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Avalanche characteristics of a transitional snow climate—Columbia Mountains, British Columbia, Canada

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Abstract

The focus of this study lies on the analysis of avalanche characteristics in the Columbia Mountains in relation to the local snow climate. First, the snow climate of the mountain range is examined using a recently developed snow climate classification scheme. Avalanche observations made by a large helicopter operator are used to examine the characteristics of natural avalanche activity. The results show that the Columbia Mountains have a transitional snow climate with a strong maritime influence. Depending on the maritime influence, the percentage of natural avalanche activity on persistent weak layers varies between 0% and 40%. Facet–crust combinations, which primarily form after rain-on-snow events in the early season, and surface hoar layers are the most important types of persistent weak layers. The avalanche activity characteristics on these two persistent weak layers are examined in detail.

The study implies that, even though the 'avalanche climate' and 'snow climate' of an area are closely related, there should be a clear differentiation between these two terms, which are currently used synonymously. We suggest the use of the term 'avalanche climate' as a distinct adjunct to the description of the snow climate of an area. The more encompassing term should also include information, such as typically important snowpack weaknesses and avalanche activity statistics, which are directly relevant to avalanche forecasting.

Keywords: Snow climate; Avalanche climate; Avalanche activity; Persistent weak layers

1. Introduction

Over the last 50 years, there have been numerous studies defining snow climates and analyzing their characteristics, particularly in the Western United States. The three snow climate types, maritime, continental, and transitional (McClung and Schaerer, 1993), are well established and have been used in many studies to describe local snow and avalanche characteristics and put them into perspective. While earlier works called the three different zones *snow climate zones* (i.e., Roch, 1949; LaChapelle, 1966), later studies gradually introduced the term *avalanche climate zones* (i.e., Armstrong and Armstrong, 1987; Mock and Kay, 1992; Mock and Birkeland, 2000). These analyses were mainly based on meteorological factors with only limited use of avalanche data. In most

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studies, conclusions about the character of avalanche activity were derived from dominant weather characteristics. Our study attempts to build on this previous work by including large-scale avalanche observations in a climate study and describing the avalanche characteristics in relation to the local snow climate.

1.1. Historical review

André Roch, a visiting scientist from the Swiss Federal Institute for Snow and Avalanche Research, carried out the initial research on snow and avalanche climatology in North America in 1949. After traveling to several ski resorts, he classified the Western United States into three different snow climate zones: a 'wet climate' along the coast, a 'drier climate' to the east of the Coast Range, and a 'Rocky Mountain climate' (Roch, 1949).

LaChapelle (1966) was the first to describe dominant weather and avalanche characteristics for the different zones. He describes the coastal snow climate to be characterized by relatively heavy snowfall and mild temperatures. Maritime snow covers are often unstable due to new snow instabilities, but generally warm temperatures promote rapid stabilization. Rain is possible anytime during the winter often leading to widespread avalanche cycles. Relatively low snowfall and cold temperatures characterize the continental snow climate of the Rocky Mountains. Snow covers are shallow and often unstable due to structural weaknesses. LaChapelle (1966) called the third snow climate intermountain zone due to its location between the two mountain zones mentioned above. He proposed that this climate zone is characterized by a combination of maritime and continental influences, which result in generally deep snowpacks with only few significant persistent weaknesses. The intensity of the continental and coastal influences can vary significantly from year to year. LaChapelle included an additional snow climate zone called coastal transitional, which is found between the coastal and intermountain snow climates in the Northwestern United States (Fig. 1). Because of its relatively small extent and the lack of data, this snow climate zone has received little attention in subsequent studies. However, this analysis shows that this snow climate zone might be particularly important for the discussions of snow climates in Canada.

The first quantitative analysis on snow climates was carried out by Armstrong and Armstrong (1987). Using climate data from 15 high-elevation sites of the Westwide Avalanche Network (WWAN), they calculated typical values of temperature, precipitation, snowfall, snow depth, and snow density for the coastal, intermountain, and continental snow climate zones. Their paper also included a simple analysis of fatal avalanche accidents in the different climate zones, but there were no truly quantitative statistical conclusions.

Recent studies have focused more on the variability of snow climates. Mock and Kay (1992) and Mock (1995) used a limited number of avalanche variables, such as monthly number of slab avalanches and number of days with slab avalanche activity, together with meteorological data from WWAN sites to determine the general characteristics and variation of the snow climate at individual locations. Mock and Birkeland (2000), the most recent study, designed a new classification procedure for the snow climate classification based exclusively on meteorological parameters. They analyzed the spatial extent of the three snow climate zones and their variation over time across the Western United States using data from WWAN stations. They confirmed the areas of individual zones sketched by LaChapelle (1966). Although certain winters are dominantly maritime or continental across the entire Western United States, the average snow climate conditions for the individual locations have been relatively stable over the past 30 years.

Although geographically similar, these snow climate analyses were not extended to Canada. The main reason for this is a lack of a Canadian equivalent to the WWAN with long-term, reliable high-elevation data and good spatial coverage that is necessary for such comprehensive studies. There are, however, a few local studies such as the analysis of major avalanche winters at Rogers Pass, British Columbia (Fitzharris, 1981, 1987), and the study of the characteristics of avalanching at Kootenay Pass, British Columbia (McClung and Tweedy, 1993), which examine local snow and avalanche characteristics (Fig. 1). Both studies show that the Columbia Mountains have a transitional snow climate, which is consistent with the classification of similar intermountain locations in the United States. The term 'transitional' snow

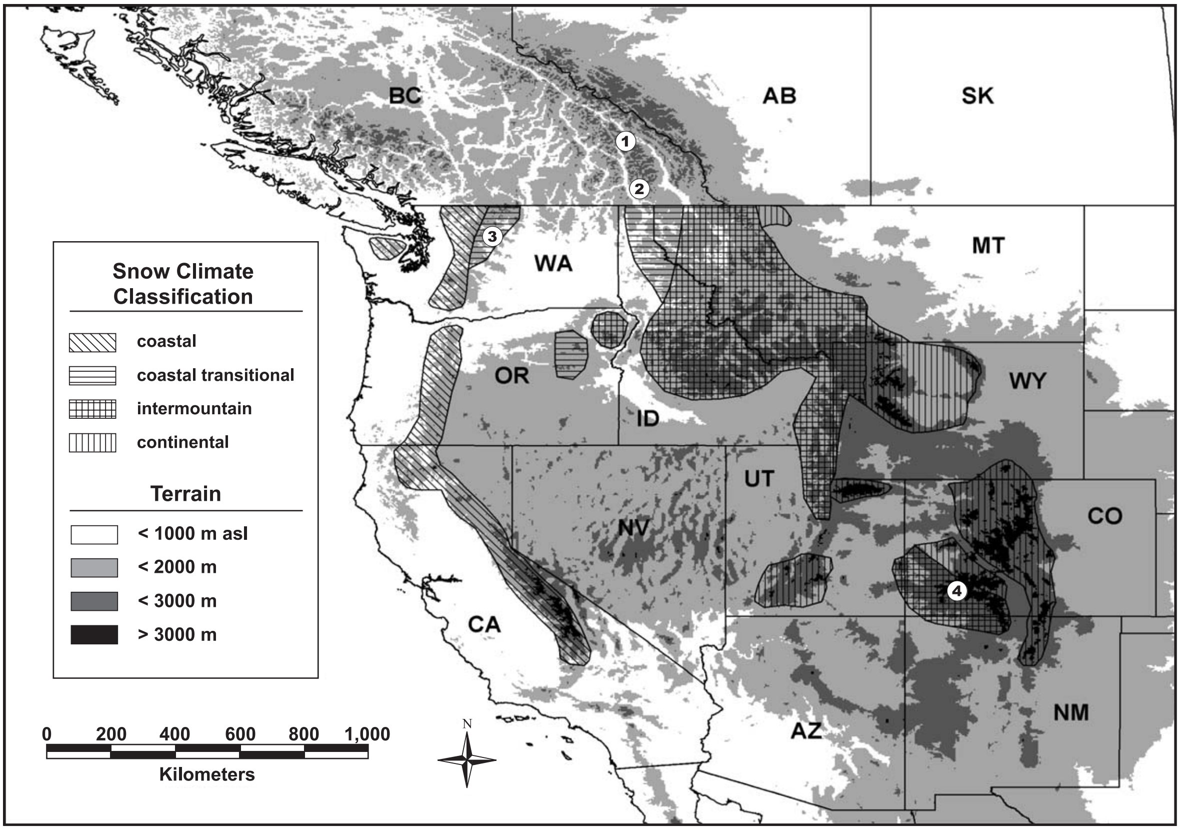

Fig. 1. Location of snow climate zones in western North America after LaChapelle (1966) in relation to Canadian mountain ranges. Numbers indicate location of local snow climate studies mentioned in this study: (1) Rogers Pass, British Columbia (Fitzharris, 1981, 1987); (2) Kootenay Pass, British Columbia (McClung and Tweedy, 1993); and (3) Mission Ridge (Mock and Birkeland, 2000), (4) Red Mountain Pass, San Juan Mountains (LaChapelle and Armstrong, 1976).

climate was introduced by McClung and Schaerer (1993) instead of LaChapelle's 'intermountain' and 'coastal transitional' snow climate. Although the term 'intermountain' has frequently been used and seems to be established in the literature, we believe the term 'transitional' describes the intermediate character of this snow climate zone more precisely. Further, the term is not attached to the geography of the Western United States and it can be used to refer to any other geographical areas (see, e.g., Sharma and Ganju, 2000). Although no extensive study has been conducted in Canada, McClung and Schaerer (1993) classified the snow climates of the Canadian mountain ranges. They describe the Coast Mountains to have a maritime snow climate, the Rocky Mountains a continental snow climate, and the Columbia Mountains, as mentioned above, a transitional snow climate. We will use this terminology for the different snow climate zones for the rest of this paper.

1.2. Discussion of important terms

In the recent past, the terms 'snow climate' and 'avalanche climate' have been used interchangeably. Although snow and avalanches are closely related, we think these two terms are distinctly different and should be used more specifically.

Existing studies have concentrated on meteorological data to determine the snow climate of a region. This method of defining a *snow climate* based on weather variables was borrowed from hydrology and climate modeling (see, e.g., Sturm et al., 1995), where the main interest lies on the spatially integrated values of snowpack properties such as total water equivalent or average surface albedo. The goal of such studies is to find parameterizations for these variables that rely on simple parameters and can easily be incorporated model calculations. These snow climate studies have revealed important general characteristics about the snowpack and related avalanche activity. The dominance of persistent weaknesses in the continental snow climate zone is an example of such general characteristics. This type of understanding has helped avalanche professionals to design appropriate avalanche safety programs in the different snow climate zones.

With respect to daily operational forecasting, however, it is the internal structure of the snowpack that is of primary importance rather than general snowpack properties. It is accepted that dry slab avalanches, the most dangerous avalanche type, release with an initial shear fracture in a thin weak layer underlying a relatively thick cohesive slab (McClung and Schaerer, 1993). This layer structure is not the result of average weather; it is mainly caused by the specific sequence of weather events during a season or a storm. Existing snow climate definitions do not take the seasonal or recent weather history into account. Consequently, snow climate definitions, which neglect a description of the snowpack layer structure are of only limited use for daily avalanche forecasting. We propose the term 'avalanche climate' as a distinct adjunct to the hydrological/meteorological term 'snow climate'. In addition to snow climate information, the more encompassing term also contains information about avalanche characteristics, such as dominant snowpack features and avalanche activity statistics. LaChapelle (1966) qualitatively made the connection between snow and avalanche climate and LaChapelle and Armstrong (1976) examined the weather, snow and avalanche characteristics along Red Mountain Pass during the San Juan project. However, no studies have comprehensively analyzed the avalanche activity of a snow climate zone quantitatively for an area comparable to a snow climate zone. The present study is a first attempt to use avalanche activity characteristics to determine significant snowpack weaknesses with respect to the local snow climate.

The development and behavior of weak layers are essential for avalanche forecasting. Weak layers are formed by a variety of crystal types depending on the conditions during their formation and burial. It is useful to classify these weak layers into non-persistent and persistent layers. *Non-persistent* layers generally stabilize within a few days of deposition and do not show any long-term avalanche activity. Examples are new snow instabilities formed by precipitation particles. Related avalanches typically contain only snow of the current storm period. *Persistent* weak layers (Jamieson, 1995), on the other hand, do not stabilize as quickly and remain active for a longer period of time. Typical examples are depth hoar, faceted crystals, and surface hoar. In the present study, weak layers are regarded to be persistent if they exhibit natural activity after the beginning of the second storm after burial. Avalanches that release on persistent weak layers also contain snow that was deposited previous to the current storm period. This definition of persistence, which depends on the timing of avalanche activity on weak layers, is slightly different from the definition used by Jamieson (1995), who based his classification solely on the weak layer crystal type.

The analysis of slab avalanche activity on persistent weak layers seems crucial for the definition and distinction of different avalanche climates. This study contains partial answers to the following questions about persistent weaknesses in the Columbia Mountains: (a) What is the fraction of avalanche activity on persistent weak layers? (b) What types of persistent weak layers are mainly present? (c) Are there characteristic spatial activity patterns within the mountain range? and (d) Do avalanche activity characteristics and spatial patterns differ significantly from season to season?

2. Study area and dataset

The Columbia Mountains are one of the three major mountain ranges in Western Canada. They lie west of the Rocky Mountains and are flanked to the west by the Interior Plateau. Valleys of the North Thomson, the Columbia, and the Kootenay River divide the mountain range into its four major subdivisions: the Cariboo Mountains, the Monashee Mountains, the Selkirk Mountains, and the Purcell Mountains from north to south (Fig. 2). The northern parts of these individual

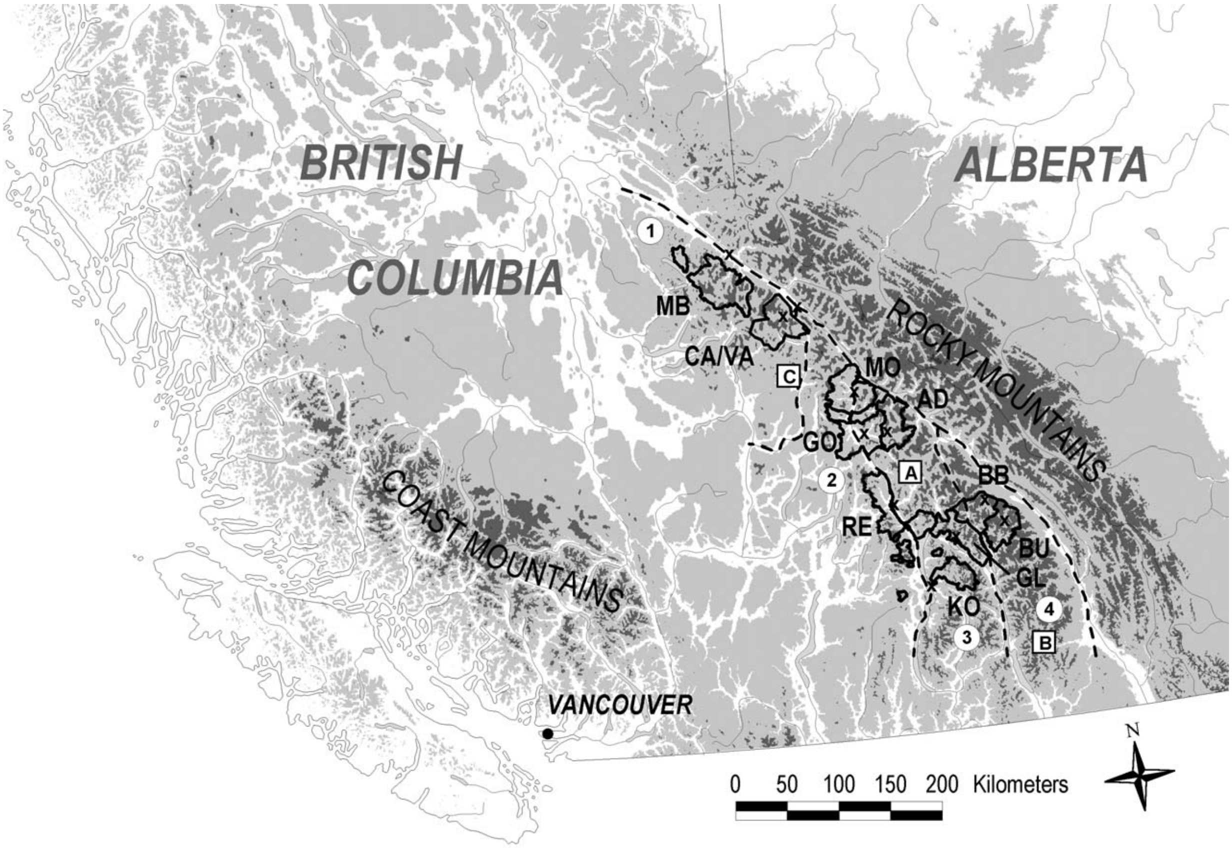

Fig. 2. Southern portion of British Columbia and Alberta showing the 11 operations of Canadian Mountain Holidays in the Columbia Mountains: McBride (MB), Cariboos and Valemount (CA/VA), Monashees (MO), Gothics (GO), Adamants (AD), Revelstoke (RE), Kootenay (KO), Galena (GL), Bobbie Burns (BB), and Bugaboos (BU). Small × indicate the location of the lodge of an individual operation. Often this corresponds with the site main weather plot. Dashed lines show the four major subdivisions of the mountains range: (1) the Cariboos, (2) the Monashees, (3) the Selkirks, and (4) the Purcells. The squares show the location high-elevation weather stations: (A) Mount Fidelity, (B) Kootenay Pass, and (C) Mount St. Anne.

ranges are generally characterized by rugged high peaks and steep-sided glaciated valleys, while the southern portions are more subdued and rounded. Elevation ranges from 400 m in valley bottoms to approximately 3500 m above sea level (a.s.l.). Previous studies (Fitzharris, 1981, 1987; McClung and Tweedy, 1993) have described the snow climate of the Columbia Mountains as transitional with a combination of maritime and continental influences.

Canadian Mountain Holidays (CMH), the world's largest helicopter ski provider, manages 11 individual operations in the Columbia Mountains of British Columbia covering a total area of approximately 20,000 km^2, an area equivalent to the entire Swiss Alps (Fig. 2). Since the winter of 1996/1997, CMH has used SNOWBASE, an extensive database system, to store data pertinent to avalanche forecasting in all operations. The information collected includes weather observations taken from study plots and field observations, avalanche observations, snowpack information, stability ratings, and run usage. The focus of this study lies on weather and avalanche activity observations.

2.1. Weather observation

Most operations maintain a primary study plot close to their lodges where standard meteorological and snow surface measurements are taken twice daily during the skiing season (see Fig. 2 for locations). The lodges are located either near valley bottoms or at tree line (580–1495 m a.s.l.). The study plot measurements yield information about the general weather development during operation, but they do not cover late fall and early winter. This time period, however, proves to be particularly important, since the shallow snowpack is especially sensitive to weather conditions and developments can have significant effects on snow stability conditions for the entire winter. The snow climate zones published by Armstrong and Armstrong (1987) and the snow climate classification scheme of Mock and Birkeland (2000) both evolved from data taken at high-elevation sites (average elevation of 2900 m a.s.l.), which were chosen to be representative of the conditions in the avalanche starting zones of the different areas. There are only a few high-elevation weather stations with reliable long-term records in British Columbia. Data from two stations are analyzed in this study. The weather plot on Mount Fidelity is located on the western side of the Selkirks, on the northern side of the highway corridor through Rogers Pass (Fig. 2). It is situated at 1875 m above sea level, which is just slightly below the average elevation of the coastal stations used in the study by Mock and Birkeland (2000). Continuous temperature and precipitation records are available continuously since 1969, while snow depth has only been recorded since 1980. The second station is Kootenay Pass, which is located in the southeast corner of British Columbia on a major highway between the towns of Salmo and Creston at 1775 m above sea level (Fig. 2). Numerous meteorological and nivological parameters have been monitored at this weather station since 1981.

2.2. Avalanche observation

CMH's avalanche observations are carried out during regular skiing operation. They are collected for operational avalanche forecasting and not primarily for research purposes. Avalanche recordings generally contain standard parameters, such as number, size, trigger, avalanche type, liquid water content, aspect, and elevation following the observation guidelines of the Canadian Avalanche Association (CAA, 1995). Avalanche sizes are recorded according to the Canadian five-step size classification (Table 1). Characteristics of the associated weak layer and bed surface are also recorded, as well as information about avalanche involvements of guides and/or guests. These observations are mainly made by guides while skiing with guests or while flying in the helicopter. This clearly impedes complete and accurate avalanche observation and many of the avalanche parameters are either well-educated estimates or left blank in the database. In addition, there is a designated 'Snow Safety Guide' in each operation, who does not lead groups and makes observations pertinent to the assessment of snow stability. This guide is able to examine individual avalanches in detail and to take more detailed measurements.

Individual operations are also far too large to be covered completely during regular operation, which results in spatially incomplete avalanche observation data. Observations can also be impossible due to bad weather or other operational constraints, such as non-skiing days due to departing or arriving guests or medical emergencies. This problem of incomplete avalanche observations is common and has been an issue in other large-scale avalanche studies (e.g., Laternser and Schneebeli, 2002). The quality of the data also varies significantly between operations and seasons, due differences in familiarity with the database program and various people recording the data.

Table 1
Canadian avalanche size classification

Size code	Description	Typical mass (tonnes)	Typical path length (m)
1	Relatively harmless to people	< 10	10
2	Can bury, injure or kill a person	10^2	100
3	Can bury and destroy a car, damage a truck, destroy a small building, or break a few trees.	10^3	1000
4	Can destroy a railway car, large truck, several buildings, or a forest area up to 4 ha	10^4	2000
5	Largest avalanche known. Can destroy a village or a forest of 40 ha	10^5	3000

Half sizes from 1.5 to 4.5 are frequently used for avalanches that are between two size classes (CAA, 1995).

Since the database system was developed in the Adamants (AD), this operation is expected to have recorded the most complete avalanche activity dataset.

However, with approximately 4500 individual avalanche observations over five winters (approximately 17,000 individual avalanches) consistently covering an area of approximately 20,000 km^2, this avalanche dataset is one of the biggest and most comprehensive backcountry datasets currently available. Although not as sound as other scientific avalanche datasets, these avalanche records give a representative documentation of the avalanche activity in the Columbia Mountains during the five seasons. However, because of the limitations on data collection, it is not appropriate to apply standard geostatistical methods to the data. Thus, the analysis is fairly descriptive and the statistical estimates presented should be interpreted with caution.

3. Methodology

The goal of this study was to analyze the snow and avalanche characteristics of the Columbia Mountains. The analysis was carried out in two steps. First, the snow climate classification scheme of Mock and Birkeland (2000) was used to examine the weather records of Mount Fidelity and Kootenay Pass in order to characterize the general snow climate of the Columbia Mountains over the time period of 1980/1981 to 2000/2001. Next, the avalanche observations of CMH from 1996/1997 to 2000/2001 were examined with a focus on the activity on persistent weak layers. Meteorological measurements taken at Mount Fidelity were used to describe the general weather conditions during these winters.

3.1. Snow climate classification scheme

The classification scheme of Mock and Birkeland (2000) was used to define and examine the snow climate of the Columbia Mountains over the period of 1980–2000 (Fig. 3). The scheme focuses on the main winter period from December 1st to March 31st and uses the following variables to determine the snow climate type: mean air temperature, total rainfall, total snowfall, and total snow water equivalent. In addition, the average December snowpack temperature gradient is used to examine the potential of depth hoar formation during the early season. This is calculated by dividing the difference of mean December air temperature and an assumed basal temperature of 0 °C by the mean December snow depth (Mock and Birkeland, 2000). Except for the snow water equivalent, all variables can be derived directly from daily snow

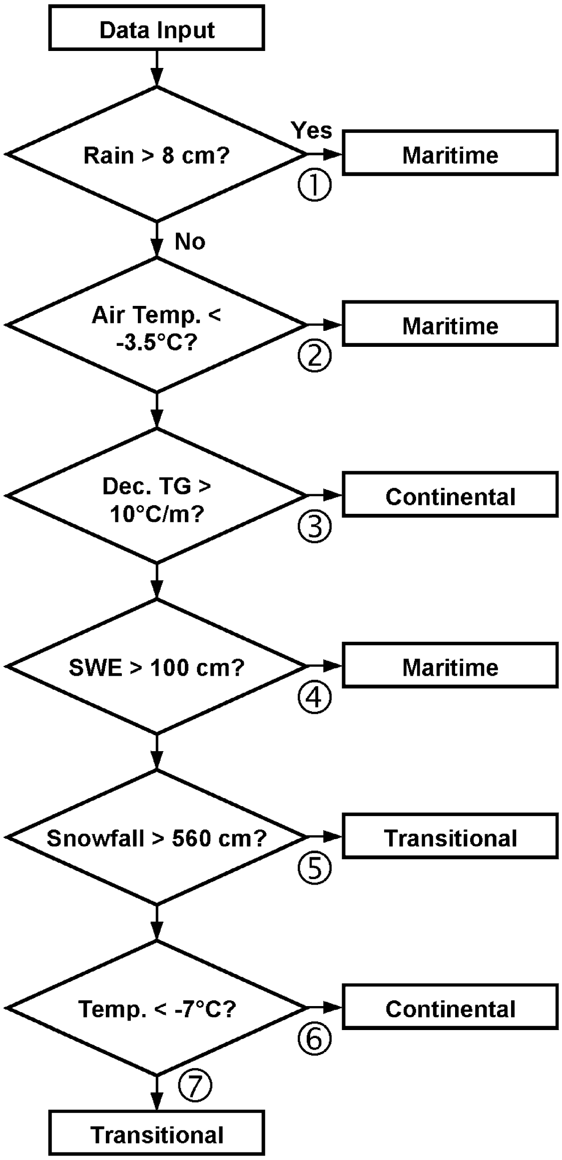

Fig. 3. Flowchart illustrating the classification procedure for the seasonal snow climate classification (after Mock and Birkeland, 2000). SWE stands for snow water equivalent.

and weather records. An average density for new snow of 100 kg m^{-3} was assumed for the calculation of the snow water equivalent from snowfall. While daily rainfall values were directly available for Mount Fidelity, values for Kootenay Pass were derived from values of total precipitation and snow water equivalent of new snow.

A detailed examination of the analysis of Mock and Birkeland (2000) shows a systematic increase of mean elevation from coastal to continental stations (coastal: 2100 m; intermountain: 2600 m; and continental: 3300 m above sea level). This elevation increase is caused by the natural geography of the Western United States (Fig. 1). Although unintentional, it has a strong effect on the classification scheme, since temperature is one of the main discrimination variables of the method. A detailed analysis of the consequence of this elevation dependence on the

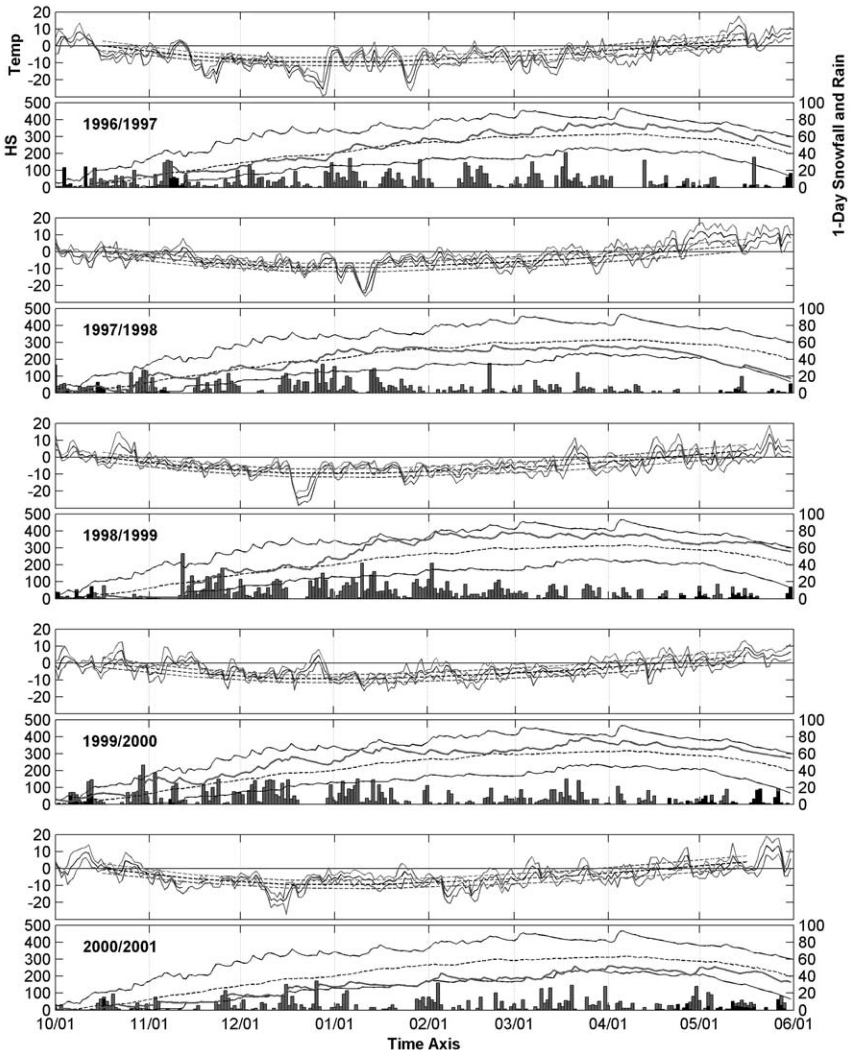

Fig. 4. Time series of weather parameters measured at Mount Fidelity for winters examined in this study. Top panel shows daily mean, maximum and minimum temperature together with climate normals of individual months (dashed lines). Bottom panel shows measured snow depth together with maximum and minimum snow depth measured since 1980. The panel also shows 1-day snowfall (light grey) and rainfall (dark grey).

classification scheme and its interpretation is beyond the scope of this paper. However, because of this elevation dependence special attention should be given to the temperature-related decisions (2, 3, 6, and 7) when applying the classification scheme.

3.2. Avalanche observation analysis

Since avalanches are the result of specific sequences of weather events during a season, it is necessary to have a closer look at meteorological conditions during these winters (Fig. 4). While the time series of meteorological factors from Mount Fidelity and Kootenay Pass cannot be used to explain individual avalanche events, we believe that they can be used, in conjunction with the weather observations at individual lodges, to discuss the general weather conditions in the Columbia Mountains.

The present study contains an analysis of naturally triggered avalanches. Natural avalanches triggered by cornice failures or ice falls were also excluded to ensure that the avalanche climate signal is as 'clean' as possible, independent of local geography, skier and explosive usage.

For the analysis, avalanche numbers were converted from categorical to numerical values (Table 2). This approximation of the number of observed avalanches allows the calculation of an avalanche activity index (AAI), which can be used as a measure of the overall observed natural avalanche activity on individual days. The daily AAI is calculated for individual operations by summing the sizes of all observed avalanches. This represents the sum of the logarithmic snow masse in tonnes involved in individual avalanches on the day in question. Other climate studies in North America have used the sum of the squared sizes as a measure of the daily avalanche activity. These studies used the U.S. avalanche size classification, which rates avalanches from 1 to 5 relative to their path. In conjunction with the Canadian size classification, this method would clearly overemphasize large avalanches. The calculated AAI are used to plot time series of observed avalanche activity for individual operations.

Table 2
List for conversion of categorical avalanche numbers in SNOWBASE into numerical values for analysis

Category	Definition	Numerical value
1	1	1
2	2	2
Several	3–9	6
Numerous	≥ 10	12

Particularly during the first year after the introduction of SNOWBASE, avalanches were often still recorded in the form of comments. For this study, these comments were converted into regular avalanche recordings as precisely as possible. Subjective comments about avalanche cycles, which could not be converted, were classified into three cycle categories (large, intermediate, and small cycles). This information was used only for the analysis of activity patterns (see, e.g., Fig. 8) and not incorporated in any calculations.

In the database, avalanches on persistent weak layers are normally tagged with the date of the burial of the weak layer. This allows the tracking of specific layers throughout the season. The naming of individual weak layers is, however, not necessarily consistent among operations and therefore these layers had to be correlated. This was done by analyzing the weather history of neighboring operations and comparing their weak layer notation.

The focus of this study was on significant persistent weak layers. In this context, 'significant' means that there were at least two entries of avalanche activity after the initial burial on this weak layer among all operations. While the analysis of single events on weak layers might be useful for avalanche forecasting, it provides only limited climatological value. Spatial and temporal activity patterns of individual persistent weak layers were examined by calculating AAI on these layers for individual operations and comparing the time series. The characteristics of the weak layers were analyzed on the basis of the recorded parameters in the avalanche records.

4. Results and discussion

4.1. Snow climate analysis

Out of the 21 winters analyzed at Mount Fidelity, 10 were classified as maritime, 10 as transitional, and 1 was considered to have continental character

(Table 3). Except for the continental winter, which was classified on the basis of the December temperature gradient (TG), all classifications were based on precipitation variables. Maritime winters were classified either because of their high amount of rain or their high value of snow water equivalent (SWE). Transitional winters were all categorized due to their snowfall values above 560 cm. With the exception of the rainfall, these variables are less elevation-dependent than the mean temperature. At higher elevations, where the rain fell as snow, the scheme would have classified all five maritime 'rain'-winters (winters with decision 1 in Table 3) as transitional. The choice of new snow density turns out to be critical for this analysis. A slightly lower density of 90 kg m^{-3} would produce two more, and a density of 85 kg m^{-3} four more transitional winters. The application of the snow climate classification scheme to the climate normals (1971–2000) resulted in a maritime snow climate classification. The value of 8.2 mm of rain is just slightly above the classification threshold. With less rain, the classification would be transitional.

The analysis for Kootenay Pass shows very similar results with a slightly stronger continental influence (Table 4). Out of 20 winters, 9 were classified as maritime, 7 as transitional, and 4 as continental. This result is in agreement with the snow climate assessment of McClung and Tweedy (1993). Although the two climate stations are classified in the same category in only six winters, the seasonal weather variables clearly exhibit similar patterns. Mean temperature and December temperature gradient values are generally comparable, whereas there are considerable discrepancies in the rainfall and smaller differences in seasonal snowfall values. The rainfall difference is partially caused by the lower altitude of the Kootenay Pass weather station. We believe, however, that the differences are mainly caused by a smaller scale variability of precipitation patterns. While the general

Table 3
Analysis of snow climate of Mount Fidelity according to classification scheme by Mock and Birkeland (2000)

Season	Classification	Decision	Rain (mm)	Temp. (°C)	December TG (°C/m)	Snowfall (cm)	SWE (cm)
80/81	MARITIME	1	64.8	− 5.0	3.3	707	70.7
81/82	MARITIME	4	0.0	− 9.3	6.1	1183	118.4
82/83	TRANS.	5	4.0	− 5.8	7.7	818	81.8
83/84	MARITIME	1	39.5	− 7.9	12.0	793	79.4
84/85	TRANS.	5	0.0	− 9.3	6.4	760	76.0
85/86	MARITIME	1	42.0	− 6.2	4.2	722	72.2
86/87	MARITIME	1	18.2	− 6.2	5.2	772	77.3
87/88	MARITIME	4	2.6	− 7.6	6.7	1128	112.8
88/89	TRANS.	5	0.0	− 9.3	5.9	918	91.8
89/90	MARITIME	4	0.0	− 7.1	3.2	1074	107.4
90/91	TRANS.	5	3.5	− 9.0	4.5	951	95.1
91/92	TRANS.	5	5.0	− 4.0	3.2	807	80.7
92/93	CONT.	3	0.0	− 8.6	10.1	548	54.8
93/94	TRANS.	5	0.0	− 6.2	4.3	936	93.6
94/95	TRANS.	5	0.0	− 6.2	4.6	675	67.5
95/96	MARITIME	1	17.3	− 8.7	3.1	658	65.8
96/97*	MARITIME	4	0.0	− 8.4	8.0	1000	100.1
97/98*	TRANS.	5	0.0	− 6.4	4.5	710	71.0
98/99*	MARITIME	4	0.0	− 7.2	5.6	1167	116.7
99/00*	TRANS.	5	0.0	− 6.2	2.3	976	97.6
00/01*	TRANS.	5	0.0	− 7.2	9.1	678	67.8
Climate normals	MARITIME	1	8.2	− 7.6	3.8	914	91.4

The table shows classification together with classification decision according to numbering in Fig. 3 and calculated variables (Temp. = temperature; TG = temperature gradient; SWE = snow water equivalent). Asterisks indicate winter seasons where avalanche observations are available.

Table 4
Analysis of snow climate of Kootenay Pass according to the scheme of Mock and Birkeland (2000)

Season	Classification	Decision	Rain (mm)	Temp (°C)	December TG (°C/m)	Snowfall (cm)	SWE (cm)
81/82	MARITIME	1	10.8	− 7.7	6.5	930	93.0
82/83	MARITIME	1	22.4	− 4.7	6.0	746	74.6
83/84	CONT.	3	4.7	− 7.0	11.1	597	59.7
84/85	CONT.	3	0.7	− 11.5	11.2	585	58.5
85/86	TRANS.	7	6.8	− 4.9	6.1	516	51.6
86/87	TRANS.	5	5.3	− 5.8	7.7	882	88.2
87/88	TRANS.	5	7.0	− 6.3	7.1	775	77.5
88/89	TRANS.	5	7.6	− 8.0	6.6	698	69.8
89/90	TRANS.	5	3.8	− 6.2	5.12	788	78.8
90/91	MARITIME	1	14.0	− 7.4	6.7	1276	127.6
91/92	CONT.	5	4.1	− 6.4	4.5	698	69.8
92/93	TRANS.	3	5.1	− 8.9	11.2	799	79.9
93/94	MARITIME	4	4.2	− 5.3	5.9	1027	102.7
94/95	MARITIME	1	13.5	− 5.4	4.6	1237	123.7
95/96	MARITIME	1	9.2	− 7.3	5.6	1084	108.4
96/97*	MARITIME	1	19.8	− 6.8	4.7	1508	150.8
97/98*	TRANS.	5	5.6	− 5.6	7.3	833	83.3
98/99*	MARITIME	4	3.53	− 6.0	4.7	1371	13.71
99/00*	MARITIME	4	2.3	− 5.7	4.2	1042	104.2
00/01*	CONT.	3	3.8	− 6.7	11.8	405	40.5

trends are often similar across the entire mountains range, local values can differ considerably related to differences of local geography, in individual storm tracks, and seasonal shifts of the jet stream (Hägeli and McClung, submitted).

Despite these issues, we feel confident with the classification of the snow climate for the entire Columbia Mountains. The analysis shows that the area is characterized by a transitional snow climate with a strong maritime influence. Mount St. Anne, a more northerly climate station in the Cariboo Range (Fig. 2), exhibits snowpack characteristics similar to two more southerly stations (Jamieson, 2003). The limited number of continental winters and the dominance of high values of snowfall and snow water equivalent indicate that the general snow climate of the area might be an example of the ‘coastal transitional’ snow climate of LaChapelle (1966). This result is in agreement with the general perception of the Columbia Mountains and particularly the Rogers Pass area, which is famous for its large amounts of snow. It is also consistent with LaChapelle’s (1966) map of snow climate zones in the Western United States, which shows an area of coastal transitional immediately to the south of the Columbia Mountain (Fig. 1). Mission Ridge, the only station in the coastal transitional zone in Mock and Birkeland (2000), shows a temporal distribution of snow climate types comparable to Mount Fidelity and Kootenay Pass.

4.2. Weather history of winter with avalanche records

To put the observed avalanche activity into perspective, it is necessary to examine the weather characteristics of the winters 1996/1997 to 2000/2001. The meteorological observations from Mount Fidelity (Fig. 4) are used to illustrate the main weather features in the Columbia Mountains for each winter season. The time series are compared to climate normals from the period 1970 to 2000.

4.2.1. 1996–1997

This winter was characterized by a cold start in November and December. The later part of the season experienced normal air temperatures. However, the cold start and three considerable cold spells resulted in the overall coldest winter in this analysis. After a snowy start of the season, the snowpack settled dramatically during a major rain event in early November. After a relatively dry December, the snowfall began again and by the end of the season the snowpack depth was above normal.

4.2.2. 1997–1998

Very mild temperatures throughout the entire season characterized the winter of 1997/98. After a major snowfall event end of October, snowfall was normal for November and December and below normal for the rest of the season. This resulted in a relatively shallow snowpack for the second half of the season, particularly at lower elevations.

4.2.3. 1998–1999

This winter was dominated by large amounts of precipitation. After a slow start, high snowfalls resulted in a snowpack depth of 110–125% of normal for most of the season. Except for a significant cold period in December and a short cold spell in late January, temperatures were mild during the winter months. However, in May temperatures dropped below normal, which, together with the existing snowpack and the above normal precipitation, resulted in an abnormally long winter for the region.

4.2.4. 1999–2000

During this winter, temperatures were slightly above normal with no significant cold weather periods. The snowpack depth was generally above normal during the entire winter, even though there were several extended dry periods. Because of the warm temperatures, the snowpack depth was generally below normal at lower elevations.

4.2.5. 2000–2001

This winter season was one of the driest winters on record in many locations in the Columbia Mountains. Together with the preceding dry fall, low snowfalls lead to an exceptionally shallow snowpack for almost the entire season. Temperatures were just slightly above normal; however, there were two considerable cold spells, particularly during the early season. This resulted in a winter with continental characteristics across the Columbia Mountains. While Kootenay Pass was classified as a continental winter by the classification scheme of Mock and Birkeland (2000), Mount Fidelity was characterized as a transitional winter. However, the calculated average December temperature gradient for Mount Fidelity was just slightly below the threshold of 10 °C/m.

This short description shows that, although there are only five winters documented, the study covers a wide range of different winters. The observations at Kootenay Pass show very similar general weather patterns to those at Mount Fidelity. In the following sections, the avalanche activity patterns that resulted from these weather patterns are analyzed in detail. The intention is to relate the observed patterns to the dominant weather influences and snow climate characteristics described above.

4.3. Avalanche activity on persistent weak layers

Avalanches on persistent weak layers make up a considerable portion of the overall natural avalanche activity recorded in the study area (Fig. 5). On average, 16% of the annually recorded natural slab avalanche activity is related to persistent weak layers. The average fraction is higher in the Adamants, with 24% of the recorded activity on persistent weak layers. Although there is considerable scatter between different operations for individual winters (see Fig. 6 for details), the average percentages appear to correspond with the general snow climate and weather characteristics of the respective winters. The continental winter of 2000/2001 showed with 32% roughly twice as much avalanche activity related to persistent weak layers, while the maritime winter of 1998/1999 had almost no activity on persistent weak layers. Other winters have values between these two extremes. These results are consistent with the char-

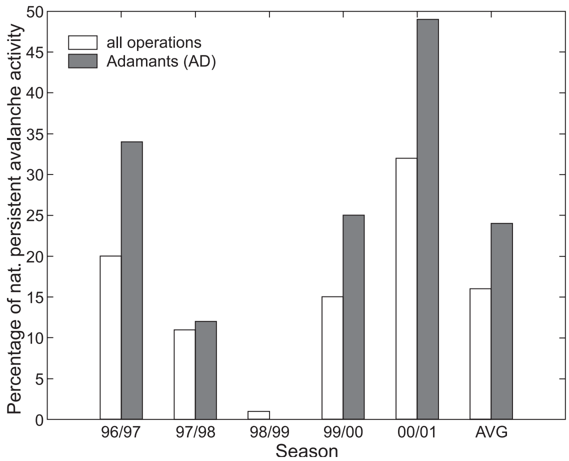

Fig. 5. Percentages of natural avalanche activity related to persistent weak layers for all of CMH and the Adamants operation individually.

	Persistent weak layer			MB	CA	VA	MO	GO	AD	RE	GL	KO	BB	BU	ALL	AVG
	Date	WKL/BSF	Type (Fig. 4)	Percentage of natural persistent avalanche activity on WKL												
Season 96/97	96/11/11	FC/CR or FC/	FC	12	7	4	21	26	9					1	9	12
	96/11/25	FC/CR	FC						16						4	16
	97/01/16	SH	SH				6	5			1			2	1	3
	97/02/11	SH/CR or SH/	SH				3	6	8	2	9		3	1	4	4
	97/02/16		N/A											3	<1	3
	97/02/28	/CR	pure CR				4		1		1		<1	1	1	1
	97/03/17		N/A				1								<1	1
	SUM			12	7	4	35	38	34	2	10		3	8	20	15
Season 97/98	97/11/10	FC/ or FC/CR	FC								1		12	8	2	7
	97/11/20	FC/CR	FC					2	9	7		1			3	5
	97/12/08	FC/ or SH/	SH				5	2			6	8			2	5
	97/12/29	/CR	pure CR							7					<1	7
	98/02/03	SH/	SH					1	2	8	1	10			2	4
	98/02/18	SH/	SH									1			<1	1
	98/02/28	SH/ or SH/CR	SH									3			<1	3
	98/03/21	SH/ or SH/CR	SH		2		1	1	<1	9	1		3	<1	1	2
	SUM			0	2	0	6	6	12	31	8	22	15	8	11	10
98/99	99/01/24		N/A									7			1	7
	99/02/16		N/A								2				<1	2
	99/03/11		N/A					1							<1	1
	SUM			0	0	0	0	1	0	0	2	7	0	0	1	1
99/00	99/11/18	FC/CR or /CR	FC		1			12	1		1	1	14	2	3	5
	99/12/30	SH/	SH			1	12	5	8	2	9	5	9	1	6	6
	00/01/31	SH/	SH					1			7				1	4
	00/02/07	SH/	SH				5	2							1	3
	00/02/20	SH/ or /CR	SH				2		15	8		4	5	1	5	6
	SUM			0	1	1	18	20	25	10	17	9	28	4	15	12
Season 00/01	00/11/19	SH/FC	FC									25			1	25
	00/11/24	FC	FC				17	58	30						17	35
	00/11/30	FC	FC											3	<1	3
	01/01/22	SH	SH				3								<1	3
	01/01/28	SH/ or /CR	SH				1		5	19	5	7			4	8
	01/02/22	SH/ or SH/CR	SH						14			5			7	9
	01/02/28	SH/FC	SH				39								3	39
	01/03/19	FC/CR	FC		6										<1	6
	SUM			0	6	0	60	58	49	19	5	37	0	3	32	21

Fig. 6. Seasonal sequence and spatial extent of observed significant persistent weak layer. First column contains the date of the last deposition day of weak layer. The second column shows the weak layer and bed surface crystal forms more frequently observed (FC = faceted crystals, CR = crust, SH = surface hoar) and the third column has the classification of the weak layer into the three main groups. The main part shows the percentage of observed persistent natural avalanche activity for the individual operations. Operations are labeled according to Fig. 2. Shaded areas indicate operations where the weak layers were observed and/or active. Fields without figures indicate what the weak layer was naturally not active in this operation. Annual sums of activity are presented at the bottom of each section. The last two columns contain the overall percentage of activity on the weak layer and the average percentage for operations with activity.

acterization of avalanche activity in previous snow climate studies. The elevated activity percentage of 1996/1997 is related to a particularly persistent weak layer, which will be discussed in detail later. The data from the Adamants operation (AD) show the same pattern and confirm this interpretation.

It is difficult to determine a representative value of activity on persistent weak layers for the Columbia Mountains due to limitations of the avalanche data. The consistently higher value in the Adamants can be attributed mainly to their more diligent recording practice. We therefore believe that the true average fraction of activity on persistent weak layer is approximately 20%. It seems reasonable to conclude that the high annual variability of the persistent activity percentage is typical for the transitional snow climate. Depending on the dominant climate influence, the percentage of avalanches on persistent weak layers fluctuates between a lower and higher value. This result is consistent with the original definitions of the transitional snow climate proposed by LaChapelle (1966) and Armstrong and Armstrong (1987). Maritime and continental snow climates might show less variability due to less variable winters characteristics. At the current time, however, we do not have data to prove this.

4.4. Large-scale spatial variability of activity on persistent weak layers

Avalanche activity on persistent weak layers exhibits its spatial variability at numerous spatial scales. Avalanches are the result of interactions of the spatial variabilities of the initial weak layer, variabilities of the overlying slab and variabilities of their combined development over time. A complete discussion of scale characteristics of weak layers and the related avalanche activity is clearly beyond the scope of this analysis (Hägeli and McClung, submitted for publication). However, it is important to assess the large-scale variability of avalanche activity within the Columbia Mountains. The analysis of the spatial extent of all significant weak layers in this study shows that the majority of these layers cover large areas (shaded area in Fig. 6). Most layers with considerable avalanche activity in individual operations are observed across the entire mountain range. Often the avalanche activity is more pronounced in certain areas, but no statistical evidence was found that either the number of persistent weak layers or the amount of associated avalanche activity is a function of geographical location within the Columbia Mountains. Operations on the drier east side of the range (e.g., Bobbie Burns and Bugaboos), and therefore closer to the continental influence, do not show consistently higher percentages of avalanche activity on persistent weak layers than other operations. This does not necessarily mean that such local variations do not exist; it may simply be due to the limitations of the present dataset.

4.5. Types of persistent weak layers with avalanche activity

Besides the total percentage of persistent avalanche activity, the type of weak layers present reveals valuable information about the local snow and avalanche characteristics. A plot of the distribution of avalanche activity versus crystal type of weak layer and bed surface clearly shows that the recorded weaknesses can be divided into three main groups: (1) weak layers with faceted crystals; (2) surface hoar layers; and (3) pure crust interfaces (Fig. 7). Other well-known weaknesses, such as depth hoar or ice layers, seem to be less common in the Columbia Mountains with respect to avalanche occurrences. The majority of avalanches on pure crust interfaces were related to either faceted crystals or surface hoar layers weaknesses. The weak layer was either unintentionally omitted or the avalanche occurred in a location where the overlying weak layer was absent and the crust interface was the primary snowpack weakness. In just two cases, pure crust interfaces were recorded as the primary weakness (Feb. 28th 1997 and Dec. 29th 1997). Because of the sparse data, this type of weak interface was not examined any further in this study.

If we classify all observed persistent weak layers into these three groups according to the crystal type most frequently reported (second and third columns in Fig. 6), weak layers of mainly faceted crystals are responsible for approximately 50% of natural persistent activity. Surface hoar layers are the second most important persistent weak layer with 45%. Other types

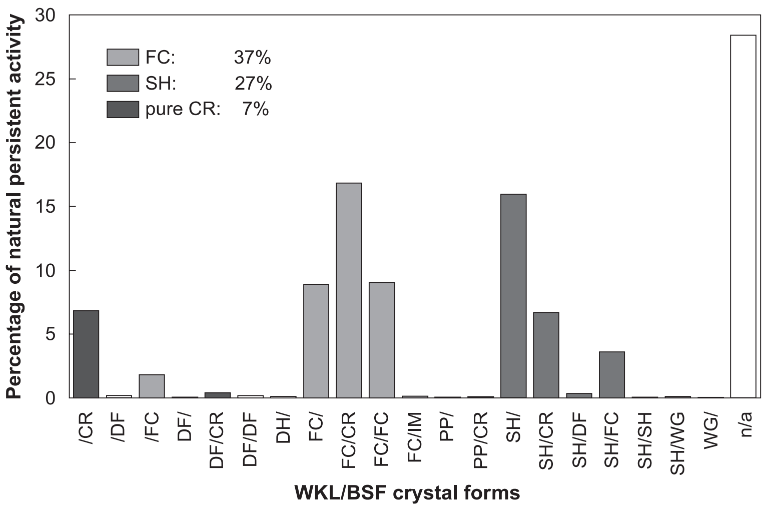

Fig. 7. Distribution of natural climax activity on different weak layer and bed surface combinations (CR = crust, DF = decomposing fragments, DH = depth hoar, FC = faceted grains, IM = ice mass, PP = precipitation particles, SH = surface hoar, WG = wet grains, n/a = not available).

of persistent weak layers, including pure crust interfaces, are responsible for the remaining 5% of persistent natural activity. In terms of number of avalanches, surface hoar layers produce slightly more avalanches than weak layers with faceted crystals.

A characteristic seasonal succession of persistent weak layers can be observed in the avalanche activity records during most winters (Fig. 6). A season is normally characterized by a weak layer of faceted crystals, which develops during the early season and is followed by several surface hoar layers that develop during clear weather periods in the main winter months. In the following sections, the characteristics of the two main weak layer types are discussed in detail.

4.5.1. Early-season weak layers of faceted crystals

An analysis of the deposition dates of this type of weak layer shows that all weak layers that have faceted crystals as their primary weakness developed during the month of November. We therefore refer to these weaknesses as early-season weak layers of faceted crystals. These weak layers are generally widespread and most operations report at least one such layer per year (Fig. 6). There is no clear evidence for a north–south or east–west variation of this frequency.

A closer look at the crystal forms most commonly observed (second column in Fig. 6) shows that in all cases except one, these faceted crystals are associated with an underlying crust. Jamieson et al. (2001) examined one of these facet–crust combinations, the November 11th 1996 layer, in great detail. A significant rain event (November 8th to 10th) created a wet snow layer on the snow surface. The layer was subsequently buried with approximately 20 cm of dry snow deposited by the next storm, which was accompanied by a significant temperature drop (Fig. 4). Under these conditions, the temperature gradient between the wet and dry snow becomes high enough to cause faceted crystals to form in the lowest part of the dry snow layer (Colbeck and Jamieson, 2001). This facet–crust combination was very widespread (Fig. 6) and produced intermittent dry slab avalanches throughout the entire season (Fig. 8a). In the following spring, many wet slab avalanches released on this persistent weakness (Fig. 8a, Monashees; also reported in Jamieson et al., 2001). Similar conditions lead to the formation of the same weak layer type in November 1997. A moderate rain event on November 6th was followed by a period of above-freezing temperatures at Mount Fidelity before the wet snow layer was buried by the next storm (Fig. 4). The associated temperature drop was, however, not as pronounced as in 1996. This layer produced less avalanche activity than the November 11th layer, but showed the same characteristics of intermittent activity throughout the season (Table 6a). Both these rain events were also recorded at Kootenay Pass.

This process was first documented by Fukuzawa and Akitaya (1993) and Birkeland (1998) termed the process melt-layer recrystallization, a special type of near-surface faceting. In order to extend the assessment of the importance of this process in the Columbia Mountains beyond the available avalanche records, the meteorological data from Mount Fidelity were examined for the potential of faceted crystal development after rain-on-snow events. Rain events were defined as consecutive days with rain of at least 1 mm on an existing snowpack. The analysis shows that almost all examined years show events in October and April (Table 5). Approximately two thirds of the years have events in November and one third in March. Events are rare during the main winter months. To examine the potential for the formation of faceted crystals above the wet snow layer, a temperature gradient was calculated for the dry snow layer above. Assuming that the wet layer is at 0 °C, the mean air temperature was simply divided by the cumulative height of new snow for the days after the rain event. In October, as well as in the spring months, the temperature normally does not become cold enough to create the necessary temperature gradient. In addition, the shallow October snowpack often completely melts out during rain events. Numerous events showed temperature gradients in the new snow well above the 10 °C/m threshold for the formation of faceted crystals for numerous days after burial (bold numbers in Table 5). In total, 18 cases were associated with considerable temperature drops after burial, which was interpreted as a strong indicator for the potential formation of faceted crystals (respective months are highlighted with diamonds in Table 5). Although this analysis is limited, it provides evidence of the importance of this type of near-surface faceting for the study area. It shows that about half of the examined years have events with a high potential for

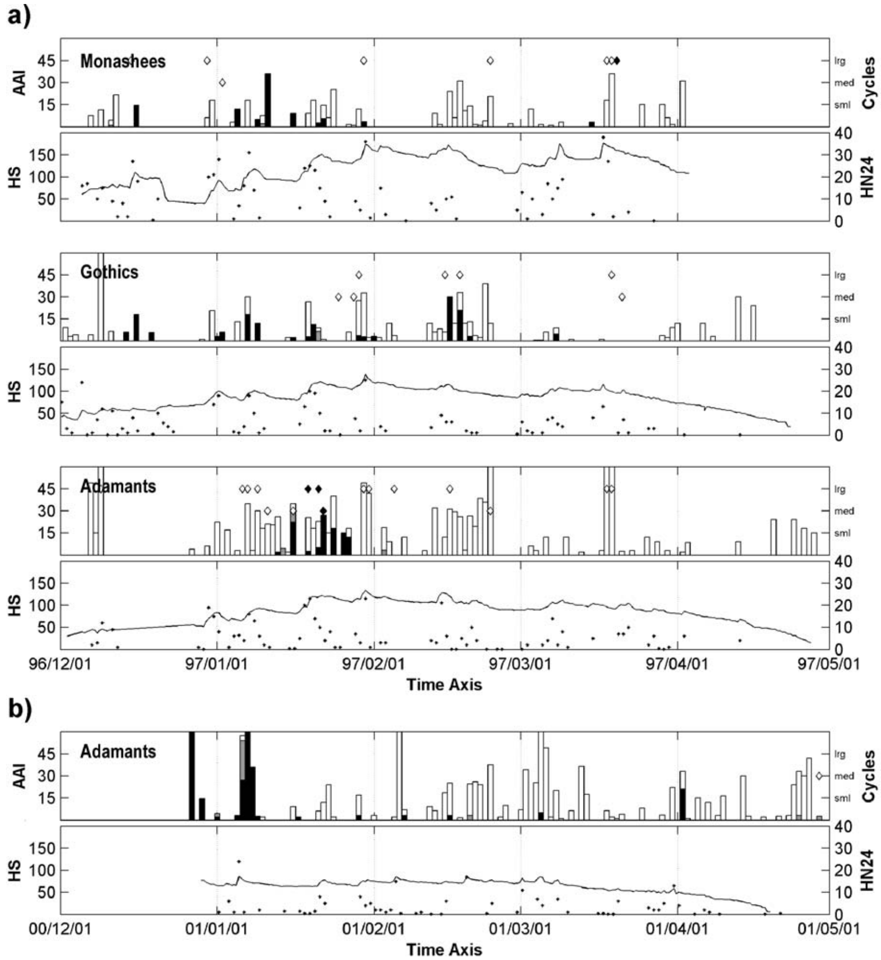

Fig. 8. Temporal activity patterns of persistent weak layers with faceted crystal. Top panel shows the activity pattern of the Nov. 11th 1996 facet–crust combination in three neighboring operations. Lower panel shows recorded activity of Nov. 24th 2000 faceted layer in the Adamants operation. The weak layer activity is displayed using an avalanche activity index (AAI) in the top panels. White bars indicate the overall recorded avalanche activity in the specific operation, black bars represent natural activity on the weak layer, and gray bars indicate activity on the weak layer due to an additional trigger, such as skiers, helicopters, or falling cornices or ice. Recorded avalanche cycles ate indicated with diamonds. Dark diamonds represent cycles on the specific WKL. The lower part of the individual graphs shows the height of the snowpack (HS) and the new snow over a 24-h period (HN24) in cm at the respective lodge.

the formation of such crust–facet combinations. In many cases, the relevant rain events occur during the early season in October and November. This period, which seems to be critical for the snow and avalanche characteristics of the Columbia Mountains, is, however, not addressed in the snow climate classification of Mock and Birkeland (2000).

The weak layers of faceted crystals of the 2000/2001 season show different characteristics. While the faceted crystals were isolated in individual layers in the previous cases, the abnormally shallow snowpack and the persistent low temperatures in mid-November 2000 (Fig. 4) resulted in the formation of cup-shaped depth hoar and faceted crystals throughout the entire early-season snowpack in many locations across the Columbia Mountains. The storm of November 24th buried the weak foundation under 40 cm of denser snow. This interface, which professionals referred to as the ‘November 24 layer’, was responsible for significant avalanche activity, particularly in the cen-

Table 5
Analysis of rain-on-snow event for Mount Fidelity

Season	Classification	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
80/81	MARITIME	5 (1)	**14 (1)**	**61 (2)**◆	**2 (1)**◆			53 (2)
81/82	MARITIME	**101 (6)**	**3 (1)**◆					
82/83	TRANS.	27 (3)					3 (1)	17 (2)
83/84	MARITIME	44 (3)	**13 (1)**		**40 (1)**			5 (2)
84/85	TRANS.							**26 (2)**
85/86	MARITIME	**90 (3)**◆				29 (1)	**12 (2)**	25 (2)
86/87	MARITIME	17 (2)	**11 (1)**◆				**17 (2)**	**31 (3)**
87/88	MARITIME	30 (3)	**11 (3)**◆				2 (1)	22 (3)
88/89	TRANS.	**30 (4)**	18 (1)					37 (3)
89/90	MARITIME	**13 (2)**◆	**53 (1)**◆					28 (5)
90/91	TRANS.	**57 (4)**◆	65 (1)				3 (1)	3 (2)
91/92	TRANS.	4 (1)					5 (2)	56 (2)
92/93	CONT.	69 (3)						4 (1)
93/94	TRANS.	**30 (3)**						21 (4)
94/95	TRANS.							10 (4)
95/96	MARITIME	**35 (3)**	**48 (5)**◆				**16 (3)**◆	**27 (4)**
96/97*	MARITIME		**38 (1)**◆					11 (2)
97/98*	TRANS.	30 (2)	**7 (1)**◆					
98/99*	MARITIME	7 (2)						15 (4)
99/00*	TRANS.	39 (2)	6 (1)					10 (2)
00/01*	TRANS.	15 (2)						17 (2)

Number indicates monthly sum of rainfall (mm) of days with more than 1 mm of rain. The number in brackets shows the number of rain events during the respective month. Bold figures specify month with the potential for melt-layer recrystallization. Diamonds indicate months with considerable temperature drops after/during burial of the wet snow layer. Asterisks indicate winter seasons where avalanche observations are available.

tral part of the Columbia Mountains (Fig. 6). Although avalanche activity was recorded only in three operations, snow profiles show that this weak layer was present across the entire mountain range. Although caused by a different process, this weak layer had similar activity characteristics as the previously discussed weak layers of faceted crystals. After significant cycles in the early season, this weakness remained active sporadically throughout the entire season (Fig. 8b). The majority of related avalanche events were observed on northerly and easterly aspects and approximately 20% of the observed avalanches ran to ground. This type of weakness is more commonly observed in continental snow climates, where shallow snow covers are common and depth hoar formation is widespread. Depth hoar crystals are large cup-shaped crystals with striations that generally develop close to the ground. Since the weakness developed during November, this particular season was not classified as continental at Mount Fidelity by the snow climate classification scheme.

All the recorded facet crystal weaknesses have the same activity pattern and avalanche characteristics (Table 6a). They are active only sporadically throughout the entire season. The low ratio of avalanche days to length of activity period is a clear indicator of this persistence. Many of these layers become active again in the spring months. Weather observations indicate that these natural cycles are likely triggered by rain events. The long activity period generally leads to large avalanches on this type of weak layer (Fig. 10).

4.5.2. Surface hoar weak layers

Surface hoar layers are the second most naturally active weak layer, accounting for approximately 45% of persistent avalanche activity. Each operation typically reports one to three persistent surface hoar layers every season (shaded areas in Fig. 6). No significant north–south or east–west variation regarding the number of observed surface hoar layers exists in the dataset. The typical activity pattern of such a weak

Table 6
Summary tables of characteristics for (a) early weak layers with faceted crystals and (b) surface hoar crystals

Persistent weak layer		Activity period				Character of natural persistent activity
Date	WKL/BSF	Last day	Days	AV days	Ratio	
(a)						
96/11/11	FC/CR or FC/	97/04/27	167	35	0.21	Intense intermittent activity throughout season, possible spring awakening
96/11/25	FC/CR	97/02/23	90	9	0.10	3 main cycles
97/11/10	FC/ or FC/CR	98/04/22	163	11	0.07	Intermittent activity throughout season, possible spring awakening
97/11/20	FC/CR	98/04/09	140	6	0.04	Weak intermittent activity throughout season
99/11/18	FC/CR or /CR	00/05/01	164	16	0.10	Intense activity in Dec., weak intermittent activity thereafter
00/11/19	SH/FC	01/03/07	108	2	0.02	Weak intermittent activity
00/11/24	FC	01/04/30	157	20	0.13	2 cycles, intermittent activity thereafter, possible spring awakening
00/11/30	FC	01/04/15	136	3	0.02	Weak intermittent activity throughout season
(b)						
97/01/16	SH/	97/02/18	33	12	0.36	Approx. 3 cycles
97/02/11	SH/CR or SH/	97/03/07	24	11	0.46	Approx. 3 cycles
97/12/08	FC/ or SH/	97/12/31	23	7	0.30	2 cycles
98/02/03	SH/	98/03/20	45	6	0.13	Short cycles, intermittent character
98/02/18	SH/	98/03/07	17	3	0.18	2 short cycles
98/02/28	SH/ or SH/CR	98/03/10	10	1	0.10	Only 1 naturally active day
98/03/21	SH/ or SH/CR	98/04/07	17	9	0.53	1–2 cycles
99/12/30	SH/	00/03/30	91	14	0.15	2–3 cycles
00/01/31	SH/	00/02/09	9	4	0.44	2–3 cycles
00/02/07	SH/	00/03/01	23	4	0.17	1–3 cycles
00/02/20	SH/ or /CR	00/03/21	30	15	0.50	2–3 cycles
01/01/22	SH/	01/02/04	13	1	0.08	Only 1 naturally active day
01/01/28	SH/ or /CR	01/03/22	53	8	0.15	1 cycle
01/02/22	SH/ or SH/CR	01/03/19	25	9	0.36	Approx. 5 short cycles
01/02/28	SH/FC	01/03/19	19	7	0.37	3 cycles

Activity period is equivalent to time period between first and last avalanche of weak layer. WKL/BSF stands for weak layer and bed surface crystal type most commonly observed (FC = faceted crystals, CR = crust, SH = surface hoar). AV days are days with recorded avalanche activity.

layer consists of one to three activity cycles. The activity pattern of the Jan. 28th 2001 layer (Fig. 9), for example, shows some activity in the two northern operations during the first snowstorm. After a few days without any activity, there is a distinct avalanche cycle on the surface hoar layer around Feb. 6th. The exact timing of the cycle depends on local weather patterns, but the cycle clearly exists in five operations. Natural avalanche activity on this surface hoar layer stopped after this cycle. In general, the natural activity on this type of weak layer stops after about three to four weeks (Table 6b). Some of the more persistent surface hoar weaknesses, such as the Dec. 30th 1999 layer, have longer activity periods with intermittent activity after the initial avalanche cycles. These surface hoar layers often also show faceted crystals, which might be an indication of the presence of other near-surface faceting processes, such as diurnal recrystallization (Birkeland, 1998), during the surface hoar formation or after a shallow, initial burial. The average ratio of avalanche days to length of activity period (0.3) is significantly higher than for the group of faceted weak layers (Table 6a and b). As a consequence, the avalanche sizes are generally smaller (Fig. 10).

Some surface hoar layers are associated with a crust bed surface (Fig. 6). While the crust was a necessary component for the formation of faceted crystals after rain-on-snow events, this combination is the result of the spatial variability of meteorological

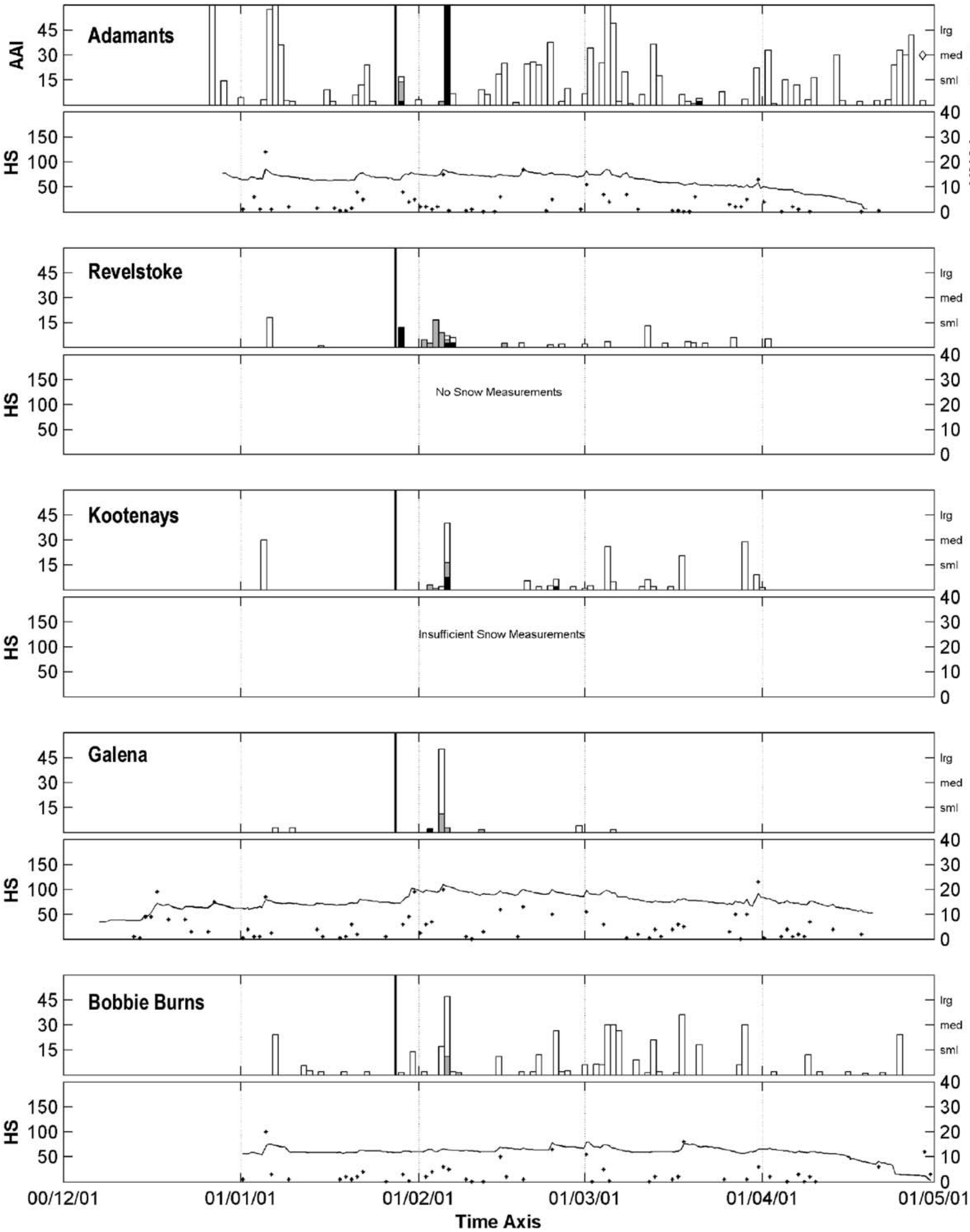

Fig. 9. Temporal activity pattern of Jan. 28th surface hoar layer in five adjacent operations. Same type of graph as shown in Fig. 8. The vertical black line represents the last deposition day of the weak layer.

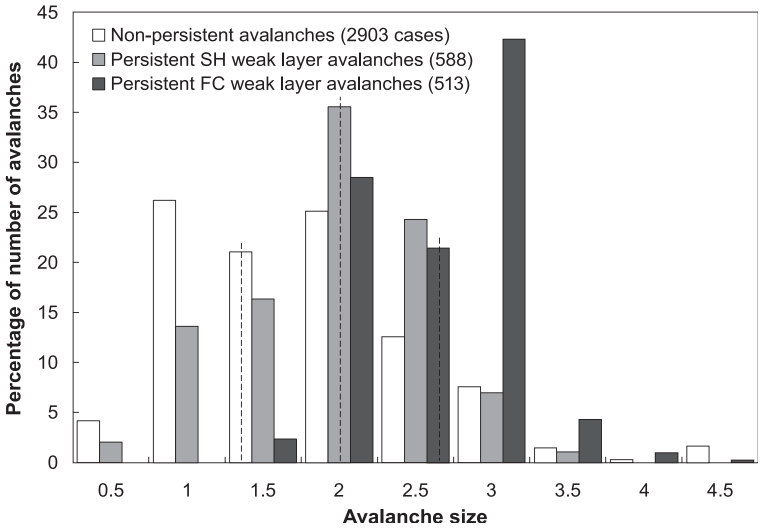

Fig. 10. Distribution of avalanches sizes for persistent natural avalanches of the two main weak layer types and non-persistent natural avalanche for reference. Dashed lines represent the median value for respective avalanche groups.

conditions. Clear weather periods necessary for the formation of surface hoar on northerly aspects can also lead to sun crust formations on southerly aspects. While the surface hoar acts as a weak layer on shady aspects, the crust presents a weak interface on the sun-exposed slopes.

5. Conclusions

Numerous studies have examined the three different snow climate zones in Western North America. The studies used mainly high-elevation meteorological data to characterize the snow climate zones. Conclusions about the character of avalanche activity were derived mainly from dominant weather characteristics. The term ‘avalanche climate’ was introduced by Armstrong and Armstrong (1987) and was subsequently used by numerous studies (e.g., Mock and Kay, 1992; Mock and Birkeland, 2000). These analyses included some avalanche variables in their analysis, but the avalanche descriptors were of minor importance for the classification. In this paper, we suggest to use the term ‘avalanche climate’ as a distinct adjunct to the term ‘snow climate’. In addition to the meteorological description of the winter climate, the avalanche climate definition should also contain information directly relevant to daily avalanche forecasting, such as the characteristics and activity pattern of persistent weak layers and avalanche activity statistics.

The present study contains an examination of avalanche characteristics of the Columbia Mountains in relation to the local snow climate. The application of the snow climate classification scheme of Mock and Birkeland (2000) to the climate data of Mount Fidelity and Kootenay Pass showed that the Columbia Mountains have a transitional snow climate with a strong maritime component. This result is in agreement with the snow climate zones definitions by LaChapelle (1966), who describes a ‘coastal transitional’ snow climate that is located on the east side of the Cascade Range and on the western slopes of the southern extension of the Columbia Mountains in the United States (Fig. 1). More studies are necessary to establish a better understanding of the distribution of the different snow climate types in Canada. However, the lack of reliable high-elevation weather records poses a serious limitation for such efforts.

The present analysis focuses on the analysis of natural avalanche activity on persistent weak layers. Based on our analysis, we believe that the natural avalanche activity on persistent weak layers is approximately 20% of the overall natural activity. Depending on the dominant climate influence, the average value can vary between 0% during a maritime winter to about 40% for a winter with a strong continental influence. This high variability is in agreement with earlier descriptions of the transitional snow climate. The incomplete avalanche observations in our study do not allow more precise estimates of these figures.

Facet–crust combinations and surface hoar layers are mainly responsible for persistent avalanche activity in the Columbia Mountains. Avalanches on other well-known weak layers and interfaces, such as depth hoar or ice crusts, are seldom observed. Weak layers primarily characterized by faceted crystals are responsible for approximately 50% of the observed naturally triggered persistent avalanche activity, while surface hoar layers account for about 45%. However, surface hoar layers are typically responsible for more avalanches than the early season faceted layers. Early season faceted layers normally undergo several initial cycles during the early season (often not observed in the present dataset) and remain intermittently active throughout the season. This results in few large avalanches during the observation period of CMH. Surface hoar weak layers, on the other hand, typically exhibit about one to three distinct avalanche activity cycles soon after burial and the activity generally stops after 3–4 weeks. Only some of these layers remain active for longer periods of time. This pattern produces a higher number of smaller slides.

Many of the observed faceted layers are associated with an underlying crust. Weather observations indicate that these facet–crust combinations develop after rain-on-snow events during the early season. An analysis of historic weather data of Mount Fidelity showed that conditions for the formation of such weak layers occur frequently in the Columbia Mountains. Depth hoar weaknesses, which are often seen in continental snow climates, were only observed during the winter 2000/2001, a season with a strong continental influence in the Columbia Mountains.

Although there are considerable gaps in the avalanche records and observations cover only five seasons, the study gives interesting insights about the avalanche climate of the Columbia Mountains. The main characteristics are the frequent occurrence of facet–crust combinations due to early season rain-on-snow events and the importance of surface hoar layers during the main winter months. In the context of existing similar studies, this leads to a few interesting conclusions. First, although the scheme of Mock and Birkeland (2000) can be used to classify the snow climate of a region according to the definitions of LaChapelle (1966), there are certain limitations to its use for the description of an avalanche climate. The method is limited because it considers only the time period from the beginning of December to the end of March. In the case of the Columbia Mountains, the method completely misses the highly important beginning of the season. Second, a comparison of the results of this study and those of a similar study on the snow and avalanche characteristics of the San Juan Mountains (Fig. 1) in Colorado shows that there can be significant differences in avalanche characteristics within the same snow climate zone. Both areas are considered to have a transitional snow climate according to the classification of Mock and Birkeland (2000). LaChapelle and Armstrong (1976) point out that radiation crystallization (Birkeland, 1998) is the primary process for the formation of snowpack weaknesses in the San Juan Mountains. These differences indicate that a variety of near-surface faceting processes might be dominant for weak layer formation in different locations throughout the transitional snow climate zone. This clearly shows that the terms 'snow climate' and 'avalanche climate' are not synonymous. More research is necessary for a better understanding of the relation between these two climatological terms.

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