# INITIAL DESCRIPTION OF AVALANCHE WINTER REGIMES FOR WESTERN CANADA

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ABSTRACT: Existing snow climate classifications rely heavily on meteorological parameters that describe the average weather during the main winter months. Field experience and measurements, however, show that the character of snowpack weaknesses including their type structure and details of formation are the primary indicators of avalanches that form. Such characteristics are not a formal part of any snow climate classification scheme. Therefore, such classifications can only be of limited use for avalanche forecasting purposes.

The focus of this study is the analysis of persistent snowpack weaknesses in Western Canada, an area with a wide range of weather and snow conditions. Observations from the industrial information exchange (InfoEx) of the Canadian Avalanche Association are used to examine the frequency, sequence and distribution of the most common snowpack weakness types and their related avalanche activity. The results show significant temporal and spatial variations, even in areas with the same snow climate characteristics. The transitional Columbia Mountains, for example, exhibit snowpack weakness characteristics that clearly go beyond a simple combination of maritime and continental influences. 'Avalanche winter regime' is suggested as a new term to describe and classify local snow and avalanche characteristics that are directly relevant for avalanche forecasting. Three distinct avalanche winter regimes are identified for Western Canada.

KEYWORDS: snow climate, avalanche climate, avalanche winter regime, avalanche forecasting

## 1. INTRODUCTION

The three main snow climate types, maritime, continental and transitional (McClung and Schaerer, 1993) are well established and have been used in many snow and avalanche related studies. While the maritime and continental snow climates represent the two extreme values of the spectrum, the transitional type exhibits intermediate characteristics. A detailed historical review of the development and usage of these terms in North America is given in Hägeli and McClung (2003). Snow climate classifications are heavily based on meteorological parameters. The most recent classification method (Mock and Birkeland, 2000), for example, focuses on the main winter months December to March and uses mean air temperature, total rainfall, total snowfall, total snow water equivalent and a derived average December snowpack temperature gradient to classify the local snow climate.

Even though LaChapelle (1966) described the average avalanche characteristics expected in the different climate regions, this type of classification can only provide little information for operational avalanche forecasting purposes. Field experience and measurements show that the character of snowpack weaknesses including their type, structure and details of formation are the primary indicators of avalanches that form. While existing classifications focus on average winter weather characteristics, snowpack weaknesses are created by sequences of specific weather events. Such characteristics are not a formal part of any snow climate classification scheme.

The goal of this study is to examine snowpack structures that are directly relevant for operational avalanche forecasting. While new snow avalanches are common in all mountain regions and can generally be correlated to individual storm cycles, it is the frequency and characteristics of avalanches related to persistent weaknesses that most often distinguish different regions for avalanche forecasting purposes. Avalanche and snowpack observations from the industrial information exchange (InfoEx) of the Canadian Avalanche Association are used to examine the fre-

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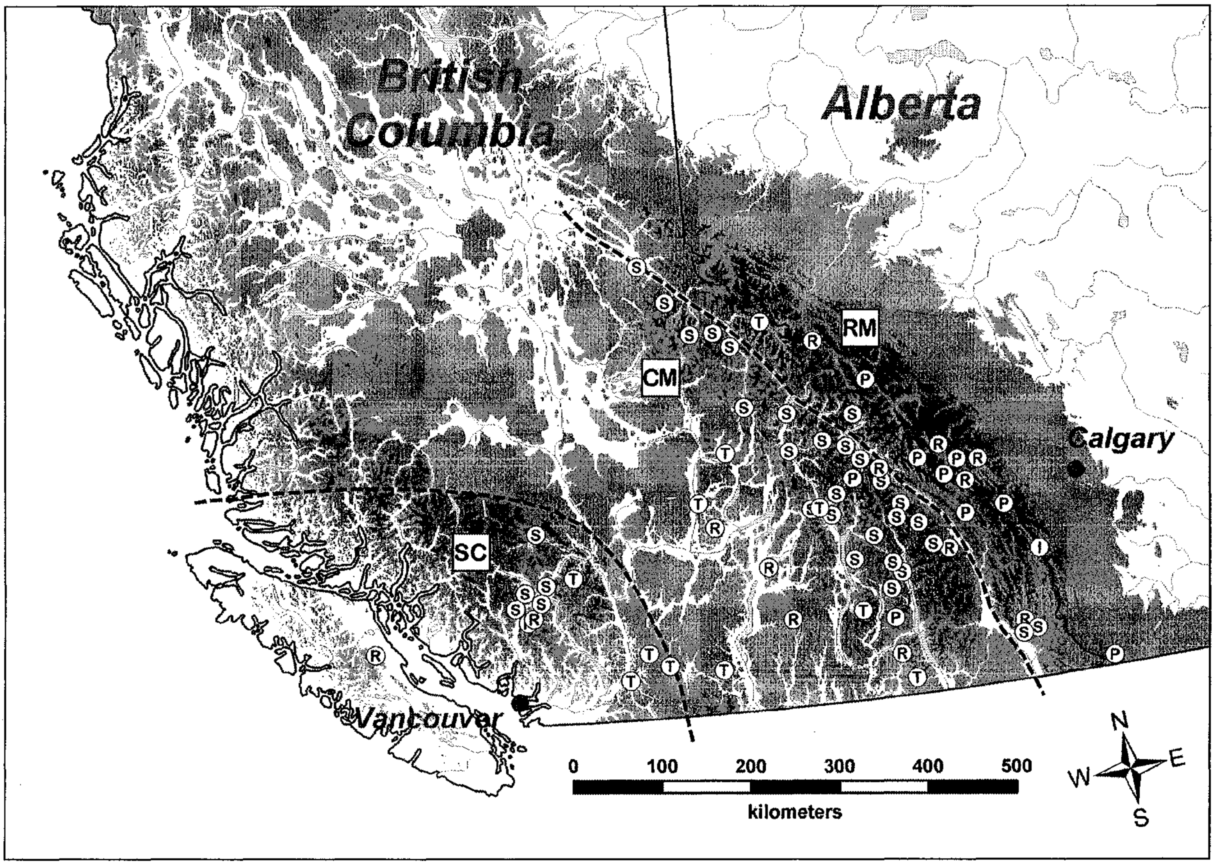

Figure 1: Main mountain ranges of the study area (SC: Southern Coast Mountains; CM: Columbia Mountains; RM: Rocky Mountains) and type and locations of operations contributing to InfoEx service (I: logging and mining operations; P: national or provincial parks; R: resort; S: backcountry skiing operation; T: highway and railway operations).

quency, sequence and distribution of the most common snowpack weakness types and their related avalanche activity in Western Canada. An 'avalanche winter regime' is suggested as a new classification term to describe the avalanche characteristics of a winter in a particular place. In this initial analysis three distinct avalanche winter regimes are identified for Western Canada.

## 2. DATA SET

Western Canada is an ideal area for studying avalanche winter regimes. The three main mountain ranges, the Coast Mountains, the Columbia Mountains and the Rocky Mountains, cover a wide range of different snow and avalanche conditions (Figure 1).

This study focuses on the analysis of avalanche and snowpack observations of the InfoEx dataset from the winter seasons 1996/97 to 2001/02. The data quality and coverage regarding snowpack weaknesses prior to 1996 is too marginal to be included in a climatological analysis.

At this point it should be pointed out that operational avalanche datasets are inherently incomplete and skewed. Avalanche information is incomplete due to observational difficulties, such as large operation areas or poor visibility (Hägeli and McClung, 2003; Laternser and Schneebeli, 2002) and snowpack observations may be skewed by the practice of targeted sampling (McClung, 2002).

The spatial patterns observed are strongly influenced by the distribution and type of submitting operations. Different regions of the study area are dominated by different mixtures of contributing operation types (Figure 1), which can introduce a significant observational bias to the data. Each operation type has different operational priorities and observational capabilities. Mechanized backcountry operations, for example, mainly deal with the undisturbed snowpack, are concerned with skier triggering and cover large areas of terrain. Highway operations, on the other side, generally focus on areas directly threatening the road and frequently use explosives for avalanche control. These operational differences clearly affect the information submitted to the InfoEx.

All these observational biases have to be kept in mind when examining the dataset. Despite these biases, the operational usage of the dataset makes us confident, that the recorded data had directly relevance to avalanche forecasting at the time.

## 3. METHOD

It is a common industry practice to label important snowpack weaknesses with their date of burial. This convention allowed the tracking of these weaknesses in the InfoEx dataset throughout a season.

The focus of this study is on persistent snowpack weaknesses (Jamieson, 1995). We defined the cut-off between persistent and non-persistent to be ten days after burial, which is distinctly longer than one meteorological synoptic period. Related snowpack and avalanche observations that were made after the cut-off are commonly referred to as 'persistent observations' or 'persistent avalanche activity'. We also distinguish between 'active' and 'inactive' areas of snowpack weaknesses. An area is considered active if locally more than one operation recorded related avalanche activity and the reported avalanches were not exclusively triggered by explosives. Persistent active areas have to exhibit consistent avalanche activity more than ten days after burial.

This definition of persistence is different from the ones used in previous studies. Jamieson's classification (1995) was purely based on weak layer crystal types, while Hägeli and McClung (2003) used snowfall data to directly determine the synoptic period and distinguish between non-persistent and persistent weaknesses. The data at hand do not permit the use of one of these more advanced definitions. However, the method used in this study does identify all significant persistent weaknesses mentioned in existing studies (e.g., Hägeli and McClung, 2003; Jamieson et al., 2001).

For the analysis, the observed snowpack weaknesses were grouped into three main categories according to the study of Hägeli and McClung (2003). The three groups are: (a) weaknesses with faceted grains including facet-crust combinations (see, e.g., Jamieson and Johnston, 1997); (b) surface hoar layers; and (c) pure crust interfaces. Together, these three groups cover approximately 95% of all avalanches with reported weak layer information in the InfoEx. The remaining 5% of avalanche are mainly related to precipitation particles and decomposing fragments.

To examine the characteristics of individual observed weaknesses, maps were produced that show the spatial distribution of related persistent snowpack observations and avalanche activity observations. Based on these spatial patterns, seasonal contour maps were produced that show the number and distribution of the three groups of persistent weaknesses across the study area (Figure 2). The same type of map was also used to examine the seasonal patterns of areas with persistent avalanche activity.

Despite significant variabilities in snowpack weakness patterns from season to season, consistent patterns of frequency and composition were found across the study area. The limited number of winters with consistent avalanche observations (1996/97 to 2001/02) analyzed in this study, however, did not allow a reliable delineation of climatological regions of different snowpack weakness characteristics. Instead, seven locations were identified to adequately represent the different regions (Figure 2).

To analyze the seasonal variations of snowpack weaknesses in more detail, idealized snow profiles were constructed for each of the chosen locations (Figure 3). These profiles present the sequences of observed active and inactive weaknesses in the different areas represented by the locations. On the basis of the six winters analyzed in this study, climatological snow profiles were generated for each location. These climatological profiles show average numbers of active and inactive snowpack weaknesses. The succession of weaknesses reflects the general sequence observed during the seasons analyzed. Profiles of individual winters were compared to these climatological profiles to examine annual variations in the weakness patterns.

Annual variabilities were also examined with respect to classical snow climate classifications. A detailed description of a snow climate analysis for Western Canada is beyond the scope of this paper. The analysis was done according to Mock and Birkeland (2000) and is described in detail in Hägeli (2004).

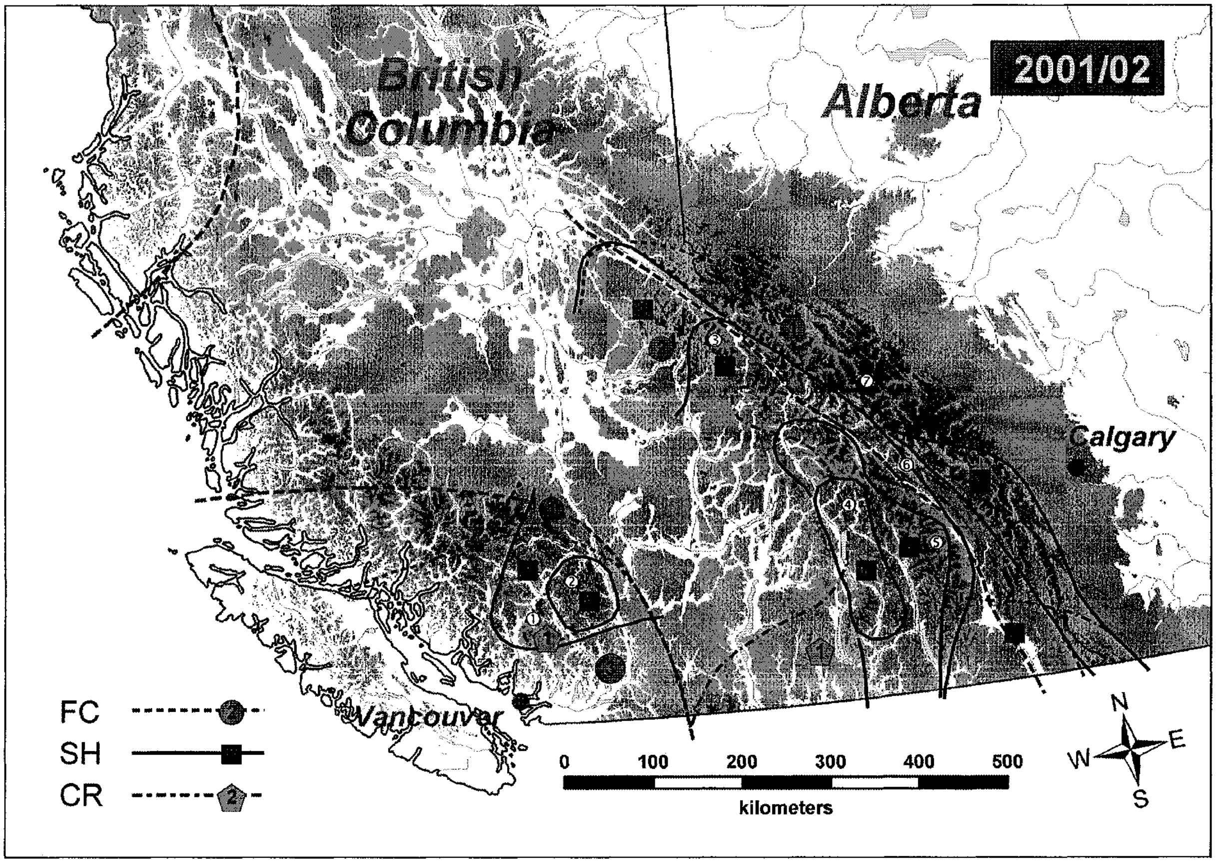

Figure 2: Distribution of persistent snowpack weaknesses observed during the 2001/02 winter season (FC: weaknesses of faceted grains including facet-crust combinations; SH surface hoar layers; CR: pure crust interfaces). The big labels indicate the number of observed weaknesses. Small numbers indicate representative locations of regions of similar snowpack weakness characteristics.

## 4. RESULTS

The results are presented by first describing the observed weakness patterns of an individual season. Regions of similar characteristics are identified and spatial and temporal variabilities are examined with respect to traditional snow climate classifications.

### *4.1 Season 2001/02*

We use the records of the 2001/02 winter season to illustrate seasonal snowpack weakness patterns (Figure 2). Other seasons examined in this study exhibit similar patterns. In general, individual persistent weaknesses are widespread and observed across significant parts of the study area. While the number of layers with faceted crystals is fairly constant across the entire area, the number of surface hoar layers varies considerably among different regions. The Southern Coast Mountains can be separated into a western and an eastern section. The dryer eastern part exhibits more surface hoar weaknesses than the western counterpart. The Columbia Mountains show the highest number of persistent surface hoar layers with a maximum occurring on the western side of the central Selkirk Mountain Range. The number of surface hoar weak layers drops from west to east and toward the northern and southern parts of the Columbia Mountains. The Rocky Mountains can also be divided in areas with different snowpack weakness compositions. The section west of the continental divide is clearly more similar to the eastern parts of the Columbia Mountains with a higher number of surface hoar layers, while the rest of the range rarely experiences persistent weaknesses of this type. The analysis suggests a possible north-south division of the Rocky Mountains. However, the division

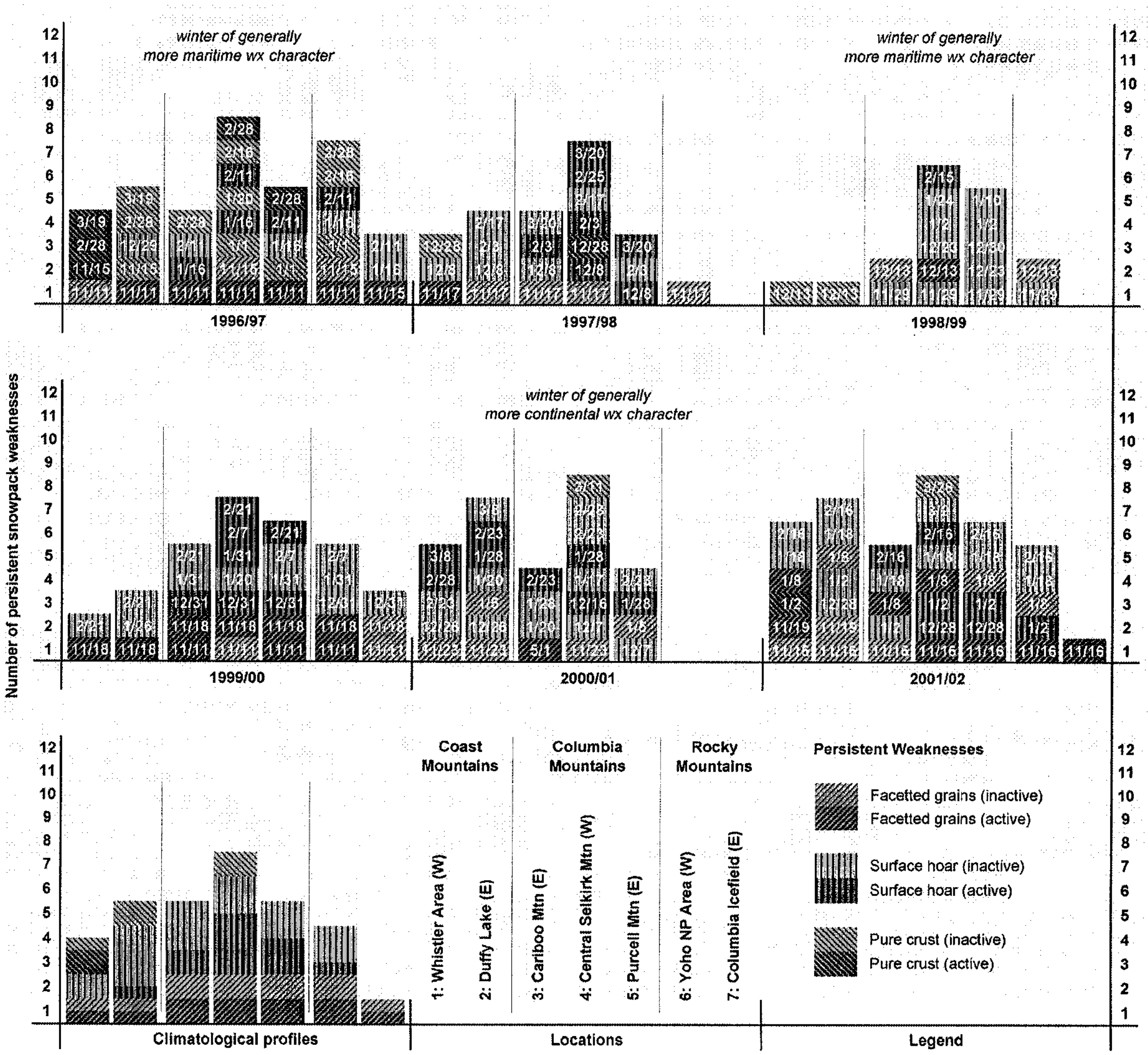

Figure 3: Idealized snow profiles for the seven locations representing different snowpack weakness regions. The weaknesses are labeled with their burial date. The three different types of weaknesses are indicated by different background shading. Active weaknesses are indicated by dark shading, while inactive weaknesses are shown in light shading. Snow climate classifications of individual seasons are discussed in detail in Hägeli (2004).

cannot be demonstrated conclusively with the data at hand.

While persistent weaknesses are generally widespread, the regions where these weaknesses lead to persistent avalanche activity are considerably smaller (Hägeli, 2004). The avalanche activity patterns observed, however, generally support the spatial patterns discussed above.

### *4.2. Climatological snow profiles*

The analysis of the spatial patterns of persistent weaknesses and related avalanche activity of all seasons suggests that the study area can be divided roughly into seven different regions. Each of these regions exhibits different average snowpack weakness and avalanche activity characteristics. The following locations were chosen to represent the different regions (Figure 2):

1) *Whistler Area* (representing western parts of the Southern Coast Mountains)
2) *Duffy Lake* (eastern slopes of Southern Coast Mountains);
3) *Cariboo Mountains* (northeastern Columbia Mountains)
4) *Central Selkirk Mountains* (central western slopes of Columbia Mountains)
5) *Purcell Mountains* (southeastern Columbia Mountains)
6) *Yoho National Park area* (western Rocky Mountains)
7) *Columbia Icefield* (Rocky Mountains east of continental divide).

Figure 3 shows idealized snow profiles for the different regions and seasons. The climatological profiles that represent average conditions for the different regions are shown on the bottom left of the figure.

Early season layers of faceted layers are observed in all areas and occasional pure crust layers predominantly occur in the Coast Range and the central Selkirk Mountains. The climatological profiles confirm that the number of surface hoar layers can be used as a distinguishing factor between different regions. The central Selkirk Mountains clearly experience the highest number of active and inactive surface hoar layers. While, on average, there are no significant surface hoar layers observed on the eastern slopes of the Rocky Mountains, the Coast Mountains experience the occasional surface hoar weakness. In addition to this variation in the west-east direction, the observations also confirm the decrease of persistent surface hoar layers towards the north and south within the Columbia Mountains.

Even though the dominance of early-season faceted layers in the Rocky Mountains is in agreement with the generally weak foundation of the snowpack in this region (McClung and Schaerer, 1993), it is rather surprising that depth hoar does not emerge as a primary weakness in the data. We suspect this to be an artifact of the reporting system, since depth hoar layers cannot easily be associated to specific burial dates.

### 4.3. Seasonal variations in snowpack weaknesses

Winters that exhibit similar snowpack weakness characteristics to the climatological average are 1999/00 and 2001/02. These two winter also exhibited average winter weather characteristics (Hägeli, 2004). In comparison to other winters examined in this study, the January 8, 2002, weak layer of faceted grains clearly stands out as a peculiarity of that season. This is in agreement with the rain-on-snow analysis by Hägeli and McClung (2003), which showed that these events primarily occur during the early months of the winter season. The season 1997/98, which was also classified as a regular snow climate winter in Hägeli (2004), was characterized by the absence of an active early season weak layer of faceted grains. The analysis of these three winters already shows that significant snowpack differences can be observed among winters with similar average weather characteristics.

This variability is even more pronounced in the more maritime winters of 1996/97 and 1998/99 (Hägeli, 2004). The first season was dominated by the November 11, 1996, facet-crust combination, a small number of surface hoar layers and numerous crust interfaces during the main winter months. The 1998/99 winter, on the other side, was characterized by an average number of surface hoar layers in the Columbia Mountains. However, the majority of them did not result in persistent avalanche activity.

The only winter with a more continental snow climate influence in the study, 2000/01 (Hägeli, 2004), is characterized by an average number of persistent weaknesses in the Columbia Mountains. In comparison to the climatological average, however, only a small number of these persistent weaknesses were active. The Coast Mountains experienced an exceptionally large number of persistent surface hoar interfaces and weak layers during this winter. No persistent interface and weak layers were reported in the Rocky Mountains.

While the continental winter does show a shift of the maximum number of surface hoar layers towards the Coast Mountains, no east-west shift of the climatological patterns seems to exist during more maritime winters. We suspect that the main reason for the absence of surface hoar weaknesses in the Rocky Mountains is the very low humidity in the region. Even a stronger maritime influence cannot provide enough moisture to create persistent surface hoar weaknesses in this region.

### 4.4 Avalanche winter regimes

'Avalanche winter regime' is suggested as a new term for describing and classifying the characteristics of local avalanche activity. This classification should contain detailed information about the characteristics of expected avalanche throughout a winter in a given area.

The present study focused on persistent snowpack weaknesses and their related avalanche activity. Within the study area, the analysis revealed three distinct regimes regarding persistent weaknesses. The Whistler area experiences approximately three to four significant persistent weaknesses per season. They are mainly pure crust interfaces. The avalanche winter regimes of the central Selkirk Mountains are dominated by an early-season facet-crust combination and numerous surface hoar layers. With about seven per year, this area exhibits the most persistent weaknesses within the study area. The region represented by the Columbia Icefield is characterized by generally only one persistent weak layer of faceted grains or potentially depth hoar per season.

The snowpack weakness characteristics of the other regions show intermediate properties that can be interpreted as combinations of these three regimes. The idealized snow profiles show that the local avalanche regimes can vary from season to season depending on the dominating processes, similarly to snow climate characteristics.

## 5. CONCLUSIONS

The analysis of persistent weaknesses clearly showed that the transitional Columbia Mountains have very distinct avalanche activity characteristics that clearly go beyond a simple combination of maritime and continental influence. Even within the mountain range, considerable variabilities were observed. The analysis of the different winters also showed that there is significant variability in the composition of snowpack weaknesses even during years with similar average winter weather. Particularly, the two more maritime winters experienced dramatically different profiles.

All these results emphasize the conclusion that, the snow climate classification is inadequate for capturing the characteristics relevant for describing the avalanche activity of a region effectively. We suggest 'avalanche winter regime' as a new term for describing and classifying the local characteristics of the expected avalanche activity. This classification should contain detailed information about the characteristics of expected avalanche throughout a winter in a given area.

The present study focused on persistent snowpack weaknesses and their related avalanche activity. Within the study area, the analysis revealed three distinct avalanche winter regimes. Other regions exhibit intermediate characters.

Persistent weaknesses are clearly only one of the aspects that determine the characteristics of an avalanche winter regime. This study can only be seen as a first step in the direction of a process-oriented definition of avalanche winter regimes. More winters with consistent avalanche activity data are needed to expand the description of the different regimes by including more relevant parameters and identifying the underlying processes. To do so, more high-elevation meteorological observation sites are necessary to better characterize the local sequence of weather events and to conclusively explain the observed large-scale avalanche activity patterns. Meteorological indicators, such as the clear-night-cold-day index used in Gruber et al. (in press) or the potential for facet-crust combinations of rain-on-snow events (Hägeli and McClung, 2003) might provide means to identify and describe different avalanche winter regimes. Similar studies in other geographic regions, particularly in regions with transitional snow climates, are necessary to identify additional avalanche winter regimes and to generalize the regime types found in Western Canada. The results of this research will lead to a set of process-oriented avalanche winter regime definitions that can be used to classify local avalanche characteristics. The resulting regions will provide natural forecast domains, which will lead to improved quality and delivery of large-scale avalanche forecast products, such as the public avalanche bulletins and industrial information exchanges, such as the InfoEx.

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## REFERENCES

Gruber, U., P. Hägeli, D. M. McClung, and E. Manners, in press: Large-scale snow instability patterns in Western Canada: First analysis of the CAA-InfoEx database 1991-2002. Annals of Glaciology, 38.

Hägeli, P., 2004: Scale analysis of avalanche activity on persistent snowpack weaknesses with respect to large-scale backcountry avalanche forecasting, Dept. Earth and Ocean Sciences, University of British Columbia, 249 pp

Hägeli, P. and D. M. McClung, 2003: Avalanche Climate of the Columbia Mountains, British Columbia, Canada. Cold Regions Science and Technology, 37, 255-276.

Jamieson, J. B., 1995: Avalanche prediction for persistent snow slabs, Dept. Civil Engineering, University of Calgary, 258 pp. [Available from Department of Civil Engineering, University of Calgary, 2500 University Drive NW, Calgary AB, CANADA, T2N 1N4]

Jamieson, J. B. and C. D. Johnston, 1997: The facet layer of November 1996 in Western Canada. Avalanche News, 52, 10-15.

Jamieson, J. B., T. Geldsetzer, and C. J. Stethem, 2001: Forecasting for deep slab avalanches. Cold Regions Science and Technology, 33, 275-290.

LaChapelle, E. R., 1966: Avalanche forecasting - A modern synthesis. IAHS Publication, 69, 350–356.

Laternser, M. and M. Schneebeli, 2002: Temporal trend and spatial distribution of avalanche activity during the last 50 years in Switzerland. Natural Hazards, 27, 201-230.

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.

McClung, D. M. and P. A. Schaerer, 1993: The Avalanche Handbook. The Mountaineers, 272 pp.

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