Analysis of Weak Layer Avalanche Activity in the Columbia Mountains, British Columbia, Canada

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Abstract: This study uses avalanche observations to characterize the spatial characteristics and temporal avalanche activity patterns on persistent weak layers. The study is situated in the Columbia Mountains in Western Canada, a mountain range with a transitional snow climate. The data was provided by Canadian Mountain Holidays, which operates 11 individual helicopter-skiing operations in this area, covering a total area of 20,000 km^2. The analysis shows that early season faceted snow layers and surface hoar weak layers are the main concern in this area. About 16% of the natural avalanche activity is on these persistent weak layers, and 28% when skier/helicopter triggered avalanches are included. It is shown that persistent weak layers with significant avalanche activity are generally widespread. While surface hoar layers seem to have fairly well defined avalanche cycles for about 2 to 3 weeks after their burial, faceted snow layers are active more sporadically throughout the entire season. The results of the analysis are promising for the development of a new statistical model for forecasting avalanche activity specifically on persistent weak layers. This has been a weak point of the currently used statistical models, which are mainly based on meteorological variables and, as a consequence, work best for new snow instabilities. An additional aspect of this work is that, for the first time, it allows the characterization of the avalanche climate of an area on the basis of actual avalanche observations. All previous studies have only used weather observations for their climate type definition.

Keywords: persistent weak layers, avalanche climate, avalanche forecasting

1. Introduction

While the use of deterministic snow cover models for avalanche forecasting purposes has gained a lot of attention in the research community, statistical models are still very popular among practical forecasters. Examples are the models of McClung and Tweedy (1994) and Buser et al. (1987). This popularity can mainly be contributed to the relative ease of implementation of these systems and their practical output. A significant drawback of these systems, however, is that they have some difficulties predicting avalanches related to persistent weak layers. This might not be very relevant for small operations, which continuously control avalanches with explosives. It is, however, a tremendous shortcoming for large backcountry operations or public forecasts that cover large areas and are often mainly concerned with persistent weak layers. The reason for this deficiency is that the input parameters of these models consist mainly of meteorological and surface snow variables and, as a consequence, the models do not contain information about the presence and condition of the current weak layers.

Numerous recent studies have examined the small-scale variability of stability and weak layer characteristics (e.g., Jamieson, 1995; and more recently Landry et al., 2002; and Kronholm and Schweizer, 2002) and have shown high variability even over very small distances. Computer-aided forecasting models, however, are designed for larger areas, such as ski areas, highway corridors, or even entire mountain ranges and their objective is to give a general overview of the stability conditions. While the studies mentioned above are very valuable for advancing our understanding of avalanche initiation and the usefulness of individual point measurements, it seems more appropriate for modelling purposes to have a closer look at larger scale patterns. With the exception of the work of Birkeland (2001) this scale has not received a lot of attention so far. The important questions are: a) What types of weak layers are present? b) What are their activity patterns? c) How widespread are these weak layers?

The present study contains stability patterns on persistent weak layers across an entire mountain range in Western Canada using avalanche activity data from helicopter skiing operations. The following section describes the geography and the climate of the Columbia Mountains as well as the type of data used for this study. Section 3 illustrates the characteristics of the two most common types of weak layers in the Colum-

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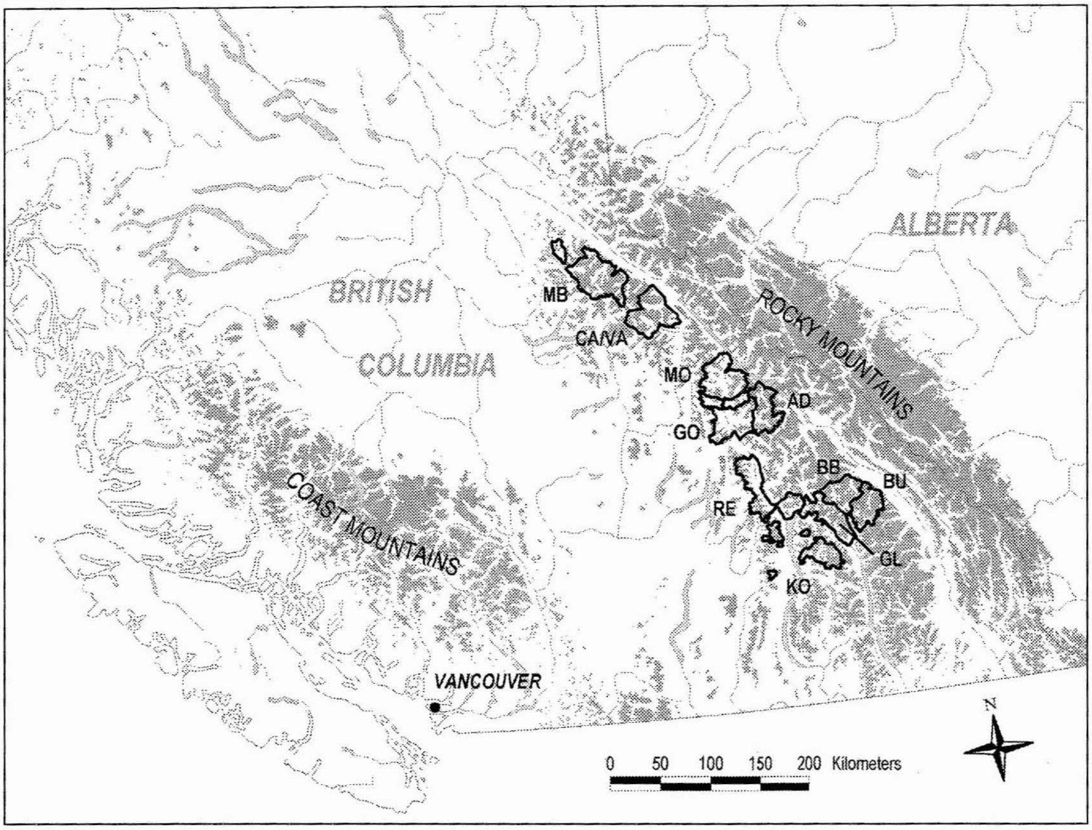

Figure 1: Southern portion of British Columbia and Alberta showing the eleven operations of Canadian Mountain Holidays in the Columbia Mountains: McBride (MB), Cariboos and Valemount (CA/VA), Monashees (MO), Gothics (GO), Adamants (AD), Revelstoke (RE), Kootenay (KO), Galena (GL), Bobbie Burns (BB), and Bugaboos (BU). Shaded areas are above 1800 m a.s.l..

bia Mountains. The last section draws conclusions about the avalanche climate of the Columbia Mountains, and the possibility of including weak layer information into avalanche forecasting models.

2. Study area and dataset

The data for this study were provided by Canadian Mountain Holidays (CMH), the largest helicopter ski providers in Western Canada. CMH operates 11 individual operations in the Columbia Mountains of British Columbia covering a total area of approximately 20,000 km^2 (Fig. 1). The Columbia Mountains have a transitional snow climate, which is characterized by a combination of maritime and continental influences (McClung and Schaerer, 1993). The maritime influence results in the large amounts of snow received by this range every winter. Depending on the location, the average annual snowfall is between 12 and 20m at 1800 m a.s.l. (CMH, 2002). However, the continental influence creates enough clear and cold periods for the formation of significant surface hoar and faceted layers.

Since the winter season 1996/97 CMH has used SNOWBASE, an extensive database system, to store all data relevant for their skiing operations. The collected information includes weather observations from study plots and field observations, avalanche observations, stability ratings, and run usage. For more information about SNOWBASE the reader is referred to Hägeli and Atkins (2002).

Avalanche recordings, which are the main focus of this study, contain all the standard parameters, such as number, size, trigger, avalanche type, liquid water content, aspect, and elevation. In addition, characteristics of the related weak layer and bed surface are also recorded, as well as information about avalanche involvements of guides and/or guests if necessary. However, the dataset was collected primarily for operational avalanche forecasting, not for research purposes. The quality of the data varies significantly between operations and seasons, due to operational constraints and various people recording the data. Adamants operation (AD), where the system was developed by R. Atkins, has the most complete dataset. Additionally, avalanche records are incomplete by nature. Individual operations are far too big to be covered completely during regular operation. Observations can also be impossible due to bad weather or other operational activities, such as non-skiing days due to departing or arriving guests.

All these aspects make it very difficult to apply standard geostatistical methods to the data. As a consequence, the presented analysis is fairly descriptive and the few statistical figures should be interpreted with caution.

3. Analysis

In SNOWBASE avalanches on specific weak layers (WKLs) are normally tagged with the date of the burial of the WKL. This allows the tracking of avalanche activity on specific layers throughout the season and between different operations. For this study, WKLs were only considered to be persistent if they showed avalanche activity after the beginning of the second storm after burial. Activity during the first storm period was treated as new snow instabilities. Figure 2 shows the percentage of avalanche activity on persistent WKLs for five seasons for naturals as well as skier and helicopter triggered slides. Avalanche activity is calculated as the sum of the

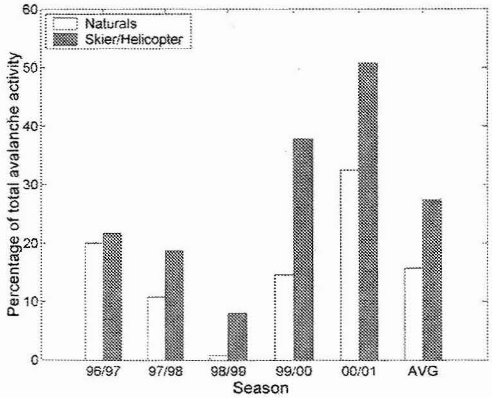

Figure 2: Percentages of avalanche activity related to persistent weak layers for natural avalanches and skier/helicopter triggered slides.

number of avalanches times their sizes according to the Canadian size classification (CAA, 1995). On average, 16% of all natural avalanche activity and 28% of all skier/ helicopter triggered slides are related to persistent WKLs. The graph clearly shows that persistent WKLs are a serious concern for the skiing operations. The obvious seasonal variations can be associated to variations in the dominance of the two climate types. The winter of 1998/99 had a strong maritime character with record snowfall, while the winter 2000/01 was dominated by the continental influence.

In order to assess the importance of different types of WKLs, avalanche activity was plotted versus crystal type combinations of WKL and bed surface (BSF). Figure 3 shows a compressed view of this distribution. The graph clearly shows that WKLs consisting of faceted grains (FC) and surface hoar (SH) are of prominent concern in the Columbia Mountains. Other well-known WKLs, such as pure crusts, ice layers, or depth hoar, are less common. While the FC layers are responsible for the majority of natural activity, it is the SH layers that are the most common concern for the skiing operation. In the following two sections, the activity patterns of these two types of WKLs are analyzed in detail.

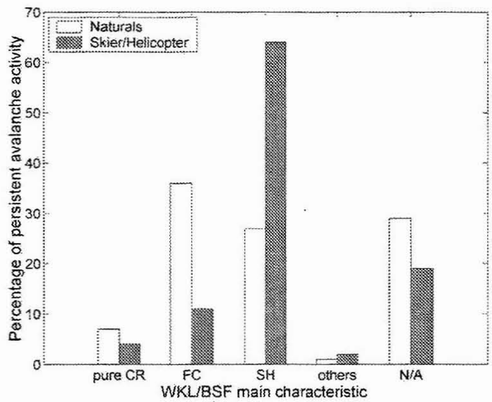

Figure 3: Distribution of persistent avalanche activity for different weak layer and bed surface combination types for naturally or skier and helicopter triggered slides (CR = crust, FC = faceted grains, SH = surface hoar, N/A = not available; Seasons 96/97-00/01)

3.1 Early season faceted snow layers

This type of WKL generally develops in the early season, when the snowpack is still shallow and the cold artic air masses create large temperature gradients within the snowpack. These conditions produce faceted grains, which weaken the early snowpack and create a 'weak foundation' for the rest of the season. As shown in Fig. 3, these forms are responsible for significant amounts of avalanche activity. In more continental snow climates these conditions often lead to the formation of depth hoar. The absence of depth hoar avalanches in the Columbia

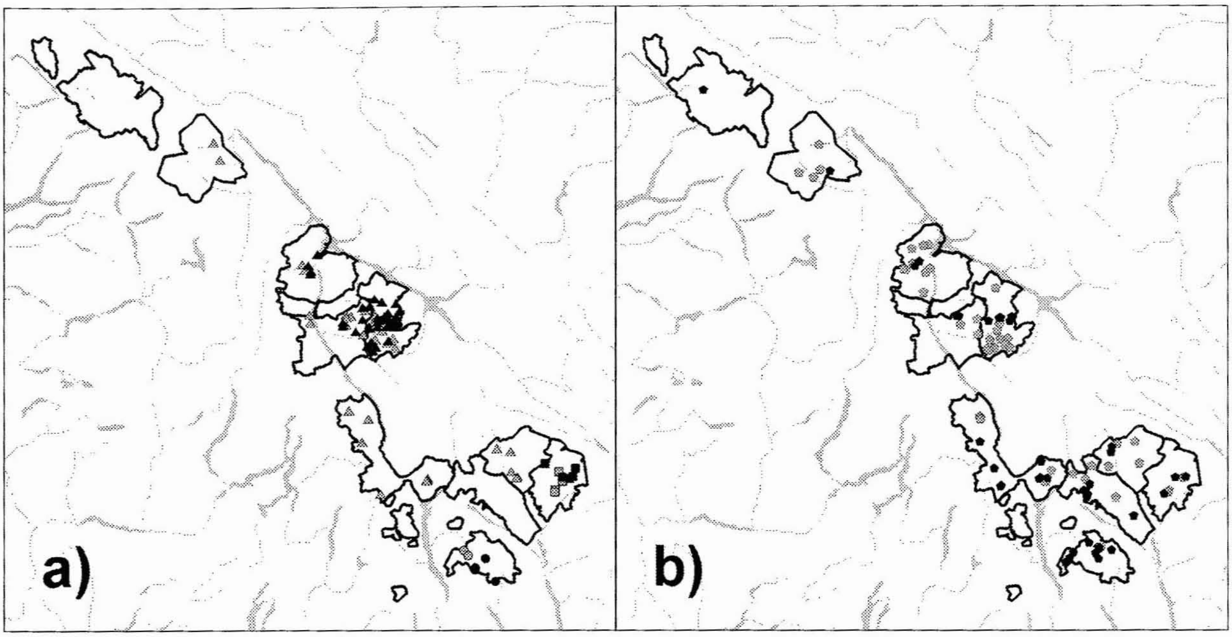

Figure 4: Example for spatial extent of two different types of persistent weak layer in the Columbia Mountains. The left panel shows the extent of all three faceted snow layers recorded during the 2000/01 season: Nov. 19th (●),Nov. 24th (▲), and Nov. 30th (■). The right panel shows the coverage of the Jan. 28th 2001 surface hoar layer (⬟). Black symbols represent avalanche occurrences, while gray symbols show the locations of snow profiles observations.

Mountains can be interpreted as a consequence of the maritime climate influence in this area.

Fig 4a shows the spatial extent of all three FC layers observed in the CMH operations during the season 2000/01. Observed avalanche occurrences on the WKLs are displayed along with their observations in snow profiles. The map clearly shows that FC layers are a concern in the entire mountain range. The main WKL, Nov. 24th, was recorded in almost all CMH operations. It is generally characterized by an obvious hardness increase in the snowpack on top of a faceted ground layer. The two other WKLs in the Kootenays and Bugaboos have the same basic characteristics. The different dates for the layers comes from additional surface hoar or crust layers, which resulted in more pronounced weakness within the FC layer. However, such additional weaknesses within the already faceted snow do not seem to have an effect on the temporal activity pattern.

Fig. 5a shows the activity pattern of the Nov. 24th WKL as recorded in the Adamants operation. Although observations only started about a month after the development of the layer, the graph clearly shows that these WKL can be responsible for significant activity cycles during the early season. After these initial cycles the WKL remains active sporadically during the entire season. An awakening of these layers in the spring, as shown here in early April, can often be observed (Hägeli and McClung, submitted).

Most avalanches are triggered naturally. However, this is the only type of avalanches where helicopter triggering seems to be significant, which is interesting from an operational point of view.

Due to the sporadic activity, avalanches on these WKLs are very difficult to anticipate. The low number of skier-triggered slides and involvements, however, indicates that these FC layers are not a major threat to the skiing operations.

3.2 Surface hoar weak layers

The necessary conditions for the development of SH are well known (see, e.g., McClung and Schaerer, 1993)and there have been numerous studies about its affect on snow stability. Fig. 4b illustrates the spatial extent of the Jan 28th SH layer, the most significant WKL of this type during the season 2000/01. The map shows that the layer was observed across the entire mountain range. Other data show that not all observed SH layers are this widespread. However, layers with significant avalanche activity generally cover considerable parts of the mountain range, and are definitely not local phenomena. Nonetheless, smaller scale variability does exist within the global extent of these WKLs. For example, SH layers are

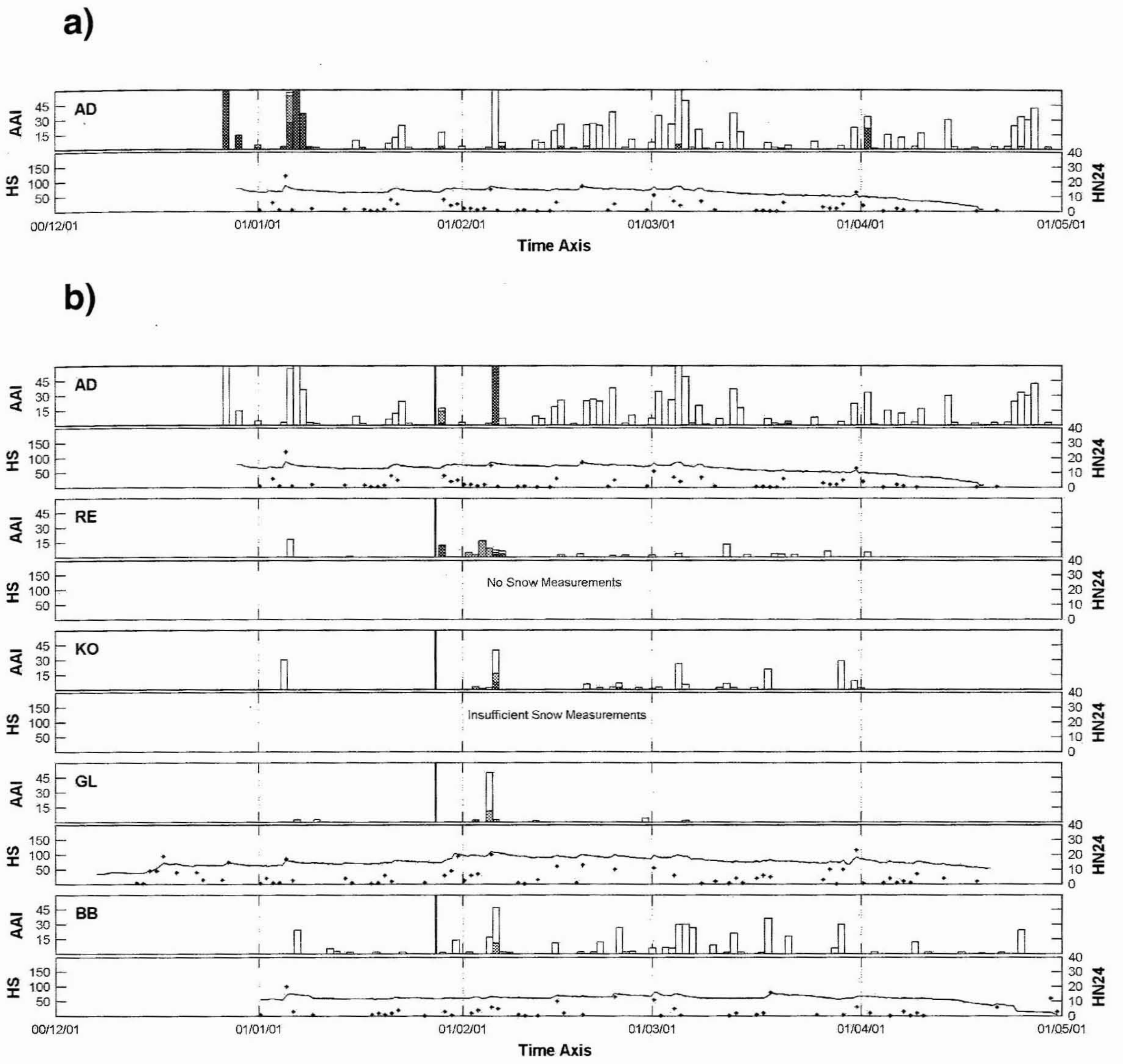

Figure 5: Temporal activity patterns of persistent weak layers. Top panel shows the activity pattern of the Nov. 24th FC layer in the Adamants operation. Lower panel displays the recorded activity of the Jan. 28th SH layer in five neighboring operations. White bars indicate the overall recorded avalanche 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. The vertical black line represents the last deposition day of the weak layer. The lower part of the individual graphs shows the height of the snowpack (HS) as well as the new snow over a 24-hour period (HN24) at the specific lodge. These heights are given in centimeters.

often dominant on northern aspects, while there is a sun crust on solar aspects, which also acts as a WKL. A small-scale variability also often exists with altitude. While the initial avalanche activity often covers the entire elevation range, the more persistent avalanche activity is frequently limited to a fairly narrow elevation band around tree line (Hägeli and McClung, submitted). This might be related to valley fog and cloud bands, which develop in the valleys during high-pressure periods. The tops of these cloud layers represent ideal growing conditions for SH with essentially unlimited moisture supply and clear skies for cold nights. The protected character of glades around tree line might enhance this process and make tree line the elevation range most susceptible for persistent SH avalanche activity.

Figure 5b shows the temporal activity pattern of the same SH layer as in Figure 4b. In the two north-

ern operations there is some avalanche activity on the layer during the first snowstorm, which can be regarded as new snow instabilities. After a few days, without any activity there is a distinct avalanche cycle on the layer around Feb. 6th. The exact timing of the cycle depends on local weather patterns, but the cycle clearly exists all five operations. Most SH layers exhibit 1 to 3 of these persistent action cycles and after approximately 2 to 3 weeks the activity on the WKL stops (Hägeli and McClung, submitted).
An analysis of all available seasons in SNOWBASE shows that skiing operations in the Columbia Mountains experience about 1 to 3 of these SH layers per season. So far it has not been possible to show a substantial east-west or north-south variation of this number with the given observations. In comparison to the FC layers, the behavior of SH layers seems to be easier to anticipate due to the fairly well defined activity cycles. An analysis of the operational stability ratings issued every morning clearly shows that the ski guides have a good idea about the state of the WKL and its development. It has to be pointed out, however, that the vast majority of involvements of guides or guests on persistent weak layers are related to SH layers.

4. Conclusions

In the previous section an overview of the spatial characteristics as well as the temporal activity patterns was given for the two most common WKLs in the Columbia Mountains. An analysis of all five seasons in SNOWBASE shows an individual operation typically experiences one early season FC layer and 1 to 3 SH layers throughout a winter. Such an analysis could be used to define the avalanche climate of an area. Numerous studies have analyzed avalanche climates, mostly with a focus on western North America (e.g., Mock and Birkeland, 2000), but most of these studies examined only meteorological variables to make conclusions about the character of the resulting snowpack and avalanche activity. Although this line of reasonaing seems reasonable, the lack of actual avalanche observation in the analysis makes the definition of avalanche climate questionable. The present study is the first attempt to characterize the avalanche climate on the basis of actual avalanche data. A more detailed description of the avalanche climate of the Columbia Mountains is given in Hägeli and McClung, (submitted). It is our intension to extend this new type of avalanche climate analysis to the maritime and continental snow climates by analysis data of skiing operations in the respective climate zones in British Columbia.

The present study also showed that persistent WKL with significant avalanche activity generally cover at least considerable parts of the Columbia Mountains. This seems in agreement with the spatial extent of the conditions necessary for their development. Significant SH layers, for example, can only develop under persistent high-pressure weather systems, which typically have a spatial scale of the order of 1000km. This widespread character of the significant WKLs is very promising for the development of prediction models specifically for activity on persistent layers. Currently used statistical models are mainly suited for the prediction of new snow instabilities since they mainly use meteorological and surface snow variables. We are currently working on a set of simple and easily obtainable variables that could represent WKLs appropriately in a statistical model. The next step will be to determine the significant input parameters for such a model using a statistical analysis prior to the development of the actual model.

5. Acknowledgements

We are grateful for the research support of Canadian Mountain Holidays, the Natural Sciences and Engineering Research Council of Canada, and the Vice President of Research of the University of British Columbia. Pascal Hägeli is partially supported by a University Graduate Fellowship of the University of British Columbia.

We would like to thank Canadian Mountain Holidays and all their guides in particular for their generous support. Without their data collection and vision to archive all avalanche-relevant data, such a study would not have been possible. We would also like to thank for the many opportunities we had to visit your operations and talk to practitioners, who are the end users of our future tools.

We would also like to thank K.W. Birkeland from Montana State University for the numerous discussions and helpful comments about this research.

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