between seasonal climate indices and seasonal prevalence of typical hazard situations. Each of these steps is described in more detail in the following sections.

All data manipulations and statistical analyses presented in this study were performed in R (R Core Team, 2016) and all statistical tests were evaluated at $\alpha = 0.05$ significance level.

Step 1: Examining the nature of avalanche problems according to type

To better understand the general nature of avalanche problems—the fundamental components of avalanche hazard—I first examined the general characteristics of eight avalanche problem types defined in the CMAH. I did not include *glide avalanches* in the analysis as this avalanche problem type was only recently added to the CMAH. I focused on the likelihood of avalanches and the destructive size as these parameters describe the primary components of avalanche hazard visualized in the avalanche hazard chart.

To describe the general characteristics of the avalanche problem types, I calculated summary statistics of each of the three assessment parameters for likelihood of avalanches (minimum, typical, maximum) and destructive size (minimum, typical, maximum) as well as the difference between the maximum and minimum value representing the assessed variability.

To compare the centre location and size of the hazard chart rectangles for each avalanche problem types, I examined the central tendency of the likelihood of avalanche and destructive size. For likelihood of avalanche and destructive size, I tested the location of the median typical values and the median difference between maximum and minimum values for differences between avalanche problem types by applying the Wilcoxon rank sum test Wilcoxon rank-sum test (Hollander & Wolfe, 1999).

To summarize the general location of the squares of avalanche problem types on the hazard chart, I prepared summary charts where each grid cell of the chart shows the counts of avalanche problems (see Figure 9 for example). To test for differences between avalanche problem types, I cut the resulting two-dimensional distribution along the vertical axis (likelihood of triggering) and horizontal axis (destructive size) through the gird cell with the maximum count and applied the Wilcoxon rank-sum test (Hollander

& Wolfe, 1999) and the Fligner-Killeen test (Conover, Johnson, & Johnson, 1981) to the count values along these axes to check for differences in median values and shape of distribution (i.e., wider or narrower) respectively. I chose non-parametric statistical tests for these comparisons since the likelihood and destructive size scale are ordinal and the count distributions are not normal.

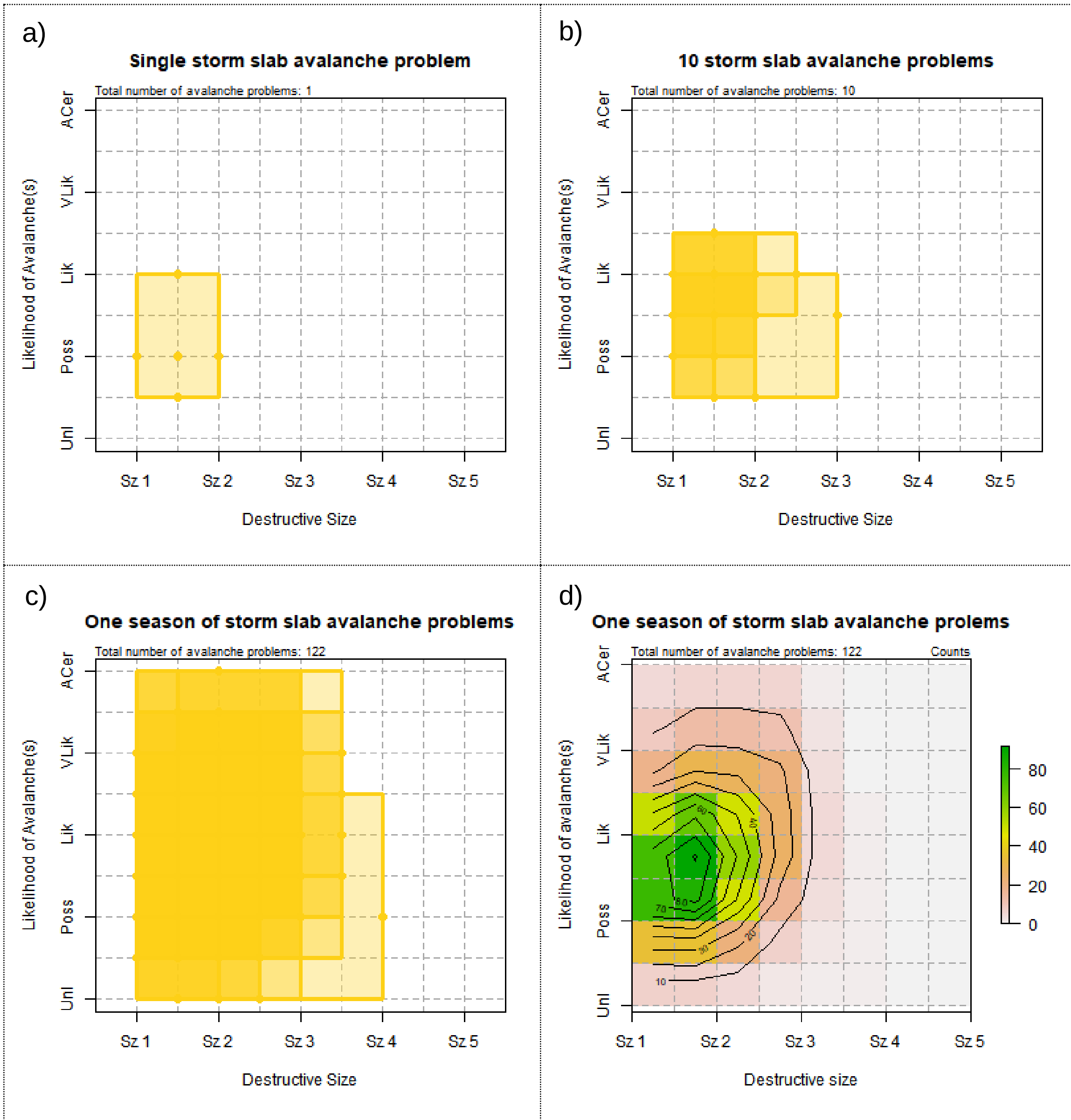


Figure 9: **Example hazard charts illustrating a single avalanche problem (a), multiple aalanche problems (b), all avalanche problems for one season (c), and areas of the hazard chart where this avalanche problem was most assessed (d).**

Step 2: Identifying typical hazard situations

An avalanche hazard assessment typically includes multiple avalanche problems. Since the number of possible combinations of different avalanche problem types with different likelihoods of avalanches and destructive size is essentially infinite, I needed a method to objectively identify a smaller number of typical avalanche hazard situations to make the dataset more manageable. Due to the high-dimensionality of my dataset and the potentially complex interactions among parameters, I used self-organizing maps (SOM; Kohonen, 2001) to identify typical avalanche hazard situations and assign each hazard assessment to one of these situations.

SOM is a type of unsupervised artificial neural network widely applied to clustering problems (Kohonen, 2013). The method reduces multidimensional data by assigning the records of an input dataset to a prescribed number of units that are arranged in a two-dimensional map space. At the beginning of the analysis, the map consists of random units, which are characterized by a weight vector and a position in the map space. The parameter vector of each record of the input dataset (i.e., input vectors) is then placed onto the map by finding the unit with the weight vector that resembles the input vector the most using the Euclidian distance. The unit with the shortest Euclidean distance is termed the "*best matching unit"* (BMU). The map then "self organizes" by updating the units in the neighbourhood of the BMU by shifting the weight vector of the unit closer to the input vector. This updating step is described by Equation 1, where *t* is the current iteration, $\boldsymbol{W}$ is the weight vector, $\boldsymbol{V}$ is the input vector, $\boldsymbol{\Theta}$ is the neighbourhood function that considers distance from the BMU, and $\boldsymbol{\alpha}$ is an iteration-dependent learning function:

$$\boldsymbol{W}(t+1) = \boldsymbol{W}(t) + \Theta(t)\alpha(t)[\boldsymbol{V}(t) - \boldsymbol{W}(t)] \quad (1)$$

The SOM is trained by applying Equation 1 to each input vector in the dataset and the training limit specifies the number of iterations this is repeated. Following the training process, each SOM unit reflects a typical pattern that emerged from the original dataset with neighbouring units representing more similar patterns and units located further away in the map space featuring more distinct patterns.

Increasing map size results in more detailed patterns and large map sizes lead to more accurate results. However there is a trade-off between compressing information and accuracy of the SOM (Liu, Weisberg, & Mooers, 2006). To select a robust map size, I trained several SOMs while examining the relationship between quantization error and topographical error. Quantization error is a measure of internal unit similarity and calculates average distance between each input vector for each unit. Topographical error measures the distance from best match unit to second best matching unit for each input vector. Readers interested in SOM are referred to Kohonen (2001), which provides a comprehensive description of the method.

The SOM analysis in this study was conducted with the Kohonen package in R (Wehrens & Buydens, 2007). The input data for the analysis were parameter vectors for each hazard assessment that consisted of the minimum, typical, and maximum values for likelihood of avalanches and destructive size for each of the eight avalanche problem types. If a particular avalanche problem type existed in an assessment, its assessments on the ordinal likelihood of avalanches and destructive size scales were represented by numerical values between 1 and 9. If an avalanche problem type did not exist, the values for its three likelihood and destructive size variables were all set to zero. This resulted in a training dataset for the SOM analysis of 38,982 assessments in the alpine, treeline, and below treeline elevation bands with 49 variables (8 x 6 parameters to characterize the hazard conditions plus the assessment ID). The final analysis was conducted with hexagonal arrays, a 4x3 grid size, and a training length of 200 iterations.

The output of the SOM analysis identified twelve typical daily combinations of avalanche problems and assigned each input assessment to one of these typical hazard situations. To facilitate the interpretation of the SOM nodes, I calculated the frequency of the avalanche problem types, the median hazard chart and the distribution of avalanche danger ratings from the hazard assessments assigned to the particular node. The median hazard chart visualizes the median likelihood of avalanche and destructive size value triplets (minimum, typical, maximum) for avalanche problems occurring in more than 50% in the assessments assigned to the particular hazard situation.

Step 3: Characterizing the nature of an avalanche winters

Traditional snow climate classification

To create a baseline characterization of avalanche winters and create the opportunity to tie the results back to the existing literature on snow and avalanche climates, I applied the snow climate classification scheme of Mock and Birkeland (2000), closely following the methods of Haegeli and McClung (2007).

The approach of Mock and Birkeland (2000) uses a simple flow-chart (Figure 10) to categorize local winter conditions into one of three snow-climate types (maritime, transitional and continental) based on daily weather and snowpack observations during the main winter months (December–March). The input parameters include mean air temperature, total rainfall, total snowfall, total snow water equivalent (SWE) and the derived average December snowpack temperature gradient. The authors derived the classification thresholds by analyzing meteorological observations from high elevation weather sites near avalanche terrain in the Western United States of America. The sites were grouped according to previously established snow-climate zones (Armstrong & Armstrong, 1986) and threshold values were identified based on box plots and the variability of the input parameters.

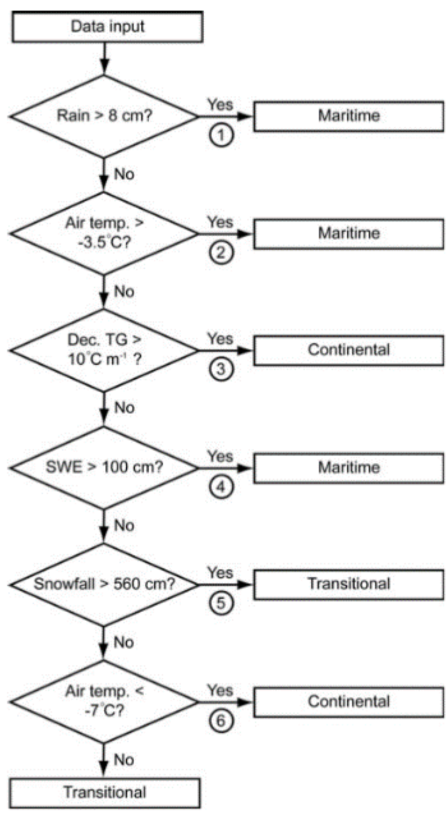


Figure 10: Flow chart illustrating the classification procedure for the seasonal snow-climate classification (after Mock & Birkeland, 2000). SWE: snow water equivalent, TG: temperature gradient.

Since the meteorological data available for this study did not have all the parameters required for this classification scheme, some of the parameters had to be derived. The SWE values for Environment Canada stations were estimated from daily snowfall records by assuming a seasonal average new snow density of 100 kg/m^3. For the Ministry of Transportation and Infrastructure (MOTI) data, I calculated daily summaries from 6-hourly observations. The daily rainfall was approximated by subtracting the SWE of new snow from values of total precipitation (Hägeli & McClung, 2003). To calculate the December temperature gradient, I assumed basal snowpack temperature of 0°C and divided the mean December air temperature by the average December snow depth (Mock & Birkeland, 2000). Records from stations that were missing a variable continuously for more than 10 days were not used for the seasonal snow climate classification.

Typical hazard situation prevalence

To provide a seasonal climate characterization that offers a more comprehensive perspective and is more closely tied to avalanche hazard and avalanche risk mitigation, I calculated the prevalence of each typical hazard situation identified in Step 2 of the analysis between December 1 and April 15 for the entire dataset together as well as individual combinations of forecast region, elevation band and winter season. Each of these combinations is therefore characterized by a set of twelve hazard situation prevalence percentage values that add up to 100%. The time period from December 1 to April 15 was chosen to ensure consistent bulletin data for all forecast regions.

To better highlight the seasonal patterns, I calculated seasonal anomaly values for the hazard situation prevalence. Due to the missing of Park Canada bulletins for the first two winter seasons (2009/10 and 2010/11), I calculated the annual prevalence anomalies in two different ways:

- Using bulletin information from only Avalanche Canada forecast regions to calculate overall means and seasonal anomalies over the entire study period.
- Using bulletin information from both Avalanche Canada and Parks Canada to calculate overall means and seasonal anomalies for the period from 2011/12 to 2016/17 winter.

While the first perspective provides insight in variation over the entire study period, it is limited to the areas covered by the bulletin regions of Avalanche Canada (i.e., Coast Mountains, Columbia Mountains, Southern Rocky Mountains). The second perspective overs a more comprehensive perspective as it also includes the Parks Canada forecast regions (primarily located in the central Rocky Mountains), but it is only available for the last six winters.

Step 4: Identifying avalanche hazard climate zones

Snow and avalanche climate zones have traditionally been defined based on the average meteorological conditions and our understanding of how these conditions relate to avalanche hazard (see, e.g., general description of snow and avalanche climate in study area section). The time series of the seasonal prevalence of typical avalanche hazard situations derived in Step 3 offers a new opportunity for examining similarities and differences of seasonal avalanche hazard conditions among forecast regions. Clustering forecast regions based on the prevalence time series should reveal avalanche climate zones that relate to the nature of avalanche hazard and avalanche risk management more closely than the traditional snow-climate classifications.

I used agglomerative hierarchical clustering (AHC; Johnson, 1967), one of the most commonly used clustering methods, to objectively group the time series of the seasonal prevalence of avalanche hazard situations in forecast regions derived in Step 3 at each elevation band. AHC builds a hierarchy of clusters from a dataset with $\boldsymbol{n}$ records by first treating each record as its own cluster. These initial clusters are then iteratively grouped by merging the two most similar clusters until all records have been merged into a single cluster. To decide which clusters are merged at every iteration, AHC uses a distance metric and linkage criterion. The distance metric determines the similarity between individual records and can be specified through a $\boldsymbol{n}$ by $\boldsymbol{n}$ distance matrix $\boldsymbol{D}$, where the distance (similarities) between records i and j is $\boldsymbol{D}_{i,j}$. The linkage criterion specifies how the distance measures $\boldsymbol{D}_{i,j}$ between clusters is determined. While it is recognized that different hierarchical clustering methods provide different results for the same input data, Ward's method often appears to return suitable results and therefore was selected for this analysis (Murtagh & Legendre, 2014). Ward's method defines the distance between clusters as the increase in the sum of squares within clusters, after merging, summed over all variables. Interested readers are referred to Everitt et al. (2011) for a more detailed account of the clustering algorithm.

While cluster analysis has been used widely in many different disciplines, determining the number of groups to select is ultimately a subjective judgment, which introduces uncertainty to the results (Suzuki & Shimodaira, 2006). To address this uncertainty, I used Suzuki and Shimodaira's (2006) multiscale bootstrap resampling method to calculate probability values for objective clusters of forecast regions. $\boldsymbol{N}$ bootstrap samples of different sizes are generated by randomly sampling from the input dataset. The frequency that a cluster appears in the bootstrap replicates is used for calculating the approximately unbiased probability values. Larger probability values represent more support for the cluster (Shimodaira & Hasegawa, 2001). Clusters with probability values larger than 0.95 are considered stable because the hypothesis that the cluster does not exist is rejected at the 0.05 significance level.

While Step 4 of my analysis produced characterizations for the 2009/10 to 2016/17 winter seasons, I only considered the 2011/12 to 2016/17 winter seasons for this part of the analysis as there were no major changes in the boundaries of the forecast regions during this period. The data for the cluster analysis, therefore, consisted of typical hazard situation prevalence values for the six winter seasons (2011/12 to 2016/17), which produced for each of the elevation bands a dataset with 72 prevalence variables in total (12 typical avalanche hazard situations x 6 seasons) for 15 forecast regions.

I used the R package pvclust (Suzuki & Shimodaira, 2015) to perform the cluster analyses to identify avalanche hazard climate areas at each of the three elevation bands (alpine, treeline, and below treeline) separately. For the distance metric, I used the Euclidean distance $\boldsymbol{D}_{ij} = \sqrt{\sum \| x_i - x_j \|^2}$, and Ward's D2 method for the linkage criterion. Once the avalanche hazard climate zones were identified, I averaged the prevalence values of the typical avalanche hazard situations within each climate zone.

Step 5: Correlating avalanche hazard characterization with climate oscillations indices

To examine the relationship between avalanche hazard in Western Canada and relevant large-scale climate oscillations, I performed a correlation analysis between the seasonal prevalence values produced in Step 4 and winter season averaged climate indices. These indices were calculated by averaging the monthly values for November to April for each winter season from 2009/10 to 2016/17.

Following the approach of Thumlert *et al.* (2014), I used Spearman rank correlation tests (Hollander & Wolfe, 1999) to identify significant rank-order correlations (*ρ*) between the average winter values of the PNA, PDO, ENSO, and AO indices and the prevalence of the twelve typical hazard situations. To test for correlations between climate oscillations, I calculated Pearson correlation coefficient (Kirch, 2008) for each pair of climate oscillations indices for the study period.

A flow chart diagram illustrating the statistical analysis steps of the weather observations, regional avalanche bulletins, and climate oscillation indices is shown in Figure 11.

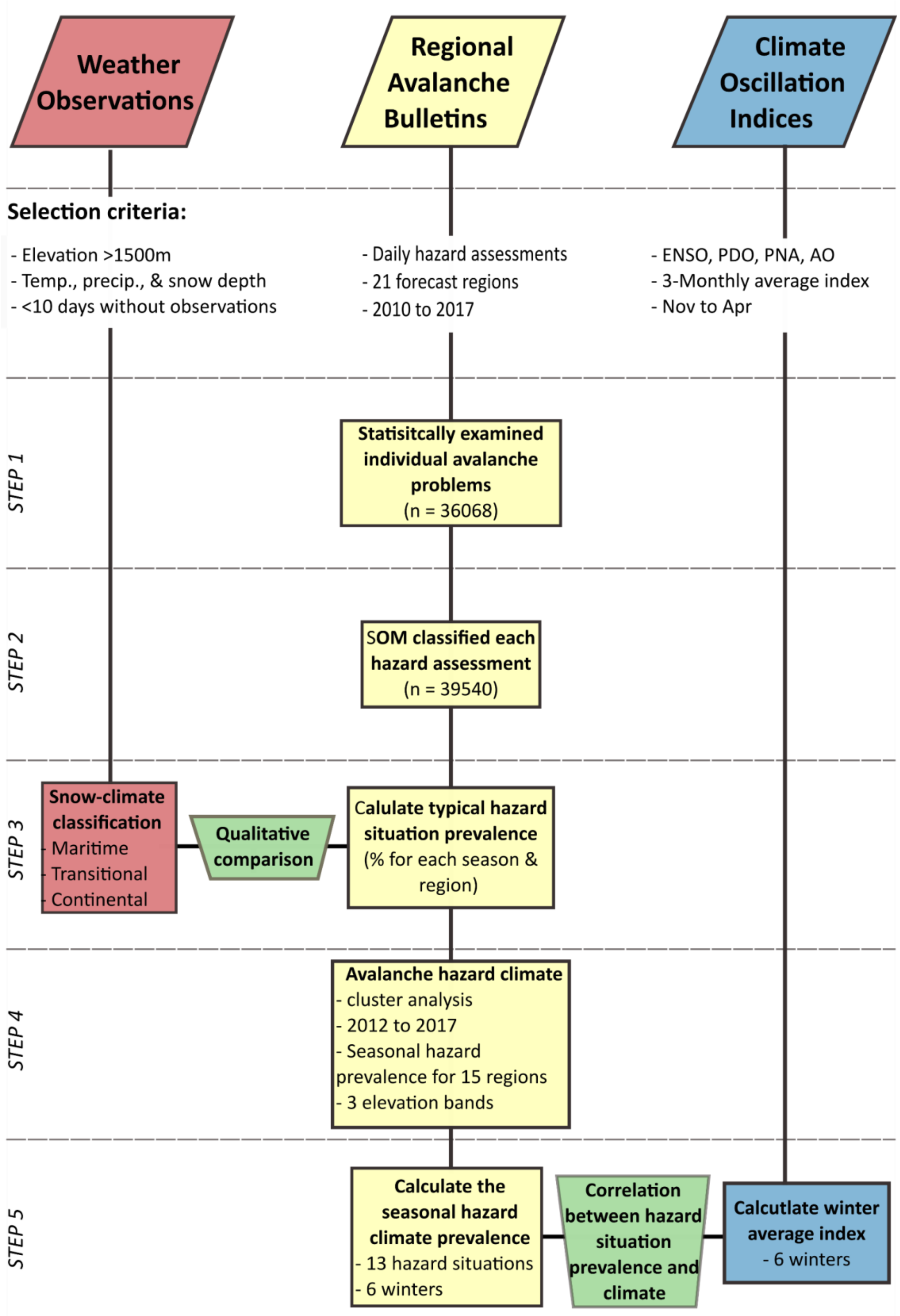


Figure 11: **The methological five steps of the statistical analysis used in this study.**

Results

Step 1: Nature of avalanche problems

Of the 36,068 avalanche problems in the present dataset, *Wind slab avalanche problems* were the most prevalent taking up 29% (n=10,447) of the dataset (Table 5). Wind slab avalanche problems were followed by *Persistent slab avalanche problems* and *Storm slab avalanche problems*, which represented 23% (n=8,315) and 18% (n=6315) of the dataset respectively. The prevalence of all other avalanche problem types was less than 10%. *Wet slab* avalanche problems were the least prevalent with slightly more than one percent of the dataset (n=482).

Table 5: Median hazard chart ordinal values (range from 1 – 9) for each avalanche problem type.

		Likelihood of avalanches[A]			Destructive size[B]		
	N	Min	Typical	Max	Min	Typical	Max
Dry loose avalanche problems	1106	3	5	6	1	2	2
Wet loose avalanche prob.	3092	3	4	6	1	2	3
Storm slab avalanche prob.	6351	3	5	6	1	2	4
Wind slab avalanche prob.	10447	2	4	5	1	2	3
Persistent slab avalanche prob.	8315	2	3	4	2	3	5
Deep persistent slab aval. prob.	3192	1	2	3	3	4	6
Wet slab avalanche prob.	482	2	3	5	2	3	5
Cornices	3083	2	3	5	1	3	5

A Key for numerical values of likelihood of avalanches scale: Unlikely (1), Possible (3), Likely (5), Very likely (7), Almost certain (9)
B Key for numerical values of destructive size scale: Size 1 (1), Size 2 (3), Size 3 (5), Size 4 (7), Size 5 (9)

Examining the median values for likelihood of avalanche and destructive size for each avalanche problem type revealed significant differences between almost all types (Table 5). As expected, *Deep persistent slab avalanche problems* had the lowest triplet values (i.e., minimum, typical and maximum) for the likelihood of avalanches and highest median triplet values for destructive size. *Dry loose avalanche problems* and *Storm slab avalanche problems* exhibited the highest median likelihood of avalanches triplet values, while *Dry loose avalanche problems* had the lowest median destructive size triplet values. Pairwise Wilcoxon rank-sum test comparisons revealed that only *Persistent slab avalanche problems* and *Wet slab avalanche problems* exhibited the same typical values for destructive size (p-value = 0.641). All other comparisons were significantly different from each other.

The height of the squares on the hazard chart (maximum minus minimum), which represent the variability and uncertainty associated with the likelihood of avalanches, showed a considerable correlation with the typical hazard situation prevalence values. *Wet loose avalanche problems*, *Storm slab avalanche problems,* and *Dry loose avalanche problems* exhibited the largest variability, while *Deep persistent slab avalanche problems*, *Persistent avalanche problems* and *Cornice avalanche problems* had the smallest. No significant differences in the height of the square were observed between *Cornice slab avalanche problems* and *Wet slab avalanche problems* (Wilcoxon rank-sum test: p-value: 0.298). Similar patterns were observed regarding the width of the hazard chart squares, which represents the variability and uncertainty regarding destructive size. Here, *Wet slab avalanche problems*, *Cornice avalanche problems* and *Deep persistent slab avalanche problems* had the widest squares, while *Dry loose avalanche problems*, *Wet loose avalanche problems* and *Wind slab avalanche problems* had the narrowest. Only *Cornice avalanche problems* and *Persistent slab avalanche problems* did not differ significantly in their width from each other (Wilcoxon rank-sum test: p-value: 0.300).

The Wilcoxon rank-sum and Fligner-Killeen tests revealed numerous significant differences consistent with the above analysis (Figure 12, Tables 5 & 6). In general, the combined squares of *Storm slab avalanche problems* were located highest on the chart (peak for likelihood of avalanches at likely) and their peak on the destructive size axis is at medium-sized avalanches (Figure 12c). The chart for the combined squares of *Wind slab avalanche problems* (Figure 12d) shows that this type of avalanche problem was typically associated with smaller avalanches that were less likely to be triggered. As expected, *Persistent slab avalanche problems* and *Deep persistent slab avalanche problems* exhibited progressively decreasing likelihoods of avalanches while the destructive size of the associated avalanches increased (Figure 12e & f).

Table 6: Likelihood of avalanches: First quartile (1 Q), median and third quartile (3 Q) and comparison between avalanche problem types (non significant differences highlighted in grey).

Avalanche problem types	Values[A]			Comparisons					
				Wet loose aval. prob.		Storm slab aval. prob.		Wind slab aval. prob.	
	1 Q	Median	3 Q	Wilcoxon[B]	Fligner[C]	Wilcoxon[B]	Fligner[C]	Wilcoxon[B]	Fligner[C]
Dry loose aval. prob.	3	5	5	<0.001	0.025	<0.001	<0.001	<0.001	<0.001
Wet loose aval. prob.	3	4	5			<0.001	<0.001	<0.001	0.001
Storm slab aval prob.	4	5	5					<0.001	<0.001
Wind slab aval. prob.	3	4	5						
Persistent slab aval. prob.	2	3	4						
Deep persistent slab aval. prob.	2	2	3						
Wet slab aval. prob.	2	3	4						
Cornice aval. prob.	3	3	4						

Avalanche problem types	Comparisons (continued)							
	Persistent slab aval. prob.		Deep persistent slab aval. prob.		Wet slab aval. prob.		Cornice aval. probl	
	Wilcoxon[B]	Fligner[C]	Wilcoxon[B]	Fligner[C]	Wilcoxon[B]	Fligner[C]	Wilcoxon[B]	Fligner[C]
Dry loose aval. prob.	<0.001	<0.001	<0.001	<0.001	<0.001	0.631	<0.001	<0.001
Wet loose aval. prob.	<0.001	<0.001	<0.001	<0.001	<0.001	0.086	<0.001	<0.001
Storm slab aval prob.	<0.001	0.296	<0.001	<0.001	<0.001	0.011	<0.001	<0.001
Wind slab aval. prob.	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Persistent slab aval. prob.			<0.001	0.001	0.016	0.063	<0.001	<0.001
Deep persistent slab aval. prob.					<0.001	<0.001	<0.001	<0.001
Wet slab aval. prob.							0.862	<0.001
Cornice aval. prob.								

A Key for numerical values of likelihood of avalanches scale: Unlikely (1), Possible (3), Likely (5), Very likely (7), Almost certain (9)

B p-value for Wilcoxon rank-sum test

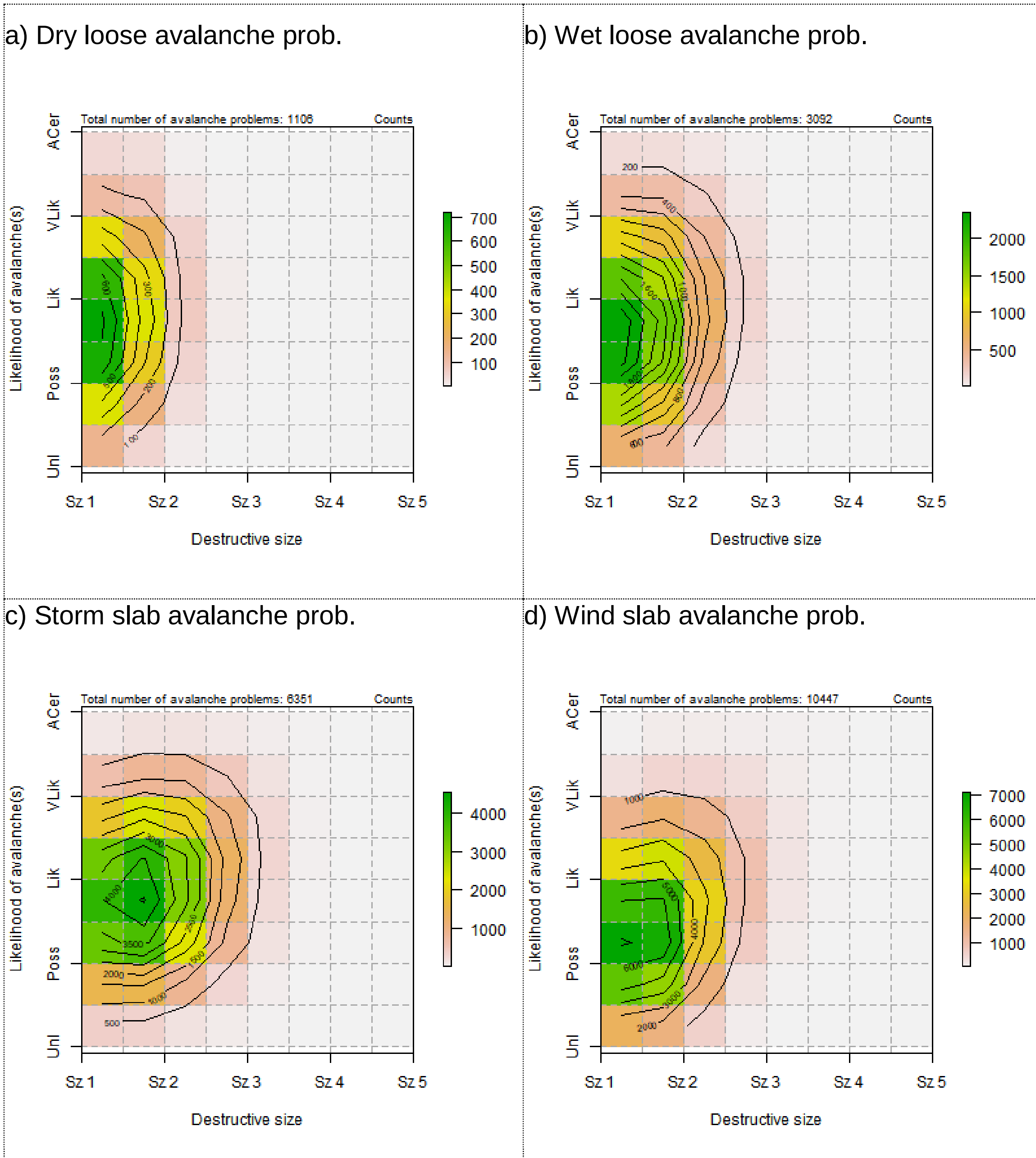
C p-value for Fligner-Killeen test

Table 7: Destructuve size: First quartile (1 Q), median and third quartile (3 Q) and comparison between avalanche problem types (non significant differences highlighted in grey).

Avalanche problem types	Values[A]			Comparisons					
				Wet loose aval. prob.		Storm slab aval. prob.		Wind slab aval. prob.	
	1 Q	Median	3 Q	Wilcoxon[B]	Fligner[C]	Wilcoxon[B]	Fligner[C]	Wilcoxon[B]	Fligner[C]
Dry loose aval. prob.	1	2	2	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Wet loose aval. prob.	1	2	2			<0.001	<0.001	<0.001	<0.001
Storm slab aval prob.	2	2	3					<0.001	<0.001
Wind slab aval. prob.	2	2	2						
Persistent slab aval. prob.	3	3	4						
Deep persistent slab aval. prob.	3	4	5						
Wet slab aval. prob.	3	3	4						
Cornice aval. prob.	2	3	3						

Avalanche problem types	Comparisons (continued)							
	Persistent slab aval. prob.		Deep persistent slab aval. prob.		Wet slab aval. prob.		Cornice aval. probl	
	Wilcoxon[B]	Fligner[C]	Wilcoxon[B]	Fligner[C]	Wilcoxon[B]	Fligner[C]	Wilcoxon[B]	Fligner[C]
Dry loose aval. prob.	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Wet loose aval. prob.	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Storm slab aval prob.	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Wind slab aval. prob.	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Persistent slab aval. prob.			<0.001	0.001	0.016	<0.001	<0.001	0.186
Deep persistent slab aval. prob.					<0.001	<0.001	<0.001	0.053
Wet slab aval. prob.							<0.001	<0.001
Cornice aval. prob.								

A Key for numerical values of destructive size scale: Size 1 (1), Size 2 (3), Size 3 (5), Size 4 (7), Size 5 (9)
B p-value for Wilcoxon rank-sum test
C p-value for Fligner-Killeen test


a) Dry loose avalanche prob.
Total number of avalanche problems: 1106
Counts
700
600
500
400
300
200
100
b) Wet loose avalanche prob.
Total number of avalanche problems: 3092
Counts
2000
1500
1000
500
c) Storm slab avalanche prob.
Total number of avalanche problems: 6351
Counts
4000
3000
2000
1000
d) Wind slab avalanche prob.
Total number of avalanche problems: 10447
Counts
7000
6000
5000
4000
3000
2000
1000
Likelihood of avalanche(s)
ACer
VLik
Lik
Poss
Unl
Sz 1
Sz 2
Sz 3
Sz 4
Sz 5
Destructive size

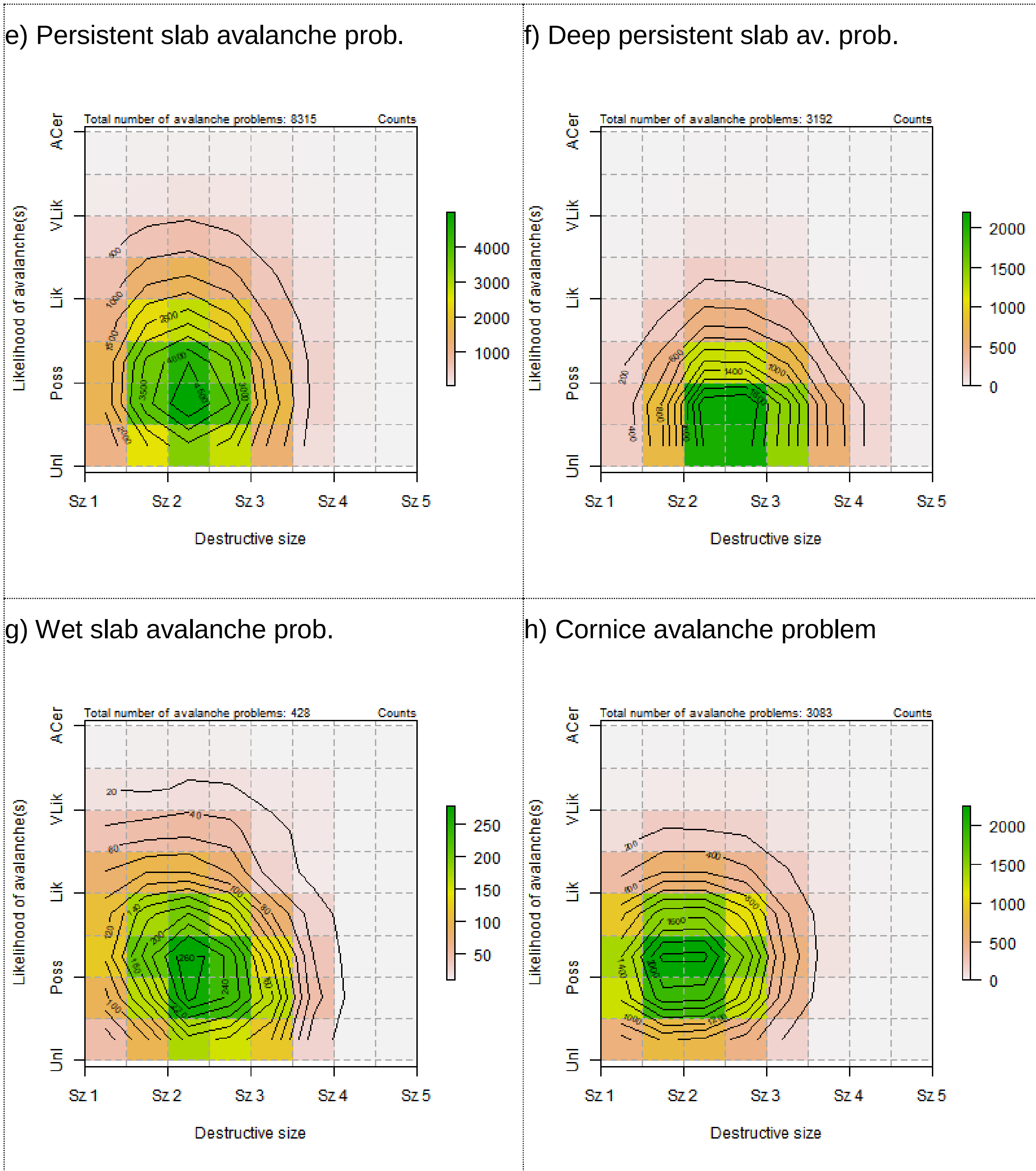


Figure 12: **Avalanche hazard summary charts comparing likelihood of avalanches with destructve size for individual avalanche problem types for all seasons, forecast regions, and elevation bands. Shading of individual grid cells goes from grey (0 avalanche problem squares in this cell) to green (maximum number of avalanche problem squares in this cell). Contour line intervals vary for each type of avalanche problem to enhance the visibility of the spatial patterns. Note the total number of avalanche problems varies for each type.**

Step 2: Typical hazard situations

The topographical and quantization error for various SOM grid sizes (Figure 13) showed that the topographic error is constant and independent of grid size while a considerable marginal reduction in the quantization error can be seen with increasing grid size.

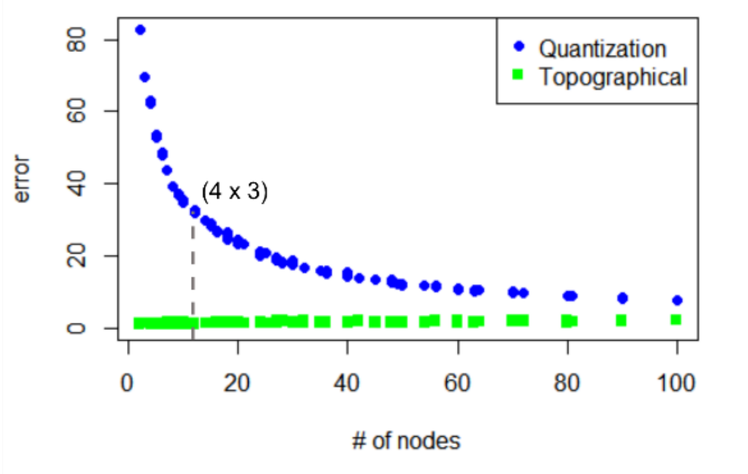


Figure 13: Quantization and topographical errors for SOM at various grid sizes.

Balancing cluster error and interpretability of the emerging clusters, I selected a 4×3 grid (i.e., 12 nodes) for the final SOM analysis. My analysis, therefore, identified twelve typical avalanche hazard situations, and each assessment in my dataset was assigned to one of these situations (Table 8). Hazard assessments that contained no avalanche problems were automatically assigned into an additional *No avalanche problems hazard situation* class separate from the SOM analysis.

Table 8: Elevation band specific distribution of SOM classified typical hazard situations.

Hazard Situation	Overall		No danger ratings		Danger ratings[A]			Alpine		Treeline		Below treeline	
	N	(%)	N	(%)	1Q	Median	3Q	N	(%)	N	(%)	N	(%)
No avalanche problems	5862	(15)	232	(4)	1	1	1	122	(1)	667	(5)	5073	(38)
Loose dry avalanche	1447	(4)	4	(<1)	1	2	2	493	(4)	520	(4)	434	(3)
Wind slab	4492	(11)	105	(2)	2	2	2	2517	(19)	1771	(13)	204	(2)
Storm slab	4475	(11)	79	(2)	2	3	3	1267	(10)	1957	(15)	1251	(9)
Storm & wind slab	1448	(4)	5	(<1)	3	3	3	765	(6)	631	(5)	52	(<1)
Storm & persistent slab	3643	(9)	8	(<1)	2	3	3	1338	(10)	1419	(11)	886	(7)
Storm & deep persistent slab	1483	(4)	0	(0)	3	3	3	674	(5)	632	(5)	177	(1)
Storm, wind, & persistent slab	1058	(3)	3	(<1)	3	3	4	455	(3)	586	(4)	17	(<1)
Persistent slab	3141	(8)	9	(<1)	2	2	3	512	(4)	706	(5)	1923	(15)
Persistent slab plus	4766	(12)	14	(<1)	2	3	3	2395	(18)	2258	(17)	113	(1)
Deep persistent slab	3572	(9)	57	(2)	2	2	3	1665	(13)	1425	(11)	482	(4)
Spring-like	3068	(8)	258	(8)	1	2	2	641	(5)	813	(6)	1614	(12)
Loose wet & persistent slab	1085	(3)	4	(<1)	2	2	3	336	(3)	501	(4)	248	(2)
Overall	**39540**		**778**					**13180**		**13180**		**13180**	

A Key for numerical danger ratings scale: Low (1), Moderate (2), Considerable (3), High (4), Extreme (5)

Table 9: Danger ratings: Comparison between typical hazard situations.

Avalanche problem types	**Values[A]**			**Comparisons**				
	1 Q	**Median**	**3 Q**	**Wind slab**	**Storm slab**	**Storm & wind slab**	**Storm & pers. slab**	**Storm & deep pers.**
No avalanche problems	1	1	1	<0.001	<0.001	<0.001	<0.001	<0.001
Loose dry avalanche	1	2	2	<0.001	<0.001	<0.001	<0.001	<0.001
Wind slab	2	2	2		<0.001	<0.001	<0.001	<0.001
Storm slab	2	3	3			<0.001	<0.001	<0.001
Storm & wind slab	3	3	3				<0.001	<0.001
Storm & persistent slab	2	3	3					<0.001
Storm & deep persistent slab	3	3	3					
Storm, wind, & persistent slab	3	3	4					
Persistent slab	2	2	3					
Persistent slab plus	2	3	3					
Deep persistent slab	2	2	3					
Spring-like	1	2	2					
Loose wet & persistent slab	2	2	3					

Avalanche problem types	**Comparisons (continued)**					
	Storm, wind & pers.	**Persistent slab**	**Persistent slab plus**	**Deep persistent slab**	**Spring-like**	**Loose wet & persistent**
No avalanche problems	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Loose dry avalanche	<0.001	<0.001	<0.001	<0.001	0.110	<0.001
Wind slab	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Storm slab	<0.001	<0.001	0.868	<0.001	<0.001	0.027
Storm & wind slab	<0.001	<0.001	<0.001	0.087	<0.001	<0.001
Storm & persistent slab	<0.001	<0.001	<0.001	<0.001	<0.001	0.066
Storm & deep persistent slab	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Storm, wind, & persistent slab		<0.001	<0.001	<0.001	<0.001	<0.001
Persistent slab			<0.001	<0.001	<0.001	<0.001
Persistent slab plus				<0.001	<0.001	0.007
Deep persistent slab					<0.001	<0.001
Spring-like						<0.001

A Key for numerical danger ratings scale: Low (1), Moderate (2), Considerable (3), High (4), Extreme (5)

In addition to the *No avalanche problem hazard situation* (median danger ratings: Q1 – 1, Med. – 1, Q3 – 1), there were two hazard situations that generally represent low hazard conditions during the main winter months. The *Loose dry avalanche* hazard situation (Figure 14b) consisted mostly of dry loose avalanche problems, but had a substantial contribution from wind slab avalanche problems. Overall, the danger ratings of this hazard situation were the lowest among all hazard situation types (median danger ratings: Q1 – 1, Med. – 2, Q3 – 2). The pure *Wind slab* hazard situation (Figure 14c) included assessments with relatively low likelihood of small avalanches and therefore had a low mean danger rating (Q1 – 2, Med. – 2, Q3 – 2). Within my dataset, these two hazard situations occurred 4% and 11% of the time, respectively. While the *Loose dry* hazard situation was assigned evenly in all elevation bands, the pure *Wind slab* hazard situation was much more dominant in the alpine and at treeline (19% and 13%), while it was hardly ever assessed below treeline (2%).

Five distinct hazard situations were identified for hazard assessments that predominantly contain a storm slab avalanche problem. The pure *Storm slab* hazard situation (Figure 14d) was generally the classification for assessments with only a storm slab avalanche problem and therefore had the lowest median danger rating of the five storm slab situations (Wilcoxon rank-sum test: p-value < 0.001). This hazard situation occurred more frequently in treeline (15%) than in the alpine and at below treeline (10% and 9% respectively). The added wind slab avalanche problem made the *Storm & wind slab* hazard situation (Figure 14e) significantly more severe. Consistent with the pure *Wind slab* hazard situation, the *Storm & wind slab* hazard situation was observed more frequently in the alpine and at treeline. The *Storm & deep persistent slab* hazard situation (Figure 14g) was more severe than the *Storm & persistent slab* (Figure 14f), but the *Storm, wind & persistent slab* hazard situation (Figure 14h) was the most severe of all the storm slab hazard situations. The three hazard situations – *Storm & wind slab*, *Storm & deep persistent slab*, and *Storm, wind & persistent slab* hazard situation – all occurred approximately 5% in the alpine and at treeline, but they were rarely observed below treeline.

Three of the identified hazard situations were dominated by persistent weaknesses in the snowpack. Both the *Persistent slab* and *Persistent slab plus* hazard situations (Figure 14i and Figure 14j) were characterized by persistent slab avalanche problems, but they differed in their severity. Despite having similar median hazard charts, the median danger rating of the *Persistent slab plus* situation was significantly higher than the median of the *Persistent slab* situation (3 versus 2; Wilcoxon rank-sum test: p-value < 0.001). Deep persistent and wind slab avalanches problems were most common for the *Deep persistent slab* hazard situation (Figure 14k). While the *Persistent slab* hazard situation was most prominent below treeline (15%), the other two situations were more frequently assigned in the alpine and at treeline. It is noteworthy that all hazard situations with persistent weaknesses frequently included wind slab avalanche problems.

The last two typical hazard situations represent conditions that generally occur during warmer temperatures. The *Spring-like* hazard situation (Figure 14l) primarily consisted of wet loose and slab avalanches. As expected, this hazard situation was significantly more prevalent below treeline (12%) than above (5% in alpine and 6% at treeline) (Chi-square test: p-value < 0.001). This hazard situation also had the highest percentage of assessments that did not have a danger rating associated with it (8%). The *Loose wet & persistent slab* hazard situation (Figure 14m) typically occurred during periods of warm wet weather caused by Pineapple Expresses events, which can occur anytime during a winter.

Over the entire study period, all forecast regions and all elevation bands, the most common hazard situations were the *Persistent slab plus* hazard situation (12% of assessments), the pure *Wind slab* hazard situation (11%) and the pure *Storm slab* hazard situations (11%). These hazard situations were closely followed by the *Storm & persistent slab* hazard situation (9%), *Deep persistent slab* hazard situation (9%), *Persistent slab* hazard situation (8%), and *Spring-like* hazard situation (8%). The prevalence of all other hazard situations was less than 5%.

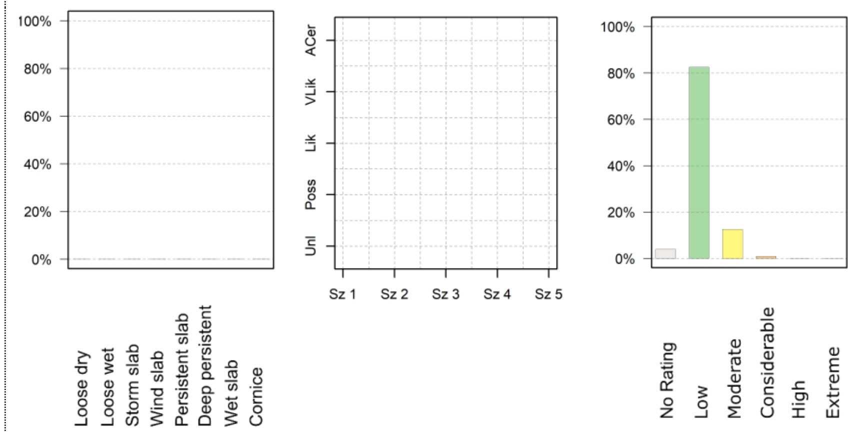
Typical avalanche hazard situations

Hazard situation avalanche problem type distribution

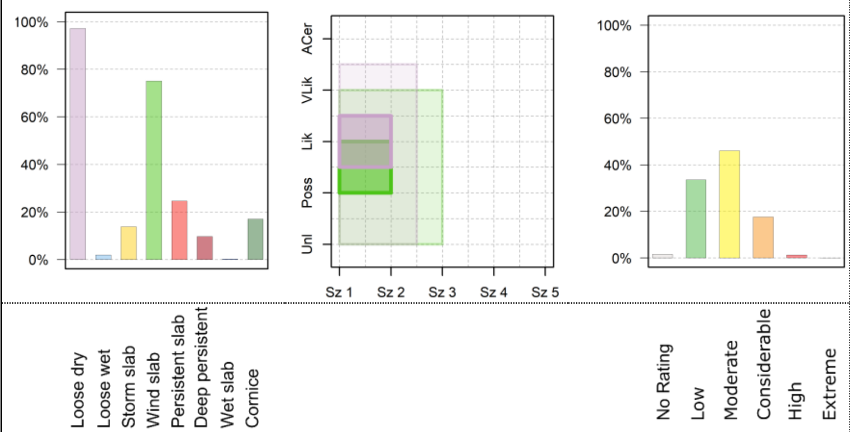
Hazard situation median hazard chart

Hazard situation danger rating distribution

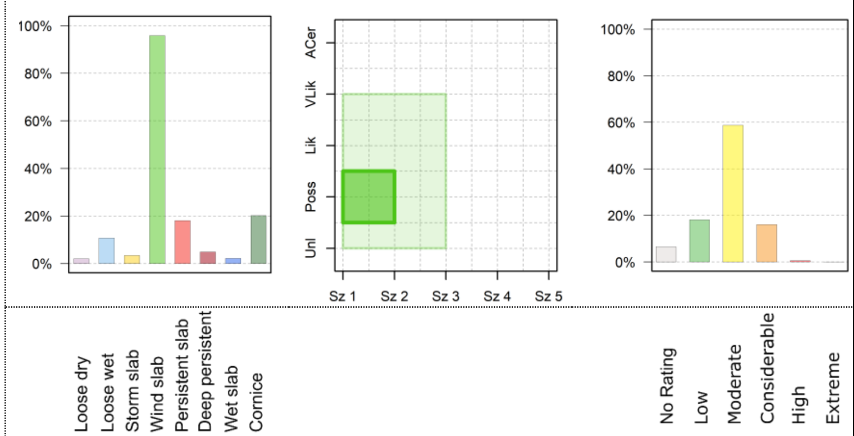
a) No avalanche problems



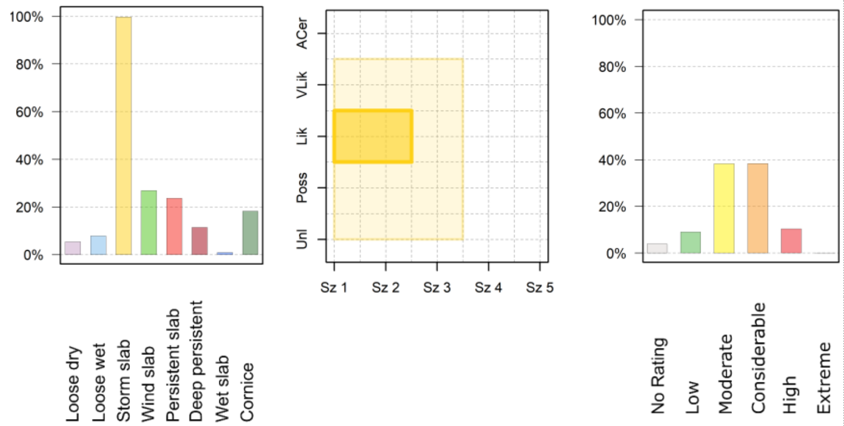
b) Loose dry and wind slab situation



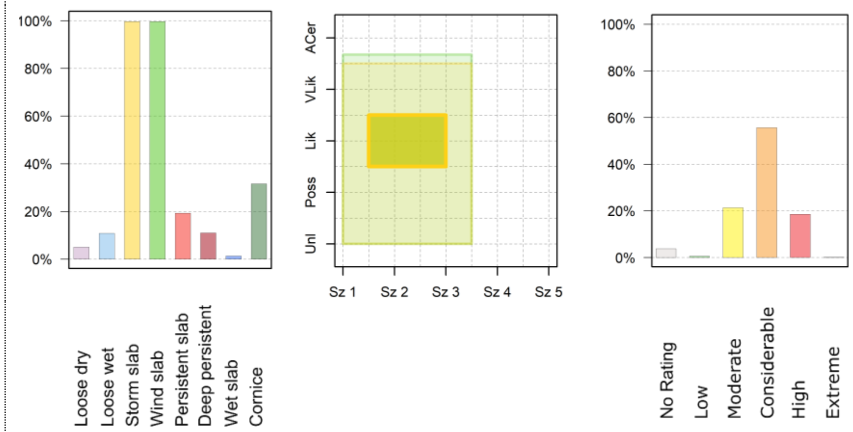
c) Wind slab situation



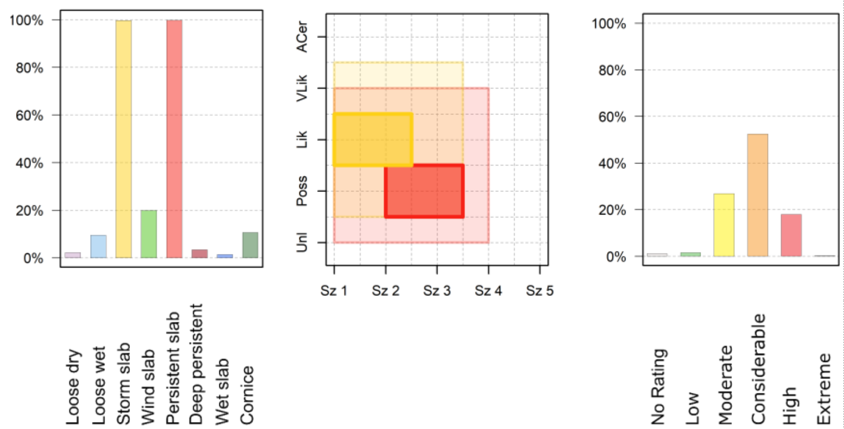
d) Storm slab situation



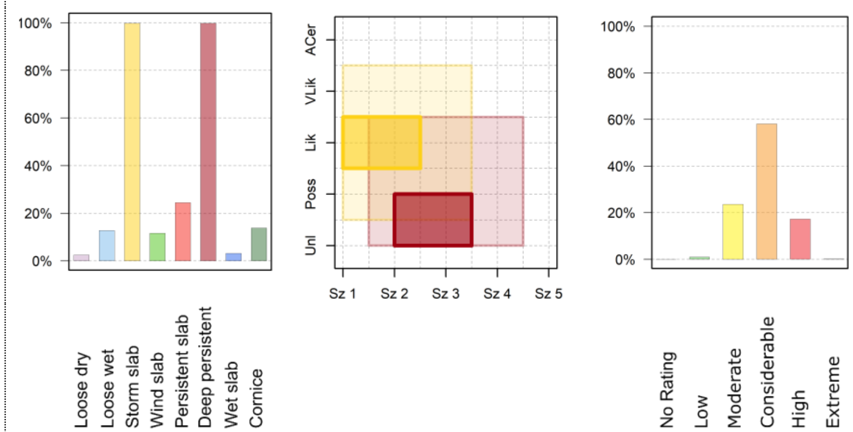
e) Storm and wind slab situation



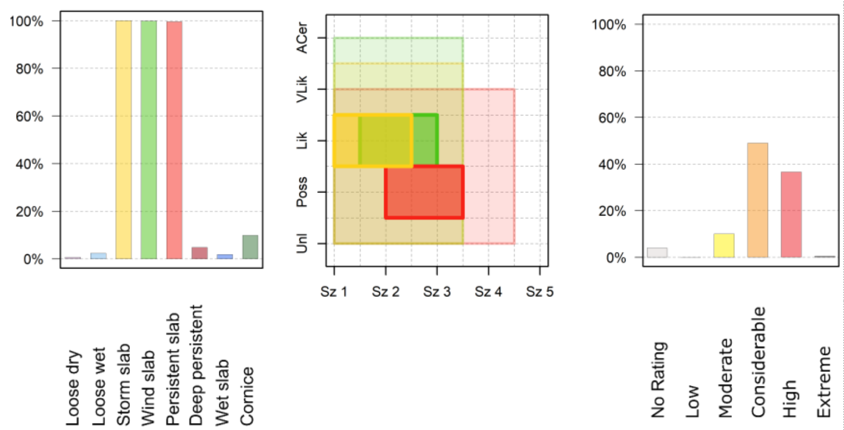
f) Storm and persistent slab situation



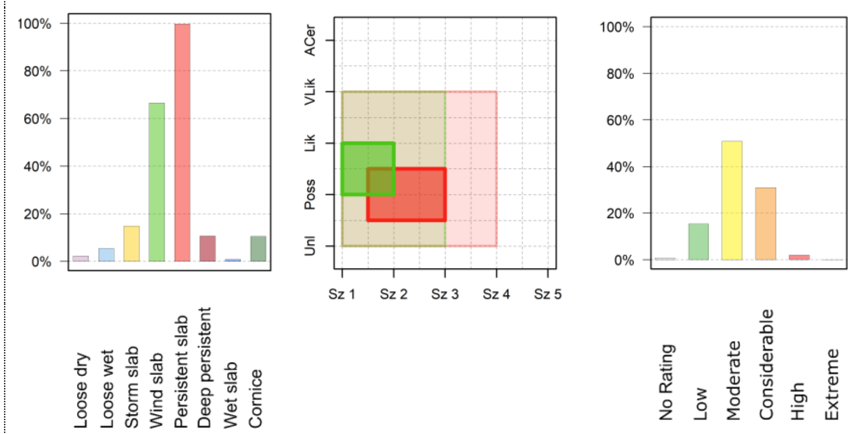
f) Storm and deep persistent slab situation



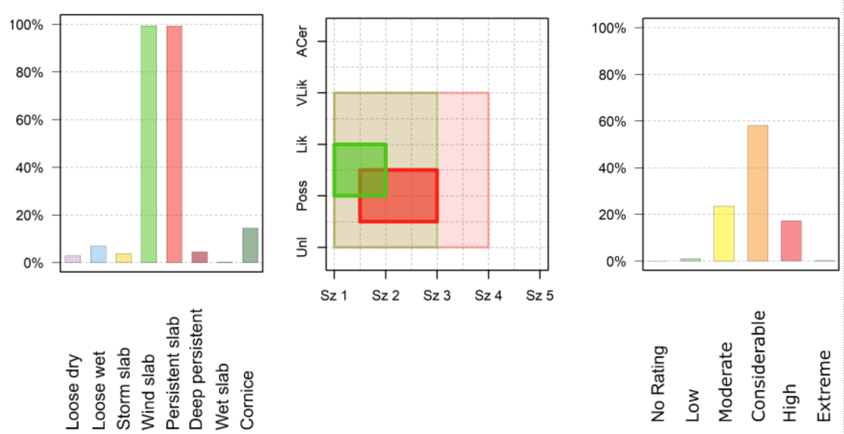
g) **Storm, wind and persistent slab situation**



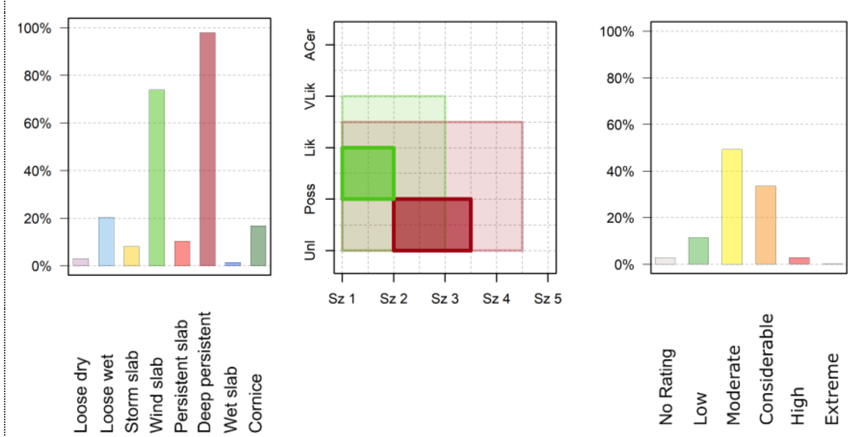
h) **Persistent slab situation**



i) **Persistent slab plus situation**



j) **Deep persistent slabs situation**



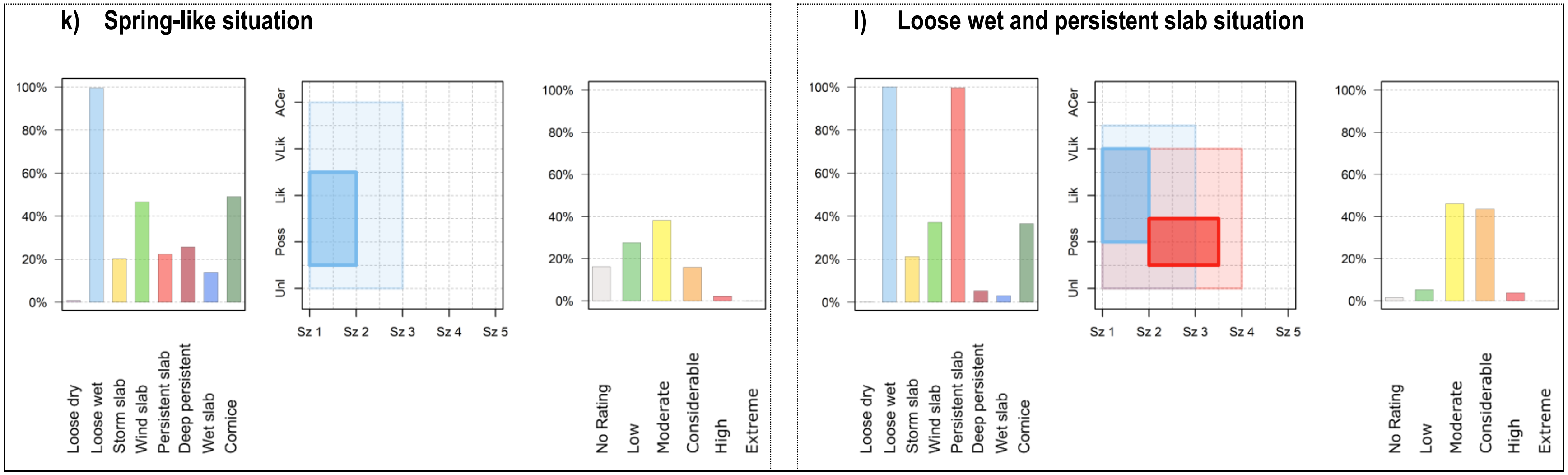


Figure 14: **Hazard characteristcs of the 12 typical hazard situations including the avalanche problem distribution, median hazard char, and danger rating distribution.**

Overall, the analysis revealed that the avalanche conditions below treeline were dominated by the *No avalanche problems* hazard situations, which account for 38% assessments. When there was an avalanche problem, the conditions were relatively simple and of lower severity. The three avalanche hazard situations *Storm slab* hazard situation (9%), *Persistent slab* hazard situation (15%) and *Spring-like* hazard situation (12%) accounted for an additional 36% of the assessments. The distribution of the typical hazard situations in the alpine and treeline elevation bands were very similar. The most common hazard situations in these elevation band were pure *Wind slabs* (19% in alpine and 13% at treeline) and the more severe *Persistent slab plus* hazard situation (18% and 17%). The three hazard situations *Storm slabs*, *Storm & persistent slabs* and *Deep persistent slabs* combined were responsible for another 30% of the hazard situations in the alpine and at treeline. These results nicely illustrate that avalanche hazard situations in the alpine and at treeline are more complex and more varied than below treeline.

Step 3: Winter characterization

Seasonal snow climate classification

The application of the Mock and Birkeland (2000) algorithm to the averages of the available weather observations over all seasons (2009/10 to 2016/17) generally agree with the traditional snow climate classification of the three general mountain ranges (Table 10). Two of the three weather stations in the Coast Mountains were classified as maritime, while Blowdown Mid-Mountain, which is located in the Eastern section of the Coast Mountains (Duffy Lake region), were classified as transitional. Five of the six weather stations in the Columbia Mountains were assessed as having a transitional snow climate. The only non-transitional weather site in the Columbia Mountains was Kootenay Pass. This weather site was classified as maritime, which is consistent with its reputation as having larger amounts of new snow. All the weather stations in the Rocky Mountains were classified as having a continental snow climate.

While the overall patterns confirm the existing snow climate classification, the winter-by-winter analysis revealed considerable variations in annual classifications. Within the study period, the 2014/15 and 2015/16 seasons emerged as the most maritime winters with more stations in the Columbia Mountains classified as maritime due to warmer average temperature and more rainfall. The 2016/17 season was the most continental winter with three weather stations in the Columbia Mountains, receiving a continental classification due to strong December temperature gradients, and the two stations in the Coast Mountains being classified as transitional. The three winters 2011/12, 2012/13 and 2013/14 had overall a slightly more continental character with more continental classifications in the Coast and Columbia Mountains due to colder average air temperatures. During the study period, the 2009/10 and 2010/11 winters exhibited characteristics that were most similar to the overall snow-climate classification.

Table 10: Overall and seasonal snow climate classifications according to Mock & Birkeland (2000): maritime (green), transitional (grey), continental (blue). The number in each field represents the decision in the classification flow chart (Figure 10). Seasons with insufficient weather observations are indicated with n/a.

	Elevation (relative location)	Overall	2009/10	2010/11	2011/12	2012/13	2013/14	2014/15	2015/16	2016/17
Coastal Ranges										
Whistler	1835 m (*mtn*)	1	1	4	2	n/a	5	1	1	5
Blowdown	1890 m (*mid mtn*)	5	7	5	5	7	5	1	5	5
Little Bear	1660 m (mtn)	1	2	1	5	5	4	1	1	n/a
Columbia Ranges										
Sliding Mountain	1675 m (mtn)	7	7	7	7	7	7	1	2	3
Sun Peaks	2055 m (mtn)	7	n/a	n/a	6	6	6	7	7	3
Apex	1750 m (mid mtn)	7	7	7	7	7	3	2	7	3
London Ridge	2070 m (mtn)	5	7	5	5	n/a	5	5	5	5
Whitewater	1950 m (mtn)	7	6	n/a	5	5	5	7	n/a	5
Kootenay Pass	1780 m (mid mtn)	1	5	5	6	n/a	5	1	2	1
Rocky Mountains										
Chatter Creek	1615 m (valley)	6	6	3	5	5	5	3	7	3
Panorama	2356 m (mtn)	3	3	3	6	3	3	3	3	3
Lake Louise	2200 m (mtn)	3	7	3	n/a	3	3	3	3	3
Kananaskis	1890 m (valley)	3	n/a	3	3	3	3	3	3	3

Typical hazard situation prevalence

Similar to the seasonal snow climate classification, the analysis of the seasonal hazard situation prevalence revealed substantial winter-to-winter variabilities (Figure 15).

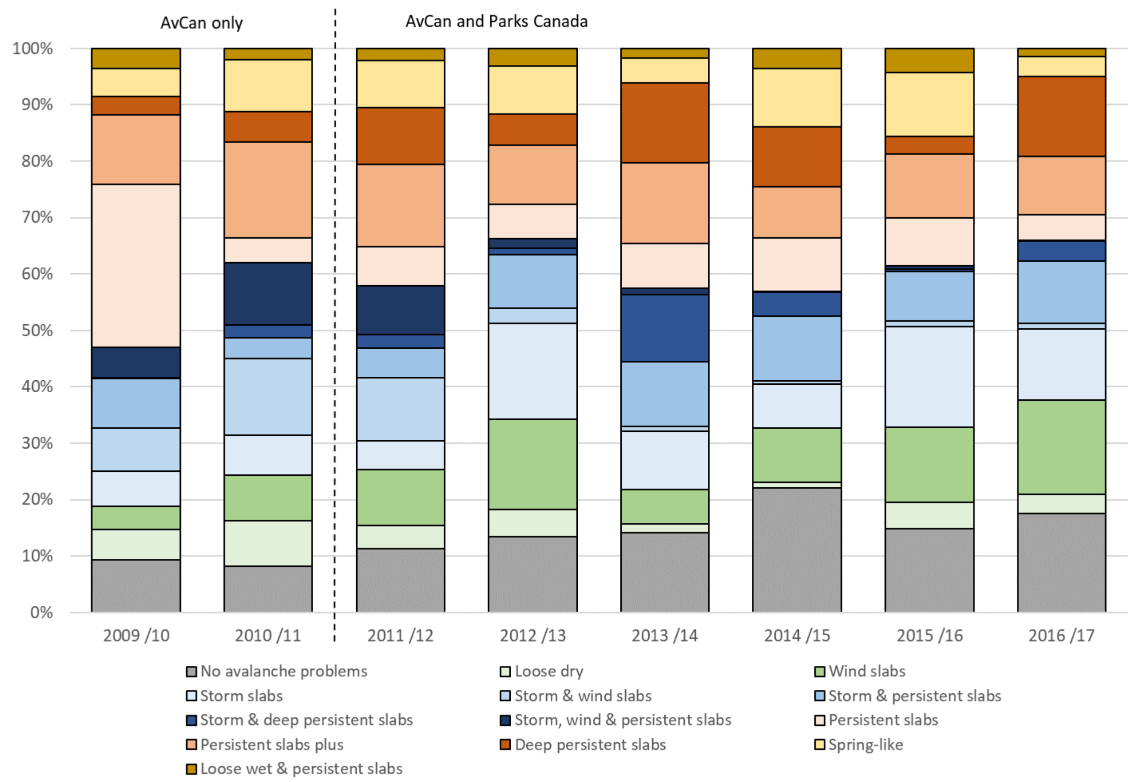


Figure 15: Seasonal prevalence of typical hazard situations.

During the winter seasons when bulletins were available from both Avalanche Canada and Parks Canada (2011/12 to 2016/17; Table 11), the 2012/13 and 2014/15 winters were most normal (i.e., most similar to long-term averages). The winter of 2011/12 was characterized by a higher prevalence of *Storm & wind slab* and *Storm, wind & persistent slab* hazard situations (+8 and +7 percentage points relative to 2011/12–2016/17 average) at the expense of the equivalent hazard situations without wind slab avalanche problems (i.e., *Storm slab* and *Storm & persistent slab* hazard situations). The 2013/14 winter was dominated by the presence of a deep persistent avalanche problem, which resulted in increased prevalence of *Deep persistent* and *Storm & deep persistent* hazard situations (+5 and +8 percentage points) and fewer *Wind slab* hazard situations (-6 percentage points). The winter of 2015/16 saw an additional 6 percentage points of *Storm slab* hazard situations, while the prevalence of *Deep persistent slab* hazard situations was 6 percentage points lower. The 2016/17 winter was substantially different again as it was characterized by more *Wind slab* hazard situations (+5 percentage points), more *Deep persistent slab* situations (+5 percentage points) and fewer *Spring-like* hazard situations (-4 percentage points).

Table 11: Typical hazard situation prevalence in percent for all of Western Canada from 2011/12 to 2016/17, overall mean and winter season anomalies. Orange shading denotes positive anomalies, and blue shading indicates negative anomalies greater than 5 percentage points.

Hazard situation	Mean	Yearly anomaly							
		2009 /10	2010 /11	2011 /12	2012 /13	2013 /14	2014 /15	2015 /16	2016 /17
No avalanche problems	15	n/a	n/a	-4	-2	-1	7	-1	2
Loose dry avalanche	3	n/a	n/a	1	2	-2	-2	1	0
Wind slab	12	n/a	n/a	-2	4	-6	-2	1	5
Storm slab	12	n/a	n/a	-7	5	-1	-4	6	1
Storm & wind slab	3	n/a	n/a	8	0	-2	-2	-2	-2
Storm & persistent slab	10	n/a	n/a	-4	0	2	2	-1	2
Storm & deep persistent slab	4	n/a	n/a	-2	-3	8	0	-3	0
Storm, wind, & persistent slab	2	n/a	n/a	7	0	-1	-2	-1	-2
Persistent slab	7	n/a	n/a	0	-1	1	2	1	-3
Persistent slab +	12	n/a	n/a	3	-1	3	-3	0	-1
Deep persistent slab	10	n/a	n/a	1	-4	5	1	-6	5
Spring-like	8	n/a	n/a	0	1	-3	3	4	-4
Loose wet & persistent slab	3	n/a	n/a	-1	0	-1	1	1	-1

Among the two winters when bulletins were only available from Avalanche Canada (Table 12), the 2009/10 winter stands out due to its extremely high prevalence of *Persistent slab* avalanche hazard situation (+21 percentage points relative to overall average with Avalanche Canada bulletins only). The winter of 2010/11 exhibited an increase in *Storm & wind slab* and *Storm, wind & persistent slab* hazard situations similar to the 2011/12 winter (+10 and +8 percentage points), but this time it was due to a lower prevalence of *Storm slab* and *Storm & persistent slab* hazard situations. While the lack of Parks Canada bulletins could at least partially be responsible for the lower prevalence of persistent slab related hazard situations during the 2011/12 winter, it cannot explain the extremely high prevalence of *Persistent slab* avalanche hazard situations in the 2009/10 winter. The similarities in the anomaly patterns for the winters 2011/12 to 2016/17 with and without the Parks Canada bulletins further support the conclusion that the observed patterns for the first two winters in my study period are meaningful representations of the overall hazard conditions.

Table 12: Typical hazard situation prevalence in percent for Avalanche Canada forecast regions over entire study period, overall mean and winter season anomalies. Orange shading denotes positive anomalies, and blue shading indicates negative anomalies great than 5 percentage points.

Hazard situation	Mean	Yearly anomaly							
		2009 /10	2010 /11	2011 /12	2012 /13	2013 /14	2014 /15	2015 /16	2016 /17
No avalanche problems	15	-5	-6	-4	-2	-1	8	1	3
Loose dry avalanche	3	3	5	1	1	-2	-2	0	-1
Wind slab	12	-8	-4	-1	4	-6	-1	3	6
Storm slab	12	-6	-5	-7	6	-1	-4	8	2
Storm & wind slab	4	4	10	9	-1	-4	-3	-3	-3
Storm & persistent slab	10	-1	-6	-5	1	3	2	0	3
Storm & deep persistent slab	4	-4	-2	-2	-3	10	0	-3	0
Storm, wind, & persistent slab	3	2	8	7	-1	-3	-3	-2	-3
Persistent slab	8	21	-3	-1	-2	0	1	-1	-3
Persistent slab plus	13	0	4	4	-2	2	-2	-2	-1
Deep persistent slab	7	-3	-1	0	-2	6	0	-4	4
Spring-like	8	-3	1	1	1	-3	3	3	-5
Loose wet & persistent slab	3	1	-1	-1	1	-1	1	2	-1

Step 4: Avalanche hazard climate zones

Clustering

The cluster analysis of the hazard situation prevalence time series was conducted at each elevation band to identify groups of forecasts regions where avalanche hazard behaved similarly during the 2011/12 to 2016/17 winter seasons. The dendrograms for each elevation band including the multiscale bootstrap probability values are shown in Figure 16.

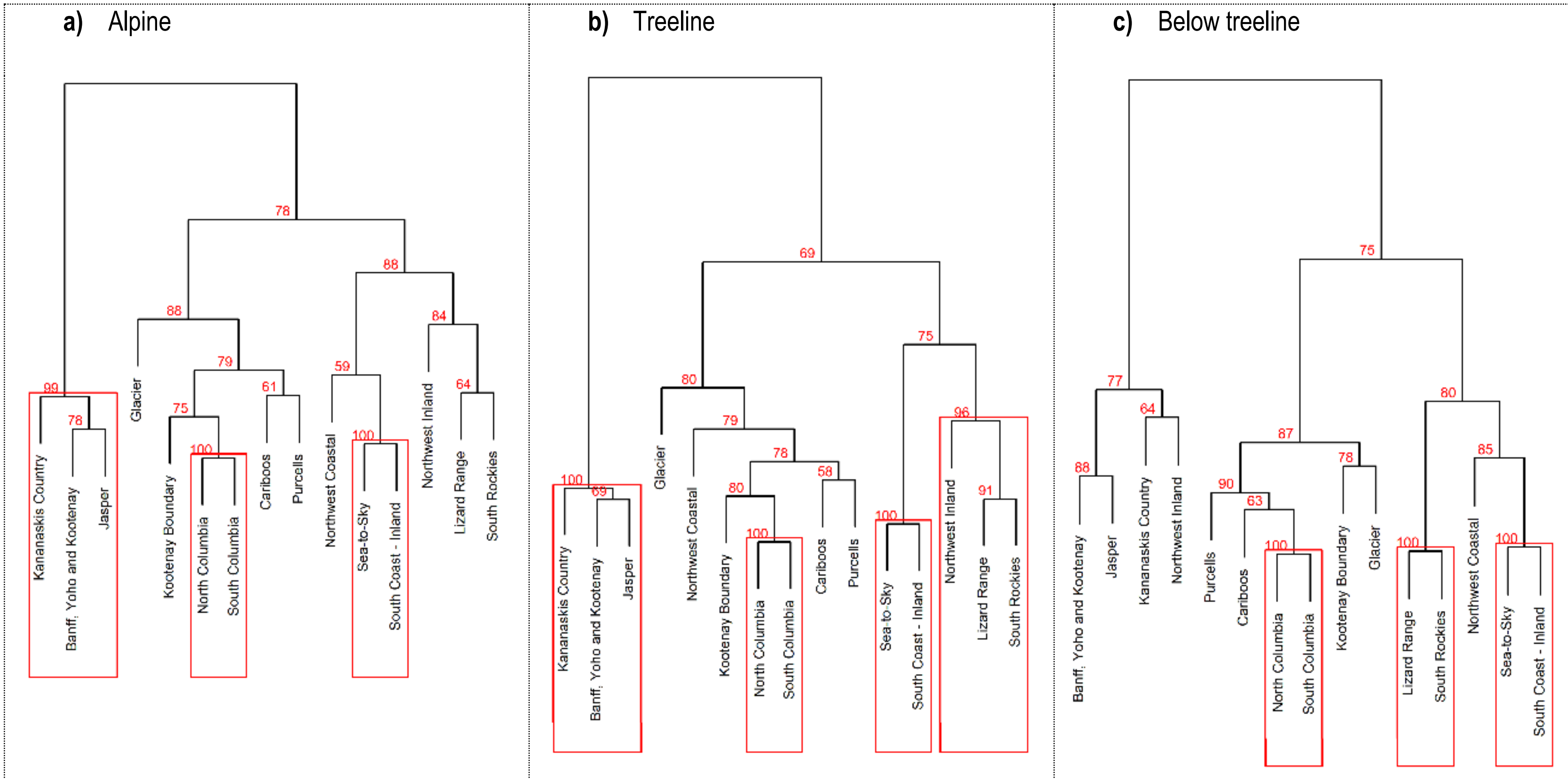


Figure 16: **Forecast region hazard prevalence cluster analysis dendrogram for alpine, treeline, and below treeline elevation bands.**

The cluster analysis of the hazard situation prevalence time series in the alpine revealed eleven areas with distinct avalanche hazard characteristics during the last six winters (Figure 17). Eight forecast regions exhibited hazard situation prevalence time series that were distinct enough to be considered independent avalanche hazard climate zones (Northwest Coastal, Northwest Inland, Cariboos, Glacier, Purcells, Kootenay Boundary, South Rockies, and Lizard Range). The remaining seven regions were clustered into three zones. First, the Sea-to-Sky and South Coast Inland were grouped into a cluster, which I will refer to as *South Coast* avalanche hazard climate zone. Secondly, the North and South Columbia forecast regions were combined into a single avalanche hazard climate zone, which I will call *Columbias*. The third grouping includes Jasper, Banff Yoho & Kootenay, and Kananaskis Country forecast regions, which I named the *Central Rocky Mountains* avalanche hazard climate zone.

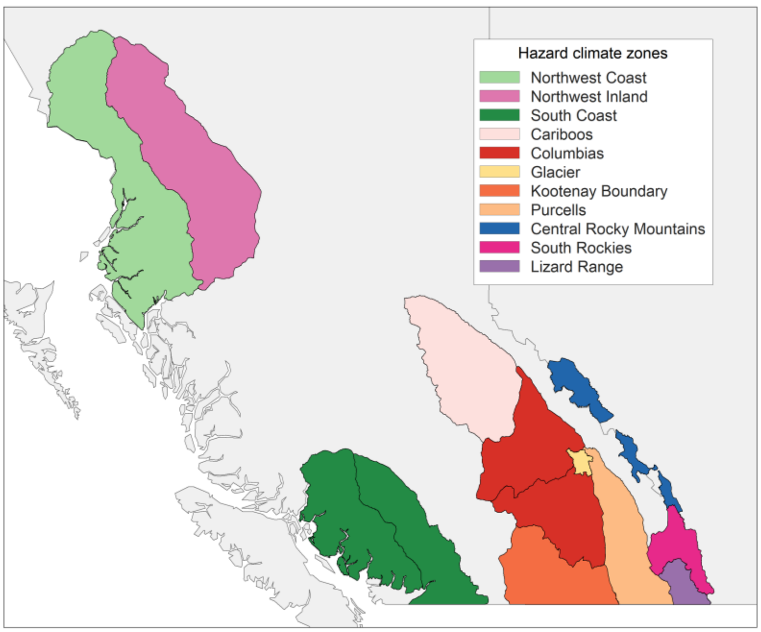


Figure 17: Avalanche hazard climate zones for alpine elevations.

The cluster analysis of treeline hazard situation prevalence time series formed areas similar to alpine with one additional grouping (Figure 18). At this elevation band, five forecast regions exhibited hazard situation prevalence time series that were distinct enough to be considered independent avalanche hazard climate zones (Northwest Coastal, Cariboos, Glacier, Purcells, and Kootenay Boundary). Similar to the alpine elevation band, the *South Coast*, *Columbias,* and *Central Rocky Mountains* avalanche hazard climate zones emerged in the treeline elevation band. However, the Northwest Inland, South Rockies, and Lizard Range forecast regions exhibited similar typical hazard situation prevalence time series to be amalgamated into a zone. I will refer to it as *Northwest Inland* and *Southern Rocky Mountains* avalanche hazard climate zone.

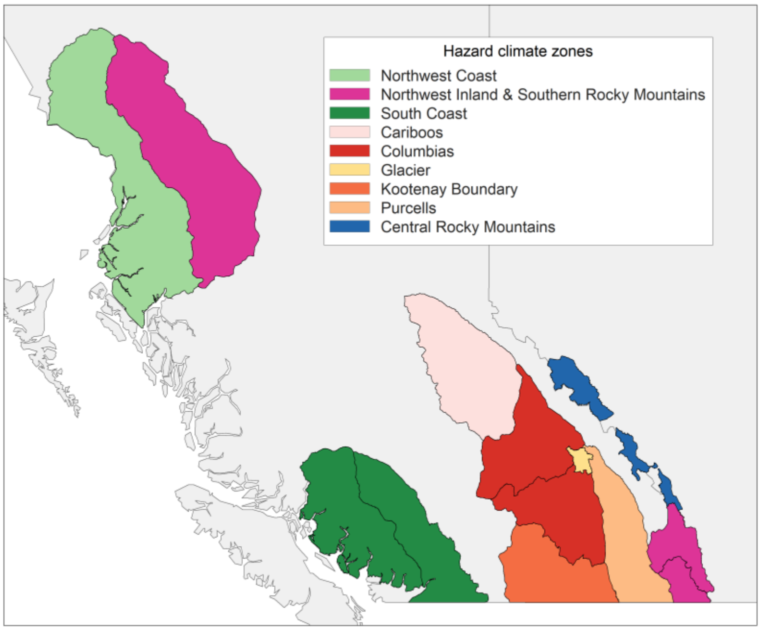


Figure 18: Avalanche hazard climate zones for treeline elevations.

The cluster analysis of hazard situation prevalence time series below treeline clustered twelve different areas with distinct hazard characteristics (Figure 19). In this case, nine forecast regions displayed unique hazard situation prevalence time series to be considered independent avalanche hazard climate zones (Northwest Coastal, Northwest Inland, Cariboo, Glacier, Purcells, Kootenay-Boundary, Jasper, Banff, Yoho & Kootenay Lake, and Kananaskis Country). Six of the forecast regions were clustered into three zones. Similar to the alpine and treeline elevation band, the *South Coast* and *Columbias* avalanche hazard climate zones were identified in the below treeline elevation band. However, the *Southern Rocky Mountains* climate zones emerged slightly different in the below treeline elevation band. While the treeline climate zones included three forecast regions (Northwest Inland, South Rockies, and Lizard Range), the below treeline cluster analysis only grouped the South Rockies, and Lizard Range and left the Northwest Inland as an independent avalanche hazard climate zone.

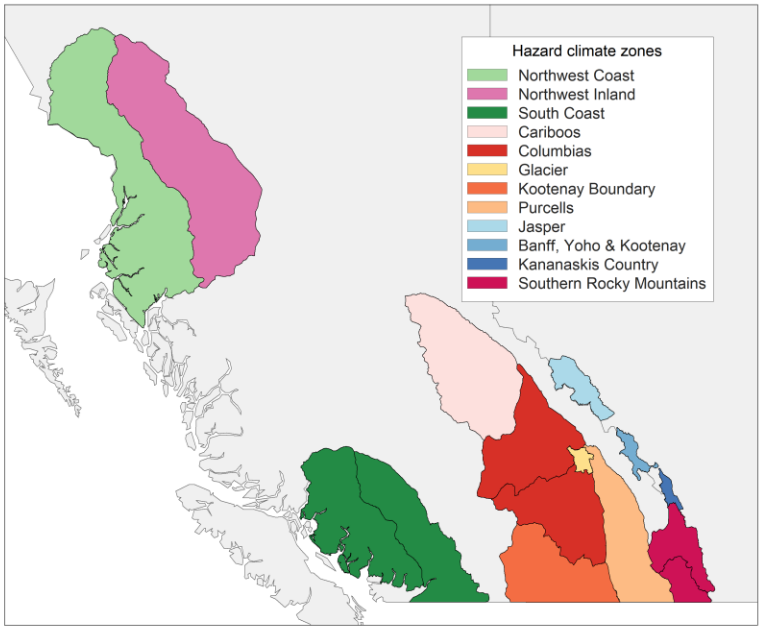


Figure 19: Avalanche hazard climate zones for below treeline elevation.

Hazard situation prevalence

The prevalence of typical hazard situations in the identified hazard climate zones provides insight into the regional differences in the avalanche hazard conditions over the last six winters of our study period. The regional mean prevalence values for the three elevations bands are shown graphically in Figure 20 to 22, whereas the associated regional anomalies are presented in Table 13 to 15.

In the alpine (Figure 20 and Table 13), the *South Coast* zone and *Northwest Inland* were characterized by a substantially higher prevalence of pure Wind slab and Strom slab hazard situations, which was at the expense of Persistent slab plus and Deep persistent slab hazard situations. The *Northwest Coast* exhibited a similar, but less pronounced pattern. Somewhat surprisingly, the region also showed a positive anomaly for the Storm & persistent slab hazard situation, which was compensated by negative anomalies in all other hazard situations involving persistent weaknesses. The interior regions generally show negative anomalies for the pure Wind slab and pure Storm slab hazard situations. In the *Cariboos* and the *Columbias* region, this was compensated with a higher prevalence of Storm & persistent slab hazard situations. The *Cariboos* also exhibited a higher prevalence of Persistent slab plus hazard situations. In *Glacier*, the decrease in pure Wind slab hazard situations was compensation by an increase in Storm & wind slab situations. *Glacier* also shows a higher prevalence of Loose dry avalanche hazard situations and a lower prevalence of deep persistent slab situations. *Kootenay Boundary* was the forecast region with the hazard situation prevalence values most closely to the overall means. The main feature of the *Purcells* and the *South Rockies* was the higher prevalence of pure Persistent slab plus hazard situations at the cost of fewer pure Storm slabs, Storm & persistent slab and Wind slab hazard situations (*Purcells* only). The *Central Rocky Mountains* zone exhibited a similar pattern, but higher prevalence was completely focused in the Deep persistent slab hazard situations (+28 percentage points). The *Lizard Range* only showed a slightly lower prevalence of Storm & persistent slab hazard situations and a slightly higher prevalence of pure Wind slabs.

The patterns observed at treeline generally mirrored what was described for the alpine (Figure 21 and Table 14), but the magnitude of the patterns varied slightly. The hazard situation prevalence values in the unique *Northwest Inland & Southern Rocky Mountains* zone were generally close to overall means, but with a small negative anomaly for *Storm & persistent slab* situations.

Below treeline, the *Northwest Coast* was characterized by a higher prevalence of Storm & wind and Storm & Persistent slab situations, which was compensated by fewer assessments with No avalanche problems. The *Northwest Inland*, and the Southern Rocky Mountains zone, were the forecast regions with the hazard situation prevalence values most closely to the overall means. The *South Coast* area exhibited a higher prevalence of pure Storm slab situations. All interior hazard areas had considerably fewer assessments with No avalanche problems. In the *Cariboos* and *Columbias* area, Persistent slab situations and Storm & persistent slab situations were responsible for approximately one-third of all assessments. *Glacier* had a higher prevalence of pure Storm slab situations, and in turn fewer situations with persistent slab problems. Aside from having fewer No avalanche problem situations, the hazard situation prevalence values for *Kootenay Boundary* were found to be close to overall mean values. The forecast regions in the Central Rocky Mountains had more situations with No avalanche problems, which was compensated with fewer pure Storm slab and Storm & persistent slab hazard situations. *Jasper* and Kananaskis Country were characterized with negative anomalies for Persistent slab situations, while both Jasper and Banff Yoho & Kootenay showed higher prevalence values for Deep persistent slab situations. It is worth highlighting that No avalanche problems hazard situations were much more prevalent in the Southern Rocky Mountain area than other forecast regions in the Rocky Mountains.

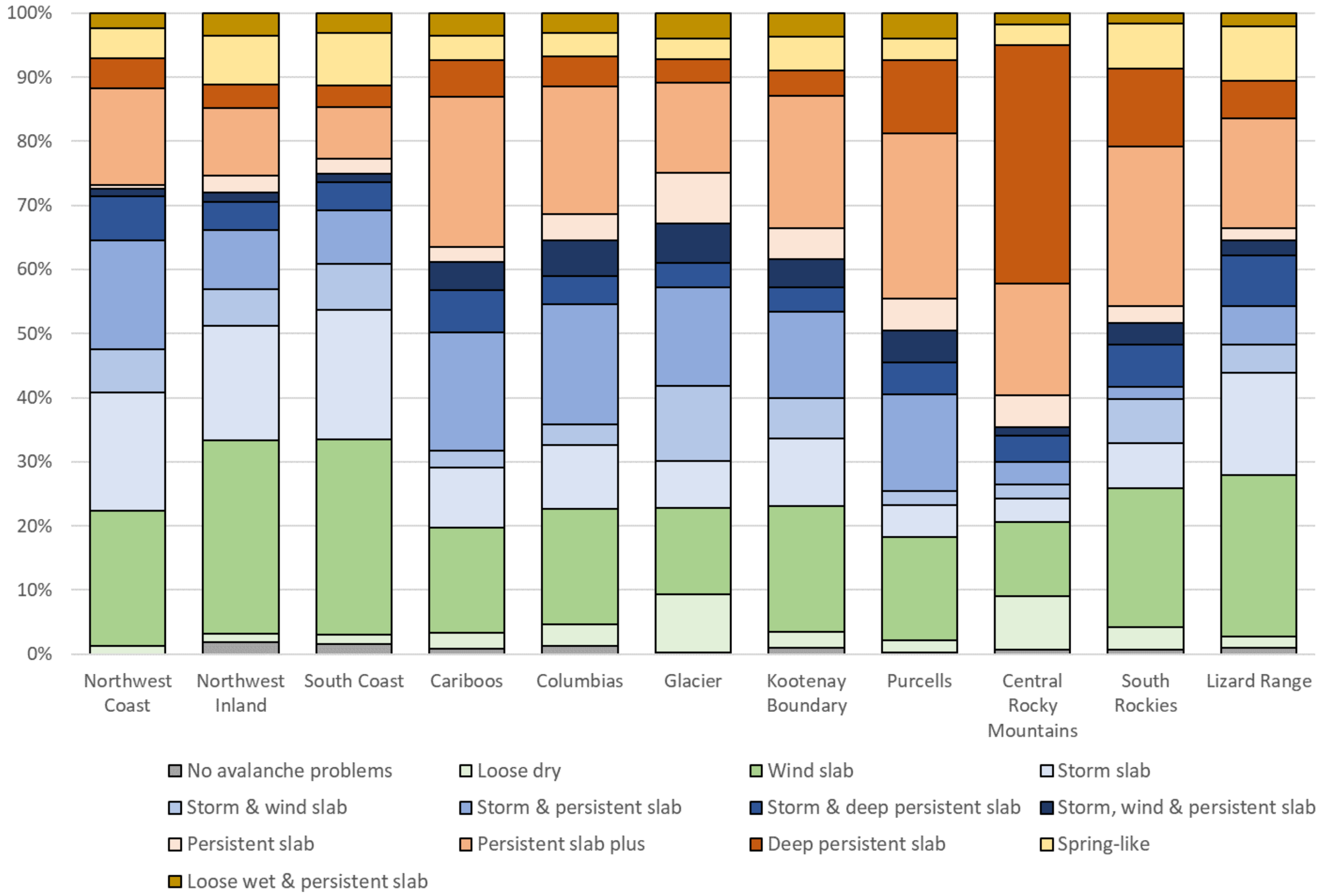


Figure 20: Hazard situation prevalence in avalanche hazard climate zones in alpine elevation band.

Table 13: **Mean hazard situation prevalence and avalanche hazard climate zone anomalies in percentage points for alpine elevation band.**

Hazard situation	Mean	Regional anomalies										
		Northwest Coast	Northwest Inland	South Coast	Cariboos	Columbias	Glacier	Kootenay Boundary	Purcells	Central Rocky Mountains	South Rockies	Lizard Range
No avalanche problems	1	0	1	1	0	0	-1	0	-1	0	0	0
Loose dry avalanche	3	-2	-2	-2	-1	0	6	-1	-2	5	0	-1
Wind slab	20	1	10	10	-4	-2	-7	-1	-4	-9	1	5
Storm slab	11	7	6	9	-2	-1	-4	-1	-6	-8	-4	5
Storm & wind slab	5	1	0	2	-3	-2	6	1	-3	-3	2	-1
Storm & persistent slab	12	5	-2	-3	7	7	4	2	4	-8	-10	-6
Storm & deep persistent slab	5	2	-1	-1	1	-1	-2	-1	0	-1	1	3
Storm, wind & persistent slab	3	-2	-2	-2	1	2	3	1	2	-2	0	-1
Persistent slab	4	-3	-1	-1	-1	1	4	1	1	1	-1	-2
Persistent slab plus	18	-3	-7	-10	6	2	-4	3	8	-1	7	-1
Deep persistent slab	9	-4	-5	-5	-3	-4	-5	-5	3	28	3	-3
Spring-like	5	-1	2	3	-2	-2	-2	0	-2	-2	2	3
Loose wet & persistent slab	3	-1	1	0	1	0	1	1	1	-1	-1	-1

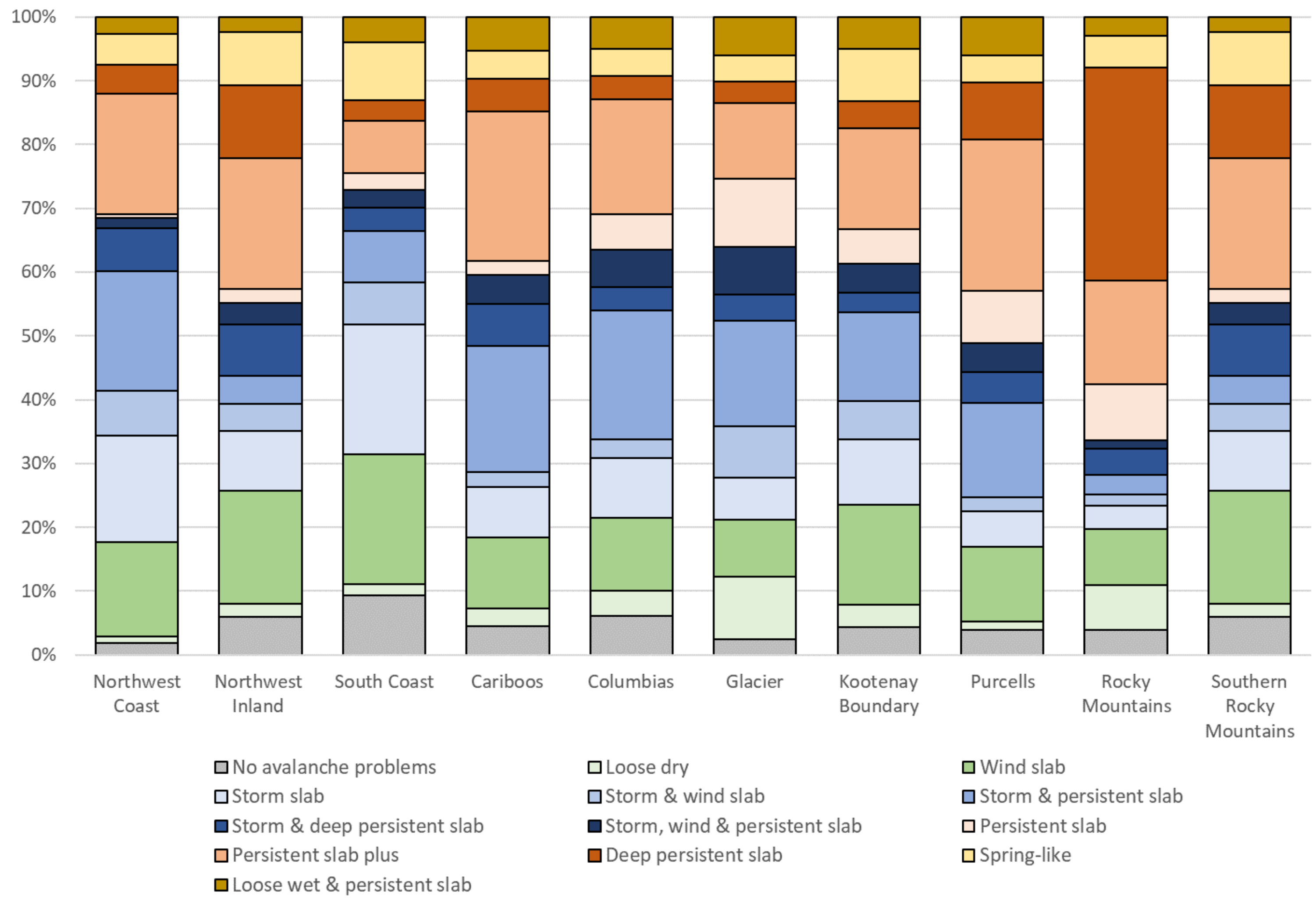


Figure 21: **Hazard situation prevalence in avalanche hazard climate zones for treeline elevation band.**

Table 14: Mean hazard situation prevalence and avalanche hazard climate zone anomalies in percentage points for treeline elevation band.

Hazard situation	Mean	Regional anomalies									
		Northwest Coast	Northwest Inland	South Coast	Cariboos	Columbias	Glacier	Kootenay Boundary	Purcells	Central Rocky Mountains	Southern Rocky Mountains
No avalanche problems	5	-3	1	4	0	1	-2	0	-1	-1	1
Loose dry avalanche	4	-3	-1	-2	-1	0	6	0	-2	4	-1
Wind slab	14	1	4	7	-3	-2	-5	2	-2	-5	4
Storm slab	10	7	-1	10	-2	-1	-3	0	-4	-6	-1
Storm & wind slab	5	2	0	2	-2	-2	4	1	-2	-3	0
Storm & persistent slab	12	6	-8	-4	7	8	4	2	2	-9	-8
Storm & deep persistent slab	5	2	3	-2	1	-2	-1	-2	0	-1	3
Storm, wind & persistent slab	4	-2	-1	-1	1	2	4	1	1	-3	-1
Persistent slab	5	-4	-3	-2	-3	1	6	1	3	4	-3
Persistent slab plus	18	1	3	-10	6	0	-6	-2	6	-1	3
Deep persistent slab	9	-4	3	-6	-4	-5	-6	-5	0	24	3
Spring-like	6	-1	2	3	-2	-2	-2	2	-2	-1	2
Loose wet & persistent slab	4	-2	-2	0	1	1	2	1	2	-1	-2

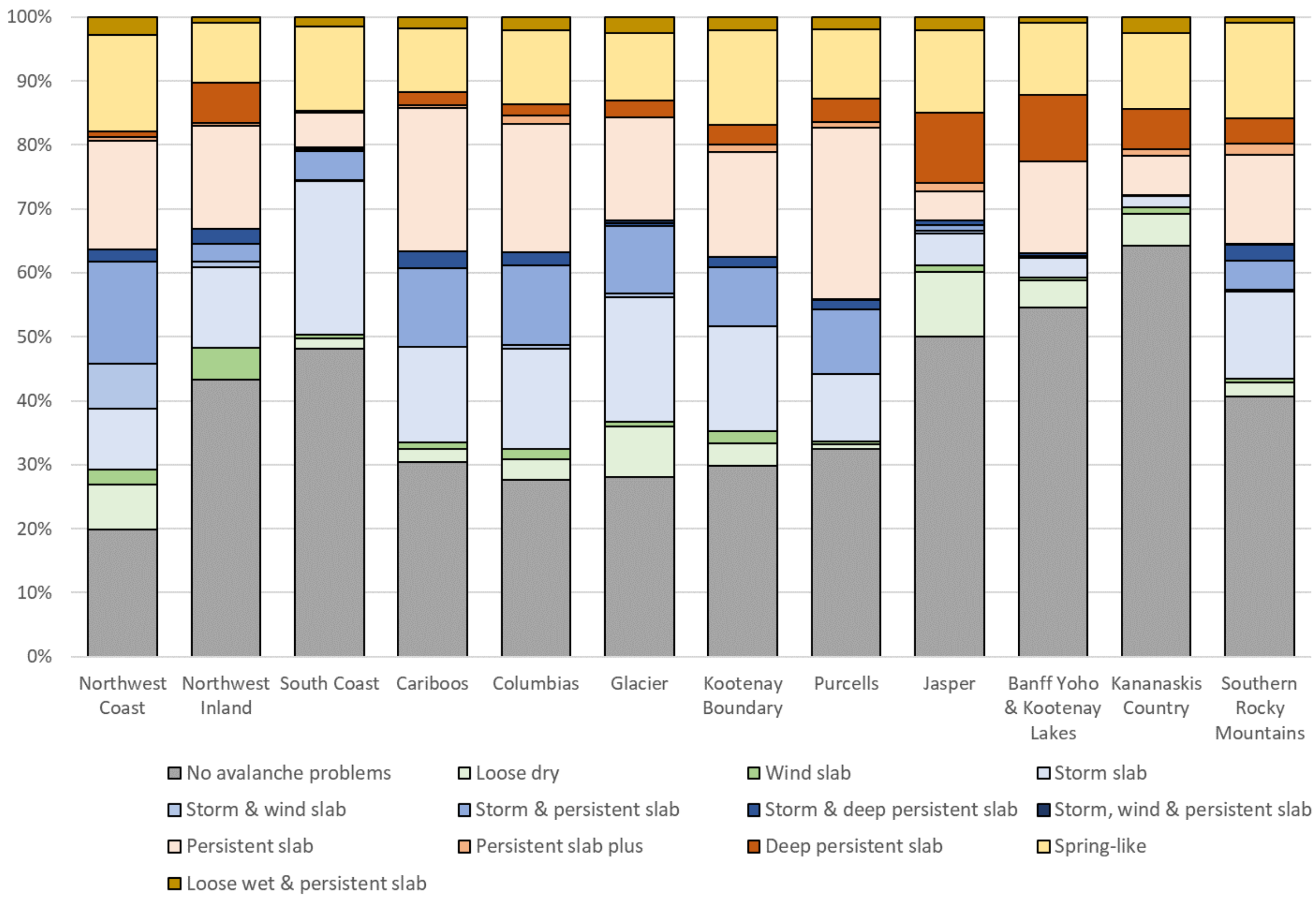


Figure 22: Hazard situation prevalence in avalanche hazard climate zones for below treeline elevation band.

Table 15: Mean hazard situation prevalence and avalanche hazard climate zone anomalies in percentage points for below treeline elevation band.

Hazard situation	Mean	Regional anomalies											
		Northwest Coast	Northwest Inland	South Coast	Cariboos	Columbias	Glacier	Kootenay Boundary	Purcells	Jasper	Banff Yoho & Kootenay Lakes	Kananaskis Country	Southern Rocky Mountains
No avalanche problems	39	-19	4	9	-9	-11	-11	-9	-7	11	15	25	1
Loose dry avalanche	4	3	-4	-2	-2	-1	4	0	-3	6	0	1	-2
Wind slab	1	1	4	-1	0	0	-1	0	-1	0	-1	0	-1
Storm slab	12	-3	0	12	3	4	7	4	-2	-7	-9	-11	1
Storm & wind slab	1	6	0	-1	-1	0	0	-1	-1	0	-1	-1	-1
Storm & persistent slab	8	9	-4	-2	5	5	4	2	3	-6	-7	-7	-2
Storm & deep persistent slab	1	1	1	-1	1	1	-1	0	0	-1	-1	-1	1
Storm, wind & persistent slab	0	0	0	0	0	0	0	0	0	0	0	0	0
Persistent slab	15	2	1	-10	8	5	1	2	12	-10	-1	-9	-1
Persistent slab plus	1	0	0	-1	0	1	-1	0	0	1	-1	0	1
Deep persistent slab	4	-3	2	-4	-2	-3	-2	-1	-1	7	6	2	0
Spring-like	12	3	-3	1	-2	-1	-2	3	-1	1	-1	0	3
Loose wet & persistent slab	2	1	-1	0	0	0	1	0	0	0	-1	1	-1

Step 5: Influence of climate teleconnections

The monthly indices of the large-scale climate oscillations included in this study during the study period represented between 45% and 61% of the historical range (Jan. 1950 to Apr. 2017) (Table 16). While the study period is limited to eight years, all four climate index variabilities exhibited both negative and positive anomalies. For ENSO, my study includes observations near the historical minimum (2010/11) and 61% of the historical range. The AO index actually exhibited its historical minimum in the winter of 2009/10, and the time series covered 45% of the historical range.

Table 16: Overview of monthly averaged climate index data.

Index	Minimum observation		Maximum observation		Range (max – min)	
	Historical	2009/10 – 2016/17	Historical	2009/10 – 2016/17	Historical	2009/10 – 2016/17*
ENSO	-1.94	-1.74	3.01	2.30	4.95	3.01 (61%)
PNA	-2.70	-1.78	2.42	2.02	5.12	2,42 (47%)
PDO	-4.25	-2.96	3.69	1.93	7.94	3.69 (46%)
AO	-4.27	-4.27	3.50	2.28	7.77	3.50 (45%)

* Absolute and in percent of historical range

Testing for correlations between the four winter averaged climate oscillations indices during the study period (Figure 23) revealed significant associations between ENSO and the two other Pacific centered climate oscillations: ENSO-PDO: 0.73; ENSO-PNA: 0.83 (both Pearson correlation: p-value < 0.05). No significant correlations were observed between the PDO and PNA as well as the AO and all three Pacific-centered indices.

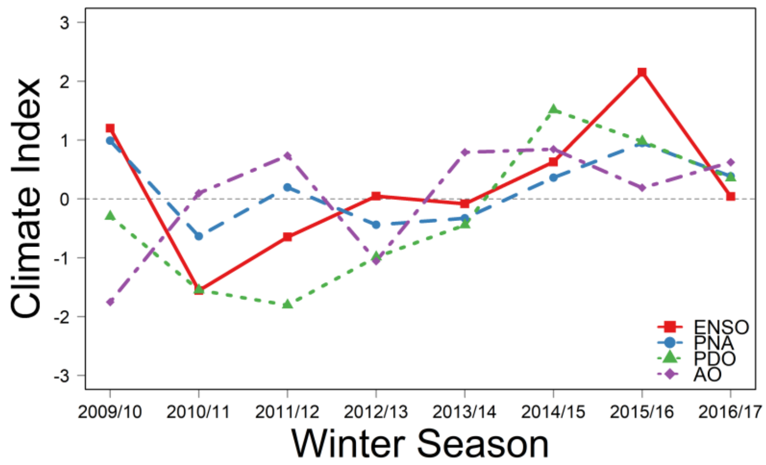


Figure 23: **Winter season averaged (November to April) climate indices over the duration of the 2009/10 to 2016/17 study period.**

The Spearman correlation analysis between the prevalence values of the typical hazard situations and the calculated winter climate oscillations indices from 2009/10 to 2016/17 revealed numerous significant patterns at all three elevation bands (Tables 17 – 20).

ENSO

ENSO had a positive relationship with the prevalence of *Loose wet & persistent slab* situations at high elevations in the Eastern and Southern parts of the Columbia Mountains. *Spring-like* situations were more prevalent during winter when the ENSO index was higher in the South Coast Mountains, Southern Columbia Mountains and central Rocky Mountains at mid to lower elevations. Prevalence of pure *Storm slab* situations was also positively associated with ENSO in the South Coast Mountains, while *Storm & persistent slab* and *Persistent slab* situations exhibited a positive relationship in the Columbia Mountains at treeline elevation and below treeline in the Rocky Mountains.

ENSO had a negative relationship with *Deep persistent slab* situations in southeastern parts of the Columbia Mountains from mid to high elevations. *Persistent slab plus* situations also exhibited a negative correlation in the Columbia Mountains at high elevations. In the Southern Rocky Mountains, I observed a negative relationship between the prevalence of *Storm & deep persistent slab* situations and the ENSO index.

PNA

Within the study period, PNA had a positive relationship with *Storm slab* and *Storm & wind slab* situations in the Central and North Columbia Mountains at low elevations. Examining the yearly anomaly values for *Loose wet & persistent slab* situations revealed a positive association in Southern Columbia Mountains and Southern Rocky Mountains. A negative relationship was observed between PNA and *Deep persistent slab* situations in the Northern Columbia Mountains.

PDO

The PDO showed a positive relationship with *No avalanche problem* situations throughout the Coast Mountains and parts of the Columbia Mountains at lower elevations. The seasonal prevalence values for *Storm & persistent slab* and *Persistent slab* hazard situations showed a positive relationship with the PDO index in the Coast and the Columbia Mountains. While *Loose wet & persistent slab* situations were positively correlated in the Northern Columbia Mountains at higher elevations, negative correlations emerged in the South Coast Mountains and Southern Columbia Mountains at lower elevations. Throughout the Columbia Mountains and the Rocky Mountains, *Loose dry* and *Wind slab* situations suggested a negative relationship with the PDO index.

AO

The AO exhibited a positive correlation with *Loose dry* situations in the Southern Coast Mountains. *Storm & deep persistent slab* situations occurred more frequently in the South Coast area at higher elevations during positive phases of the AO. *Persistent slab* situations had a positive relationship in part of the Columbia Mountains and the Rocky Mountains at higher elevations. The AO had a negative relationship with *Wind slab* and *Storm slab* situations throughout the study area.

Table 17: Significant correlations with ENSO and elevation band specific hazard situation prevalence values. Red font indicates positive rank-correlations and blue font indicates negative rank-correlations with p-values < 0.05 (* indicates significance level, α = 0.01).

<table>
<tr><th></th><th>Regions</th><th>Alpine</th><th colspan="2">Tree line</th><th colspan="2">Below tree line</th></tr>
<tr><td rowspan="3">Coast Mtn</td><td>NW Coast</td><td>Storm & wind slab*</td><td colspan="2">Storm & wind slab*</td><td colspan="2"></td></tr>
<tr><td>NW Inland</td><td></td><td colspan="2">Wind slab</td><td colspan="2">No avalanche problems</td></tr>
<tr><td>South Coast</td><td></td><td colspan="2">Storm slab
Spring-like</td><td colspan="2">Spring-like</td></tr>
<tr><td rowspan="5">Columbia Mtn</td><td>Cariboos</td><td>Loose wet & pers. slab</td><td colspan="2">Loose wet & pers. slab</td><td colspan="2"></td></tr>
<tr><td>Columbias</td><td>Persistent slab plus</td><td colspan="2">Storm & persistent slab*
Loose wet & pers. slab</td><td colspan="2"></td></tr>
<tr><td>Glacier</td><td></td><td colspan="2">No avalanche problems</td><td colspan="2"></td></tr>
<tr><td>Purcells</td><td>Deep persistent slab
Loose wet & pers. slab*</td><td colspan="2">Storm & wind slab
Persistent slab
Deep persistent slab
Loose wet & pers. slab*</td><td colspan="2">Storm & persistent slab</td></tr>
<tr><td>Kootenay Boundary</td><td>Deep persistent slab
Spring-like*
Loose wet & pers. slab*</td><td colspan="2">Storm & persistent slab
Deep persistent slab*
Spring-like
Loose wet & pers. slab</td><td colspan="2">Wind slab
Spring-like</td></tr>
<tr><td rowspan="5">Rocky Mtn</td><td rowspan="3">Central Rocky Mountains</td><td rowspan="3"></td><td colspan="2" rowspan="3"></td><td>Jasper</td><td>Persistent slab plus
Loose wet & persistent slab</td></tr>
<tr><td>Banff, Yoho, & Kootenay Lakes</td><td>Storm & persistent slab
Spring-like*</td></tr>
<tr><td>Kananaskis Country</td><td></td></tr>
<tr><td>South Rockies</td><td>Storm & persistent slab</td><td rowspan="2">Southern Rocky Mountains</td><td rowspan="2">Wind slab</td><td colspan="2" rowspan="2">Wind slab*
Storm & deep pers. slab</td></tr>
<tr><td>Lizard Range</td><td>Loose dry</td></tr>
</table>

Table 18: Significant correlations with PDO and elevation band specific hazard situation prevalence values. Red indicates positive correlation and blue indicates negative correlation (* indicates significance level, α = 0.01).

	Regions	Alpine	Tree line	Below tree line
Coast Mtn	NW Coast	Storm & persistent slab		No avalanche problems*
Coast Mtn	NW Inland	**Storm & wind slab***	No avalanche problems Storm & wind slab	
Coast Mtn	South Coast		Persistent slab	No avalanche problems Wind slab Loose wet & pers. slab
Columbia Mtn	Cariboos		Loose wet & pers. slab	
Columbia Mtn	Columbias		Storm & persistent slab **Persistent slab plus*** Loose wet & pers. slab	Loose dry
Columbia Mtn	Glacier	Storm & wind slab Loose wet & pers. slab	**No avalanche problems*** Loose dry Persistent slab	Loose dry Storm & persistent slab
Columbia Mtn	Purcells	Storm slab Storm, wind & pers. slab	**Storm & wind slab*** Storm, wind & pers. slab	**Storm & persistent slab***
Columbia Mtn	Kootenay Boundary		Deep persistent slab	Spring-like Loose wet & pers. slab
Rocky Mtn	Central Rocky Mountains	Persistent slab	Storm & wind slab	Jasper: **Wind slab*** Banff, Yoho, & Kootenay Lakes: Kananaskis Country: **Loose dry***
Rocky Mtn	South Rockies	**Loose dry***	Southern Rocky Mountains: No avalanche problems	
Rocky Mtn	Lizard Range	Loose dry	Southern Rocky Mountains: No avalanche problems	

Table 19: Significant correlations with PNA and elevation band specific hazard situation prevalence values. Red indicates positive correlation and blue indicates negative correlation (* indicates significance level, α = 0.01).

	Regions	Alpine	Tree line	Below tree line
Coast Mtn	NW Coast		**No avalanche problem*** Loose dry	
Coast Mtn	NW Inland			
Coast Mtn	South Coast	Loose wet & pers. slab		Wind slab
Columbia Mtn	Cariboos		No avalanche problem **Deep persistent slab***	Storm slab*
Columbia Mtn	Columbias			Storm & wind slab
Columbia Mtn	Glacier			
Columbia Mtn	Purcells	Persistent slab plus		Loose wet & pers. slab
Columbia Mtn	Kootenay Boundary			
Rocky Mtn	Central Rocky Mountains			Jasper Banff, Yoho, & Kootenay Lakes Kananaskis Country
Rocky Mtn	South Rockies		Southern Rocky Mountains	Loose wet & pers. slab
Rocky Mtn	Lizard Range			

Table 20: **Significant correlations with AO and elevation band specific hazard situation prevalence values. Red indicates positive correlation and blue indicates negative correlation (* indicates significance level, α = 0.01).**

<table>
<tr><th></th><th>Regions</th><th>Alpine</th><th colspan="2">Tree line</th><th colspan="2">Below tree line</th></tr>
<tr><td rowspan="3">Coast Mtn</td><td>NW Coast</td><td></td><td colspan="2">Loose wet & pers. slab</td><td colspan="2">Persistent slab plus</td></tr>
<tr><td>NW Inland</td><td></td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td>South Coast</td><td>Loose dry
Storm & deep pers. slab</td><td colspan="2">No avalanche problems
Loose dry</td><td colspan="2">Loose dry</td></tr>
<tr><td rowspan="5">Columbia Mtn</td><td>Cariboos</td><td>Wind slab</td><td colspan="2">Wind slab</td><td colspan="2">Loose dry</td></tr>
<tr><td>Columbias</td><td></td><td colspan="2">Persistent slab</td><td colspan="2"></td></tr>
<tr><td>Glacier</td><td>Loose dry
Storm & persistent slab</td><td colspan="2"></td><td colspan="2">Storm & deep pers. slab</td></tr>
<tr><td>Purcells</td><td></td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td>Kootenay Boundary</td><td>Storm slab</td><td colspan="2"></td><td colspan="2">Storm slab</td></tr>
<tr><td rowspan="5">Rocky Mtn</td><td rowspan="3">Central Rocky Mountains</td><td rowspan="3"></td><td colspan="2" rowspan="3">Wind slab
Storm & wind slab*
Persistent slab</td><td>Jasper</td><td>Storm & wind slab</td></tr>
<tr><td>Banff, Yoho, & Kootenay Lakes</td><td></td></tr>
<tr><td>Kananaskis Country</td><td></td></tr>
<tr><td>South Rockies</td><td>Wind slab
Persistent slab plus*</td><td rowspan="2">Southern Rocky Mountains</td><td rowspan="2"></td><td colspan="2" rowspan="2">Storm slab*</td></tr>
<tr><td>Lizard Range</td><td>Storm slab</td></tr>
</table>

Discussion

Using avalanche bulletin data to address the research question of how large-scale climate oscillations affect avalanche hazard in Western Canada required many intermediate steps. First, I identified and characterized typical hazard situations. Then, I calculated prevalence values for the hazard situations for individual seasons and groups of forecast regions that exhibited similar avalanche hazard characteristics during the study period to represent the nature of avalanche hazard numerically. Anomaly patterns were then compared to existing descriptions of snow and avalanche climate characteristics for Western Canada. In the final step, I correlated the seasonal prevalence values with climate oscillations indices to address my actual research question.

Each of these steps is innovative and provide new insight into the nature of avalanche hazard in Western Canada. I will therefore elaborate on the main contributions of the intermediate steps before discussing the results with respect to the main research question.

Typical hazard situations

The identification of typical hazard situations represents an important step for quantitatively describing the nature of avalanche hazard conditions in Western Canada. My SOM analysis revealed twelve typical hazard situations that are combinations of the eight avalanche problem types identified in the CMAH (Statham et al., under review). The twelve hazard situations can roughly be grouped into four main classes: 1) situations typically associated with low danger ratings including the *No avalanche problems*, *Loose dry avalanche* and pure *Wind slab* hazard situations; 2) hazard situations dominated by storm slabs, which include pure *Storm slab* hazard situations and various combinations with wind slab and persistent slab avalanche problems; 3) hazard situations with a dominant persistent avalanche problem (*Persistent slab*, *Persistent slab plus*, and *Deep persistent slab hazard situations*); and 4) hazard situations that occur during warmer conditions (*Spring-like* and *Loose wet & persistent slab hazard situation*). While the *No avalanche problems* situation was the most common hazard situation overall, this situation rarely occurred in the alpine and treeline.

The next most frequent situations were pure *Wind slab hazard situations*, pure *Storm slab hazard situations*, and *Persistent slab plus hazard situations*. Together these three hazard situations account for slightly more than one-third of the hazard situations across all seasons, forecast regions and elevation band.

While avalanche problems represent building blocks of avalanche hazard, the identified hazard situations can describe the complexity and severity of daily avalanche conditions much more comprehensively.

Elevation band differences in hazard conditions

The elevation band-specific prevalence values for the hazard situations exhibit expected patterns. All the hazard situations, including wind slab avalanche problems, were considerably more prevalent in the alpine and at treeline. Similarly, the more severe *Persistent slab plus* and *Deep persistent slab hazard situations* were more prevalent in the alpine and at treeline. However, pure *Storm slab*, the less severe *Persistent slab*, and the *Spring-like hazard situation* were considerably more prevalent below treeline. Together, these three hazard situations accounted for more than one-third of the hazard situations below treeline. The below treeline elevation band also had the highest frequency of *No avalanche problem* situations accounting for more than one-third. Together, these results highlight that avalanche hazard conditions in the alpine and treeline elevation bands are considerably more complex and severe than below treeline.

While conditions in the alpine and at treeline might differ on individual days, the prevalence of the different hazard situations across the entire study period was extremely similar between the two elevation bands. The biggest difference between these two elevation bands was that the prevalence of pure *Wind slab hazard situations* was 6 percentage points higher in the alpine than at treeline (20% versus 14%).

The realism of these results nicely confirms the ability of the SOM approach to group avalanche hazard situations into a set of meaningful patterns.

Seasonal differences in avalanche hazard conditions

My comparison of the interseasonal variability in the snow climate classification of Mock and Birkeland (2000) and the prevalence of the twelve hazard situations across

Western Canada revealed that the nature of avalanche hazard can be dramatically different among winters that were classified similarly by the Mock and Birkeland (2000) algorithm. For example, the nature of avalanche hazard in the 2009/10 and 2010/11 winter varied dramatically even though the Mock & Birkeland (2000) algorithm assessed the two winters to be the most normal (i.e., the most similar to the classification based on the average winter weather conditions during the entire study period). The 2009/10 winter was dominated by the Persistent slab hazard situations, whereas the 2010/11 had a higher prevalence of Storm & wind slab and Storm, wind & persistent slab hazard situations. Equally interesting is that the 2014/15 winter, which is one of the two most maritime winters, exhibited hazard situation prevalence values closest to the overall mean values for the entire study period. However, there were also similarities between the snow climate scheme and the typical hazard prevalence values. For example, the winter 2015/16, the most maritime winter in the dataset, exhibited the highest seasonal prevalence of spring-like hazard conditions.

These results highlight that examining the seasonal prevalence of typical hazard situations can offer a more insightful perspective on the avalanche hazard conditions of a winter than the Mock and Birkeland (2000) algorithm. Haegeli and McClung (2007) already pointed out the limitations of the Mock and Birkeland (2000) approach because avalanches and their particular character are the result of specific sequences of weather events and not the average weather conditions of a winter. Whereas Haegeli and McClung (2007) simply used the number of persistent weak layers to characterize the nature of avalanche hazard of a winter, including all types of avalanche hazard situations into the analysis provides a much more complete and therefore meaningful perspective on what a winter was like.

Regional differences in avalanche hazard conditions and avalanche climate zones

My comparison of the prevalence of typical hazard situations across the different forecast regions in Western Canada also revealed the expected patterns. Generally, the avalanche hazard conditions in forecast regions located in the *Coast Mountains* are dominated by pure Wind slab hazard situations and pure Strom slab hazard conditions. In the alpine elevation band, these two hazard situations make up close 50% of the hazard conditions. Below treeline, No avalanche problems hazard situations comprise half of the assessments, and pure Storm slab hazard situations alone are responsible for approximately one-quarter of the hazard situations in the South Coast region. On the other hand, the Persistent slab plus and Deep persistent hazard situation are much less frequent in these forecast areas. This picture generally agrees with the existing descriptions of the nature of avalanche hazard in the maritime snow climate of Coast Mountains (McClung & Schaerer, 2006). The hazard situations are simpler (i.e., fewer simultaneous avalanche problems) and persistent avalanche problems are rare. If they occur, they are generally less severe than in the other climate zones.

In the Columbia Mountains, the snowpack gets more complex, and hazard situations that include persistent avalanche problems become more prevalent. Whereas the Cariboo and the North and South Columbia forecast regions exhibited higher prevalence value for Storm & persistent slab hazard situations, the Cariboo and the Purcell forecast regions also had more Persistent slab plus hazard situations. These observations are consistent with the perspective presented by Haegeli and McClung (2007) and the general understanding of the transitional snow climate in Canada. The fact that the centrally located Glacier forecast region does not exhibit a similar increase in hazard situation involving persistent avalanche problems is a bit surprising. However, possible explanations for this deviation could be a) the unique geographic location of the forecast area, which is well known for its abundant snowfall (e.g., CCBFC (1995) cited in Haegeli and McClung, 2007), b) the fact that it is the only Parks Canada forecast region in the Columbia Mountains, or c) the relatively small size of the forecast region. Kootenay Boundary, the most Southern forecast region in the Columbia Mountains also does not the higher prevalence of hazard situations involving persistent avalanche problems.

The most striking characteristic of the avalanche hazard conditions in the Rocky Mountains is the high prevalence of Deep persistent slab situations in the alpine and at treeline in the Central Rocky Mountain region. In the more southern forecast regions in the Rockies Mountains (South Rockies and Lizard Range), the dominance of the deep persistent slabs disappears again and the Persistent Slab Plus (South Rockies) and pure Storm slab hazard situations (Lizard Range) become more prevalent. At treeline, the avalanche hazard characteristics of the Southern Rocky Mountains is similar to the Northwest Inland region in the Northern Coast Mountains. While this grouping might be surprising at first, it does seem to make sense as these forecast regions exhibit avalanche hazard characteristics that are grounded in a continental snow climate, but have strong maritime influences. This combination of continental and maritime influences is distinctly different from the traditional transitional snow climate of the Columbia Mountains.

The observed hazard characteristics match the traditional perspective on the nature of avalanche hazard in the different mountain ranges in Western Canada quite well (e.g., McClung and Schaerer, 2006). At the same time, the cluster analysis also confirms that there are distinct sub-regions within the main mountain ranges, supporting the spatial variability of avalanche hazard described in previous studies (Gruber et al., 2004; Haegeli & McClung, 2007; Hägeli & McClung, 2003). The most significant advancement of the approach presented in this thesis is, however, that it provides a much more detailed perspective on the type of avalanche hazard situations experienced in these regions and explicitly quantifies their prevalence. The quantitative nature of the characterization offers new opportunities for examining the observed differences statistically.

Effect of climate oscillations on avalanche hazard in Western Canada

Previous studies exploring the connection between avalanche activity and large-scale climate oscillations trends in Western Canada (McClung, 2013; Thumlert et al., 2014;) have been limited to individual point locations and relied on activity datasets that have the potential to be incomplete and affected by factors other than variabilities in the local weather conditions. Furthermore, these studies have focused on trends in the physical characteristics of the recorded avalanches (i.e. size, slab or cohesionless, wet or dry). While these studies were able to provide initial insight, they have not offered a comprehensive view on how climate oscillations affect the nature of avalanche hazard. My approach aimed to provide a more holistic perspective by using a dataset that covers Western Canada more completely and is more informative for avalanche risk management as it integrates information on all avalanche problem types.

Over Western Canada, El Niño (positive ENSO phase) winters are associated with a shift towards warmer than normal temperatures, while La Niña (negative ENSO phase) winters exhibit colder than normal temperature (Shabbar & Bonsal, 2004; Shabbar & Khandekar, 1996; Stahl et al., 2006). The signal in precipitation is less distinct. My correlation analysis shows that avalanche hazard situations associated with warmer temperatures (i.e., No avalanche problems, Spring-like, and Loose wet & persistent slab hazard situations) are more during El Niño oscillation winters in all elevation bands, and the opposite effect during La Niña winters, which is consistent with the ENSO effects on weather. This observation also confirms the results of McClung (2013) and Thumlert et al (2014), who both found that El Niño winters produced fewer avalanches and a higher percentage of wet avalanches. Whereas McClung (2013) stated that the effect is stronger in the maritime Coast Mountains due to their proximity to the Pacific Ocean, my analysis shows that the effect is more dominant in the Columbia Mountains (alpine and treeline). The effect is observed a bit more broadly below treeline, but local variabilities exist as this pattern does not exist in all forecast regions.

My analysis also shows that hazard situations involving smaller persistent slab avalanche problems (i.e., pure Persistent slab and Storm & persistent slab hazard situations) tend to be more during El Niño oscillation winters in the central Columbia Mountains at treeline. In the Purcells and the Kootenay-Boundary forecast regions, this trend is compensated by a decreased prevalence of Deep persistent slab hazard situations in the alpine and at treeline. This compensation might be smaller in these forecast regions during El Niño phase winters, and larger during El Niño winters. Overall, these observations clearly show that the effect of climate oscillations on avalanche hazard is highly spatially variable. This is consistent with the description of the effect of ENSO in temperature and precipitation patterns in the Pacific Northwest by McAfee and Wise (2010).

The effect of the PDO on the weather in Western Canada is similar to ENSO, with the negative phase being associated with cooler conditions and increased snowfall, but the pattern is generally weaker (Manuta & Hare, 2002). Accordingly, my correlation analyses between the prevalence of hazard situations and the PDO generally revealed similar patterns as the ENSO analyses. I found a higher prevalence of low hazard conditions as well as the pure Persistent slab and Storm & persistent slab situations during positive PDO phases and higher prevalence of Persistent slab plus and Deep persistent slab hazard situations during negative PDO phases. However, the correlations were not necessarily observed in the same forecast regions. These results generally confirm the results of Thumlert et al. (2014), who found a link between the PDO and avalanche activity in a few highway passes throughout British Columbia.

The effect of the PNA on winter weather in Western Canada is similar to ENSO and PDO. Negative phase PNA conditions are characterized with greater snowfall and colder than average temperatures, and positive phase PNA winters are warm and dry with below average snowfall. (Brown & Goodison, 1996; Kluver & Leathers, 2015; Stahl et al., 2006). My correlation analysis of the PNA revealed a similar pattern as the ENSO analyses, in that the negative relationship between the PNA and Deep persistent slab situations in the Northern Columbia Mountains at tree elevations.

The AO is independent of the Pacific processes (Moore et al., 2009) and affects the surface pressure of Western Canada. Positive phase AO winters generally have higher midlatitude surface pressure anomalies and strong westerly flow, while negative phase AO conditions negative midlatitude surface pressure anomalies and weaker westerly flow. While Thumlert et al. (2014) did not find any significant correlations between AO and avalanche activity, my analysis revealed a positive relationship with hazard situations that involve persistent weak layers. This is an intuitive result as the positive AO represents longer periods of cold clear weather, which facilitate the development of persistent weak layers in the Eastern part of the study area. During the negative phase of the AO, hazard situations involving storm slab avalanche problems and/or wind slab avalanche problems are more prevalent.

Limitations

This study is not without limitations. Typically, a dataset of only eight winters would be considered too short to gain meaningful insight into the effect of large-scale climate oscillations. However, the fact that the study period included both El Niño and La Niña winters, covered 61% of the historical range of the included climate oscillations indices and confirmed the results of previous studies makes me confident that the observed patterns provide meaningful initial insights into the effects of large-scale climate oscillations on avalanche hazard in Western Canada. However, I suggest that this study should be repeated in five to ten years to provide a more robust understanding of these dynamics.

While the use of avalanche hazard assessments included in avalanche bulletins allowed me to avoid the known shortcomings of avalanche activity records, this dataset is not without challenges. Since the avalanche hazard assessments are human judgements, they are susceptible to human errors and biases as well as changes in operational procedures. For example, Avalanche Canada informed that at the beginning of the 2012/13 winter, the forecaster team decided to no longer include Storm slab avalanche problems and Wind slab avalanche problems in the avalanche hazard assessments at the same time. This change in forecasting policy resulted in a general drop in the prevalence for Storm, wind, & persistent slab and Storm & wind hazard situations after the 2011/12 winter. Results including storm slab and wind slab avalanche problems should therefore be treated with caution. Geographic differences between forecast areas (e.g., size) as well as organizational and operational differences between Avalanche Canada and Parks Canada might also cause systematic discrepancies among forecast regions unrelated to local weather and climate effects.

Due to the strong correlations among the three Pacific-focused climate oscillations (ENSO, PDO, and PNA) during the study period, it was not possible to properly separate the effects that each of these climate oscillations may have on avalanche hazard in Western Canada individually. This is an inherent limitation of short time series that can only be remedied once a longer dataset becomes available.

Conclusion

In this study, I examine the nature and variability of avalanche hazard in Western Canada and its relationship to large-scale climate oscillations. Whereas previous studies in this research area have been based on meteorological observations or local avalanche activity records, I used CMAH-based avalanche hazard assessments from Avalanche Canada and Parks Canada’s public avalanche bulletins from the 2009/10 to 2016/17 winter seasons. Addressing my research question required many distinct processing steps. First, I statistically examined key characteristics of the eight different avalanche problem types defined in the CMAH to better understand the fundamental building blocks of avalanche hazard. Second, I used SOM to identify typical avalanche hazard situations among the countless combinations of avalanche problems in the CMAH dataset and assign each individual assessment to one of these archetypes. Third, I calculated the overall prevalence of each typical hazard situation for the entire dataset as well as seasonal prevalence values for each forecast region and elevation band to describe the nature of the experienced avalanche hazard in a quantitative way. Fourth, I grouped individual forecast regions that exhibited similar patterns of seasonal prevalence values for typical avalanche hazard situations throughout the study period using AHC to identify larger, homogenous climate zones. In the fifth and final step, I examined the relationship between climate oscillations and seasonal avalanche hazard conditions in identified avalanche climate zones by calculating correlations between the seasonal prevalence of typical hazard situations and seasonal climate indices.

My research contributes to the existing literature on avalanche climate and its variability in multiple ways. First, the identification of typical hazard situations and the calculation prevalence values provides an innovative approach for describing the nature of the seasonal avalanche hazard conditions in a concise quantitative way that still provides a comprehensive picture and has direct links to avalanche risk management. While my comparison of the seasonal variability in the prevalence of the typical hazard situations with seasonal snow climate classifications according to Mock and Birkeland (2000) showed that both methods are able to capture large-scale variabilities, it also highlighted that the nature of avalanche hazard in western Canada can be dramatically different among winters that were classified similarly by the Mock and Birkeland (2000) algorithm. I believe that my method is more informative for avalanche safety workers as the explicit link to avalanche problem types relates more directly to risk mitigation methods. Second, the clustering of forecast regions based on prevalence time series of typical avalanche hazard offers a new way for identifying avalanche climate zones that exhibit comparable avalanche hazard characteristics and behave similarly under large-scale changing meteorological conditions. My analysis confirms the traditional perspective on avalanche climates in western Canada–maritime Coast Mountains, transitional Columbia Mountains and the continental Rocky Mountains—but also highlights considerable variability within these mountain ranges. Third, the results of my correlation analysis between large-scale climate indices and the prevalence of typical hazard situations affirm and expand our knowledge of the effect of climate oscillations on avalanche hazard in western Canada (McClung, 2013; Thumlert et al., 2014). Increased prevalence values of avalanche hazard situations associated with warmer temperatures as well as hazard situations involving smaller persistent slab avalanche problems are consistent with the effect of ENSO and PDO on local weather patterns during positive phases. Negative PDO and PNA phases result in a greater prevalence of more severe persistent slab situations and deep persistent slab situations. AO has a positive relationship with hazard situations that involve more persistent weak layers. While previous studies have only been able to speculate on the effect of PNA and AO on avalanche hazard in western Canada (Mock & Birkeland, 2000; Thumlert et al., 2014), this study provides the first observational evidence about these relationships.

The findings presented in this thesis also opens new opportunities for avalanche research and developing practical tools for avalanche workers. First, the concept of typical hazard situations offers an interesting step towards the development of numerical models that predict danger ratings based on the CMAH. Second, coupling the findings of this study with seasonal ENSO forecasts could lead to the development of seasonal avalanche hazard forecasts to help set the tone for avalanche awareness messaging of a winter and aid avalanche professionals with season planning. Third, the approach developed for identifying typical hazard situations and quantitatively describing the seasonal nature of avalanche hazard provides new possibilities for exploring the effects of climate change on avalanche hazard in Western Canada.

References

Armstrong, R. L., & Armstrong, B. R. (1986). Snow and avalanche climates of the western United States: A comparison of maritime, intermountain and continental conditions. In *Avalanche Formation, Movement and Effects* (pp. 281–294). Davos: IAHS Publ.

Atkins, R. (2004). An avalanche characterization checklist for back-country travel decisions. In *International Snow Science Workshop* (pp. 462–468). Pentiction, British Columbia.

Bellaire, S., Jamieson, B., Thumlert, S., Goodrich, J., & Statham, G. (2016). Analysis of long-term weather, snow and avalanche data at Glacier National Park, B.C., Canada. *Cold Regions Science and Technology*, *121*, 118–125. https://doi.org/10.1016/j.coldregions.2015.10.010

Bonsal, B. R., Shabbar, A., & Higuchi, K. (2001). Impacts of low frequency variability modes on Canadian winter temperature. *International Journal of Climatology*, *21*(1), 95–108. https://doi.org/10.1002/joc.590

Brown, R. D., & Goodison, B. E. (1996). Interannual variability in reconstructed Canadian snow cover, 1915-1992. *Journal of Climate*. https://doi.org/10.1175/1520-0442(1996)009<1299:IVIRCS>2.0.CO;2

Canadian Avalanche Association. (2015). *Technical Aspects of Snow Avalanche Risk Management - Resources and Guidelines for Avalanche Practitioners in Canada*. *Canadian Avalanche Association (Campbell, C. Conger, B. Gould, B. Haegeli, P. Jamieson, B. Statham, G.* Revelstoke, BC, Canada.

CCBFC. (1995). *Canadian Commission on Building and Fire Codes*. (National building code of Canada (NBC), Ed.). Ottawa, Ontario: National Research Council of Canada.

Christensen, J. H., Kumar, K. K., Aldria, E., An, S. I., Cavalcanti, I. F. a., Castro, M. De, … Zhou, T. (2013). *Climate Phenomena and their Relevance for Future Regional Climate Change Supplementary Material*. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom. https://doi.org/10.1017/CBO9781107415324.028

Conover, W., Johnson, M., & Johnson, M. (1981). A comparative study of tests for homogeneity of variances, with applications to the outer continental shelf bidding data. *Technometrics*, *23*, 351–361.

Everitt, B., Landau, S., Leese, M., & Stahl, D. (2011). *Cluster analysis* (5th ed.). Chichester, West Sussex, U.K. : Wiley.

Fitzharris, B. B. (1987). A Climatology of Major Avalanche Winters in Western Canada. *Atmosphere-Ocean*, *25*(2), 115–136. https://doi.org/10.1080/07055900.1987.9649267

Fleming, S. W., Moore, R. D., & Clarke, G. K. C. (2006). Glacier-mediated streamflow teleconnections to the Arctic Oscillation. *International Journal of Climatology*, *26*(5), 619–636. https://doi.org/10.1002/joc.1273

Gruber, U., Haegeli, P., McClung, D. M., & Manners, E. (2004). Large-scale snow instability patterns in western Canada : first analysis of the CAA-InfoEx database 1991-2002. *Annals Of Glaciology*, *38*, 15–20.

Haegeli, P. (2008). Avalanche Hazard Assessment Website. Retrieved from http://avalanchehazard.avisualanche.ca/

Haegeli, P., Atkins, R., & Klassen, K. (2010). *Auxiliary material for Decision making in avalanche terrain: a field book for winter backcountry users.* Revelstoke, British Columbia, Canada: Canadian Avalanche Center. Retrieved from http://old.avalanche.ca/cac/pre-trip-planning/decisionmaking

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*(181), 266–276. https://doi.org/10.3189/172756507782202801

Haegeli, P., Obad, J., Harrison, B., Murray, B., Engblom, J., & Neufeld, J. (2014). INFOEX 3.0 - Advancing the data analysis capabilities of Canada's diverse avalanche community. In *International Snow Science Workshop* (pp. 910–917). Banff, Alberta.

Hägeli, P., & McClung, D. M. (2003). Avalanche characteristics of a transitional snow climate-Columbia Mountains, British Columbia, Canada. *Cold Regions Science and Technology*, *37*(3), 255–276. https://doi.org/10.1016/S0165-232X(03)00069-7

Hollander, M., & Wolfe, D. (1999). *Nonparametric Statistical Methods* (2nd ed.). New York: John Wiley & Sons.

Jamieson, B., Haegeli, P., & Gauthier, D. (2010). *Avalanche Accidents in Canada* (5th ed.). Revelstoke, BC, Canada: Canadian Avalanche Association.

Jamieson, B., & Johnston, C. (1997). The facet layer of November 1996. *Avalanche News*, (52), 10–15.

Jin, J., Miller, N. L., Sorooshian, S., & Gao, X. (2006). Relationship between atmospheric circulation and snowpack in the western USA. *Hydrological Processes*, *20*(4), 753–767. https://doi.org/10.1002/hyp.6126

Johnson, S. (1967). Hierarchical clustering schemes. *Psychometrika*, *32*, 241. https://doi.org/https://doi-org.proxy.lib.sfu.ca/10.1007/BF02289588

Kirch, W. (Ed.). (2008). Pearson's Correlation Coefficient. In *Encyclopedia of Public Health* (pp. 1090–1091). Dordrecht: Springer Netherlands. https://doi.org/10.1007/978-1-4020-5614-7_2569

Kluver, D., & Leathers, D. (2015). Regionalization of snowfall frequency and trends over the contiguous United States. *International Journal of Climatology*, *4358*(February), 4348–4358. https://doi.org/10.1002/joc.4292

Kohonen, T. (2001). *Self organizing maps* (3rd ed.). New York, Berlin: Springer.

Kohonen, T. (2013). Essentials of the self-organizing map. *Neural Networks*, *37*, 52–65. https://doi.org/10.1016/j.neunet.2012.09.018

LaChapelle, E. (1980). The Fundamental Processes in Conventional Avalanche Forecasting. *Journal of Glaciology*, *26*(94), 75–84. https://doi.org/10.1017/S0022143000010601

Liu, Y., Weisberg, R. H., & Mooers, C. N. K. (2006). Performance evaluation of the self-organizing map for feature extraction. *Journal of Geophysical Research: Oceans*, *111*(5), 1–14. https://doi.org/10.1029/2005JC003117

Lute, A. C., & Abatzoglou, J. T. (2014). Role of extreme snowfall events in interannual variability of snowfall accumulation in the western United States. *Water Resources Research*, *50*(4), 2874–2888. https://doi.org/10.1002/2013WR014465

Mantua, N. J., & Hare, S. R. (2002). The Pacific Decadal Oscillation. *Journal of Oceanography*. https://doi.org/10.1023/A:1015820616384

Mantua, N. J., Hare, S. R., Zhang, Y., Wallace, J. M., & Francis, R. C. (1997). A Pacific Interdecadal Climate Oscillation with Impacts on Salmon Production. *Bulletin of the American Meteorological Society*, *78*(6), 1069–1079. https://doi.org/10.1175/1520-0477(1997)078<1069:APICOW>2.0.CO;2

McAfee, S. A., & Wise, E. K. (2016). Intra-seasonal and inter-decadal variability in ENSO on impacts on the Pacific Northwest. *International Journal of Climatology*, *36*(1), 508–516. https://doi.org/10.1002/joc.4351

McClung, D. M. (2002). The elements of applied avalanche forecasting part II: The Physical Issues and the Rules of Applied Avalanche Forecasting. *Natural Hazards*, *26*, 131–146. https://doi.org/10.1023/A:1015665432221

McClung, D. M. (2013). The effects of El Niño and La Niña on snow and avalanche patterns in British Columbia, Canada, and central Chile. *Journal of Glaciology*, *59*(216), 783–792. https://doi.org/10.3189/2013JoG12J192

McClung, D. M., & Schaerer, P. (2006). *The Avalanche Handbook* (3rd ed.). Seattle, WA: Mountaineers Books. https://doi.org/10.1016/0148-9062(77)90015-8

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. https://doi.org/10.1175/1520-0477(2000)081<2367:SACOTW>2.3.CO;2

Moore, R. D., Fleming, S. W., Menounos, B., Wheate, R., Fountain, A., Stahl, K., … Jakob, M. (2009). Glacier change in western North America: influences on hydrology, geomorphic hazards and water quality. *Hydrological Processes*, *23*, 42–

61. https://doi.org/10.1002/hyp

Murtagh, F., & Legendre, P. (2014). Ward ’ s Hierarchical Agglomerative Clustering Method : Which Algorithms Implement Ward ’ s Criterion ? *Journal of Classification*, *31*(October), 274–295. https://doi.org/10.1007/s00357-

NOAA. (2017). Climate Prediction Center. Retrieved June 1, 2017, from http://www.cpc.noaa.gov/data/

R Core Team. (2016). R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing. Retrieved from http://www.r-project.org/

Schweizer, J., Reuter, B., Herwijnen, A. Van, & Gaume, J. (2016). Avalanche Release 101. In *International Snow Science Workshop* (p. 11). Breckenridge, Colorado.

Shabbar, A., & Bonsal, B. (2004). Associations between Low Frequency Variability Modes and Winter Temperature Extremes in Canada. *Atmosphere-Ocean*, *42*(2), 127–140. https://doi.org/10.3137/ao.420204

Shabbar, A., Bonsal, B., & Khandekar, M. (1997). Canadian precipitation patterns associated with the Southern Oscillation. *Journal of Climate*, *10*(12), 3016–3027. https://doi.org/10.1175/1520-0442(1997)010<3016:CPPAWT>2.0.CO;2

Shabbar, A., & Khandekar, M. (1996). The Impact of EL Nino-Southern Oscillation on the Temperature Field over Canada. *Atmosphere-Ocean*, *34*(2), 401–416. https://doi.org/10.1080/07055900.1996.9649570

Shimodaira, H., & Hasegawa, M. (2001). CONSEL: for assessing the confidence of phylogenetic tree selection. *Bioinformatics (Oxford, England)*, *17*(12), 1246–1247. https://doi.org/10.1093/bioinformatics/17.12.1246

Sinickas, A., Jamieson, B., & Maes, M. A. (2016). Snow avalanches in western Canada: investigating change in occurrence rates and implications for risk assessment and mitigation. *Structure and Infrastructure Engineering*, *12*(4), 490–498. https://doi.org/10.1080/15732479.2015.1020495

Stahl, K., Moore, R. D., & McKendry, I. G. (2006). The role of synoptic-scale circulation in the linkage between large-scale ocean-atmosphere indices and winter surface climate in British Columbia, Canada. *International Journal of Climatology*, *26*(4), 541–560. https://doi.org/10.1002/joc.1268

Statham, G., Campbell, S., & Klassen, K. (2012). The AvalX public avalanche forecasting system. In *International Snow Science Workshop* (pp. 523–527). Anchorage, Alaska.

Statham, G., Haegeli, P., Birkland, K., Greene, E., Israelson, C., Tremper, B., … Kelly, J. (2010). The North American Public Avalanche Danger Scale. In *International Snow Science Workshop* (pp. 717–719). Squaw Valley, CA.

Statham, G., Haegeli, P., Greene, E., Birkeland, K., Israelson, C., Stethem, C., … Kelly,

J. (n.d.). A Conceptual Model of Avalanche Hazard.

Suzuki, R., & Shimodaira, H. (2006). Pvclust: an R package for assessing the uncertainty in hierarchical clustering. *Bioinformatics*, *22*(12), 1540–1542. https://doi.org/10.1093/bioinformatics/btl117

Suzuki, R., & Shimodaira, H. (2015). pvclust: Hierarchical Clustering with P-Values via Multiscale Bootstrap Resampling. Retrieved from https://cran.r-project.org/package=pvclust

Thompson, D. W. J., & Wallace, J. M. (1998). The Arctic oscillation signature in the wintertime geopotential height and temperature fields. *Geophysical Research Letters*, *25*(9), 1297–1300. https://doi.org/10.1029/98GL00950

Thumlert, S., Bellaire, S., & Jamieson, B. (2014). Relating Avalanches to Large-Scale Ocean – Atmospheric Oscillations. In *International Snow Science Workshop 2014 Proceedings* (pp. 522–526). Banff, Alberta. Retrieved from http://arc.lib.montana.edu/snow-science/item/2099

Wehrens, R., & Buydens, L. M. C. (2007). Self- and Super-organising Maps in R: the kohonen package. *Journal of Statistical Software*, *21*(5). Retrieved from http://www.jstatsoft.org/v21/i05

Whitfield, P. H., Moore, D., Fleming, S. W., & Zawadzki, A. (2010). Pacific Decadal Oscillation and the Hydroclimatology of Western Canada—Review and Prospects. *Canadian Water Resources Journal*, *35*(1), 1–28. Retrieved from http://www.tandfonline.com/doi/pdf/10.4296/cwrj3501001

Wise, E. K. (2010). Spatiotemporal variability of the precipitation dipole transition zone in the western United States. *Geophysical Research Letters*, *37*(7), 1–5. https://doi.org/10.1029/2009GL042193

Wolter, K., & Timlin, M. S. (2011). El Niño/Southern Oscillation behaviour since 1871 as diagnosed in an extended multivariate ENSO index (MEI.ext). *International Journal of Climatology*, *31*(7), 1074–1087. https://doi.org/10.1002/joc.2336

Wu, R., & Kirtman, B. P. (2006). Changes in Spread and Predictability Associated with ENSO in an Ensemble Coupled GCM. *Journal of Climate*, *19*, 4378–4396. Retrieved from http://journals.ametsoc.org.proxy.lib.sfu.ca/doi/pdf/10.1175/JCLI3872.1

Zhao, H., Higuchi, K., Waller, J., Auld, H., & Mote, T. (2013). The impacts of the PNA and NAO on annual maximum snowpack over southern Canada during 1979-2009. *International Journal of Climatology*, *33*(2), 388–395. https://doi.org/10.1002/joc.3431