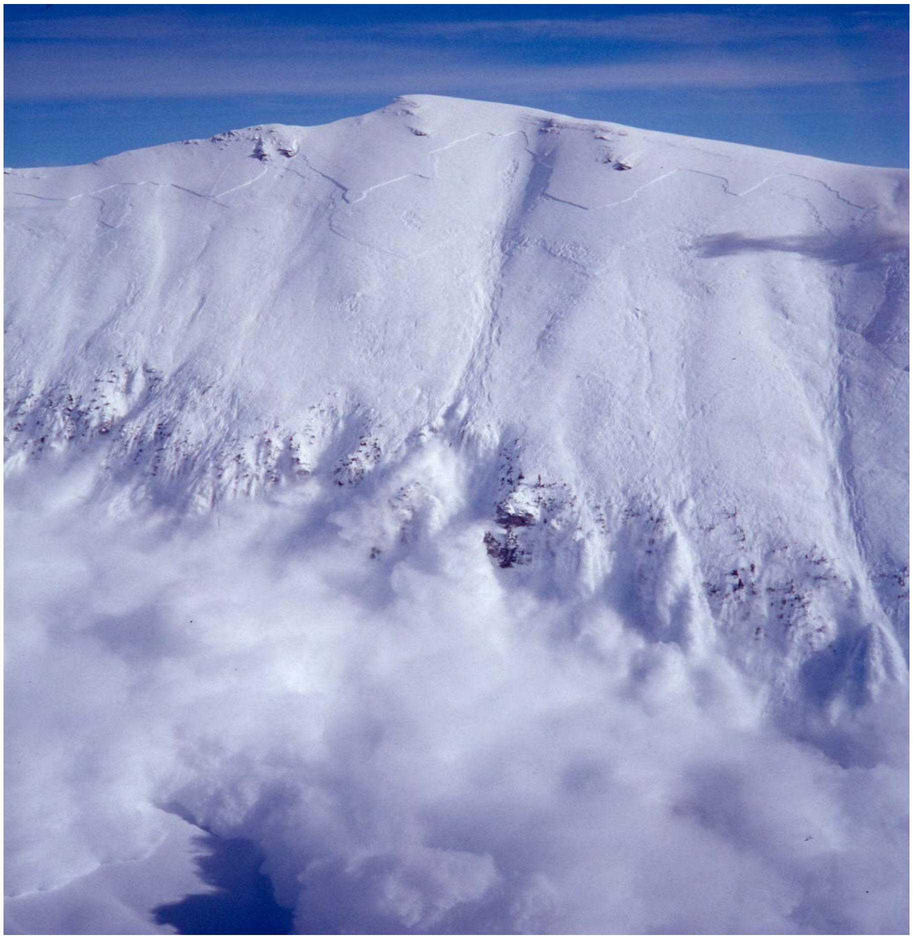
SCALE ANALYSIS OF AVALANCHE ACTIVITY ON PERSISTENT SNOWPACK WEAKNESSES WITH RESPECT TO LARGE-SCALE BACKCOUNTRY AVALANCHE FORECASTING



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October 2004

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by

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Dipl. Erdw. ETH, Swiss Federal Institute of Technology, 1998

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF
THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

in

THE FACULTY OF GRADUATE STUDIES

Department of Earth and Ocean Sciences
Atmospheric Science Program

We accept this thesis as conforming
to the required standard

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October 2004

ABSTRACT

Information about existing snowpack weaknesses is essential for backcountry avalanche forecasting. However, the incorporation of detailed information about snowpack weaknesses significantly increases the complexity of the forecasting process. The goal of this research is to examine the scale characteristics of persistent snowpack weaknesses and related avalanche activity with respect to large-scale backcountry avalanche forecasting (≥ 1000 km^2). The study focuses on the snowpack of the mountain ranges in Western Canada, namely the maritime Southern Coast Mountains, the transitional Columbia Mountains and the continental Rocky Mountains.

Scaling and scale issues are of fundamental importance in the avalanche forecasting process due to the multi-scale character of the avalanche phenomenon. Although professionals have developed successful strategies to use information across scales, scaling needs to be incorporated explicitly into formalized forecasting approaches. Hierarchy theory (Ahl and Allen, 1996) is used in this research as a conceptual framework for discussing scale issues in avalanche forecasting. The two-dimensional reference system consists of a temporal hierarchy of seven levels representing the main groups of factors contributing to avalanches. Within each temporal level, there is an embedded spatial hierarchy of processes.

In this research, the SNOWBASE database of Canadian Mountains Holidays (1996/97 – 2000/01) and the InfoEx dataset of the Canadian Avalanche Association (1991/92 – 2001/02) were used to examine the temporal and spatial characteristics of three main types of persistent snowpack weaknesses (weak layers of faceted grains, surface hoar layers and pure crust interfaces) and their related avalanche activity. While significant weaknesses of all types were often consistently observed across large parts of the study area, the related avalanche activity exhibited distinct smaller-scale patterns in space and time specific to the weakness types.

This research suggests using ‘Avalanche winter regimes’ as a new classification scheme for describing local avalanche characteristics with respect to forecasting. While existing snow climate classifications (see, e.g., Mock and Birkeland, 2000) focus only on the average winter weather characteristics, it is the comprehensive character of a winter, including the sequence of events that produce persistent weaknesses, which is of crucial importance for backcountry avalanche forecasting. The analysis of this research reveals three distinct initial avalanche winter regimes for Western Canada.

TABLE OF CONTENTS

Appendices:

LIST OF TABLES

LIST OF FIGURES

PREFACE

This thesis is based on a collection of published, ‘in press’ and submitted manuscripts. Each of these manuscripts is presented as an individual chapter that addresses a different research question and/or uses a different dataset. The individual chapters are introduced by a General Introduction, which presents a comprehensive overview and explains the role of each manuscript within the thesis. The Conclusions chapter draws comprehensive conclusions from the research findings of each manuscript and discusses suggestions for future research. Background information supporting the research findings presented in the manuscript chapters is provided in several appendices.

This work is dedicated to the guides of Canadian Mountain Holidays,
the most passionate experts on snow and avalanche safety
who truly guided my research.

Photo: Greg Yavorsky (CMH)

ACKNOWLEDGEMENTS

I enjoyed the help and expertise of many people while doing this research. I am grateful to my supervisors Drs. David M. McClung and Douw G. Steyn for their continuous support and guidance of my research. I would also like to thank my other committee members Drs. Jürg Schweizer and R. Dan Moore for their constructive comments and support during different stages of this research.

I would like to thank the institutions that provided financial support for this research. During my studies, I received several fellowships from the University of British Columbia, Nortel Networks and the Dr. Husmann Foundation. The NSERC-Canadian Mountain Holidays Chair for Snow and Avalanche Science at the University of British Columbia also provided financial support for this research.

I am grateful to Canadian Mountain Holidays, whose vision and generosity made this research possible in the first place. Thanks to all their staff in Banff and at the different lodges for the incredible experience. In particular, I would like to express my thanks to Walter Bruns, Rob Rohn, Colani Bezzola, Roger Atkins and Jan Bergstrom. Their comments and assistance helped shape this research.

Without the InfoEx community, this research would have not been possible. I would like to thank the community for collecting such a comprehensive dataset and for allowing me to use the data for my research. My thanks also go to the staff of the Canadian Avalanche Centre for answering all my questions about the dataset.

I had countless discussions about my research ideas with a great number of people. Dr. Karl Birkeland deserves special thanks for numerous stimulating discussions about snow, systems and scale. Without the help of Dr. Urs Gruber-Schmid, I would have not been able to tap into the InfoEx dataset. Claudio Donofrio and Zack Simone helped with the transformation of the InfoEx dataset. I would also like to thank Dr. Kalle Kronholm, Chris Landry, Chris McCollister, Dr. Chris Pielmeier and Claudia Röger for interesting discussions about different parts of my research.

I thank my parents, Urs and Rita Hägeli, for their continuous support and especially for dragging me into the mountains, putting me on skis from the time I could barely walk, and instilling in me a love for mountains, skiing and snow. I also thank my brother Philipp Hägeli for being my early ski partner, even after once being left behind on the bed in a full ski suit on a rainy morning. I could just not close the top buckle of his ski boot!

Drs. H.P. Schmid and Timothy Oke deserve special thanks for providing me with an incredible experience when I came to UBC the first time. That first summer in Vancouver made a significant impression and substantially shaped my future path.

I would like to thank Tricia Armstrong, who read this thesis like nobody else and fixed all the little typos that went unnoticed before.

I express my deepest thanks to my friends Bruce Ainslie, Roger Atkins, Heather Baid, Ian Baker, Karl Birkeland, Nicole Deiss, Adrian Gilli, Urs and Kathrin Gruber-Schmid, Russ Fretenburg, Ben Johnson, Niki Lepage and Paul Vidalin, Marcel Müller, Elin and Peter Oberholzer, Kathy Osterman, Melanie Primeau, Pat Spink, Kevin Riddell, Sarah Roberts, Magdalena Rucker, Bob Wilson and all others, who have provided support whenever necessary and made sure that I still spent time in the mountains.

Finally, I would like to thank Lisa Ochowycz, whose enthusiasm for life has changed mine.

CHAPTER 1

GENERAL INTRODUCTION

1.1 Background

The combination of vast and majestic mountain landscapes, pristine wilderness and ample snow supply of Western Canada create some of the world's best skiing conditions. Each winter the mountains of British Columbia and Alberta attract thousands of locals and tourists alike to enjoy their favourite winter sport. In the early 1930s the first ski resorts opened in the Rocky Mountains close to Banff on Mount Norquay and at Sunshine (Pole, 1993). In 1964, Hans Gmoser and Leo Grillmayer, two Austrian mountain guides who later founded Canadian Mountain Holidays (CMH), took the first guests helicopter skiing in the Bugaboos, a small mountain range in south-eastern British Columbia (CMH, 1996). Since then winter tourism and the skiing industry have become an important sector of the economy of Alberta and particularly British Columbia. The skiing industry of Western Canada has an overall impact on the local industry of approximately $400 million per year (Brent Harley and Associates Inc., 2002). The helicopter and snowcat skiing industry alone, accounts for $100 million of spending across all regions of British Columbia. Over 88% of helicopter and snowcat skiing guests come from outside Canada, making the industry a significant source of revenue for British Columbia (Brent Harley and Associates Inc., 2002).

However, since 1970, 347 people have been killed in avalanches in Canada (CAA, 2004). Accident data show that the vast majority of these people were amateur recreationists engaged in winter backcountry activities in the western parts of the country. Over the last decade, the average number of fatalities has increased notably and is now at approximately fifteen cases per winter (Figure 1.1). This increase can be attributed to a recent increase in popularity of outdoor recreation in general and to many more people venturing into the mountains in winter. Avalanches are now the leading source of fatalities caused by natural hazards in Canada. The estimated number of people injured by avalanches is at approximately 75 cases per year (Bhudak Consultants Ltd., 2003).

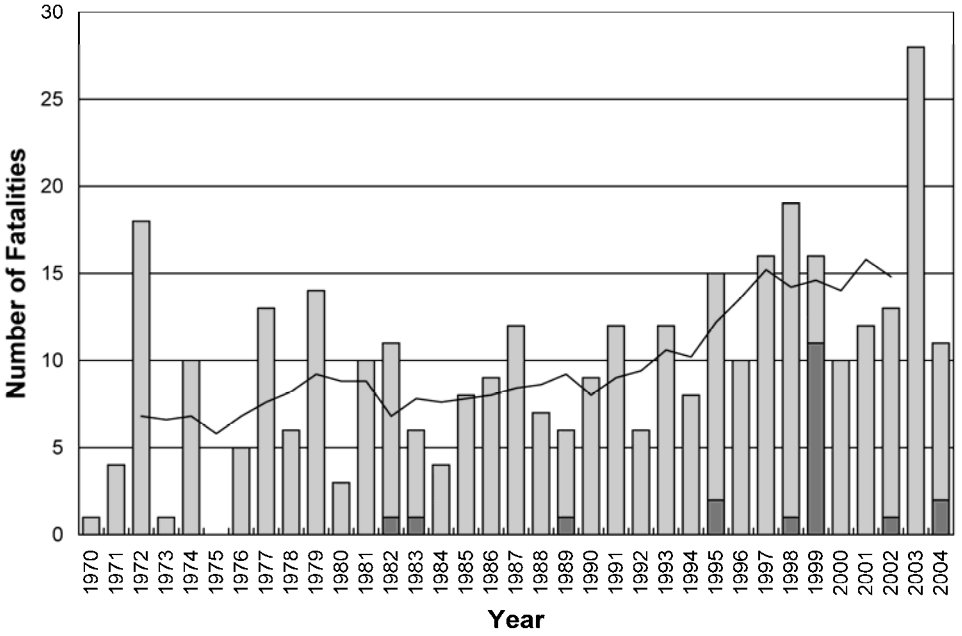

Figure 1.1:
Number of avalanche fatalities in Canada between 1970 and 2004. Dark grey bars show number of residential/industrial fatalities, while light grey bars present the number of recreational cases. Black line represents five year moving average (data from CAA, 2004).

Avalanches resulting in fatalities have far reaching consequences for the entire region. The high number of fatalities during the winter of 2002/03 (29 fatalities in total, 14 of them in two accidents) created a crisis of public confidence causing immediate economic impacts to winter tourism. This loss of confidence resulted in $1 million worth of cancellations in the helicopter and snowcat skiing industry alone and an estimated $10 million loss to supporting sectors (Bhudak Consultants Ltd., 2003).

Since most winter recreational activities are enjoyed in prime avalanche terrain, the use of permanent safety measures such as widespread closures is inappropriate. European statistics show that public avalanche safety programs with temporary methods of risk mitigation can significantly reduce the loss of lives (Bhudak Consultants Ltd., 2003). The main aspects of such safety schemes are a) public avalanche warnings; b) public awareness programs; and c) public education programs. In Canada, public avalanche warnings are closely connected with the commercial skiing industry. The Canadian Avalanche Association (CAA) is Canada's national organization promoting avalanche safety. This non-profit organization is rooted in the professional avalanche safety community and has a wide variety of members including ski resorts, commercial backcountry operations, highway and park safety programs, independent guides and academic researchers. The daily information exchange among commercial operators (InfoEx) builds the foundation for the public bulletin, which is published three to four times a week by the Canadian Avalanche Centre in Revelstoke, British Columbia. The bulletin covers the main mountain ranges in Alberta and British Columbia. Due to the large areas covered by the advisories, the public forecasters are highly dependent on the assessment and support of local avalanche professionals.

While all three aspects of the public avalanche safety system are important, this thesis mainly addresses issues related to large-scale backcountry avalanche forecasting. The main goal of this research is to examine the scale characteristics of persistent snowpack weaknesses and related avalanche activity. In order to familiarize the reader with the different aspects of the forecasting process, the next section presents the main characteristics of the applied avalanche forecasting process. It is followed by a description of existing computer forecasting models and their role in the forecasting process. The General Introduction concludes with a summary of issues faced in avalanche forecasting and an outlook on the individual manuscript chapters of the thesis.

1.2 The Applied Avalanche Forecasting Process

Over the last century, guides and scientists together have developed sophisticated methods for assessing avalanche hazards and mitigating the resulting risk for travellers in avalanche terrain. Avalanche forecasting procedures currently used by professionals and methods taught to recreationists are the result of this accumulation of practical and theoretical experience. McClung (2002a; 2002b) presents a detailed description of different elements of the applied avalanche forecasting process. The seven inter-connected elements are: 1) definition, 2) goal, 3) human factors and perception, 4) reasoning process, 5) information types and informational entropy, 6) scales in space and time and 7) decision-making. In order to predict avalanches it is necessary to master all seven aspects. This section presents a brief discussion of the most important aspects of the forecasting process.

1) Definition

The definition of avalanche forecasting is the prediction of current and future instabilities in space and time relative to a given triggering level.

2) Goal

The goal of avalanche forecasting is to minimize the uncertainty about snowpack instabilities with regard to temporal and spatial variability of the snow cover, changes in snow and weather conditions and variations in human perception and estimation (McClung, 2002a). This goal is significantly different from other forecasting tasks in neighbouring disciplines. While it is often sufficient to predict the average state of a system (e.g., total water equivalent in a watershed in snow hydrology) or spatially integrated characteristics of an event (e.g., flood warnings), it is the exact timing and location of individual events on the smallest scales that is the main interest in avalanche forecasting. This special quality clearly requires different forecasting approaches.

3) Human factors and perception

Human factors and perception are fundamental aspects of avalanche forecasting (McClung, 2002a). Perception is a forecaster's picture of reality based on the information and experience available at the time. Since most avalanche victims in Europe and North America trigger their own avalanche, the root cause of most accidents is a failure in human perception (McClung, 2002a). Perception is highly personal, subjective and a function of a person's character traits and physiology. It can be positively affected by targeted education and experience. Negative influences include human biases, such as inconsistency or conservatism.

4) Reasoning process

The fundamental reasoning process in avalanche forecasting is a dynamic, mostly inductive process, which is probabilistic and has an intuitive component that is difficult to reduce (LaChapelle, 1980). The appropriate understanding of the physical processes involved, such as snow metamorphism, fracture initiation and fracture propagation, is highly valuable in the forecasting process and enhances the learning experience of a practitioner, particularly during the early stages of a professional career. These two approaches complement each other and allow a quick, comprehensive and problem-oriented evaluation of the situation at hand.

Avalanche forecasting is not an event, but rather an evolutionary process that starts with the first snowfall of the season and ends with the melting of the snowpack in the spring (McClung, 2002a). It consists of a constant re-evaluation of the prediction in space and time as new information becomes available.

Redundancy is another, related method used in forecasting for reducing uncertainty (LaChapelle, 1980). Weak insights into snow instability are strengthened by either searching for additional pieces of information or sharing data among peers. The new information either reinforces or questions the perception of the current conditions.

5) Information types and informational entropy

Data used in avalanche forecasting are highly diverse in character, information content and scale properties. The information content consists of two basic types: singular data about the specific situation at hand and distributional information representing data about similar situations in the past (McClung, 2002b). While the first type contains direct information about the state of the instability, the second type enters the process as knowledge and experience.

Individual pieces of information have traditionally been grouped into three classes according to their informational entropy or ease of interpretation (LaChapelle, 1980; McClung and Schaerer, 1993). The three classes are snow and weather factors (class III), snowpack factors (II) and stability factors (I). This sequence of classes follows the chain of causation from distant to proximate and the interpretation of a particular piece of information becomes easier with decreasing class number (Figure 1.2). Not included in this system are terrain and ground cover, which are other crucial, but more static pieces of information necessary for avalanche prediction. Data choice for a prediction can strongly depend on the situation at hand. While meteorological parameters might be sufficient for predicting storm snow avalanches, snow profile information becomes crucial when forecasting avalanches on a persistent weaknesses (see LaChapelle, 1966).

McClung (2002a) points out that data collection in avalanche forecasting should be dominated by the technique of ‘targeted sampling’. While random sampling is the preferred method in scientific studies, it does not present the best strategy for detecting instability. A more successful strategy used by professionals is to specifically search for instability within the terrain and extrapolate worst-case scenarios.

6) Scales in space and time

Scales in space and time are fundamental properties of individual pieces of data and related scale issues are crucial in avalanche forecasting. Even though this issue has received considerable attention in related disciplines, such as hydrology and geomorphology, it has not been studied extensively in the context of avalanche forecasting.

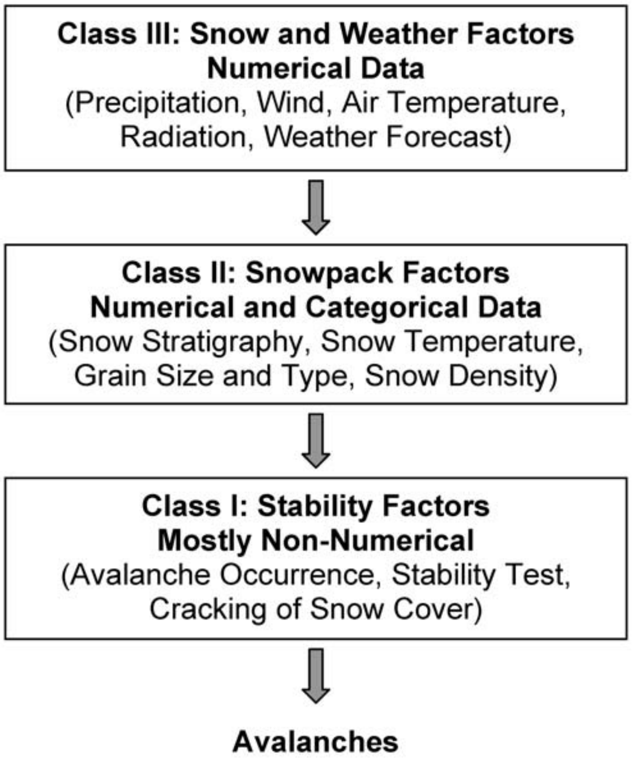

Figure 1.2:
Classification of data used in avalanche forecasting according to informational entropy (after LaChapelle, 1980; McClung and Schaerer, 1993). The lower the class number the more relevant and easily interpreted is the information.

7) Decision-making

Applied avalanche forecasting is generally a *decision-oriented* process. At the end of the evaluation one of the following three decisions has to be made: ‘Go’ (e.g., open ski terrain, proceed through backcountry ski terrain, remove a warning in a public avalanche advisory); ‘No Go’; or seek more relevant information to resolve the uncertainty (McClung, 2002b).

The example of a professional helicopter ski guiding team at CMH is used to illustrate the different aspects of the avalanche forecasting process in an operational setting. Superscript numbers are used in the following text to highlight the different forecasting elements as summarized in Table 1.1.

Table 1.1:
Summary of avalanche forecasting elements and related characteristics mentioned in text

Num.	Avalanche forecasting element/characteristic
1	Definition
2	Goal
3	Human factors and perception
4	Reasoning process
	a) Inductive reasoning
	b) Deductive reasoning
	c) Evolutionary process
	d) Redundancy
5	Information types and informational entropy
	a) Singular data about situation at hand
	b) Distributional data about similar situations in the past
	c) Three data classes according to informational entropy
	d) Targeted sampling
6	Scales in space and time
7	Decision-making

Numbers and letters used in the following paragraph refer to the individual elements and characteristics.

A guiding day starts in the morning with weather and snow observations at a nearby study plot$^{(5a)}$. During the morning meeting, the guiding team discusses overnight changes to avalanche conditions observed on the previous day$^{(5b,\ 4c)}$ and collectively forms a perception$^{(3)}$ of the nature, distribution and sensitivity of the current conditions$^{(1,2)}$ (Atkins, 2004). While individual guides might focus on different pieces of information and use different approaches (LaChapelle, 1980: 'There is more than one way to forecast an avalanche'), the group setting allows the team to benefit from its diversity and wealth of knowledge and experience$^{(4d,\ 5b)}$. Depending on the guiding team, these meetings can have either an informal(4a) or a more structured(4b) character. It is the perception of current conditions and the confidence of the guiding team that is the basis of any subsequent guiding decision. In the case of CMH, the morning meeting results in the formulation of a 'run list'(7). On this list, predefined runs are marked as either available or closed for skiing for the day. An 'open' run does not mean that all of the terrain on the run is considered to be completely safe. It rather means that guides feel confident that there are ski lines on this run that can be skied safely with groups of guests. The resulting run list is binding for the guiding team for the day. In order to make more detailed guiding decisions(6) during skiing, new information is constantly gathered through the observation of recent effects of weather, snow profile analyses, observations of avalanches or other signs of instability(5a, 5c) and deliberate slope tests(5d). As new and generally more detailed information(6) becomes available the perception is constantly updated(3) allowing guides to safely lead their groups through avalanche terrain(7). While four guides are skiing with guests, an additional 'snow safety guide' takes more detailed information about specific stability concerns(5a,5d). All guides are in constant radio contact and continuously update each other about their findings(5a, 4d). At the guides' meeting in the evening experiences of the day are shared and the group as a whole forms a new perception of the existing avalanche conditions(1, 2). At the end of the meeting, there is a radio exchange with all other CMH operations, where guiding teams share the most important findings of the day(5a, 4d). This evening assessment of the guiding team becomes the starting point(5b) for the following day, where the process starts again. Schedules of guides are staggered to ensure optimal information exchange and continuity from one guiding team to the next(4c). Even though the details are different, highway safety teams or writers of public avalanche advisories go through comparable steps and their evaluation process has similar characteristics.

The guiding teams at CMH are supported by a sophisticated database system called SNOWBASE. In addition to traditional data entry forms, charts and reports(5a), the system has sophisticated tools that allow the recording and retrieval of information and experience against images of terrain(5b, 6). Avalanches, for example, can be drawn on oblique images of ski runs (Hägeli and Atkins, 2002). This functionality, which is specifically tailored to how guides work, has proven to be one of the most useful aspects of the entire system. Many other operators have similar, even though often less sophisticated data systems. Currently, the CAA is in the process of developing a comprehensive, industry-wide information system that will allow a more sophisticated data exchange among all interest groups in the avalanche community including the public (Atkins and Hägeli, 2004).

The extensive data collection, the significance of human aspects in the forecasting process and the existence of database systems naturally raise the question of whether computer-aided forecasting tools could significantly improve the quality of the prediction process. The following section gives a short overview of existing approaches used in computer forecasting models and discusses their application.

1.3 Existing Avalanche Forecast Models

The purpose of computer-aided forecast models is to give practitioners an additional instrument that helps them do their job. Particularly due to the significance of human aspects in the process, an objective evaluation tool may be highly desirable. Over the last thirty years a variety of forecasting models have been developed with different focuses and purposes.

Statistical models have a long history in avalanche forecasting. The basic idea behind these models is that similar environmental conditions are expected to create comparable avalanche activity. A variety of different statistical approaches have been used, but the most successful ones are the nearest neighbour method (Buser and others, 1987; Buser, 1989) and a combination of parametric discriminant analysis and cluster technique using Bayesian statistics (McClung and Tweedy, 1994). In both models, meteorological and snow surface parameters of the current day are compared to a database of historic data. The expected avalanche activity is calculated on the basis of the observed activity on a number of meteorologically similar days. The output of the models is a probability of avalanching for the day in question and a list of historic avalanches that occurred on comparable days. Models based on these methods have been successfully used operationally at ski resorts and in highway settings. Other statistical approaches that have been explored are regression analysis (Judson and Erickson, 1973), fuzzy factorial analysis (Jaccard, 1990) and regression and classification trees (Davis and others, 1999). Neural networks can be viewed as an extension of the traditional statistical approach. Despite the relaxed data requirements of this method, only a few attempts have been made (see, e.g., Schweizer and others, 1994; Stephens and others, 1994) to use the approach for forecasting purposes.

The ultimate goal of *deterministic models* is to simulate avalanche release. Modeling the evolution of the snowpack throughout a season based on meteorological input data is a necessary first step in this process. Currently the most sophisticated snow cover models are Crocus (Durand and others, 1999) and SNOWPACK (Lehning and others, 1999). While SNOWPACK simulates the snowpack structure at the location of a high-quality weather station, Crocus uses large-scale, assimilated[1] meteorological data to calculate the snowpack development for different aspects and elevation zones in 38 ‘massifs’ (forecast areas of approximately 500 km^2 each) in the French Alps and the Pyrenees. These snow cover models are regularly used for research and forecasting purposes in Switzerland and France. However, no reliable numerical routines have yet been developed that can accurately predict the release of avalanches from snowpack forecasts.

Expert systems use a completely different approach. With non-numerical rules and knowledge they simulate the thinking and decision-making process of a human expert. This approach has been used for a variety of different forecasting problems. The AVALOG system (Bolognesi, 1991) has been used to predict

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[1] Data assimilation:
The combining of diverse data, possibly sampled at different times and intervals and different locations, into a unified and consistent description of a physical system, such as the state of the atmosphere (AMS, 2002)

slope-by-slope avalanche activity within a ski resort. DAVOS and MODULE (Schweizer and Föhn, 1996) are expert systems that were developed to determine the avalanche hazard at the regional level. Based on a variety of measured and predicted weather and snowpack information, the systems forecast the degree of hazard for different aspects and elevation ranges. MÉPRA (Giraud, 1992) and a similar system by McClung (1995) interpret snow profile information by identifying the most relevant snowpack weaknesses and assessing the related avalanche hazard.

When used in operational forecasting, each of these modeling approaches has clear strengths and weaknesses due to specifics of the data used and/or the characteristics of the analysis method. In the case of statistical models, for example, the list of historic avalanche observations during similar days can be an important memory aid for the forecaster in charge. On the other hand, these systems are highly dependent on the underlying database content and generally perform poorly under conditions that have not been experienced previously. It is, however, particularly in these situations that forecasters would appreciate help from a forecasting tool. Similar arguments can be made for other modeling approaches. One possible solution to this issue is the combination of approaches described above. An example of such a *hybrid system* is the French Safran–Crocus–MÉPRA (Durand and others, 1999), which consists of a data assimilation module, a snowpack model, and a stratigraphy interpretation component. Other examples of hybrids are NivoLog (Bolognesi, 1998), a system that combines the advantages of the statistical approach with the strength of an expert system, and ALUDES (Schweizer, 1995), which is a combination of an expert system and a neural network.

1.4 Summary and Outlook

Avalanches are the result of numerous interactions of various contributing factors and processes that act over large ranges of different spatial and temporal scales. As a consequence, the forecasting process is highly dynamic and requires the simultaneous processing of a wide range of different types of information. The variety of model approaches presented in the last section reflects the numerous facets of the forecasting task. In an operational setting, forecasting tools should add to the forecasting process by contributing an additional skill, new information, a different perspective and/or extra insights. To be accepted by practitioners, the use of the tool also has to naturally fit into the existing forecasting routine of an operation.

The goal of a forecasting tool is to help guides and/or recreationists to make good travel decisions in the backcountry by reducing the user's uncertainty about the current instability conditions. McClung (2002a) points out that uncertainty can only be truly reduced by providing more or new information of the right kind.

Forecast tools often use stability or hazard ratings(for Canadian definitions see CAA, 2002) to summarize avalanche conditions. Examples are stability indexes (e.g., DAVOS, MODULE, Safran-Crocus-MÉPRA chain), probabilities of avalanching (e.g., nearest neighbour models) or the simple classification into avalanche or non-avalanche days (discriminant model). The appeal of this output is the simplicity of the numerical value that lends itself to computing. For advanced backcountry travellers, however, this model output provides only very limited information for the decision-making processes. When traveling in uncontrolled backcountry, avalanches are always a concern and 'non-avalanche days' generally do not exist. Professionals who spend most of their winters in the field generally have a good sense about the current conditions and do not need an extra tool for this information. At CMH, stability ratings are assigned twice daily at the end of morning and evening meetings. These ratings are a summarized expression of the team's perception of the current conditions, which can easily be communicated among operations. The stability ratings, however, are not a major consideration when making any guiding decisions (Atkins, 2004).

Information that can truly contribute to the decision-making process includes answers to the questions 'What is the character and spatial distribution of the dominant weakness?', 'What is the likelihood of triggering?' or 'What are the likely characteristics of potential avalanches?'. This type of information is highly relevant for backcountry avalanche forecasting, but its non-numerical character is not ideal for computations. The nearest neighbour method does partially provide this type of information to the user via a list of observed avalanches under conditions similar to the day in question. This output has proven to be one of the most useful features of this type of forecasting tool (Buser, 1989) and is responsible for the success of the nearest neighbour method. Derived models have been successfully applied in ski resorts and highway safety programs. These types of operations, however, generally cover relatively small areas that permit the collection of virtually complete avalanche datasets. The frequent use of explosives for avalanche control eliminates persistent snowpack weaknesses (Jamieson, 1995), and allows the main focus to be on new snow avalanches, which can mainly be related to individual storms.

In the backcountry of Western Canada, however, persistent snowpack weaknesses are often the main stability concern (see, e.g., Jamieson, 1995). Including data about snowpack weaknesses significantly increases the complexity of the forecasting process. The goal of this thesis is to examine the scale characteristics of persistent snowpack weaknesses and related avalanche activity in the context of large-scale backcountry (≥ 1000 km^2) avalanche forecasting. The results of this research may guide the incorporation of information about snowpack weaknesses into future avalanche forecast models.

Chapter 2 focuses on examining the scale characteristics of data generally used in avalanche forecasting and discusses related scale issues in detail. After a detailed discussion of the important terms, a two-dimensional hierarchy in space and time is suggested as a potential conceptual framework. With the help of this reference system, the use of information in professional guiding is examined and compared to the data used in existing prediction models.

Chapter 3 examines the scale characteristics of the most prominent snowpack weaknesses in the Columbia Mountains of British Columbia. The main focus is the characteristics of temporal activity patterns. The analysis uses the SNOWBASE dataset of CMH from 1996/1997 to 2000/2001.

Chapter 4 presents large-scale instability patterns across Western Canada. The basis of this analysis is the InfoEx data set of the CAA from 1991/1992 to 2001/2002. This dataset also includes information about the maritime Coast Mountains and the continental Rocky Mountains. The study generally confirms the traditional perception of the different snow climate types in the area. Meteorological indicator variables are used in an attempt to explain the observed differences in snowpack instability.

Chapter 5 goes one step further and uses the InfoEx data to expand the analysis of persistent snowpack weaknesses presented in Chapter 3 to the neighbouring mountain ranges. The study mainly examines the spatial characteristics of persistent weaknesses and their related avalanche activity. The analysis also shows that the existing snow climate classification definitions are inadequate for describing the avalanche characteristics of a given location. An ‘avalanche winter regime’ is suggested as a new term for describing the characteristics of a winter directly relevant to avalanche forecasting.

Chapter 6 summarises the conclusions of all four manuscript chapters and draws some general conclusions about the use of weak layer information in forecasting models. The chapter also presents suggestions for future work in this field.

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CHAPTER 2

HIERARCHY THEORY AS A CONCEPTUAL FRAMEWORK FOR SCALE ISSUES IN AVALANCHE FORECAST MODELING

Manuscript:
Hägeli, P. and McClung, D.M., in press. Hierarchy theory as a conceptual framework for scale issues in avalanche forecast modeling. Annals of Glaciology, 38[1]*.*

2.1 Introduction

Avalanches are the result of numerous interactions of various contributing factors and processes that act over a large range of different spatial and temporal scales. Examples range from avalanche initiation on the scale of metres to synoptic weather systems that can span thousands of kilometres. Avalanches are complex phenomena in which small changes in individual components can result in considerably different activity characteristics. Predicting the behaviour of such a complex system is highly challenging since it requires addressing multiple levels of scale simultaneously. Over the last century, avalanche practitioners such as mountain guides have developed highly successful decision-making strategies to deal with this complexity (LaChapelle, 1980). These rules, sometimes applied intuitively, are able to comprehensively deal with the numerous processes and multi-scale nature of the avalanche phenomenon. In recent years, considerable effort has been put into the development of statistical and numerical models to facilitate the work of avalanche professionals. In order to develop appropriate strategies and models, it is necessary to have a thorough understanding of the scale characteristics of the phenomenon

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and all the contributing factors. Although scale has been called one of the most important issues in current geosciences (UCGIS, 1998), scale and scale issues have received only limited attention in avalanche research. The main focus has been on small-scale studies (e.g., Kronholm and others, 2002; Landry and others, 2002), which have produced interesting insights, but are of limited value for avalanche forecasting at operational scales, such as entire ski resorts, highway corridors or numerous drainages in the case of backcountry operations.

The goal of this paper is to highlight scale issues in avalanche forecasting and present a conceptual framework for dealing with them across a wide range of scales.

2.2 Scale, Scaling and Scale Issues

The term ‘scale’ refers to a characteristic length or time of a process, measurement or model (Blöschl and Sivapalan, 1995). Process scales can be described by single parameters in space and time, such as the duration or frequency of a process. The scale characteristics of a measurement or model have to be defined by scale triplets in space and time: ‘extent’, ‘spacing’ and ‘support’ (Blöschl and Sivapalan, 1995). In the case of a monitoring network, ‘spacing’ (also called grain by Ahl and Allen, 1996) refers to the distance between samples, ‘extent’ stands for the overall coverage of the data, and ‘support’ represents the integration volume or area of a sample. The knowledge of these scale characteristics is essential because they determine which components of the true process scale can be captured with an observation. The apparent process scale displayed in measurements is the result of the observational scales superimposed on the true process scale. Similar arguments can be made for model scales and the apparent scale characteristics of their outputs.

‘Scaling’ involves transfer of information across scales. ‘Scale linkage’ (Phillips, 1999) refers to the information transfer between processes that act over fundamentally different scales, and is crucial for understanding the overall scale characteristics of a complex system. Another aspect is the scaling of information between processes and observations or models, which is described in detail by Blöschl and Sivapalan (1995).

Difficulties that arise when dealing with scale and scaling are generally referred to as 'scale issues.' Phillips (1999) classifies them into four general categories. First is the basic problem of determining the natural spatial and temporal scales of a process. Here, the goal is to gain fundamental understanding of the process or phenomenon. Popular geo-statistical methods are semi-variogram or wavelet analyses. Second, is the problem of matching the observational and model scale with the natural scale of the process in question. This aspect deals with the technicalities of setting up suitable monitoring systems and choosing the appropriate spatial and temporal model resolutions. Third, are the problems with information transfer across scales when the observation and model scales are different from the true process scale. This involves the distribution of localized information through space and time. An example for a geostatistical extrapolation method is Gaussian process regression (kriging). Fourth, are the issues of dimensionality and similarity. These address the range of scales over which patterns or relationships are constant or valid. A related example of this scaling aspect is the effects of size in fracture mechanics as discussed by Bažant and others (2003).

These four scaling issues are interrelated and they are all significant in avalanche forecasting. The most urgent aspect, however, is a clear understanding of the scale characteristics and scale linkage of the factors and processes that lead to avalanching. This basic knowledge is fundamental for the development of appropriate monitoring networks and useful forecasting models.

Scale issues are strongly debated in many geosciences. This has resulted in the development of many discipline-specific solutions. Unfortunately, there is a fundamental difference in the goals of avalanche forecasting and neighbouring disciplines such as geomorphology or hydrology. Avalanche forecasting is the prediction of current or future snow instability in space and time relative to a given triggering level (McClung, 2002a). This goal is different from, for example, snow hydrology, where one of the main interests is the determination of the total water equivalent stored in a given area. This question centres on up-scaling of point measurements to an entire area. The focus of avalanche forecasting lies in determining possible locations of trigger spots within an area, which requires detailed point-to-point extrapolation and interpretation of individual observations. The ability to extrapolate depends highly on the similarity of locations and knowledge of the influencing parameters. This fundamental difference prevents the application of existing approaches for scale issues and necessitates the to development of new strategies specifically for avalanche forecasting.

2.3 Application of Hierarchy Theory to Avalanche Forecast Modeling

Hierarchy theory (Ahl and Allen, 1996) has been suggested as a conceptual framework for organizing complex systems and highlighting related scale issues. Examples of its application are de Boer (1992) in geomorphology and Allen and Hoekstra (1992) in ecology.

The theory is less practical for determining natural scales, which is generally the field of geostatistics (e.g., Webster and Oliver, 2000). Because of ‘targeted sampling’ techniques (McClung, 2002b) and generally incomplete avalanche observations (Hägeli and McClung, 2003 [Chapter 3]), it is impossible to apply these methods to avalanche data sets that match the scale of interest of this research. Discussion will therefore be limited to a theoretical framework that highlights scale issues relevant to avalanche forecasting and related modeling efforts.

Hierarchy theory is a holistic approach that includes the observer in the problem space. Although the observer generally does not control a system, the observed behaviour is viewed in the context of the question posed and the observer’s observational protocol. The incorporation of the observer in the problem space seems particularly appropriate in avalanche forecasting because of the crucial role of human perception (McClung, 2002a).

2.3.1 Temporal Hierarchy

Hierarchy theory uses a relatively simple set of rules to organize the processes and interactions in a complex system. Contributing factors are grouped into hierarchical levels according to their temporal or spatial scale characteristics. In the time domain, higher levels exhibit lower frequency behaviour and represent the context or constraint for entities at lower levels. With regard to lower level activity, higher-level behaviour can often be regarded as constant and may contain the memory component of the complex system.

In the case of avalanche forecasting one can distinguish seven different interacting temporal levels. These are terrain, ground cover, snowpack, weather, artificial triggers, the avalanche phenomenon (the level of interest of this research) and snow physics. These levels can be ordered into a hierarchy according to their typical time scales with regard to a typical operational forecasting period of one day (Figure 2.1). Evolving in geological time scales, terrain clearly changes most slowly and represents the ultimate constraint for the occurrence of avalanches. Terrain parameters can be regarded as constant for normal avalanche forecasting applications. Ground cover entities, such as glaciation or vegetation, are important parameters for avalanche forecasting, particularly during the early season and for full-depth avalanches. Typical temporal scales of this level are shorter than geological time scales, but still longer than regular forecasting periods. The characteristics of the existing snowpack, including the behaviour of persistent weak layers (Jamieson, 1995), are tremendously important for predicting avalanches. Hägeli and McClung (2003 [Chapter 3]) show that the typical time scale for avalanche activity on such weak layers ranges from approximately three weeks to the entire season. Weather represents the next lower level. Typical synoptic weather systems have a lifespan of a few days. When forecasting avalanches with regard to non-natural triggers, artificial triggers represent an additional hierarchical level. The shorter temporal characteristics of the trigger level places it right above the avalanche level. Situated below the avalanche level is the level of snow physics, which contains the principles of fracture mechanics with typical temporal scales of seconds.

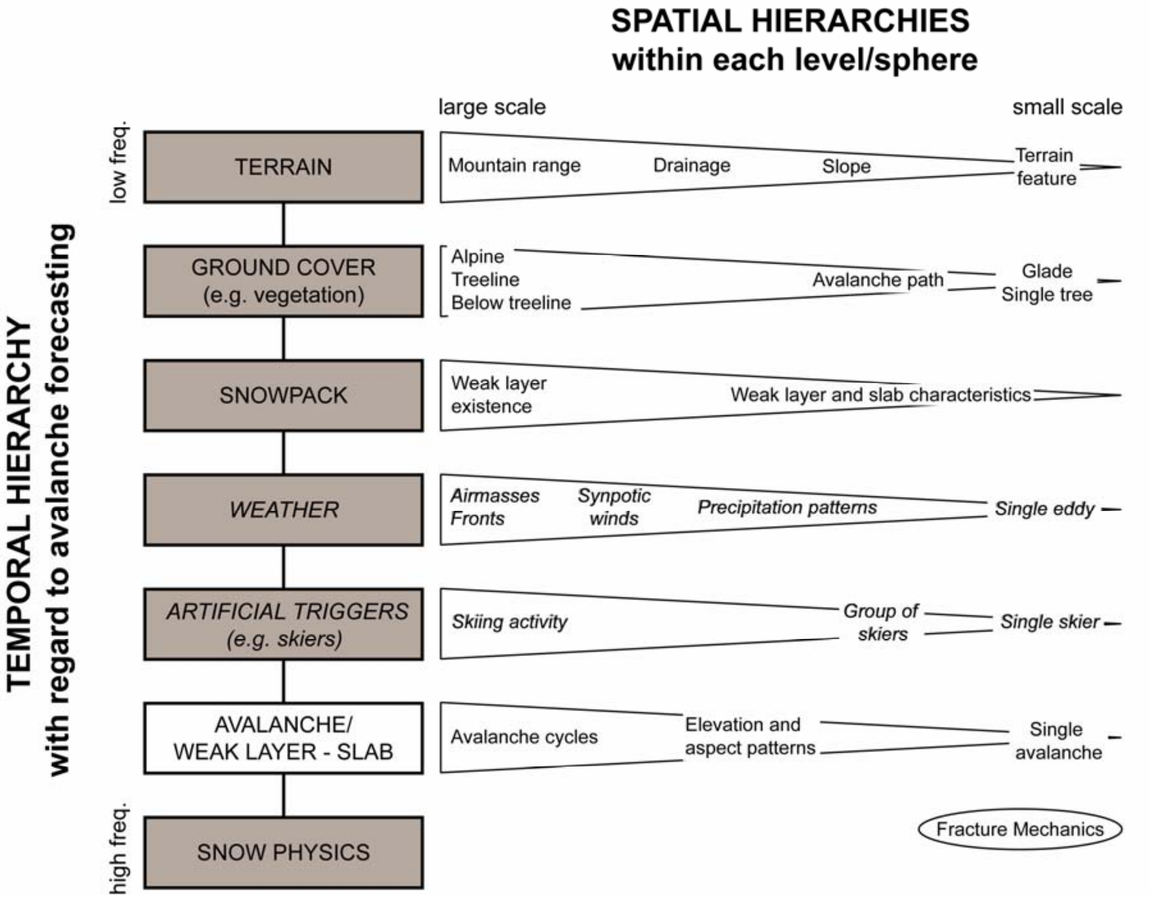

Figure 2.1:
Two-dimensional hierarchical framework for avalanche forecast modeling with examples. Italic elements represent incorporated disturbances.

While levels above the avalanche level represent environmental conditions that allow or disallow avalanches to occur, the level below contains the underlying principles necessary for avalanches to take place. This leads to the concept of the ‘constraint envelope’ (O'Neill and others, 1989), which states that avalanches must occur within a window that is defined by a combination of low-level principles and upper-level environmental constraints. An excellent example of this concept is the fact that the majority of slab avalanches occur on slope angles between 25° and 55° (McClung and Schaerer, 1993). The principles of fracture mechanics generally do not allow avalanches on slopes below 25° while frequent sluffing (loose snow avalanches) on slopes above 55° prevents slabs from forming (McClung and Schaerer, 1993). More important from an operational point of view is that this constraint envelope changes over time. During periods of low stability the envelope is large, and numerous combinations of environmental factors lead to widespread avalanching. During times of high stability the envelope is small and avalanches are rare. A useful forecast model should point out all possible combinations that might lead to avalanching under the current conditions.

In order to forecast avalanches accurately it is necessary to include information from all the levels presented. Depending on the time frame of the forecast, a greater or fewer number of levels have to be incorporated in a dynamic way. When forecasting over time spans of minutes during control work, all levels except artificial triggers are static, while in the case of forecasting over a few days, the weather and snowpack levels must also be incorporated dynamically.

The present hierarchy is a partially nested hierarchy, where the higher snowpack level contains the avalanche level. For most forecasting applications, there is only a downward transfer of information/matter/energy in this hierarchy. Only when forecasting on individual slopes is there a significant feedback of an avalanche event on the characteristics of the local snowpack. In this case, the snowpack can be viewed as the memory of the system. There is no effect of avalanches on the levels of weather and artificial triggers. These can be regarded as incorporated disturbances (Ahl and Allen, 1996) that interact only in a one-way fashion within the nested avalanche system. However, weather also plays a crucial role for the development of the snowpack. The illustrated hierarchy in Figure 2.1 was specifically designed with respect to operational avalanche forecasting. A hierarchical system for the development of the snowpack will be significantly different from the framework presented, although the systems are closely related. Similarly, a hierarchy that focuses on avalanche prediction for the purpose of hazard mapping might have a different order of levels and different kinds of interactions among them. These different hierarchies do not have to be contradictory. Instead, they demonstrate the strength of hierarchy theory to provide problem-specific frameworks.

2.3.2 Spatial Hierarchy

So far in this paper we have ordered the seven levels roughly according to their temporal scale characteristics. Each of these levels contains processes that exhibit a wide range of spatial scales. These levels can also be organized in individual hierarchies. Similar to the temporal hierarchies, large-scale phenomena and processes represent the context for small-scale processes. In order to understand the resulting spatial scale characteristics of the avalanche phenomenon, it is necessary to have knowledge of the spatial hierarchies within each level of the temporal hierarchy (Figure 2.1). It is beyond the scope of this paper to discuss the scale characteristics of each of these levels in detail. We will therefore limit our analysis to a few crucial aspects.

Terrain has been described to be fractal or self-similar (see, e.g., Klinkenberg and Goodchild, 1992). This implies that there exists a continuous hierarchy of topographic features from large to small sizes. Numerous ecological studies have examined the scale aspects of vegetation. Allen and Hoekstra (1992), for example, argue that the spatial scale characteristics of vegetation can be conceptualized with spatially nested hierarchies.

There have been many studies about the spatial variability of the snowpack in the context of snow hydrology (e.g., Elder, 1995; Blöschl, 1999). Spatial studies with regard to avalanche prediction, however, are rare. Hägeli and McClung (2003 [Chapter 3]) examined the spatial characteristics of persistent weak layers across a mountain range based on avalanche observations. They show that persistent weak layers with considerable avalanche activity generally cover significant fractions of a mountain range. Within these general areas of activity, they also show embedded smaller-scale variabilities. For example, surface hoar weaknesses on northern aspects are often found in combination with weak sun crust interfaces on southerly aspects. Birkeland (2001) found similar characteristics when analyzing stability patterns across a small mountain range.

Studies that examined snowpack characteristics on individual slopes (e.g., Jamieson, 1995; Birkeland and others, 1995) reveal numerous variabilities on even smaller scales.

Modern texts in atmospheric science (see, e.g., Storch and Zwiers, 1999) suggest that there is a continuous spectrum of atmospheric processes from small to large scales. Similar to terrain, they can be organized in nested hierarchical systems.

Artificial triggers, such as skiers, on-snow vehicles, or explosives, can also be organized in a nested hierarchy. In the case of skiers, for example, we can distinguish between skiing activity in a mountain range in general, the activity of different groups of skiers, and the influence of the track of an individual skier.

All environmental constraints exhibit some sort of spatial hierarchies. They can be continuous, as in the case of terrain, or have more of a stepwise, discontinuous character such as artificial triggers. Fracture mechanics, however, acts only over a narrow range of spatial scales. Most models for dry snow slab avalanche release mention previously existing imperfections on the order of metres (Schweizer, 1999). Depending on conditions, fracture propagation within the weak layer can cover hundreds of metres. The fact that the avalanches are based only on a small-scale principle is a major difference to many other complex systems where hierarchy theory has been applied. For the most part, avalanches are independent events that do not influence each other. Large avalanche cycles are accumulations of individual avalanche occurrences rather than a dynamic system of interacting events. This has important consequences on how avalanche activity can be modeled at different scales.

The scale properties exhibited by avalanches are the result of the interacting spatial characteristics of all environmental constraints and underlying principles. In order to understand spatial avalanche patterns it is important to relate them to the scale characteristics of the contributing factors. Avalanche activity on persistent weak layers, for example, displays spatial characteristics that are a combination of the storm pattern at the time and the distribution of the active weak layer in the snowpack in relation to terrain, ground cover and existing triggers.

The two-dimensional hierarchy suggested here is comparable to other hierarchical frameworks suggested for other complex systems. Examples are the layered-cake model for a unified ecology by Allen and Hoekstra (1992) or the two-dimensional hierarchy suggested by Kljin and Udo de Haes (1994) for land classification.

2.4 Discussion

After presenting the basic characteristics of the hierarchical framework, we will compare this framework to an existing data classification scheme and discuss its importance for avalanche forecast modeling.

2.4.1 Comparison to Informational Entropy Data Classification

LaChapelle (1980) classified information used in avalanche forecasting into three categories: 3) meteorological factors; 2) snowpack factors; and 1) stability factors. The data classes are ordered according to informational entropy. This is defined as the relevance and ease of interpretation with respect to estimating instability and human perception (McClung, 2002b).

The most obvious difference between the two frameworks is the order of data classes (see Appendix A: Figure A.1). While LaChapelle's classification is based on information characteristics and perception, the hierarchical structure presented is process-oriented and orders levels according to behaviour frequency. LaChapelle (1980) focuses on the evaluation of avalanche conditions at the time, and views weather mainly as an input for the development of the snowpack. The hierarchical framework has a different perspective and sees weather as a trigger agent that acts on the current snowpack. The two perspectives clearly emphasize the two-sided role of the weather level. Besides its short-term effect on instability, weather is also the main driving force for the development of the snowpack and has longer-term consequences on instability.

As the spatial forecasting scale decreases, the difficulty of the forecasting problem and the need for accuracy increases (McClung, 2000). This problem can be overcome by including more low entropy data (McClung, 2002b). We believe that this implied link of lower entropy data and smaller scale is mainly a result of the perception of the different data classes and general observation practices. Meteorological data from study plots are generally used to monitor large-scale weather patterns, while snow pit analyses are used to examine smaller-scale snowpack characteristics. Avalanche observations and stability tests reveal information about local instability. However, meteorological observations also contain detailed information about the local conditions that act on the snowpack at a study plot. Similarly, there are observations from snow pit analyses and stability tests that are representative over larger scales. Johnson and Birkeland (2002), for example, suggest that shear quality is easier to correlate to widespread signs of instability than the score of individual stability tests. In order to predict avalanches at a specific scale it is necessary to take information from all levels into account. The challenge lies in finding the variable that properly represents the processes on a level at the scale of interest. While it is sufficient to know about the existence of an active weak layer when forecasting across an entire mountain range, it is necessary to have more detailed information about its characteristics when predicting for individual drainages.

2.4.2 Avalanche Forecast Modeling

In operational helicopter skiing, guides forecast avalanches on a range of spatial scales (see Appendix A: Figure A.2). During morning meetings, general avalanche conditions for the entire operation are discussed on the basis of the conditions observed on the previous day and the changes overnight. During the day, as more small-scale information becomes available, the forecast is continuously up-dated and becomes more detailed until the focus lies on individual terrain features during skiing. Generally, the entire spectrum of contributing factors is taken into account during all stages. Depending on the scale in question and the conditions at hand the importance of individual factors can change.

We believe that in order to be successful, computer models must mimic the evolutionary and comprehensive character of avalanche forecasting in time and space.

While human forecasters and guides have developed skills for dealing with scale issues in the forecasting process, these problems have to be explicitly addressed in numerical models. In the following paragraphs we will briefly elaborate on the scale issues in two different modeling approaches.

Statistical forecasting models are based on the idea that similar weather conditions lead to comparable avalanche hazard levels. Examples are the nearest neighbour approach (Buser and others, 1987) or the method based on discriminant analysis by McClung and Tweedy (1994). Observations from a representative weather plot are used to monitor large-scale weather patterns. In this context 'representative' means that it is possible make conclusions about the conditions in the entire operation from this single location. These weather observations are combined with avalanche occurrence data (see Appendix A: Figure A.3). Depending on the perspective, these observations represent an intermediate scale when looking at the avalanche activity in the entire operation, or stand for a small scale when examining individual avalanche paths. Even though there is a difference in scale between the two data groups, their combination in the model resolves the related scale issues. Since the recorded avalanches are the result of the interaction of all levels, the historic avalanche observations indirectly contain small-scale information about the static hierarchical levels such as terrain and ground cover as well as trigger information. The fact that these models include only limited information about snowpack characteristics makes them most suited for applications where new snow instabilities are the main concern. The proximity of the weather level to the avalanche level indicates why these models predict avalanche days with reasonable accuracy.

Another approach is the modeling of snowpack characteristics on the basis of weather observations. In the case of the Swiss SNOWPACK model (Lehning and others, 1999), high-quality, small-scale weather observations are used to simulate the evolution of the snowpack at particular locations (see Appendix A: Figure A.4). The French Safran-Crocus-MÉPRA model chain (Durand and others, 1999) simulates and analyzes the development of the snowpack on a larger scale using more generalized meteorological observations (see Appendix A: Figure A.5). In order to use these models for operational avalanche forecasting it is necessary to explicitly address the question of how these simulations relate to the surrounding area. Since this model approach does not include avalanche observations that indirectly contain this information, it is necessary to develop methods that deal with these issues. These methods need to incorporate information from all hierarchy levels at the appropriate avalanche forecast scale. By simulating the snowpack evolution for different elevation ranges and aspects, the French model chain addresses this issue to a certain extent.

2.5 Summary

The goal of avalanche forecasting is to minimize uncertainty about instability introduced by three principal sources of uncertainty: (1) the temporal and spatial variability of the snow cover, including terrain influences; (2) incremental changes from snow and weather conditions; and (3) human factors including variations in human perception and estimation (McClung, 2002a). The purpose of avalanche forecasting models is to facilitate this process. The advantage of models is their ability to give objective evaluations independent of human perception. However, it is tremendously challenging to incorporate all necessary components into a model that can produce forecasts that are truly helpful to avalanche professionals. While human forecasters have developed skills to transfer relevant information across scales, these relationships must be integrated explicitly into a numerical forecasting model. In order to develop useful prediction models, an in-depth understanding of the scale issue related to avalanche forecasting is crucial.

The focus of this paper is on the presentation of hierarchy theory as a conceptual framework for gaining insights into the scale characteristics of the avalanche phenomenon and related scale issues. We suggest a two-dimensional scheme with a temporal hierarchy of seven levels with spatially nested hierarchies. A short discussion of scale characteristics of the individual levels suggests that the resulting avalanche activity can exhibit spatial variabilities on a wide range of scales. In addition to these spatial patterns, the avalanche phenomenon also has a probabilistic component, which adds an additional level of complexity. Intensive field research is necessary to improve our understanding of the overall complexity of the avalanche phenomenon. The challenge is to plan large-scale campaigns that allow the study of patterns relevant to forecast applications. A better understanding of the underlying processes will be useful for designing improved monitoring networks and more useful prediction models.

The framework is compared with the data classification of LaChapelle (1980). The main difference between the two points of view is the reversed order of the weather and snowpack level. While LaChapelle sees weather as 'snowpack engineer,' it is viewed as a trigger agent in the hierarchical framework. LaChapelle's approach is highly suitable for evaluating the avalanche conditions at the time, where it is most effective to examine direct signs of instability. However, for true prediction purposes it maybe more useful to view weather as a trigger agent.

In order to develop a useful model at a specific scale, it is necessary to include information from all levels. The challenge is to find the appropriate variable that properly represents the level of the scale of interest. The current perception of data relevant to avalanche forecasting is reflected in the three data classes by LaChapelle (1980). In order to use the available observations most effectively and improve predictability, it may be necessary to review some of the traditional observation protocols.

We discuss some of the scale issues in avalanche forecast modeling. While statistical models contain information about scaling relationships, scale issues must be dealt with explicitly when using numerical snowpack simulations.

To apply these models successfully in avalanche forecasting, these questions have to be thoroughly addressed in the near future.

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CHAPTER 3

AVALANCHE CHARACTERISTICS OF A TRANSITIONAL SNOW CLIMATE – COLUMBIA MOUNTAINS, BRITISH COLUMBIA, CANADA

Manuscript:
Hägeli, P. and McClung, D.M., 2003. Avalanche Characteristics of a Transitional Snow Climate – Columbia Mountains, British Columbia, Canada. Cold Regions Science and Technology, 37, 255-276.[1]

3.1 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, namely 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 types *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 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.

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3.1.1 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 and often leads 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 a generally deep snowpack with 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 (Figure 3.1). 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.

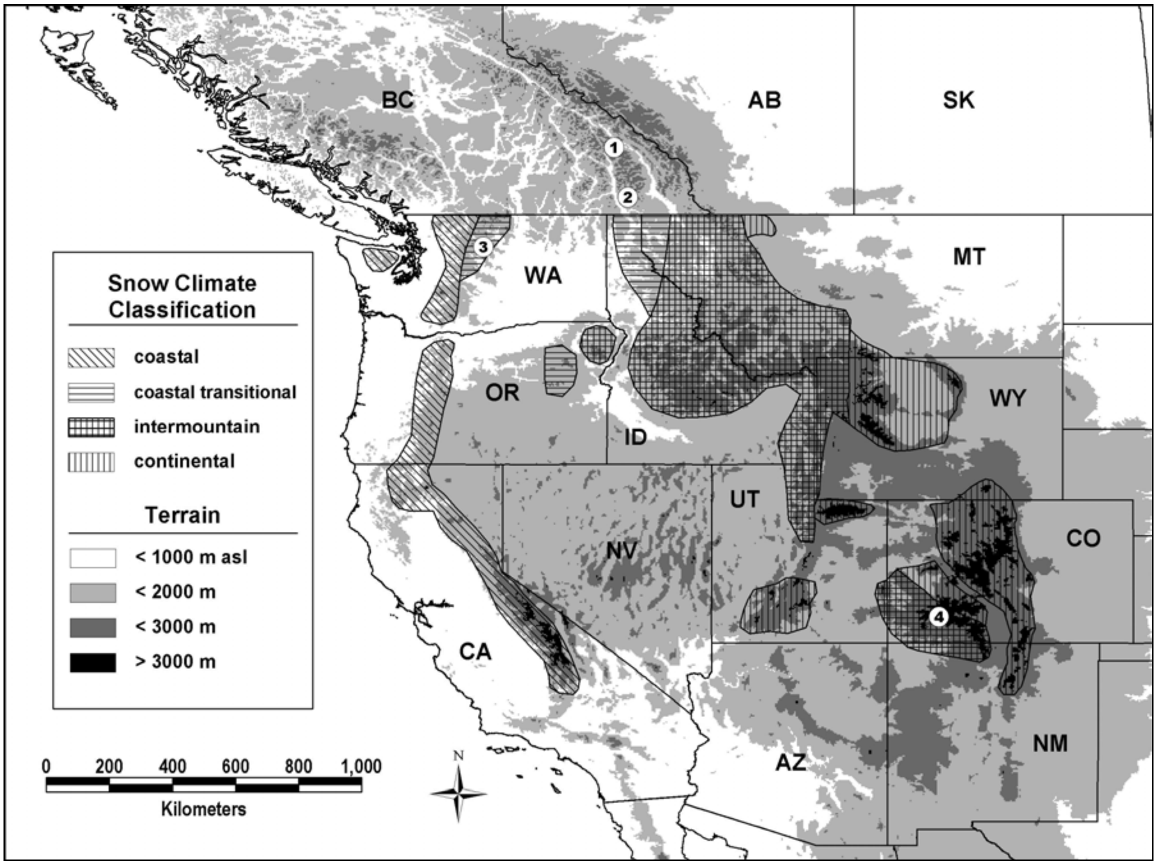


Figure 3.1:
Location of snow climate zones in western North America after LaChapelle (1966) in relation to Canadian mountain ranges. Numbers indicate location of local snow climate studies mentioned in this study: (1) Rogers Pass, British Columbia (Fitzharris, 1981 and 1987); (2) Kootenay Pass, British Columbia (McClung and Tweedy, 1993); (3) Mission Ridge (Mock and Birkeland, 2000) ; and (4) Red Mountain Pass, San Juan Mountains (LaChapelle and Armstrong, 1976).

The first quantitative analysis of 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 (Figure 3.1). Both studies show that the Columbia Mountains have a transitional snow climate, which is consistent with the classification of similar intermountain locations in the U.S. The term ‘transitional’ snow 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.

3.1.2 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 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 and others, 1995), where the main interest is 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 into 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 behaviour 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 considered 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?

3.2 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 from north to south: the Cariboo Mountains, the Monashee Mountains, the Selkirk Mountains, and the Purcell Mountains (Figure 3.2). The northern parts of these sub-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. 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 eleven 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 (Figure 3.2). Since the winter of 1996/97 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.

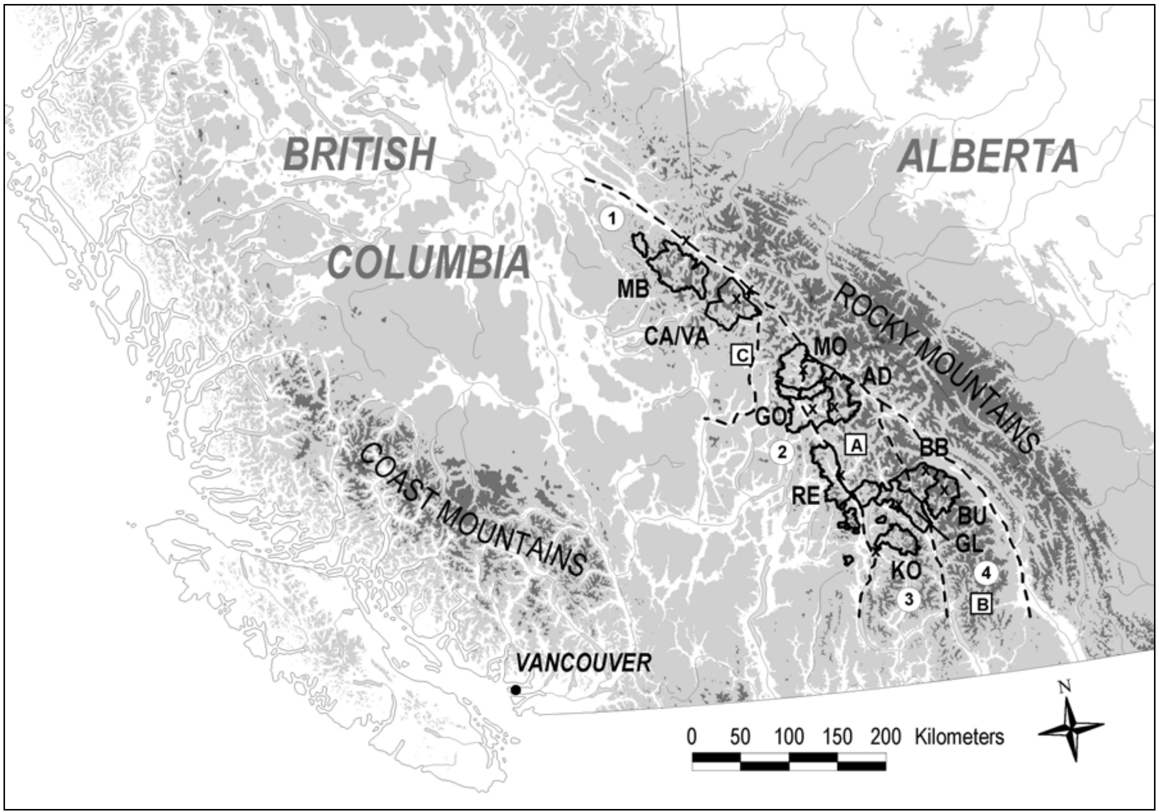


Figure 3.2:
Southern portion of British Columbia and Alberta showing the eleven operations of Canadian Mountain Holidays in the Columbia Mountains: McBride (MB), Cariboos and Valemount (CA/VA), Monashees (MO), Gothics (GO), Adamants (AD), Revelstoke (RE), Kootenay (KO), Galena (GL), Bobbie Burns (BB), and Bugaboos (BU). Each small x indicates the location of the lodge of an individual operation. Often this corresponds with the site of the main weather plot. Dashed lines show the four major subdivisions of the mountain range: (1) the Cariboos, (2) the Monashees, (3) the Selkirks, and (4) the Purcells. The squares show the location of high-elevation weather stations: (A) Mount Fidelity, (B) Kootenay Pass, and (C) Mount St. Anne.

3.2.1 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 Figure 3.2 for locations). The lodges are located either near valley bottoms or at tree line (580 – 1495 m asl). 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 asl), 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 (Figure 3.2). 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). Temperature and precipitation have been recorded 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 3.2). Numerous meteorological and nivological parameters have been monitored at this weather station since 1981.

3.2.2 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 5-step size classification (Table 3.1). 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.

Table 3.1:
Canadian avalanche size classification

Size	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	105	3000

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

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 to differences in familiarity with the database program and various people recording the data. 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 geo-statistical methods to the data. Thus, the analysis is fairly descriptive and the statistical estimates presented should be interpreted with caution.

3.3 Methods

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 of the activity on persistent weak layers. Meteorological measurements taken at Mount Fidelity were used to describe the general weather conditions during these winters.

3.3.1 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 (Figure 3.3). 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 snowpack 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 and weather records. An average density for new snow of 100 kg m^{-3} (Röger, 2001) was assumed for the calculation of the snow water equivalent from snowfall.

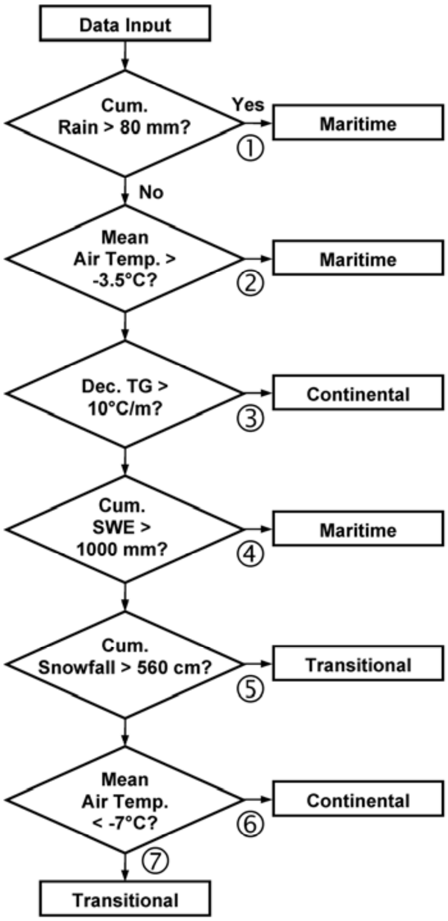


Figure 3.3:
Flowchart illustrating the classification procedure for the seasonal snow climate classification (after Mock and Birkeland, 2000). SWE: snow water equivalent; TG: temperature gradient.

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 (maritime: 2100 m; transitional: 2600 m; and continental: 3300 m above sea level). This elevation increase is caused by the natural geography of the Western United States (Figure 3.1). 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 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 in Figure 3.3) when applying the classification scheme.

3.3.2 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 (Figure 3.4). 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 icefalls were 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 3.2). 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 mass in tonnes involved in individual avalanches on the day in question.

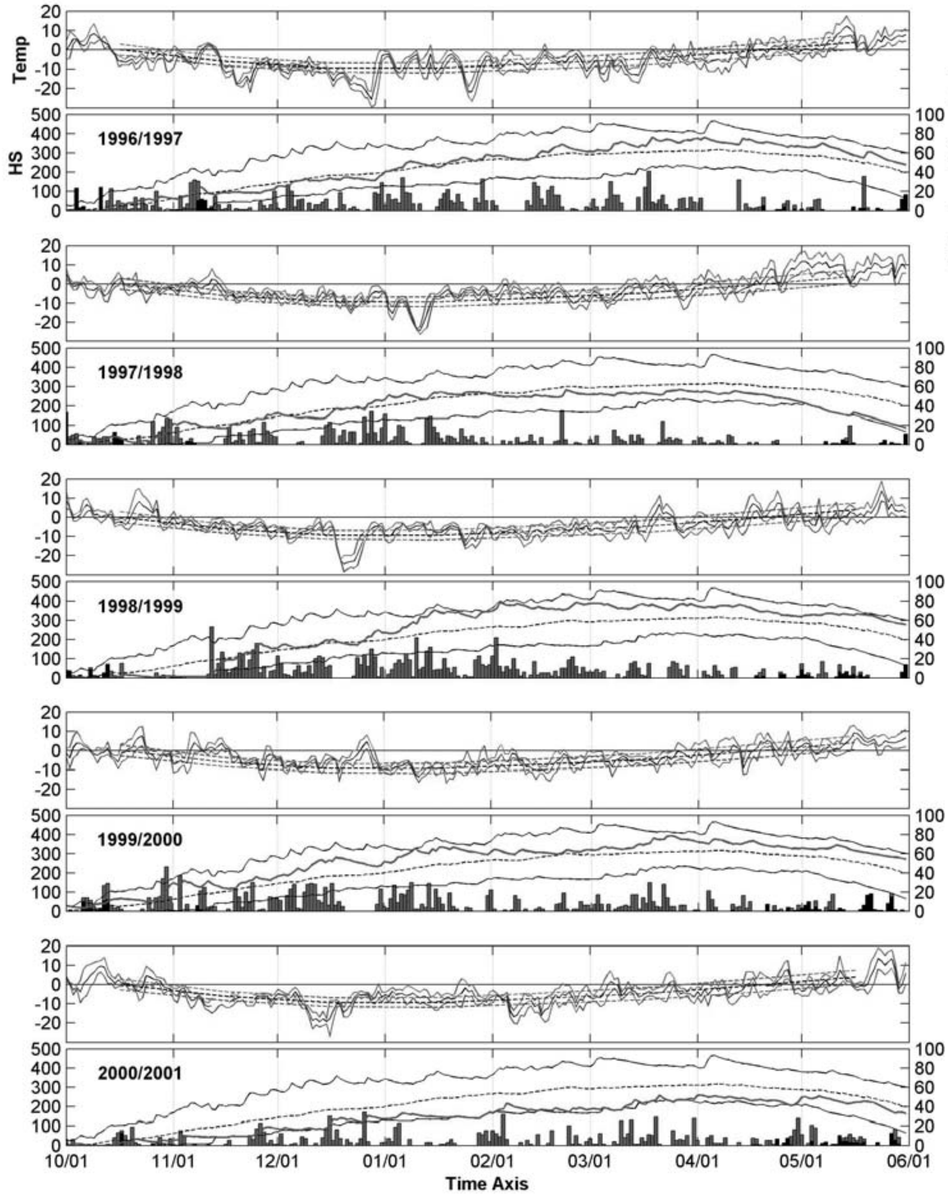


Figure 3.4:
Time series of weather parameters measured at Mount Fidelity for winters examined in this study. Top panel shows daily mean, maximum and minimum temperature (in °C) together with climate normals of individual months (dashed lines). Bottom panel shows measured snow depth together with maximum and minimum snow depth measured since 1980 (in cm). The panel also shows 1-day snowfall (in cm, light grey bars) and rainfall (in mm, dark grey bars).

Other climate studies in North America (e.g., Mock and Kay, 1992)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 values are used to plot time series of observed avalanche activity for individual operations.

Table 3.2:
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., Figure 3.8) 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 neighbouring 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.

3.4 Results and Discussion

3.4.1 Snow Climate Analysis

Out of the 21 winters analyzed at Mount Fidelity, ten were classified as maritime, ten as transitional, and one was considered to have continental character (Table 3.3). 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 3.3) 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 82 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 3.4). Out of twenty winters, nine were classified as maritime, seven as transitional and four 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

Table 3.3:
Analysis of snow climate of Mount Fidelity according to classification scheme by Mock and Birkeland (2000)

Season	Classification	Decision	Rain (mm)	Temp (°C)	Dec. TG (°C/m)	Snowfall (cm)	SWE (mm)
80/81	MARITIME	1	648	-5.0	3.3	707	707
81/82	MARITIME	4	0	-.9.3	6.1	1183	1183
82/83	TRANS.	5	40	-5.8	7.7	818	818
83/84	MARITIME	1	395	-7.9	12.0	793	793
84/85	TRANS.	5	0	-9.3	6.4	760	760
85/86	MARITIME	1	420	-6.2	4.2	722	722
86/87	MARITIME	1	182	-6.2	5.2	772	772
87/88	MARITIME	4	26	-7.6	6.7	1128	1128
88/89	TRANS.	5	0	-9.3	5.9	918	918
89/90	MARITIME	4	0	-7.1	3.2	1074	1074
90/91	TRANS.	5	35	-9.0	4.5	951	951
91/92	TRANS.	5	50	-4.0	3.2	807	807
92/93	CONT.	3	0	-8.6	10.1	548	548
93/94	TRANS.	5	0	-6.2	4.3	936	936
94/95	TRANS.	5	0	-6.2	4.6	675	675
95/96	MARITIME	1	173	-8.7	3.1	658	658
96/97*	MARITIME	4	0	-8.4	8.0	1000	1000
97/98*	TRANS.	5	0	-6.4	4.5	710	710
98/99*	MARITIME	4	0	-7.2	5.6	1167	1167
99/00*	TRANS.	5	0	-6.2	2.3	976	976
00/01*	TRANS.	5	0	-7.2	9.1	678	678
Climate normals	MARITIME	1	82	-7.6	3.8	914	914

The table shows classification together with classification decision according to numbering in Figure 3.3 and calculated variables (Temp.: temperature; TG: temperature gradient; SWE: snow water equivalent). Asterisks indicate winter seasons where avalanche observations are available.

Table 3.4:
Analysis of snow climate of Kootenay Pass according to classification scheme by Mock and Birkeland (2000)

Season	Classification	Decision	Rain (mm)	Temp (°C)	Dec. TG (°C/m)	Snowfall (cm)	SWE (mm)
81/82	MARITIME	1	108	-7.7	6.5	930	930
82/83	MARITIME	1	224	-4.7	6.0	746	746
83/84	CONT.	3	47	-7.0	11.1	597	597
84/85	CONT.	3	7	-11.5	11.2	585	585
85/86	TRANS.	7	68	-4.9	6.1	516	516
86/87	TRANS.	5	53	-5.8	7.7	882	882
87/88	TRANS.	5	70	-6.3	7.1	775	775
88/89	TRANS.	5	76	-8.0	6.6	698	698
89/90	TRANS.	5	38	-6.2	5.12	788	788
90/91	MARITIME	1	140	-7.4	6.7	1276	1276
91/92	CONT.	5	41	-6.4	4.5	698	698
92/93	TRANS.	3	51	-8.9	11.2	799	799
93/94	MARITIME	4	42	-5.3	5.9	1027	1027
94/95	MARITIME	1	135	-5.4	4.6	1237	1237
95/96	MARITIME	1	92	-7.3	5.6	1084	1084
96/97*	MARITIME	1	198	-6.8	4.7	1508	1508
97/98*	TRANS.	5	56	-5.6	7.3	833	833
98/99*	MARITIME	4	353	-6.0	4.7	1371	1371
99/00*	MARITIME	4	23	-5.7	4.2	1042	1042
00/01*	CONT.	3	38	-6.7	11.8	405	405

The table shows classification together with classification decision according to numbering in Figure 3.3 and calculated variables (Temp.: temperature; TG: temperature gradient; SWE: snow water equivalent). Asterisks indicate winter seasons where avalanche observations are available.

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 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.

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 (Figure 3.2), 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 (Figure 3.1). 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.

3.4.2 Weather History of Winters 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 (Figure 3.4) 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.

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.

1997-1998:

Very mild temperatures throughout the entire season characterized the winter of 1997/1998. After a major snowfall event at the 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.

1998-1999:

This winter was dominated by large amounts of precipitation. After a slow start, high snowfalls resulted in a snowpack depth of 10 to 25% above 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.

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.

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 autumn, 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.

3.4.3 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 (Figure 3.5). 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 Figure 3.6 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 roughly twice as much avalanche activity related to persistent weak layers as average, 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 characterization 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.

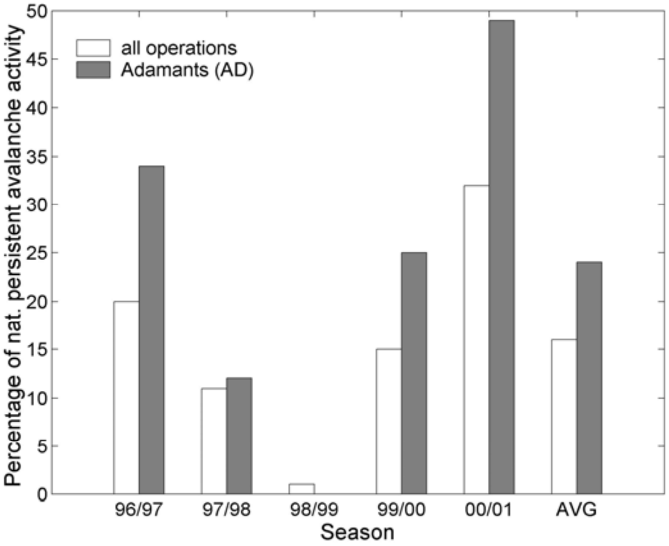
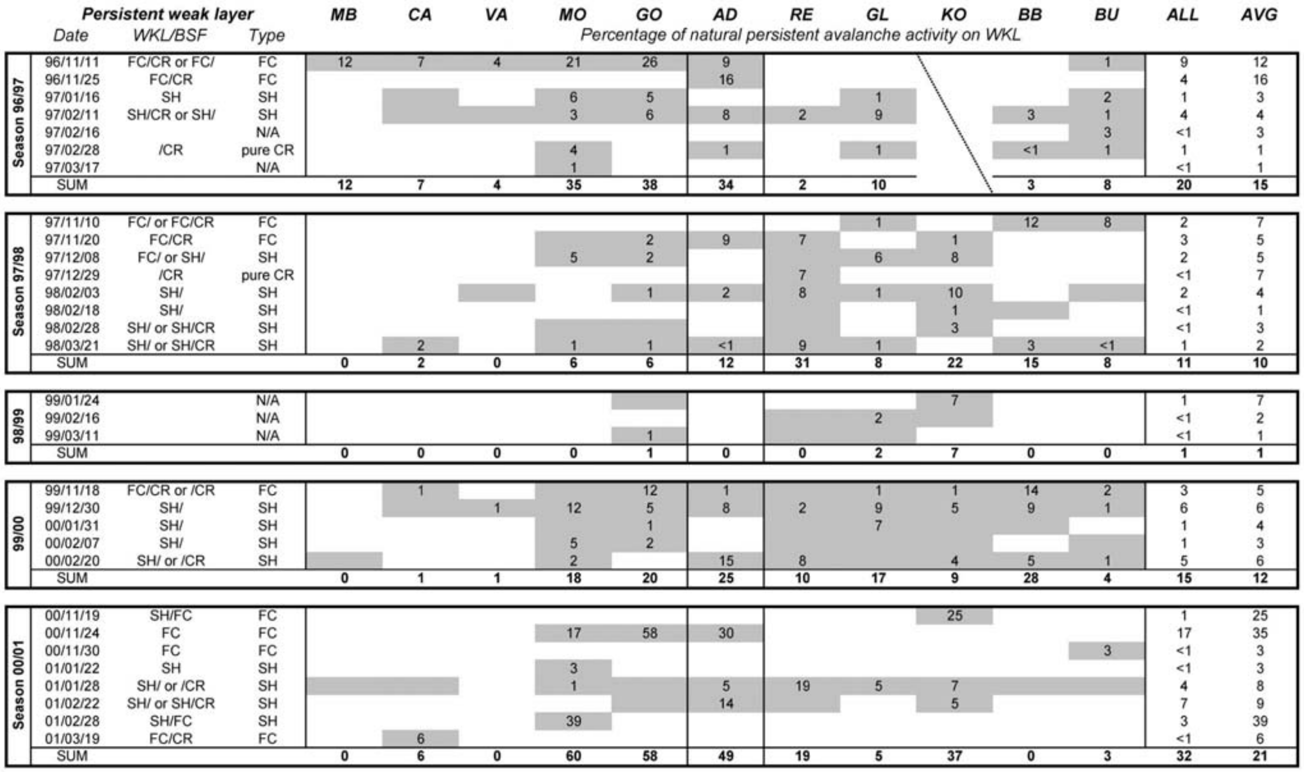


Figure 3.5:
Percentages of natural avalanche activity related to persistent weak layers for all of CMH and separately for Adamants operation.

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 a more diligent recording practice. We therefore believe that the true average fraction of activity on persistent weak layers 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.



	Persistent weak layer			MB	CA	VA	MO	GO	AD	RE	GL	KO	BB	BU	ALL	AVG
	Date	WKL/BSF	Type	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**

Figure 3.6:
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 Figure 3.2. 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.

3.4.4 Large-scale Spatial Variability of Activity on Persistent Weak Layers

Avalanche activity on persistent weak layers exhibits 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 (see Hägeli and McClung, in press [Chapter 2]). 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 Figure 3.6). 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.

3.4.5 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 (Figure 3.7). 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.

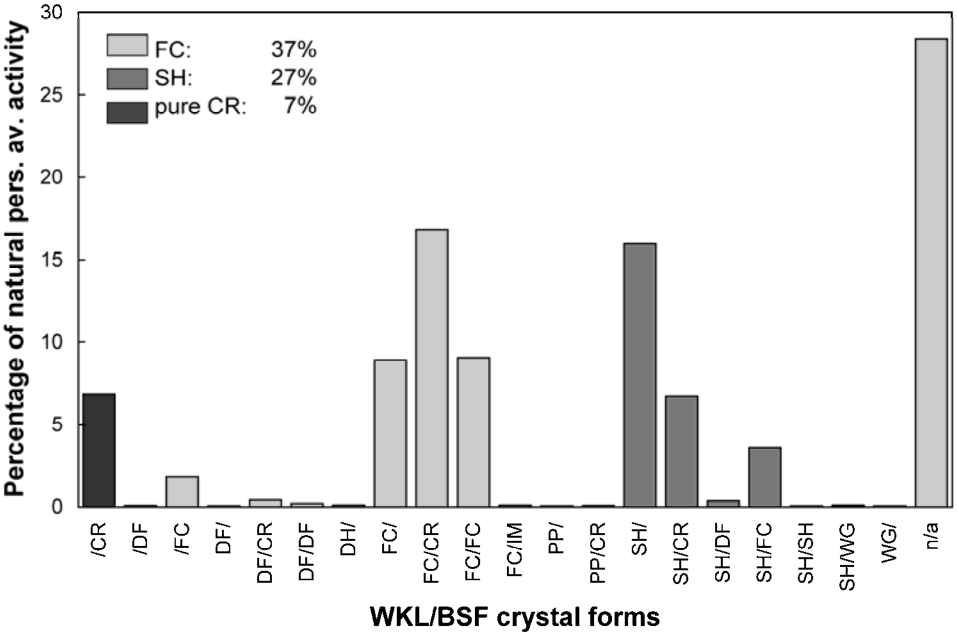


Figure 3.7:
Distribution of natural climax activity on different weak layer and bed surface combinations (CR: crust, DF: decomposing fragments, DH: depth hoar, FC: faceted grains, IM: ice mass, PP: precipitation particles, SH: surface hoar, WG: wet grains, n/a: not available)

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 Figure 3.6), 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 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 (Figure 3.6). 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.

a) 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 (Figure 3.6). 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 3.6) 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 (Figure 3.4). 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 (Figure 3.6) and produced intermittent dry slab avalanches throughout the entire season (Figure 3.8a). In the following spring, many wet slab avalanches released on this persistent weakness

(Figure 3.8a Monashees; also reported in Jamieson and others, 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 (Figure 3.4). 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 3.6a). 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 3.5). 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 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

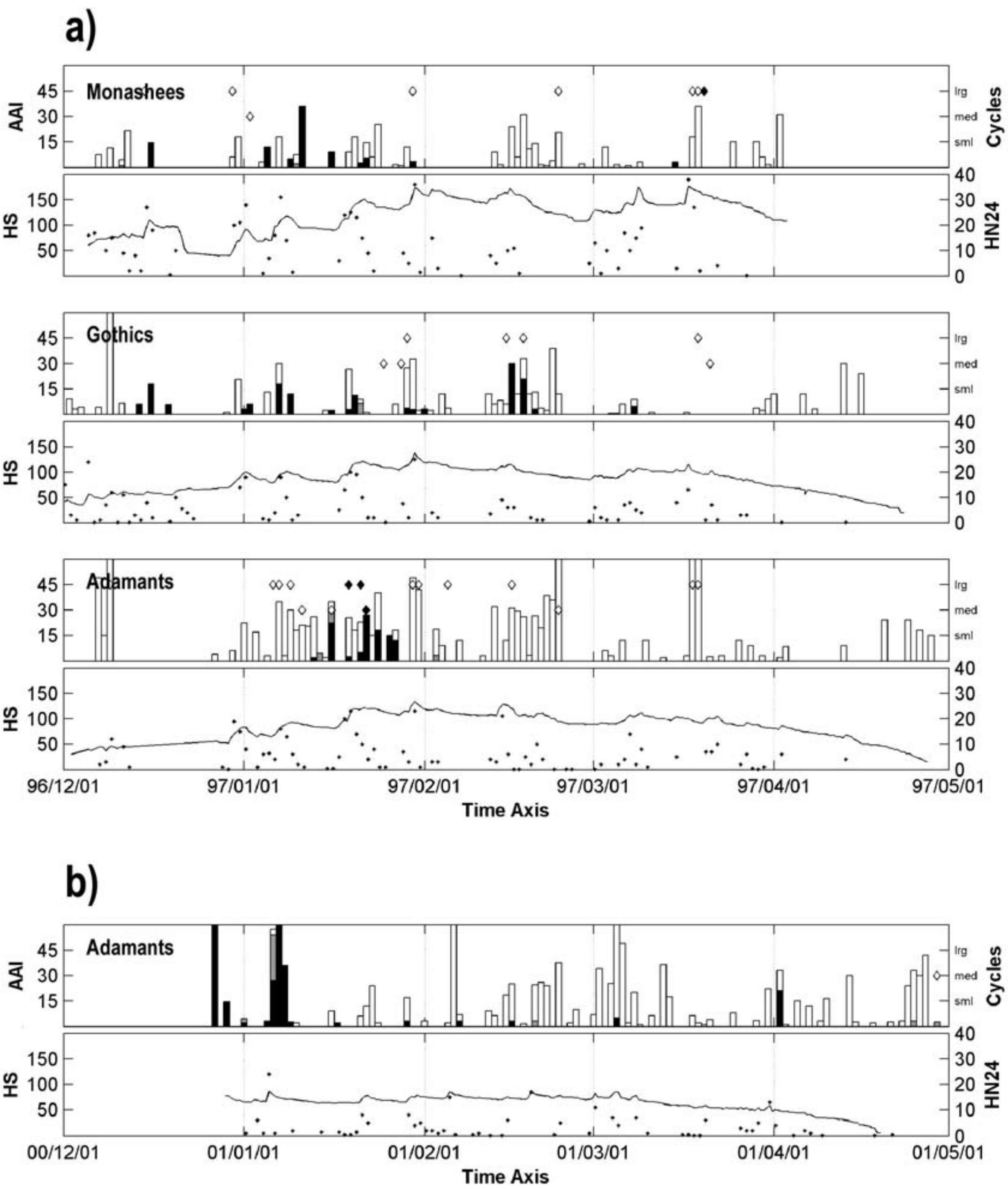


Figure 3.8:
Temporal activity patterns of persistent weak layers with faceted crystal. Top panel a) shows the activity pattern of the Nov. 11th 1996 facet-crust combination in three neighbouring operations. Lower panel b) shows recorded activity of Nov. 24th 2000 faceted layer in the Adamants operation. 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 grey bars indicate activity on the weak layer due to an additional trigger, such as skiers, helicopters, or falling cornices or ice. Recorded avalanche cycles are indicated with diamonds. Dark diamonds represent cycles on the specific weak layer. The lower part of the individual graphs shows the height of the snowpack (HS) and the new snow over a 24-hour period (HN24) in cm at the respective lodges.

Table 3.5:
Analysis of rain-on-snow events 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)

Numbering indicates monthly sum or 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 months with the potential for melt-layer recrystallization. Diamonds indicate months with considerable temperature drops after/during burial of the wet snow layer. Asterisks indicate winters where avalanche observations are available.

burial (bold numbers in Table 3.5). 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 3.5). 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 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 (Figure 3.4) 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 24th layer’, was responsible for significant avalanche activity, particularly in the central part of the Columbia Mountains (Figure 3.6). 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 (Figure 3.8b). 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 similar activity pattern and avalanche characteristics (Table 3.6a). 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

Table 3.6a:
Summary table of characteristics for early season weak layers with faceted crystals

Persistent weak layer		Activity period				Character of natural persistent activity
Date	WKL/BSF	Last day	Days	AV days	Ratio	
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

Activity period is equivalent to time period between first and last avalanche of weak layer WKL/BSF stand 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.

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 (Figure 3.10).

b) 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 Figure 3.6). 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 layer consists of one to three activity cycles. The activity pattern of the Jan. 28th 2001 layer (Fig 3.9), 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 3.6a and b). As a consequence, the avalanche sizes are generally smaller (Figure 3.10).

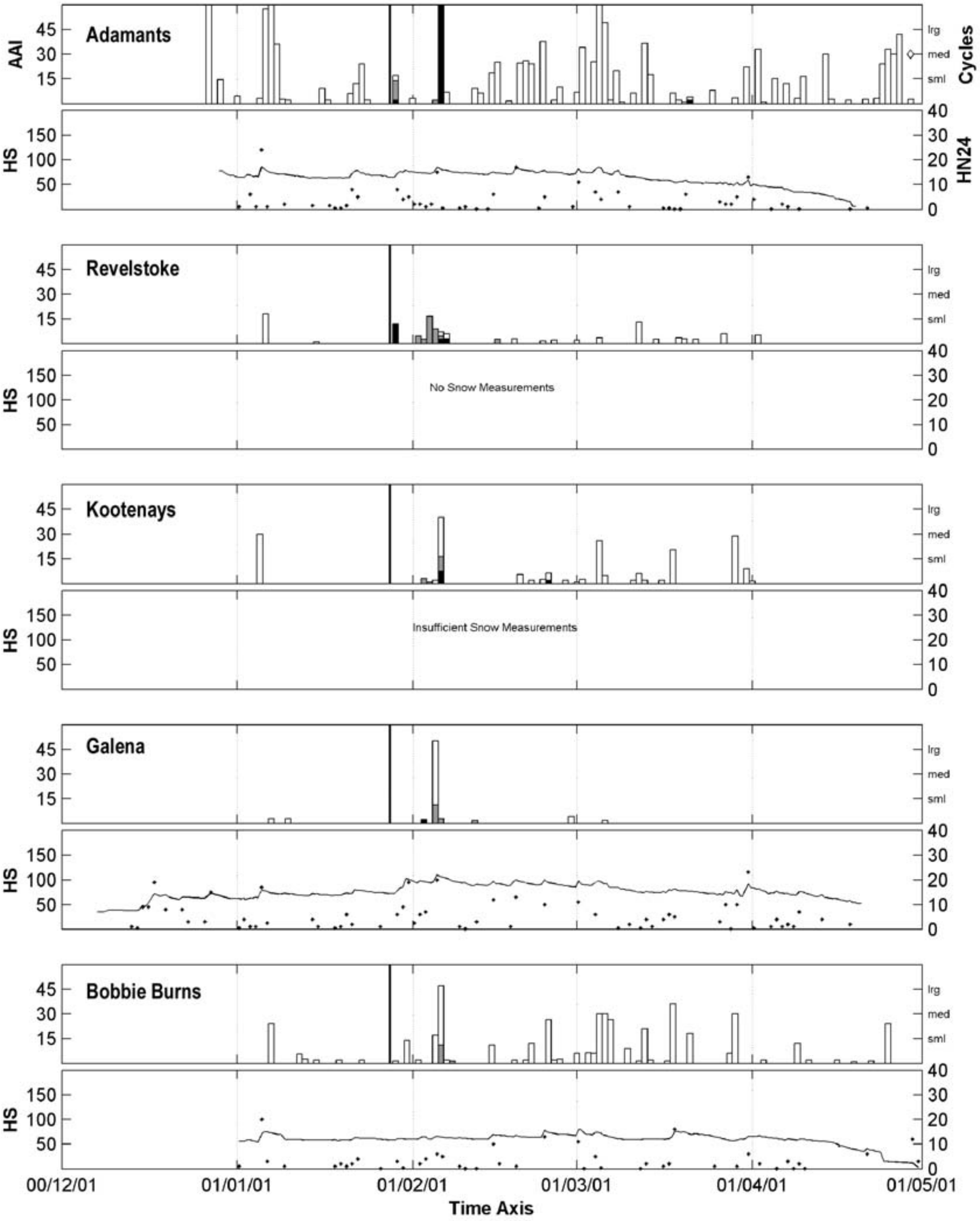


Figure 3.9:
Temporal activity pattern of Jan. 28th 2001 surface hoar layer in five adjacent operations. Same type of graph as shown in Figure 3.8. The vertical black line represents the last deposition day of the weak layer.

Table 3.6b:
Summary table of characteristics for weak layers with surface hoar crystals

Persistent weak layer		Activity period				Character of natural persistent activity
Date	WKL/BSF	Last day	Days	AV days	Ratio	
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 stand 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.

Some surface hoar layers are associated with a crust bed surface (Figure 3.6). 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 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.

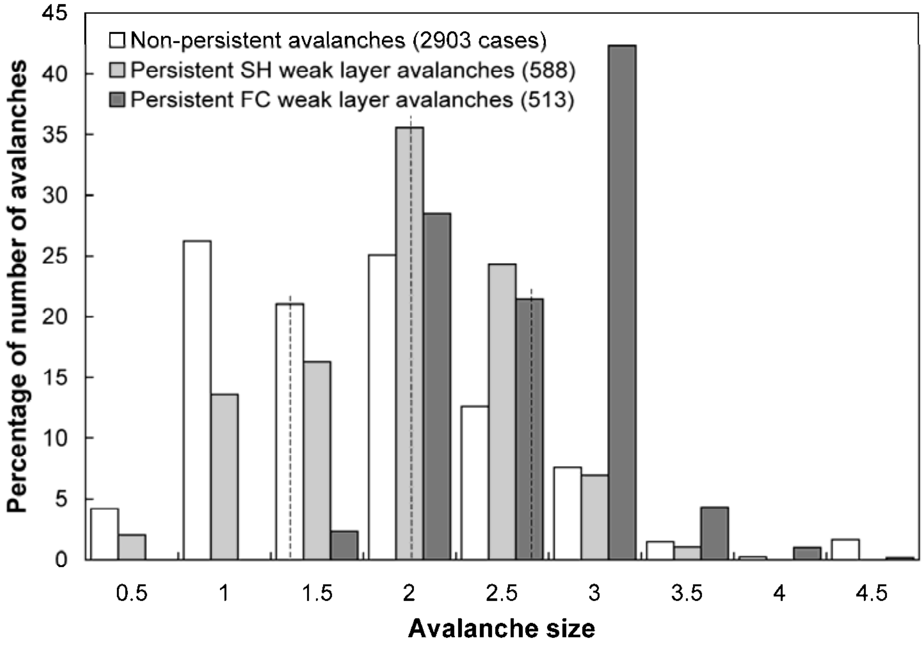


Figure 3.10:
Distribution of avalanche sizes for persistent natural avalanches of the two main weak layer types and non-persistent natural avalanche for reference. Dashed lines represent the median value for respective avalanche groups.

[The activity patterns of all persistent weak layers examined in this study are presented in Appendix B.]

3.5 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 studies included some avalanche variables in their analysis, but the avalanche descriptors were of minor importance for the classification. In this paper, we suggest the use of 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 (Figure 3.1). 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 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 three to four 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 (Figure 3.1) 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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CHAPTER 4

LARGE-SCALE SNOW INSTABILITY PATTERNS IN WESTERN CANADA: FIRST ANALYSIS OF THE CAA-INFOEX DATABASE 1991-2002

Based on:
Gruber, U., Hägeli, P., McClung, D.M. and Manner, E., in press. Large-scale snow instability patterns in Western Canada: First analysis of the CAA-InfoEx database 1991-2002. Annals of Glaciology, 38.[1]

4.1 Introduction

The different mountain ranges of British Columbia and Western Alberta experience a wide variety of snow and avalanche conditions. The Coast Mountains have a maritime snow climate, while the snowpack in the Rocky Mountains exhibits a continental character. The transitional Columbia Mountains display intermediate snowpack characteristics (McClung and Schaerer, 1993). The data used in this study is based on the Information Exchange (InfoEx) service of the Canadian Avalanche Association (CAA). To facilitate data exchange among avalanche safety programs, the CAA has managed the InfoEx since the winter of 1991/1992. During the winter season, safety programs contributing to the InfoEx send their observations to the CAA every evening. Their submissions contain weather data from study plots and/or field observations, general comments about observed snowpack characteristics, detailed avalanche observations including comments about weak layers, and stability ratings. The data are compiled by the CAA and redistributed as a comprehensive bulletin to all subscribers by ftp,

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email, or fax before the next morning. To receive the confidential information, individual safety programs pay an annual fee and are required to regularly contribute their data to the exchange. InfoEx subscribers are backcountry ski operations, highway and rail safety programs, ski resorts, parks, and a few mine and logging operations.

In this paper, we present a preliminary analysis of this dataset. The focus is on differences in snow instability patterns among different InfoEx regions in relation to observed weather characteristics and number of persistent snowpack weaknesses (Jamieson, 1995). The goal of this study is to gain insights into the link between snow climate and the resulting avalanche hazard characteristics.

4.2 Data Description

In this section we provide details about the InfoEx dataset and the study area including more detailed information about the snow climate characteristics of the three main mountain ranges.

4.2.1 InfoEx Dataset

Since the beginning of the information exchange in 1991/1992, InfoEx bulletins have been archived by the CAA as text files. While weather observations are presented in a table structure, the majority of snow and avalanche observations are reported in semi-structured comments. In order to use these data for scientific purposes, the information had to be transferred into a relational database. A parsing code was developed based on flex/bison technology (Levine and others, 1992). This code is able to recognize predefined text structures in the InfoEx files, extract the related information and store it into database tables. The historic InfoEx information was transferred into the following tables: (a) weather observations at study plots, (b) field weather observations, (c) stability ratings, (d) avalanche observations, (e) skied or visited drainages, (f) general description of the snowpack characteristics, (g) weak layer observations, and (h) avalanche involvements. We believe that the resulting database is one of the richest and most comprehensive backcountry avalanche datasets currently available. In particular, the vast observational area and the detail of avalanche observations make it distinctly superior to other existing avalanche datasets. Individual avalanche records generally include number, size, and trigger and are often complemented by detailed information about location, avalanche dimensions, fracture depth and characteristics of weak layer and bed surface. On a daily basis, the database covers an observation area of approximately 40,000 km^2 across the three major mountain ranges of Western Canada. Overall, the database consists of more than 50,000 daily submissions from individual safety programs.

To ensure the data used in the analysis are sufficiently homogenous, we are using only data of operations that fulfil the following three criteria: (a) a minimum of 50 observation days per winter season (i.e., on average at least one observation every 3 days), (b) observations for at least three winter seasons and (c) a focus on skiing (i.e., ski resorts, helicopter or snowcat ski operations and parks). The resulting study dataset consists of more than 17,000 daily submissions of stability and weather data from 23 different operations (Figure 4.1). Despite these efforts, the data set is still too heterogeneous to apply vigorous statistical methods. Average values will be used to examine general patterns, but measures of statistical spread are omitted to avoid an implication of statistical robustness.

For this study, we assume that the snow stability ratings are correct. It is planned to test this assumption in a follow-up paper by comparing the stability ratings to the natural avalanche events occurring at the same time. The main reason preventing us from integrating avalanche observations in the present analysis is that operational avalanche datasets are inherently incomplete (see Laternser and Schneebeli, 2002; Hägeli and McClung, 2003 [Chapter 3]). In addition, sizes of operations differ considerably between ski resorts, parks and snowcat/helicopter skiing operations. The observed avalanche activity in the different operations might therefore be dominated by operation size and not necessarily represent the local instability conditions adequately. Since spatial scaling of the avalanche activity observations is non-trivial, avalanche observations were not included in this study.

4.2.2 Study Area

LaChapelle (1966) was the first to describe the weather and avalanche characteristics for the different snow climates in North America.. The maritime climate is characterized by frequent new snow instabilities, which stabilize rapidly due to generally warm temperatures. Rain is possible anytime during the winter, often leading to widespread avalanche cycles. The continental snow climate is characterized by relatively low snowfall and cold temperatures, which leads to a generally shallow snowpack that is often unstable due to structural weaknesses. The transitional zone lies between these extremes and is characterized by a mix of maritime and continental influences. A more detailed discussion of snow climates and a review of the different classification terms is discussed in Hägeli and McClung (2003 [Chapter 3]).

McClung and Schaerer (1993) classify the snow climate of the different Canadian Mountain ranges. Coast Mountains have a maritime snow climate, the Rocky Mountains exhibit a continental snow climate, and the snowpack of the Columbia Mountains has transitional characteristics. In the InfoEx, the transitional Columbia Mountains have traditionally been divided further into the North and South Columbia Mountains along the Rogers Pass highway corridor (Figure 4.1). On first sight, this separation, which splits the Selkirk and Monashee Mountain ranges, seems to be mainly administrative.

Even though the snow climate classification of the Canadian mountain ranges is well-established, it was not based on extensive data analyses. One aspect of this study is to examine whether the analysis of the InfoEx data confirms the existing snow climate classification. Secondly, the analysis will also look at whether the separation of the Columbia Mountains for the InfoEx has a climatological justification or is purely administrative.

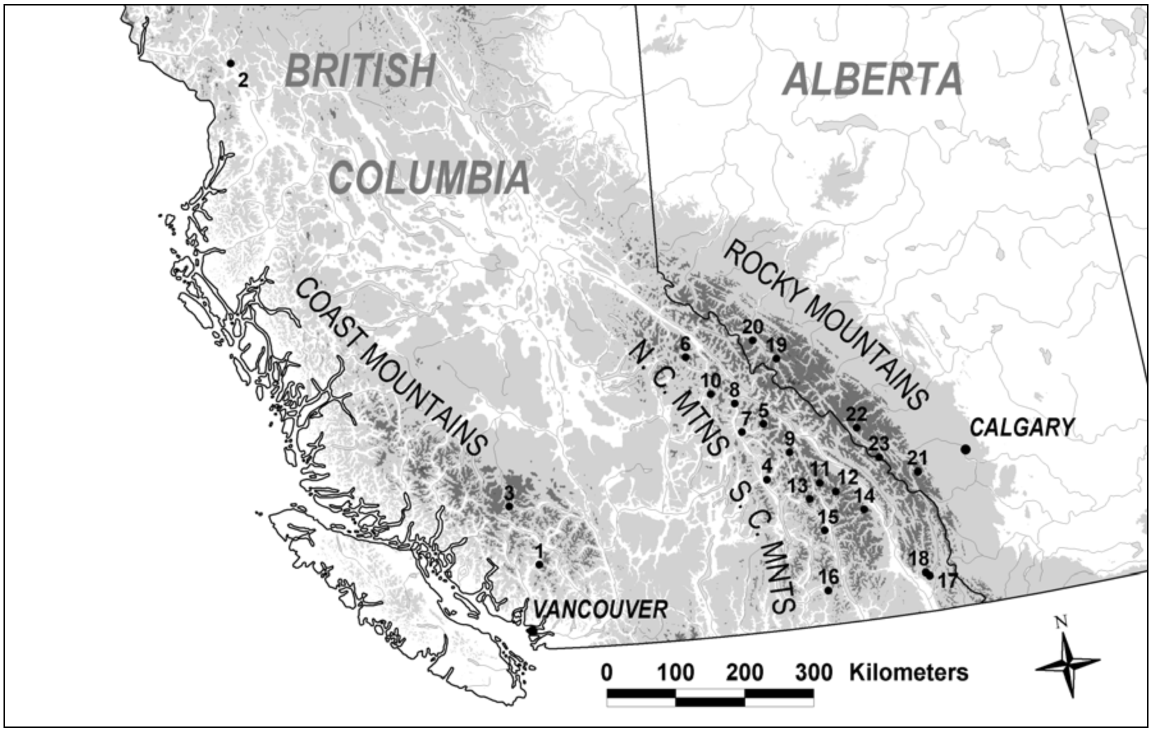

Figure 4.1:
Map of the study area with locations of the observation stations and mountain ranges. (Legend: Coast Mountains: 1. Whistler Mountain; 2. Last Frontier Heliskiing 3. TLH Heliskiing; North Columbia Mountains: 4. Cat Powder Skiing Resort; 5. CMH Adamants; 6. CMH Cariboos; 7. CMH Gothics; 8. CMH Monashees; 9. Glacier National Park; 10. Mike Wiegle Helicopter Skiing; South Columbia Mountains: 11. CMH Bobby Burns; 12. CMH Bugaboos Park; 13. CMH Galena; 14. Panorama Mountain Village; 15. Selkirk Wilderness Skiing; 16. Whitewater Ski Resort; Rocky Mountains: 17. Fernie Alpine Resort; 18. Island Lake Lodge; 19. Jasper National Park; 20. Marmot Basin Ski Lifts; 21. Peter Lougheed Prov. Park/Kananaskis Country; 22. Skiing Louise; 23. Sunshine Village)

The data density and coverage of the operations used in this study is best in the Columbia Mountains followed by the Rocky Mountains (Figure 4.1). The operations in the Rocky Mountains are mainly local ski resorts, with relatively small observation areas, and National Park avalanche safety programs, where forecasting is mainly done for a few high usage areas (Table 4.1). In the Columbia Mountains, helicopter and snowcat ski operations with large observation areas dominate the InfoEx dataset. These differences introduce an observational bias to the dataset that has to be kept in mind when interpreting the results presented in this study. There are only three stations in the Coast Mountains that fulfil the requirements for the analysis (Figure 4.1). The observations from these operations can clearly not be considered to be representative for the whole mountain range. Among the three stations, Whistler Mountain dominates the dataset with the longest records of eleven seasons while the other two helicopter skiing operations measured only during three seasons. In addition, Last Frontier Heliskiing is located much further north than the other two stations (Figure 4.1). In order to reflect the sparse information from the Coast Mountains we will use the term ‘three stations in the Coast Mountains’ instead of ‘Coast Mountains’.

Table 4.1:
Observation days and station types in the four main regions

Description	Coast Mtn	Columbia Mountains South	North	Rocky Mtn
Number of observation days	1889	3176	6316	6054
Number of helicopter ski operations	2	5	5	1
Number of ski resorts	1	1	2	2
Number of parks	0	0	0	4
Total number of stations	3	6	7	7

4.3 Analysis

The analysis of large-scale instability patterns is presented in the following section. It is followed by an analysis of weather patterns and a study of persistent snowpack weaknesses in order to explain some of the observed instability patterns.

4.3.1 Stability Ratings

Snow stability ratings submitted to the InfoEx represent the forecasting team’s perception of the average snow stability of the undisturbed snowpack within a given operation. Separate ratings are given for the three elevation bands ‘alpine’ (ALP), ‘tree line’ (TL) and ‘below tree line’ (BTL). Ratings go from ‘very poor’ (numerical code 1), ‘poor’ (3), ‘fair’ (5), ‘good’ (7) to ‘very good’ (9). Definitions of the different stability ratings (CAA, 2002) include characteristics of observed or expected avalanche activity with respect the different triggers. Although not officially sanctioned by the guidelines, InfoEx contributors often use intermediate steps between official ratings to express the observed conditions ('poor to very poor' (2), 'poor to fair' (4), 'fair to good' (6) and 'good to very good' (8)). This stability classification scheme has been in use since 1995. Previous to 1995, the Canadian hazard rating system with the steps 'low', 'moderate', 'considerable', 'high' and 'very high' was in use (McClung and Schaerer, p.257, 1993).

An analysis of average stability ratings shows that the three stations of the Coast Mountains show the highest stability rating in all elevation classes. They are followed by the South Columbia Mountains and – with almost the same ratings – the North Columbia Mountains and Rocky Mountains (Table 4.2). The difference between the ALP and BTL stability rating becomes greater the more continental the local snow climate.

Table 4.2:
Stability values for the four main regions (1991 to 2002)

Description	Coast	Columbia Mountains		Rocky
	Mtn	South	North	Mtn
Average stability ALP	5.6	5.4	5.0	5.0
Average stability TLN	6.0	6.0	5.4	5.5
Average stability BTL	6.5	6.3	6.0	6.2
Ratings of poor or lower ALP (%)	12.0	14.7	18.8	15.9
Ratings of poor or lower TLN (%)	7.1	8.4	11.0	9.5
Ratings of poor or lower BTL (%)	4.2	5.6	7.6	5.3
Average recovery period ALP (days)	2.3	2.6	3.2	2.9
Average recovery period TLN (days)	2.0	2.5	3.0	3.0
Average recovery period BTL (days)	2.0	2.4	2.9	2.1

Values are for period from December to April. Values for Coast Mountain region are only based on three stations. ALP: alpine; TLN: at tree line; BTL: below tree line. Recovery period is number of days it takes to recover from poor to fair.

We also examined the percentages of stability ratings equal to or less than 'poor' and the average recovery time for the stability rating from 'poor' to 'fair' for the different InfoEx regions (Table 4.2). The recovery time represents the number of days needed to regain a 'fair' stability rating after dropping to 'poor'. The recovery time was calculated using the stability ratings of consecutive observation days. While observational gaps of one day were tolerated, the recovery time was assumed to be the shortest possible time period in case of observation gaps longer than one day (e.g., 02/02/99: ‘poor’; 02/04/99: ‘poor’; 02/05/99: ‘fair’ equals to three days of recovery, whereas 02/02/99: ‘poor’; 02/04/99: ‘poor’; 02/08/99: ‘fair’ equals to three days of recovery, assuming that the stability rating could have improved to “fair” on 02/05/99). Recovery times are likely to be underestimated with this definition.

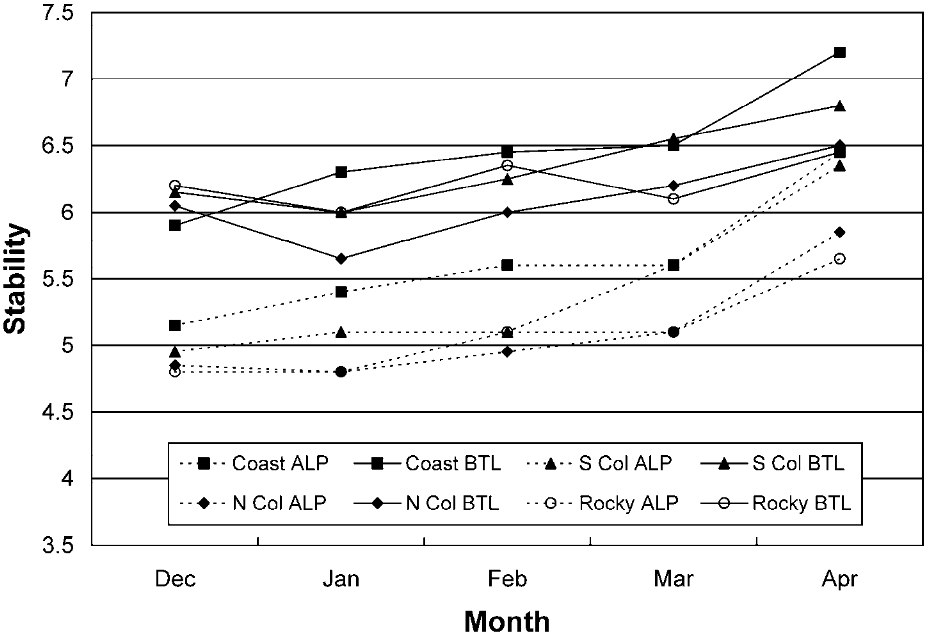

Figure 4.2:
Average seasonal stability development in the four main InfoEx regions for the different elevation bands (ALP: alpine; BTL: below tree line). The numerical values on the *y*-axis translate as following: 4: ‘poor to fair’; 5: ‘fair’; 6: ‘fair to good’; 7: ‘good’.

The analysis shows that the rating ‘poor’ occurs less often in the three stations of the Coast Mountains than in the other InfoEx regions. It also shows that the time to recover from a ‘poor’ situation in the three stations of the Coast Mountains is faster than in the other regions, which is in agreement with the characterization of the maritime snow climate by LaChapelle (1966). The North Columbia Mountains exhibit the highest number of ‘poor’ days and also experience the longest recovery times.

The development of stability ratings over a season was examined by calculating monthly averages from InfoEx stability ratings of all winters (Figure 4.2). For the three stations of the Coast Mountains, December is the month with the lowest stability rating. It is followed by a steady improvement of the stability throughout the season. In all other regions, the stability conditions generally deteriorate in January. While the stability rating in the Rocky Mountains does not substantially change throughout a season, the North and South Columbia Mountains experience apparent improvements in snow stability starting in February.

4.3.2 Weather Observations

In this section, we examine the weather data in order to explain some of the regional stability rating differences presented in the previous section. Average values of some of the most relevant parameters that influence the avalanche activity and instability (McClung and Tweedy, 1993; 1994) are presented in Table 4.3. The overall temperatures as well as the temperatures during precipitation events in the Rocky Mountains are considerably lower than in the other InfoEx regions. The lower temperature values can mainly be attributed to the more continental climate. The higher average elevation of the Rocky Mountain weather stations, however, introduces an observational bias which causes a temperature deviation in the same direction.

An analysis of wind observations shows that the observed average wind speed is considerably higher in the North Columbia Mountains than in the South Columbia Mountains, even though the average station elevation in the North Columbias is approximately 100 m lower than in the South Columbias. Average observed wind speed might therefore be one of the main distinguishing factors between the two regions.

LaChapelle (1966) states that the precipitation in the maritime snow climate is considerably higher than in the continental or transitional snow climates. The snow depth data of the InfoEx examined in this study do not confirm this statement. Within the Coast Mountains, however, snow depth strongly depends on elevation. The average snow depth of Whistler Mountain is 212 cm at an altitude of 1890 m asl, whereas the base stations of the two other helicopter operations are at lower elevations and have notably lower snow depth values. Extended periods with temperatures above the melting point and frequent rain events in the Coast Mountains considerably reduce snow depth values at lower elevations.

Table 4.3:
Average station characteristics and average weather values for the four main regions in Western Canada

Description	Coast	Columbia Mountains		Rocky
	Mtn	South	North	Mtn
Station elevation (m asl)	1484	1458	1344	1923
Maximum temperature (°C)	-1.2	-1.8	-2.4	-3.9
Minimum temperature (°C)	-7.4	-9.9	-10.8	-12.4
Wind speed (km/h)	15.6	5.2	11.5	14.6
Max. temperature during precip. events (°C)	-2.1	-2.4	-3.0	-4.2
Min. temperature during precip. events (°C)	-4.3	-5.2	-5.7	-7.9
Wind speed during precip. events (km/h)	19.9	5.7	12.6	15.5
Snow depth (cm)	147	114	165	144
Num. precip. cycles per season	19.2	19.3	19.2	23.0
Num. precip. cycles > 10 cm per season	4.4	4.1	4.3	5.1
Num. precip. cycles > 30 cm per season	1.0	0.5	0.9	0.7
Storm snow depth for precip. Cycles > 30 cm	91	51	58	56
Duration of precip. cycles > 10 cm (days)	3.3	3.3	4.9	4.0
Duration of precip. cycles > 30 cm (days)	3.1	3.2	6.4	4.8

Values are average values for period from December to April from 1991 to 2002. Values for Coast Mountain region are only based on three stations.

Since avalanches are the result of specific sequences of weather events, an analysis of average winter weather conditions can provide only limited insights into snow stability development. The following analysis of precipitation cycles is a first attempt to relate sequences of weather events to snowpack stability. Precipitation cycles are examined to study the characteristics of considerable snowfall events and their effect on snow stability in the different InfoEx regions.

InfoEx weather records store precipitation type (Rain/Snow) and intensity (mm/hour or cm/hour) in the combined variable ‘Precipitation Type and Intensity’

(PrTI). A day was identified as a precipitation day if either PrTI indicated precipitation, or in case of a missing value, if the snow depth increased from this day to the next. A precipitation cycle consists of consecutive precipitation days. For the three stations of the Coast Mountains the average duration of precipitation cycles of more than 30 cm accumulation is notably lower than in the more continental regions (Table 4.3). This can be interpreted as an indication for generally higher snowfall intensities in the maritime snow climate. Despite these intense snowfall periods, the recovery time from 'poor' to 'fair' is considerably lower in the Coast Mountains than in the other regions (Table 4.2). While these intense snowfall periods create high instability during storms, generally warmer temperatures and homogenous and thick snow layers result in a faster recovery and contribute to the overall higher snow stability in the maritime Coast Mountains. The snowfall intensity might also be another factor that differentiates the North Columbia Mountains from the South Columbia Mountains, where the average duration of considerable precipitation cycles is considerably shorter (Table 4.3).

4.3.3 Persistent Weak Layer Analysis

Hägeli and McClung (2003 [Chapter 3]) extensively analyzed persistent weak layer patterns in the Columbia Mountains, using data from Canadian Mountain Holidays. They found that in an average winter, the transitional Columbia Mountains exhibit usually one persistent weak layer of faceted grains that forms in the early winter and one to three persistent surface hoar weak layers that develop during the main winter months.

The avalanche and snowpack records in the InfoEx database provide information about weak layers, which allows a comparison of weak layer patterns among the different InfoEx regions. It is industry practice to label weak layers with their burial date. In this study, we simply compare the average number of persistent weak layers observed by operations in the different InfoEx regions. A future study will examine the weak layer information of the InfoEx dataset in more detail [Chapter 5]. We define weak layers to be persistent if they are referred to more than ten days after burial. Non-persistent weak layers were not included in the analysis. To ensure that only significant persistent weak layers were included in the analysis, weak layers had to be mentioned at least three times in the data-set. The number of the weak layers observed in the different regions throughout the entire study period (1991/1992 – 2001/2002) is much higher than expected (Table 4.4). This can partially be explained by inconsistencies in weak layer labelling among operations, which often differ by one or two days. A weak layer that is labelled as 11/11/99, 11/12/99 and 11/13/99 is wrongfully counted as three individual layers in our analysis. While it is not the aim of this study to establish a precise count of how many weak layers exist on average per year, this limited analysis is still able to show trends between the different regions. In a more detailed weak layer study, however, these inconsistencies have to be resolved.

The most important result of the present weak layer analysis is that the Rocky Mountains experience considerably fewer persistent weak layers than the other InfoEx regions. This result is somewhat counterintuitive since the Rocky Mountains generally show the lowest snow stability values. The obvious questions that follow are 'What causes this lack of persistent weak layers?' and 'What is responsible for the generally more unstable conditions in Rocky Mountains?'.

Hägeli and McClung (2003 [Chapter 3]) stated that the most important types of persistent weak layers in the Columbia Mountains are surface hoar and layers of faceted grains. To examine the weak layer differences among the different InfoEx regions we define indicators for the formation of these two types of snowpack weaknesses based on weather parameters.

a) Surface hoar weaknesses

A necessary condition for the creation of surface hoar is clear weather without daily temperatures above 0 °C. Temperatures below freezing ensure that the surface hoar that was built during the night does not melt during the day. In order to extract some of these elements out of the weather records of individual operations, a "Clear night – cold day" (CNCD) day was defined using the following rules: (a) difference between the maximum and minimum temperature has to be more than 5°C; (b) maximum temperature has to be below 0°C; and (c) no observed wind speed above 25 km/h. The last condition ensures that potential surface hoar is not destroyed by wind. Consecutive CNCD days create a CNCD cycle (Table 4.4). As a first reasonable estimate, we assume that potential for the formation of persistent surface hoar weaknesses exists when three CNCD days, which do not need to be consecutive, are followed by a precipitation event without an immediate temperature increase above 0°C and wind speeds below 25 km/h.

Table 4.4:
Weak layer related characteristics for the four main regions

Description	Coast	Columbia Mountains		Rocky
	Mtn	South	North	Mtn
Number of reported persistent WKL (all season)	167	186	202	89
Average number of CNCD cycles	5.3	6.2	4.1	8.5
Average number of CNCD ≥ 3 days	0.6	0.5	0.5	0.5
Average number of CNCD ≥ 5 days	0.3	0.1	0.1	0.1
Average number of surface hoar periods	0.4	0.6	0.5	0.3
Average length of rain events (days)	1.3	0.5	1.1	0.6

Weak layer (WKL) numbers are for all seasons (1991/1992 – 2001/2002); CNCD values, number of surface hoar periods and length of rain events are average values per season and operation. Values for Coast Mountain region are only based on three stations.

The high number of CNCD cycles in the Rocky Mountains shows that clear nights exist, but the sky seldom remains clear for an extended period of three days or more (Table. 4.4). The surface hoar indicator is lower in the Rocky Mountains than in the other regions. Overall, the average number of surface hoar periods per operation in the different InfoEx regions is considerably lower than expected, particularly in the Columbia Mountains. This might be explained by the fact that some of the most favourable conditions for significant surface hoar formation are not detected by the proposed indicator. Significant surface hoar formation in the Columbia Mountains is often related to valley fog situations. In such situations, the moisture trapped under the temperature inversion acts as an ideal moisture source for the formation of surface hoar right at the top of the fog layer, where clear skies allow maximum radiative cooling. Weather stations of most InfoEx contributors are located in valley bottoms and are therefore not able to recognize the high potential for surface hoar development above the valley fog layer. Hence the present surface hoar indicator generally underestimates the occurrence of surface hoar layers.

b) Facet-crust combination weaknesses

Jamieson and others (2001) relate the creation of facet-crust combination weaknesses to substantial rain events that create layers of saturated snow on the snow surface. When subsequently covered by layers of cold and dry snow, the resulting temperature gradient between the wet and dry snow becomes high enough for the formation of faceted crystals (Colbeck and Jamieson, 2001). The process stops once the layer of wet snow is completely frozen and the temperature gradient disappears. We use the average length of rain events in the months of December, January and February as a simple indicator to estimate the potential for the formation of facet-crust combination weaknesses. The three stations of the Coast Mountains and the North Columbia Mountains clearly show the highest values for this indicator (Table 4.4).

The analysis of the two indicator variables for the formation of persistent weaknesses provides some insights into the observed stability patterns. The generally low snowpack stability observed in the North Columbia Mountains might be related to the high number of persistent weak layers observed in this region. This is confirmed by the analysis of the two indicator variables. The low number of observed snowpack weaknesses in the Rocky Mountains, however, does not explain why the snow cover is generally more unstable in the region. Further research is necessary to answer this question. We can think of two possible hypotheses that may help to initiate more detailed investigations about this matter:

(1) The numerous lakes in the Columbia Mountains (see Figure 4.1) are a significant moisture source that often leads to the formation of valley fog under high pressure conditions. As mentioned above, this situation is very favourable for surface hoar formation. The air in the Rocky Mountains is generally much

drier and the area does not have a comparable moisture source. This might inhibit the formation of serious surface hoar layers. Reliable long-term time series of humidity measurements from high-elevation sites are necessary to examine this hypothesis.

(2) The generally low amount of snow and the cold temperatures in the Rocky Mountains lead to faceting throughout the entire snowpack. This leads to a generally weak snowpack with a poor foundation for the entire season. This weakness cannot necessarily be assigned to an individual weak layer with a distinct burial date. This indistinctness introduces a substantial observational bias with regard to snowpack weaknesses.

4.4 Conclusions and Outlook

The analysis of the InfoEx dataset confirms the well established snow climate classifications of the main mountain ranges of Western Canada. The three stations located in the Coast Mountains indicate that the maritime climate is characterized by high temperatures and intensive snowfalls. Even though the snowfall periods are intense, the recovery time is faster than in the other InfoEx regions and the homogenous snow layers of the large storms contribute a higher overall stability.

The Rocky Mountains are characterized by low temperatures, relatively high wind speeds and a generally weak snowpack, which is indicated by a lower average stability rating. The analysis of persistent weak layers shows, however, that the number of persistent weaknesses in the Rocky Mountains is considerably lower than in the other InfoEx regions. Further research is necessary to determine what exactly is causing the higher instability. We stated two hypotheses that may be a starting point for future research.

Snowfall periods of intermediate intensities and large amounts of snow emerge as main characteristics for the transitional Columbia Mountains. The analysis presents results that justify the separation of the North and South Columbia Mountains in the InfoEx. The South Columbia Mountains generally exhibit lower wind speeds, higher snowfall intensities, higher stability and a much earlier increase in stability in the spring. The North Columbia Mountains, on the other hand, have – together with the Rocky Mountains – the most unstable conditions. In comparison to the Rocky Mountains, however, the reasons for the low snowpack stability in this area might be the higher potential for persistent weaknesses.

The analysis of weather pattern sequences can provide useful results. The surface hoar indicator may help to explain the lack of persistent weak layers in the Rocky Mountains, but it fails to sufficiently reproduce the frequency of persistent surface hoar weak layers in the Columbia Mountains reported by other studies (see Hägeli and McClung, 2003 [Chapter 3]). One problem of the present surface hoar indicator is that it is not able to recognize surface hoar that forms above the valley fog layer. Better meteorological data are necessary to establish a better indicator for the formation facet-crust weaknesses (see, e.g., Hägeli and McClung, 2003 [Chapter 3]). The late start of the InfoEx and the limited weather observations, however, prevent more thorough analyses of the relevant weather patterns. More reliable long-term observations from high-elevation weather sites are necessary to considerably improve this research.

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CHAPTER 5

LARGE-SCALE ANALYSIS OF PERSISTENT SNOWPACK WEAKNESSES – INITIAL DESCRIPTION OF AVALANCHE WINTER REGIMES FOR WESTERN CANADA

Manuscript:
Hägeli, P. and McClung, D.M.. Large-scale analysis of persistent snowpack weaknesses – Initial description of avalanche winter regimes in Western Canada. In preparation for Journal of Glaciology.

5.1 Introduction

The climate characteristics of a location are determined by the slowly varying aspects of the atmosphere-hydrosphere-cryosphere system. Different climate definitions provide problem-specific reference systems that are typically described by a small number of value averages or ranges of relevant parameters. A well-known example is the Köppen climate classification, which is based on annual and monthly means of temperature and precipitation in combination with vegetation limits. Such a reference system allows the grouping of similar locations together into larger-scale spatial patterns. If done correctly, these spatial patterns and their temporal changes can reveal important information about underlying larger-scale processes. The knowledge of these processes can advance the understanding of the phenomenon and simplify the forecasting process at the given scale.

The three main snow climate types, namely maritime, continental and transitional (McClung and Schaerer, 1993) are well established and have been used in many snow and avalanche related studies. A detailed historical review of the development and usage of these terms in North America is given in Hägeli and McClung (2003 [Chapter 3]). The snow climate classification is heavily based on meteorological parameters. While the maritime and continental snow climates represent the two extreme values of the spectrum, the transitional type exhibits intermediate characteristics and high variability. The snow climate classification scheme of Mock and Birkeland (2000), the most recent method, uses the average snow and weather conditions of the main winter months to classify the local snow climate. With these input parameters, the snow climate classification can only give a general impression of the expected avalanche characteristics at a given location, as described by LaChapelle (1966). This classification type is well suited for studies relating average winter characteristics to other large-scale atmospheric phenomena, such as composite height anomalies in the 700 mb patterns over the northern Pacific (Mock, 1996) or the Pacific-North American teleconnection patterns (Mock and Birkeland, 2000).

Another climate related term is avalanche climate, which focuses on catastrophic avalanche events, even though no comprehensive definition exists for this term. Fitzharris (1981; 1987), for example, examined the frequency and magnitude of major avalanche winters along the Rogers Pass transportation corridor in Western Canada. He found that a single, intense storm, even without being a deviation from the local snow climate, is often the cause of a catastrophic avalanche cycle. The primary parameter of interest in this case is the return period of meteorological events that provide sufficient amounts of new snow. This type of climate information is related to avalanche hazard mapping and the application of long-term risk mitigation measures.

Even though the existing snow and avalanche climate definitions contain avalanche related information, they 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. Such characteristics are not a formal part of any snow climate classification scheme (see, e.g., Mock and Birkeland, 2000). While existing classifications focus on average winter weather characteristics, snowpack weaknesses are created by sequences of specific weather events. New snow avalanches are common and can be correlated to individual storm cycles. However, it is the frequency and characteristics of avalanches related to persistent weaknesses that most often distinguish different regions for avalanche forecasting purposes.

In the past, the terms snow and avalanche climate have been used almost synonymously (see Hägeli and McClung, 2003 [Chapter 3]). Even though snow and avalanches are closely related, these climate terms have different objectives and should be used separately. The goal of this study is to identify a new classification system for winters that directly addresses aspects that are relevant for avalanche forecasting. In this study, the term "avalanche winter regime" is introduced and used to examine the characteristics of the different regimes in Western Canada. The focus is on persistent snowpack weaknesses. Avalanche and snowpack observations are used to examine the frequency, sequence and distribution of most common weakness types and their related avalanche activity. Avalanche winter regimes are evaluated with respect to the existing snow climate classifications in Western Canada. While a previous study (see Hägeli and McClung, 2003 [Chapter 3]) was limited to the transitional Columbia Mountains, this study extends the analysis to the maritime Southern Coast Mountains and the continental Rocky Mountains (Figure 5.1). The new avalanche winter regime classification system will allow a more process-oriented division of Western Canada into regions of similar avalanche characteristics. This may lead to improvements in large-scale forecasting programs, the quality and delivery of public avalanche bulletins and the structure of the industrial information exchange.

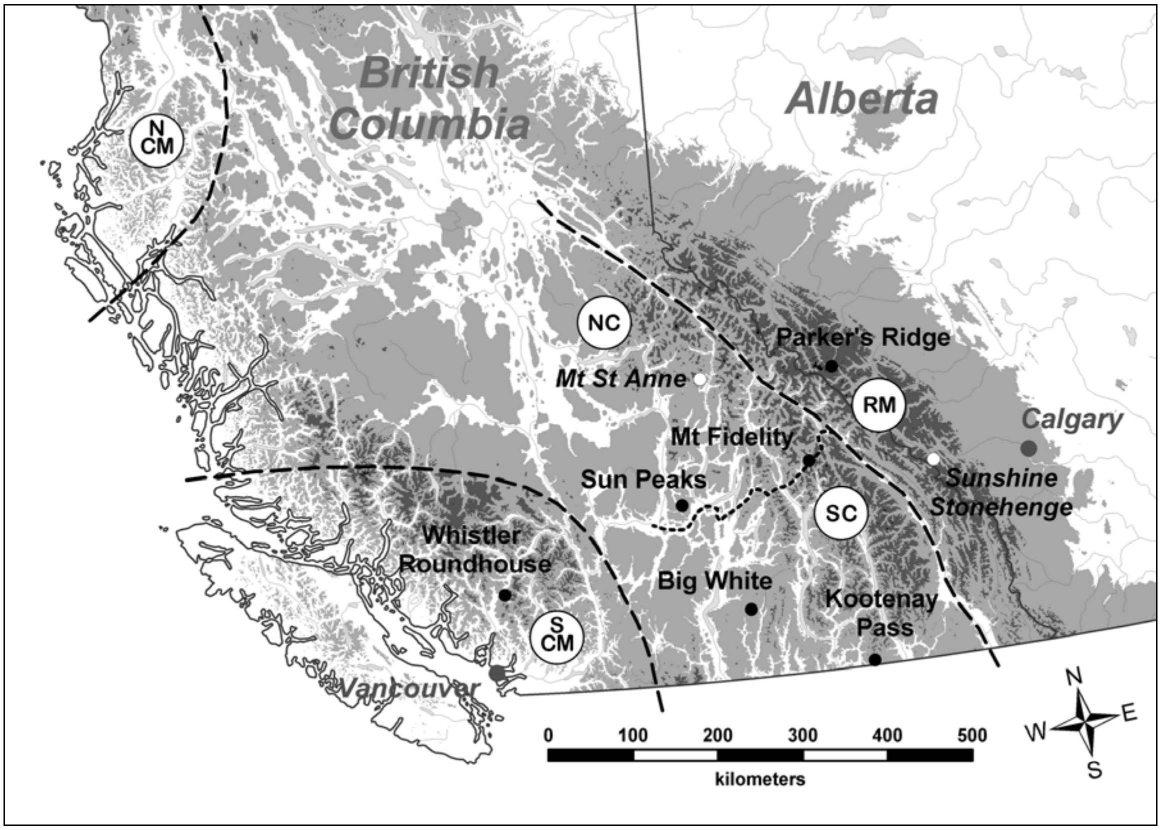


Figure 5.1:
Main mountain ranges in Western Canada with InfoEx data coverage (NCM: Northern Coast Mountains; SCM: Southern Coast Mountains; NC: North Columbia Mountains; SC: South Columbia Mountains; RM: Rocky Mountains). Black dots indicate locations of weather study plots used for the meteorological snow climate analysis. White dots show other weather sites referred to in the text.

5.2 Study Area and Dataset

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

In the winter of 1991/1992 a group of Canadian avalanche safety programs initiated a regular exchange of information pertinent to avalanche forecasting with the goal of improving overall safety in the industry. The hope was that combined knowledge and experience would lead to a better understanding of the conditions at hand. As an independent facilitator, the Canadian

Avalanche Association (CAA) has managed this industrial information exchange (InfoEx) from the very beginning. Avalanche safety operations from across Western Canada submit daily weather data from study plots, field weather observations, information about observed avalanche activity, comments about the current snowpack structure and stability ratings to the CAA. With minimal editing the CAA compiles the information into a comprehensive daily report that is redistributed to all safety programs before the next morning. While weather and avalanche data are organized in tables (avalanche data only since season 2000/2001), much of the important information is presented in semi-structured, sometimes anecdotal comments. Often, these comments contain the most relevant information about the conditions at hand (Hägeli and Atkins, 2002). Originally, the operations in the report were grouped into five main geographic areas: Northern Coast Mountains and Northwest Ranges, Southern Coast Mountains, North Columbia Mountains, South Columbia Mountains and Rocky Mountains (Figure 5.1). More recently, the operations of the Columbia Mountains have been separated into the four main sub-ranges: the Cariboo, Monashee, Selkirk and Purcell Mountain ranges. To allow an open and fair exchange the information is confidential and all participating operations are required to submit data on a regular basis. Subscribers pay an annual fee to cover operating costs at the CAA.

Since the beginning of the service, the CAA has archived the InfoEx reports as text files. A parsing code based on the flex/bison technology (Levine and others, 1992) was designed to extract as much information as possible and transfer it into an accessible database format. The resulting database consists of the following tables (Gruber and others, in press [Chapter 4]): weather observations from study plots, field weather observations, avalanche observations and avalanche involvements, description of snowpack characteristics, specific weak layer observations and stability ratings. The resulting database includes approximately 45,000 avalanche records, 43,000 weather observations and 41,000 comments regarding snowpack structure and stability ratings. The average observation area is about 40,000 km^2 and includes observations from all three major mountain ranges, making the InfoEx database one of the most comprehensive backcountry datasets currently available (Gruber and others, in press [Chapter 4]).

In this study, we examine data of the winter seasons 1991/1992 to 2001/2002. Over time, the format and structure of the InfoEx has become more consistent and better structured. In addition, data recording standards have advanced (CAA, 1995; 2002) and reporting practices improved over the decade. During the study period, the number of contributing operations increased from about 35 to 55 for a peak-reporting day. All these factors have contributed to a significant increase in data quality over time. The InfoEx service generally runs from mid-November to the end of April. Within a season the most consistent data stream generally occurs during the peak winter months from the beginning of January to the end of March, when most operations are reporting.

The different InfoEx areas include various types of contributing operations (Figure 5.2), which have a significant effect on the data content. Each operation type has different priorities, needs and capabilities. For example, mechanized backcountry operations, which 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 differences in operational constraints are clearly reflected in the information submitted by the respective operations.

The InfoEx information for the Rocky Mountains data is mainly provided by National and Provincial Park Services supplemented by the data of several ski resorts. Data from the Columbia Mountains are dominated by mechanized and non-mechanized backcountry skiing operations complemented by a small number of ski resorts, highway operations and one National Park avalanche safety program. The overall spatial coverage in the Columbia Mountains is comprehensive and homogeneous. The Southern Coast Mountains data are concentrated mainly in two areas. The general Whistler area is represented by five backcountry skiing operations, two ski resorts and one highway program reporting. The other focal point is the northern end of the Cascades where three highway operations regularly submit observations. Due to the vast area of the Northern Coast Mountains and the sparse data reported, this area was omitted in this analysis.

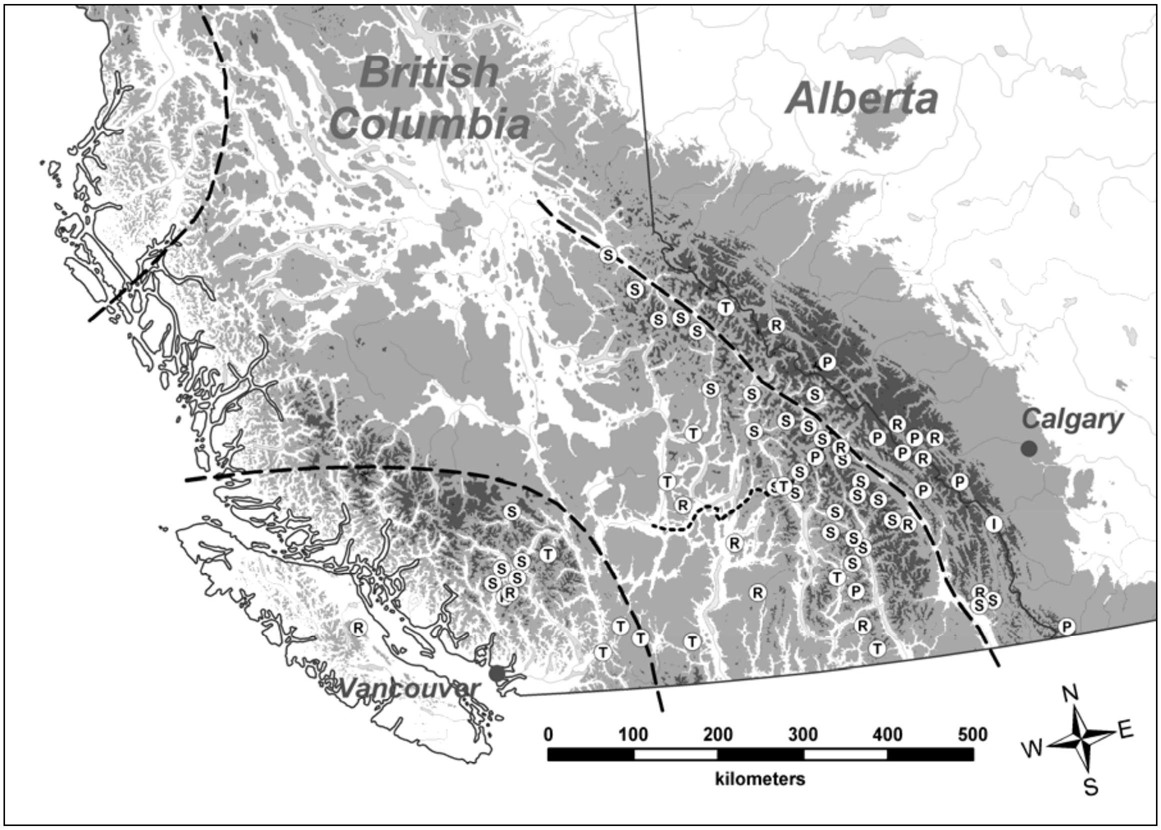


Figure 5.2:
Locations of operations reporting to InfoEx (I: mine or logging operation; P: park; R: ski resort; S: commercial mechanized and non-mechanized backcountry ski operation; T: highway or railway operation).

To study the snow climate characteristics, it is necessary to have continuous meteorological data from high-elevation sites representative of starting zone conditions. Since the majority of InfoEx weather observations are taken at valley bottoms and generally cover only the time period of the peak winter months, they were of limited use for this study (see Gruber and others, in press [Chapter 4]). The Meteorological Service of Canada (MSC) maintains five high-elevation weather stations with reliable long-term records that allow a climatological analysis (Figure 5.1). The locations are Whistler Roundhouse (Coast Mountains, 1835 m asl), Sun Peaks (North Columbia Mountains, 1814 m asl), Glacier Park Mount Fidelity (North Columbia Mountains, 1875 m asl), Big White (South Columbia Mountains, 1841 m asl) and Parker's Ridge (Rocky Mountains, 2023 m asl). These stations have daily records since 1980 of minimum, maximum and mean temperature, amounts of snowfall and precipitation, and height of snow on the ground.. The dataset is complemented with weather information from the highway operation at Kootenay Pass (South Columbia Mountains, 1775 m asl). Numerous meteorological and nivological observations have been monitored there since 1981. These meteorological time series were also used to characterize the sequence of weather events during the different winter seasons.

5.3 Method

The analysis builds heavily on the work of Hägeli and McClung (2003 [Chapter 3]). The analysis was carried out in two main steps. First, the snow climate classification scheme of Mock and Birkeland (2000) was used to examine the main meteorological characteristics for the winters of 1980/1981 to 2001/2002. In a second step, relevant snowpack features were examined using avalanche and weak layer records of the InfoEx database from 1991/1992 to 2001/2002. The emerging spatial and temporal patterns were used to distinguish areas of different avalanche characteristics across Western Canada and examine their spatial and temporal variabilities. Finally, the results of the two steps were combined to define different avalanche winter regimes. This new classification is provided to specifically address characteristics relevant for avalanche forecasting.

5.3.1 Snow Climate Classification

The classification scheme of Mock and Birkeland (2000) categorizes local winter conditions into one of the three traditional snow climates: maritime, transitional and continental (McClung and Schaerer, 1993). The scheme focuses on the main winter months December to March and uses the parameters of mean air temperature, total rainfall, total snowfall, total snow water equivalent and the derived average December snowpack temperature gradient for the classification (Figure 5.3). The temperature gradient was calculated by dividing the difference of mean December air temperature and an assumed basal snowpack temperature of 0°C by the average December snow depth (Mock and Birkeland, 2000). The classification thresholds of the scheme are based on an analysis of meteorological data from 23 Westwide Avalanche Network sites in the Western United States with at least 15 years of complete winter data. The sites were grouped according to the snow climate discussion of Armstrong and Armstrong, (1987) and threshold values were derived by analyzing box-plots of the different variables for the three different climates (Mock and Birkeland, 2000). In their study, Mock and Birkeland (2000) use the classification scheme to examine variations in spatial distribution of snow climates across the Western United States as well as the temporal variations of winter characteristics at individual locations.

Meteorological data used in the first step of the analysis did not have all the necessary parameters for this classification scheme. The snow water equivalent (SWE) values were estimated from daily snowfall records by assuming an seasonal average new snow density of 100 kg m^{-3} (see Röger, 2001). In the case of Kootenay Pass, daily rainfall was approximated from values of total precipitation and snow water equivalent of new snow (Hägeli and McClung, 2003 [Chapter 3]). Missing data on snow depth at Parker’s Ridge in the Rocky Mountains were linearly interpolated in time. Whenever a station was missing a variable continuously for more than ten days, its climate classification of the particular season was discarded from the analysis.

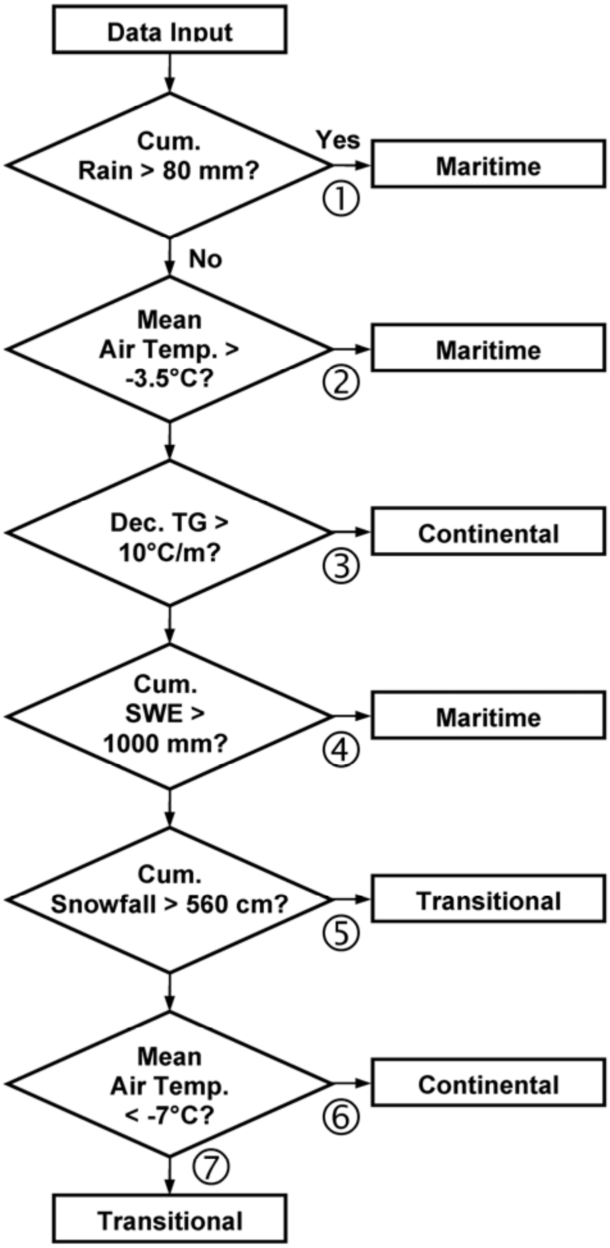


Figure 5.3:
Flowchart illustrating the classification procedure for the seasonal snow climate classification (after Mock and Birkeland, 2000). SWE: snow water equivalent, TG: temperature gradient.

5.3.2 Analysis of Snowpack Weaknesses

The goal of the second step of the analysis was to identify important snowpack characteristics relevant for avalanche forecasting. The focus was the analysis of the frequency and spatial distribution of persistent snowpack weaknesses (Jamieson, 1995) and their related avalanche activity.

Before examining the spatial and temporal patterns, 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 (Laternser and Schneebeli, 2002; Hägeli and McClung, 2003 [Chapter 3]) and snowpack observations may be skewed by the practice of targeted sampling (McClung, 2002). While scientific datasets are commonly based on random or systematic sampling techniques, avalanche professionals specifically seek information about snow instability, which is clearly reflected in characteristics of the resulting data. In addition, the observed information is filtered and processed during the creation of the InfoEx report, and the database transformation undertaken for this study introduced additional inaccuracies to the data. Because of all these limitations, it is not suitable to apply geostatistical methods and, as a result, the analysis presented here is mainly qualitative.

It is a common practice to label snowpack weaknesses important for avalanche forecasting with their respective date of burial. This convention allowed the tracking of these weaknesses throughout a season. The exact labelling of individual weaknesses was not always consistent among reporting operations and burial dates often differed by plus or minus one or two days (Gruber and others, in press [Chapter 4]). However, with the help of weather records it was relatively easy to group the weaknesses correctly.

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* weaknesses. For this study, weaknesses are considered active if more than one operation recorded related avalanche activity and the reported avalanches were not exclusively triggered by explosives. Persistent weaknesses were only labelled active if consistent avalanche activity was observed more than ten days after burial. We define the number of days between burial and the day of the last related avalanche occurrence as the *activity period* to register the degree of persistence of the layer at a specific location.

This definition of persistence is different from the ones used in previous studies. Jamieson's classification (1995) is purely based on weak layer crystal types, while Hägeli and McClung (2003 [Chapter 3]) 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., Jamieson and others, 2001; Hägeli and McClung, 2003 [Chapter 3]).

For the maximum amount of available information, the snowpack and avalanche observations of all reporting operations were used for this analysis. To examine the spatial distribution and characteristics of each weakness, maps were produced that show the number of related persistent snowpack observations and the number of related non-persistent and persistent avalanche activity observations (Figure 5.4). These numbers, presented on the maps as cumulative circles, were interpreted as proxies for the local importance, severity and persistence of a given snowpack weakness. Since the number of observed avalanches in a record was often only described qualitatively (few, several, numerous), we could not use an avalanche activity index to describe the level of avalanche activity (see, e.g., Hägeli and McClung, 2003 [Chapter 3]). The exclusive presence of snowpack observations within the first ten days after burial of a specific weakness at operations was simply marked by a small cross on the map.

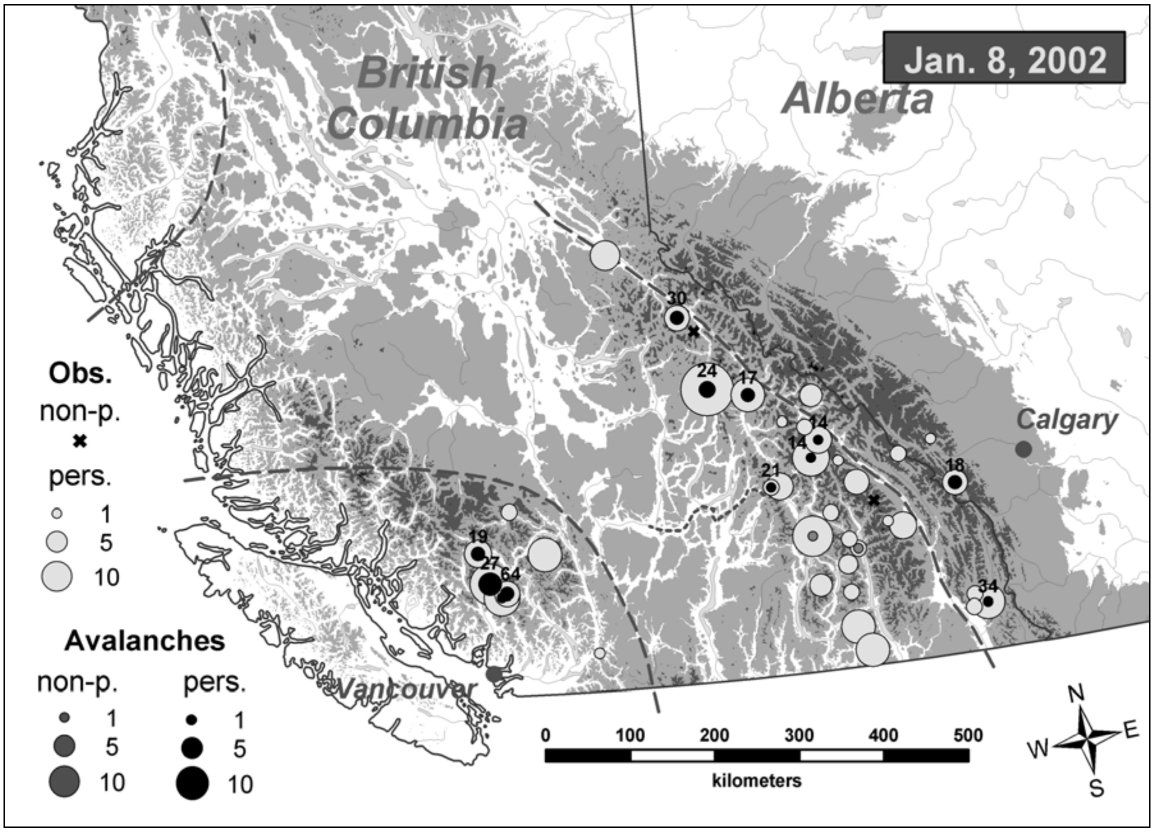


Figure 5.4:
Spatial extent of January 8, 2002 facet-crust combination weak layer. Black and dark grey circles represent number of related persistent and overall avalanche observations respectively. Light grey circles represent the number of related avalanche and snowpack observations more than ten days after burial. Crosses indicate operations that only observed the weakness within ten days of burial and did not observe related avalanche activity. Numbers present the number of days between burial and last related avalanche observation.

The resulting maps allowed the delineation of the following patterns for a given weakness: (a) overall extent of weakness; (b) effective area of persistent weakness; (c) area of observed avalanche activity related to weakness and (d) area with observed avalanche activity on persistent weakness. In addition, operations were labelled with the observed activity period to allow a more detailed examination of the spatial distribution of persistence.

InfoEx avalanche records sometimes include information about number, size, trigger, location references, avalanche dimensions, fracture depth and characteristics of weak layer and bed surface. Even though only 20% of all avalanche records contain weak layer data, this information was used to determine the dominant crystal types of persistent weaknesses. The snowpack comments were used to further characterize the weaknesses, particularly in the case of inactive weaknesses. In accordance with existing studies (e.g., Hägeli and McClung, 2003 [Chapter 3]) persistent weaknesses are grouped into three main categories in this study: (a) layers with faceted crystals as the main weakness, including facet-crust combinations; (b) surface hoar layers; and (c) pure crust layer interfaces [see Appendix E for details].

A different type of map was used to summarize the characteristics of persistent snowpack weaknesses and related avalanche activity for individual seasons. Based on the spatial patterns presented in the previous maps, contour maps were produced that show the number of persistent weaknesses (Figure 5.5) across the study area. For these maps, the weaknesses were grouped into the three main types and their spatial distributions are displayed with separate contour lines. The same type of map was also used to examine the seasonal patterns of areas where the weaknesses resulted in persistent avalanche activity.

A thorough analysis of these seasonal maps revealed consistent patterns of frequency and composition of weaknesses across the study area. However, the limited number of winters with consistent avalanche observations (1996/1997 to 2001/2002) analyzed in this study did not allow a reliable delineation of climatological regions of different snowpack weakness characteristics. Instead, we identified seven locations, which are representative of the different regions identified in this study.

In order to examine the seasonal variations of snowpack weaknesses in more detail, idealized snow profiles were constructed for each of the chosen locations. These profiles present the observed sequences of active and inactive weaknesses in the different areas represented by the locations for each winter. 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 in these climatological profiles reflects the general sequence observed during the seasons analyzed. Profiles of individual winters are compared to these climatological profiles to examine annual variations in the weakness patterns. The observed variations are also studied with respect to the snow climate classifications of the respective winters.

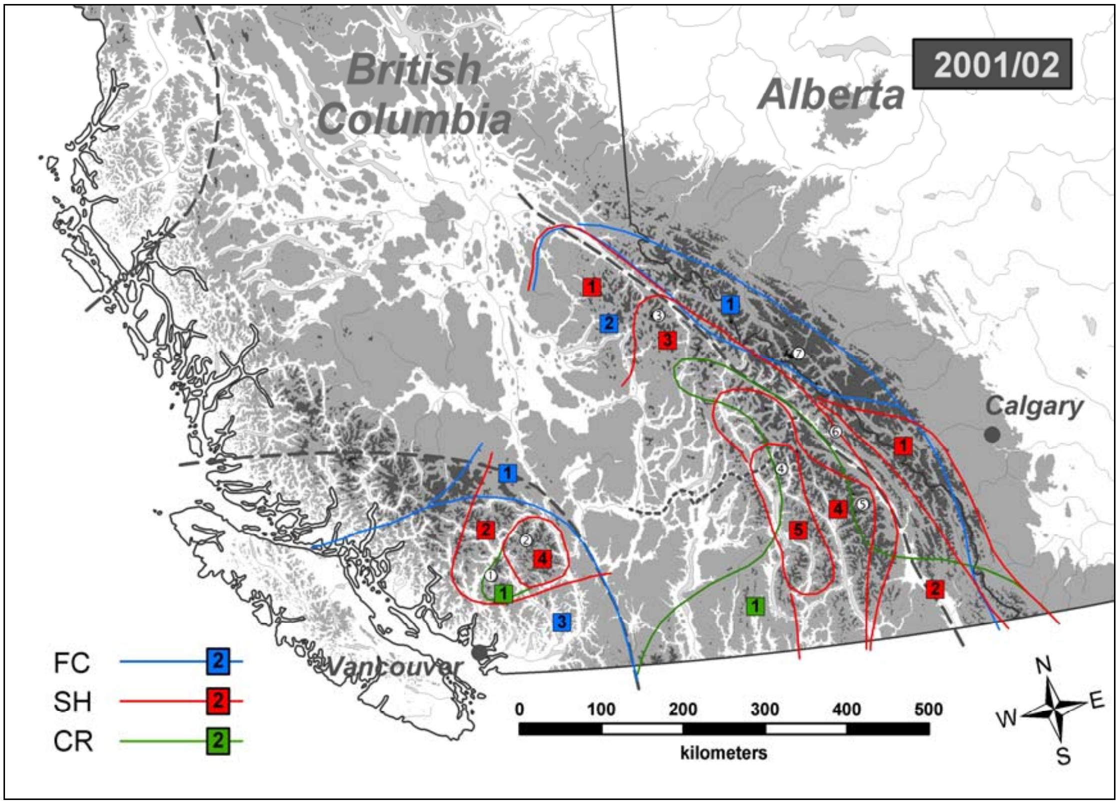


Figure 5.5:
Contour map showing the number of observed persistent snowpack weaknesses across the study area during the winter season of 2001/2002 (FC, blue: layers of faceted grains; SH, red: surface hoar layers; CR, green: pure crust layers). White numbers indicate general locations of idealized profiles.

5.4 Results and Discussion

First, this section presents the results of the different steps of the analysis separately. The results are followed by a comprehensive discussion that ties them together and presents avalanche winter regimes as a more avalanche-oriented classification scheme.

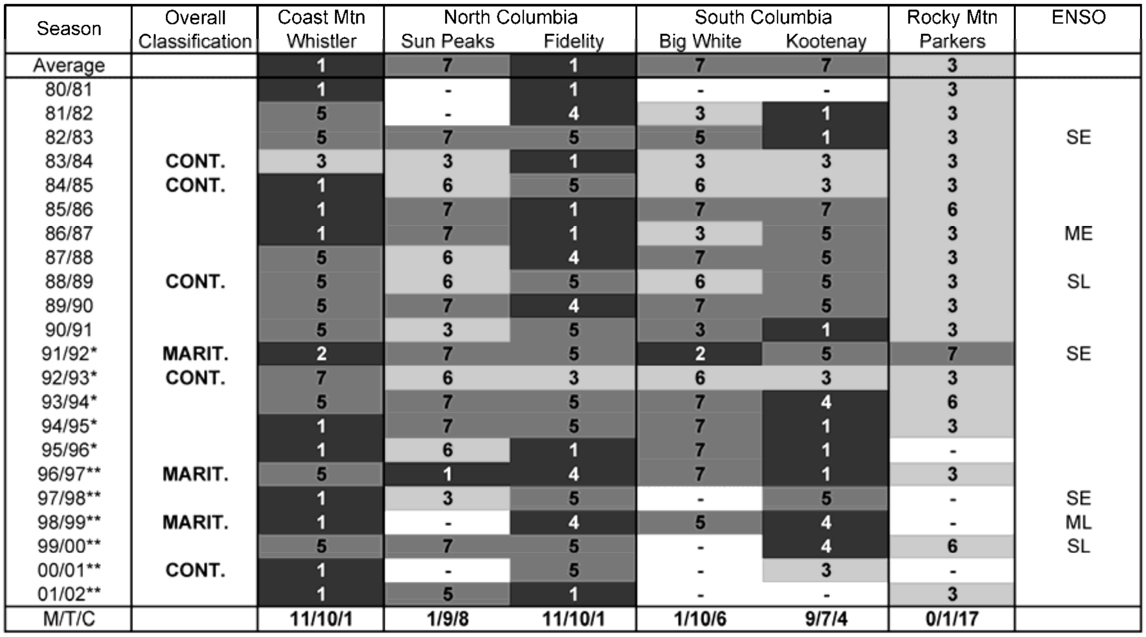
5.4.1 Snow Climate Analysis

The classification scheme of Mock and Birkeland (2000) was used first to examine the spatial distribution of snow climates across the study area. In a second step, the scheme was applied to examine temporal variations in the winters' characteristics.

a) Spatial analysis

In order to establish a baseline for the analysis of spatial and temporal variabilities of snow climates across the study area, the classification scheme of Mock and Birkeland (2000) was applied to the average values of the weather parameters at the different weather stations [see Appendix D for details]. The analysis suggested Whistler, the only station in the Coast Mountains, to have a maritime snow climate (Figure 5.6). The average amount of winter rain of 307 mm during the months of December to March is clearly above the classification threshold of 80 mm. All stations in the Columbia Mountains except Mount Fidelity are considered to have a transitional snow climate. Mount Fidelity is classified as maritime due to an average amount of rain of 82 mm, which is just barely above the threshold. Parker's Ridge, the only station in the Rocky Mountains, is clearly characterized by a continental snow climate. These results are in general agreement with the traditional snow climate classification of these mountain ranges by McClung and Schaerer (1993). The maritime influence at Mount Fidelity agrees with the reputation of the Rogers Pass region as an area with particularly high amounts of precipitation (see, e.g., Schweizer and others, 1998).

However, an examination of the individual snow climate classifications during the time period from 1980/1981 to 2001/2002 uncovered significant spatial and temporal variabilities (Figure 5.6). In the case of Whistler, only half of the winters were classified as maritime. In all but one case, the classification was because of the high winter rainfall amount. Ten winters were classified as transitional mainly due to high amounts of snowfall and there was only one continental winter.



Season	Overall Classification	Coast Mtn	North Columbia		South Columbia		Rocky Mtn	ENSO
		Whistler	Sun Peaks	Fidelity	Big White	Kootenay	Parkers	
Average		1	7	1	7	7	3	
80/81		1	-	1	-	-	3	
81/82		5	-	4	3	1	3	
82/83		5	7	5	5	1	3	SE
83/84	CONT.	3	3	1	3	3	3	
84/85	CONT.	1	6	5	6	3	3	
85/86		1	7	1	7	7	6	
86/87		1	7	1	3	5	3	ME
87/88		5	6	4	7	5	3	
88/89	CONT.	5	6	5	6	5	3	SL
89/90		5	7	4	7	5	3	
90/91		5	3	5	3	1	3	
91/92*	MARIT.	2	7	5	2	5	7	SE
92/93*	CONT.	7	6	3	6	3	3	
93/94*		5	7	5	7	4	6	
94/95*		1	7	5	7	1	3	
95/96*		1	6	1	7	1	-	
96/97**	MARIT.	5	1	4	7	1	3	
97/98**		1	3	5	-	5	-	SE
98/99**	MARIT.	1	-	4	5	4	-	ML
99/00**		5	7	5	-	4	6	SL
00/01**	CONT.	1	-	5	-	3	-	
01/02**		1	5	1	-	-	3	
M/T/C		**11/10/1**	**1/9/8**	**11/10/1**	**1/10/6**	**9/7/4**	**0/1/17**	

Figure 5.6:
Results of snow climate analysis: maritime (dark shading), transitional (intermediate shading), continental (light shading) and missing data (unshaded). Numbers represent decision in classification flowchart (Figure 5.3). First column shows the character of large-scale snow climate deviations from average conditions across the entire study area. Last column indicates El Niño-Southern Oscillation (ENSO) classification of respective winter based on sea surface temperature anomalies (SE: strong El Niño; ME: moderate El Niño; ML: moderate La Niña; SL: strong La Niña). Asterisks indicate winter with InfoEx data, double asterisks winters considered in the snowpack weakness analysis. Bottom row (M/T/C) summarizes numbers of snow climate classifications of each type (Maritime/Transitional/Continental).

A strong west-east pattern can be observed in the Columbia Mountains. Sun Peaks and Big White, both stations on the far western side of the mountain range (Figure 5.1), are dominated by winters with transitional and continental characteristics. Sun Peaks, the more northerly station of the two, has slightly more continental winters, while both stations experienced only one maritime winter during the entire study period. Mount Fidelity and Kootenay Pass, which are located more centrally in the Columbia Mountains, clearly have more of a maritime influence despite their location further inland. In the case of Mount Fidelity, half the winters are classified as maritime. Kootenay Pass has nine maritime classifications within 20 winters. These classifications are the result of high amounts of rain or accumulated snow water equivalent exceeding 1000 mm. In our analysis this amount is equivalent to an accumulated snowfall of 1000 cm from the beginning of December to the end of March. We attribute the more maritime character of the two latter stations to the additional lift experienced by air masses approaching the main crest of the range. These results are in agreement with previous discussions of this area (e.g., McClung and Tweedy, 1993) and the experience of contributing operators in the area. Mount St. Anne (Figure 5.1), a more northerly site in the Columbia Mountains, experiences similar weather characteristics (Jamieson, 2003).

Parker's Ridge in the Rocky Mountains is the most stable station with only continental winters except the transitional season of 1991/1992. The station is characteristic for weather conditions along the continental divide. Stations further south in the range (e.g., Stonehenge at Sunshine; see Figure 5.1), experience similar average weather conditions (Ledwidge, 2004).

b) Temporal analysis

After describing the characteristics of individual locations, the next step is to examine the overall snow climate characteristics across the study for individual winters. Figure 5.6 shows that, despite the apparent spatial variabilities, the snow climate classifications of an individual winter often exhibit similar deviations from the average conditions at the different locations. For the winter seasons of 1983/1984, 1984/1985, 1992/1993, and 2000/2001 the majority of the weather station locations exhibited more continental conditions (Figure 5.6) [see Appendices C and D for more details]. Weather records show, that the continental classification of 1983/1984 was mainly due to an exceptional cold spell in December that resulted in extremely strong December snowpack temperature gradients. It was also a dry winter with little snowfall at the stations of Whistler, Sun Peaks and Kootenay Pass. Mount Fidelity, the only non-continental station of that winter, was classified as maritime due to a considerable rain event in early January. The following winter, 1984/1985, also had a more continental influence. Weather records show that it was generally a cold (Mount Fidelity, Kootenay Pass) and dry (Whistler, Kootenay Pass, Parker's Ridge) winter. The next continental winter was in 1992/1993. Cold temperatures during the end of December and early January (Whistler, Big White, Sun Peaks, Parker's Ridge) and a shallow early snowpack (Whistler, Mount Fidelity, Kootenay Pass) were responsible for this classification. The most recent continental winter was 2000/2001, which was one of the driest winters on record at many locations in British Columbia. Temperatures were just slightly above normal, but there were two substantial cold spells, one in December and one in February. In combination with a shallow early season snowpack the former spell resulted in a strong snowpack temperature gradient during the early season.

The more maritime influenced winters during the observation period were 1991/1992, 1996/1997 and 1998/1999 [see Appendices C and D for more details]. Winter 1991/1992 was the warmest winter during the observation period for all stations except Kootenay Pass. It was also the driest winter for Sun Peaks and Big White. The maritime winter of 1996/1997 had completely different characteristics. It was one of the snowiest winters at Sun Peaks, Kootenay Pass and Parker's Ridge. There were also large rain events at Sun Peaks and Kootenay Pass. The winter of 1998/1999 brought the most snow to Whistler, Mount Fidelity, Big White and Kootenay Pass.

All other winters examined in this study exhibited generally average conditions with respect to the local snow climate classifications.

c) Relation to large-scale climate variability modes

Oscillations such as El Niño–Southern Oscillation (ENSO) (e.g., Shabbar and Bonsal, 2004), the North Atlantic Oscillation (NAO) (e.g., Cassou and others, 2003) and the Pacific Decadal Oscillation (PDO) (e.g., Deser and others, 2004) have been associated with particular aspects of North American climates. It seems reasonable that there might be a direct relationship between these climate variabilities and the snow climate classification presented in this study. It is beyond the scope of this analysis to study this aspect in detail. However, as a first attempt, the relationship between ENSO and the snow climate classification is examined. Classification of warm (El Niño) and cold (La Niña) ENSO events is based on the magnitude of sea surface temperature anomalies in the Niño 3.4 region of the tropical Pacific for the January-February-March period. Years with moderate to strong ENSO events are identified when the magnitude of the anomaly was more (less) than 0.5 (-0.5) standard deviations from the long-term seasonal mean for El Niño (La Niña) events (Shabbar and Bonsal, 2004). ENSO classifications for this study were taken from the MSC web site (http://www.msc-smc.ec.gc.ca/education/elnino/comparing/enso1950_2002_e.html). A limited comparison shows (Figure 5.6) that based on the data at hand, there is no obvious direct relationship between ENSO and snow classification variabilities presented in this study. For example, the strong La Niña winter of 1988/89 was associated with a more continental snow climate classification across the study area, while the moderate La Niña winter of 1998/99 was related to a more maritime winter. However, more detailed analyses are necessary to examine this relationship conclusively.

In conclusion, the analysis presented shows that the classification scheme of Mock and Birkeland (2000) is able to capture the general meteorological character of a winter adequately. However, the discussion of individual winters also shows that there are considerable spatial and temporal variations and that the classifications can be based on completely different factors at neighbouring locations during the same winter. Further, the analysis reveals that the use of the classification scheme for the characterization of a winter is highly sensitive and single events, such as a major rain storm or an important cold spell, often dictate the classification.

5.4.2 Spatial Patterns of Snowpack Weaknesses

A proper analysis of spatial patterns is highly dependent on consistent high-quality data for the entire study area. The reporting quality of persistent snowpack weaknesses dramatically increased during the season 1996/1997. It was the significant facet-crust combination of November 11, 1996 (Jamieson and Johnston, 1997) that heightened the general awareness of the importance of sharing this type of information within the industry. Therefore, we focused on the winters 1996/1997 to 2001/2002 for this analysis. The general reporting patterns for these seasons was sufficiently homogenous to allow an analysis.

We have used the season of 2001/2002 to illustrate the spatial patterns of the different type of weak layers and generalize the results at the end of this section [see Appendices C and E for other seasons]. The winter 2001/2002 was characterized by an average snowpack and normal air temperatures (Figure 5.7). The most dramatic weather events of the season were a long dry period in late December and the widespread rain events in mid-November and on January 7/8. The latter rain event resulted in the maritime snow climate classification of Mount Fidelity (Figure 5.6) for this season.

In the following paragraphs we discuss the spatial characteristics of the three main types of persistent snowpack weaknesses and their related avalanche activity.

a) Early season weak layers of faceted grains

Weather data from MSC show that the beginning of the 2001/2002 season was characterized by a significant rain event on November 15 and 16 (Figure 5.7). Rain and generally above-freezing temperatures were observed across the entire study area. The subsequent moderate temperature drop resulted in the development of a significant facet-crust combination weak layer that remained an issue for the rest of the season. The weakness was observed across the entire study area (Figure 5.8). Since the InfoEx did not start until November 24, all reported snowpack and avalanche observations related to this weak layer are considered to be persistent. While almost all reporting operations observed the weak layer, related avalanche observations were less frequent. Related avalanche activity was basically absent in the Coast Mountains and observed avalanche activity in the Columbia Mountains was concentrated in the central parts. Even within this area, only less than half of the reporting operations submitted avalanche observations related to this weak layer, which results in a spatially very inhomogeneous pattern of avalanche activity (Figure 5.8). The majority of stations in the Rocky Mountains reported snowpack and avalanche

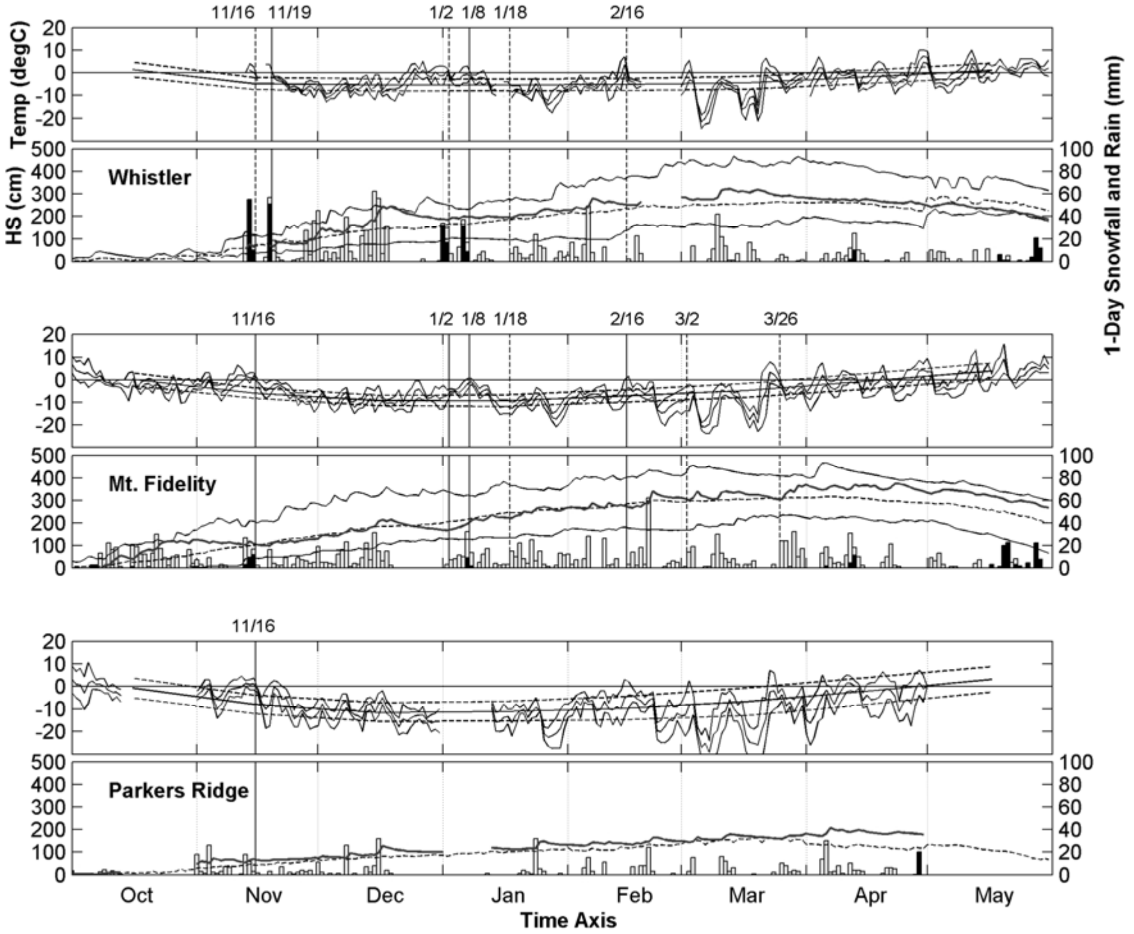


Figure 5.7:
Weather history for 2001/2002 winter at weather plots representing the three main mountain ranges. Top panel shows maximum, mean and minimum temperature with climate normals for individual months (dashed lines). Bottom panel presents height of snow on ground together with maximum, average and minimum snow depth measured since 1980. The panel also shows 1-day snowfall (light grey bars) and rainfall (dark grey bars). Vertical lines represent the interfaces (dashed) and weak layers (solid) observed in the areas.

observations related to this weakness. The pattern of the activity periods shows the layer to be most persistent in the Rocky Mountains and with more variability in the central Columbia Mountains. The average activity period is approximately four months, which is consistent with the results of Hägeli and McClung (2003 [Chapter 3]).

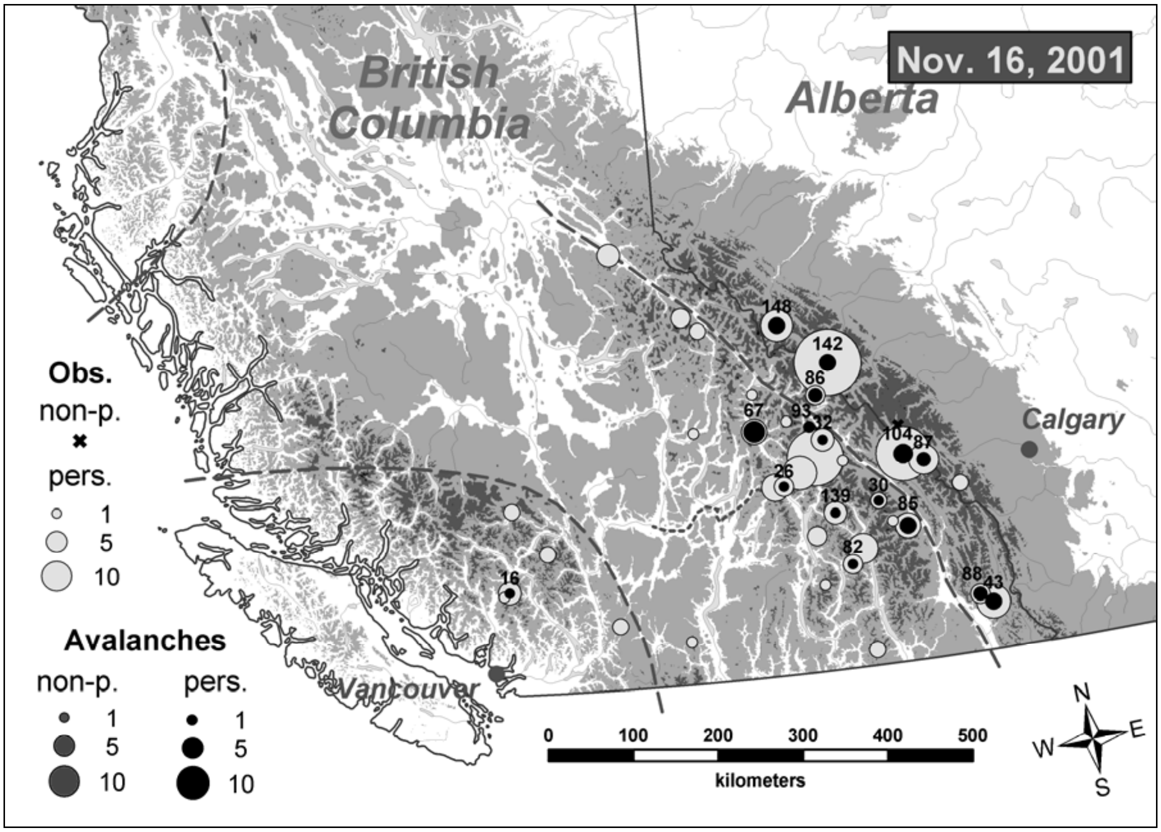


Figure 5.8:
Spatial extent of November 16, 2001 facet-crust combination. Symbols and labels same as in Figure 5.4.

The spatial analyses of the ten early-season weak layers of faceted grains of the InfoEx dataset show that the characteristics described above are typical for this type of weakness [see Appendix E for details]. During the seasons of 1996/1997 to 2001/2002, one to three of these weaknesses were observed within the study area every winter. Most of these weaknesses are facet-crust combinations that formed during the early part of the season in November and December after rain-on-snow events. Out of ten facet-crust weak layers observed in this study in total, only two occurred in January. The spotty spatial character of related avalanche activity matches the intermittent temporal activity pattern described in Hägeli and McClung (2003 [Chapter 3]).

b) Surface hoar layers

The February 16 weakness was one of five surface hoar layers observed during the 2001/2002 season. A clear weather period of approximately two to five days across the entire study area (Figure 5.7) caused the formation of a persistent surface hoar weakness that resulted in avalanche activity in the Columbia Mountains and the western slopes of the Rocky Mountains (Figure 5.9). While the layer was also observed in the Coast Mountains, it was not observed east of the continental divide. Nearly all stations reporting weak layer observations in the Columbia Mountains also reported related avalanche activity. The area of persistent avalanche activity is strongly concentrated on the Selkirk

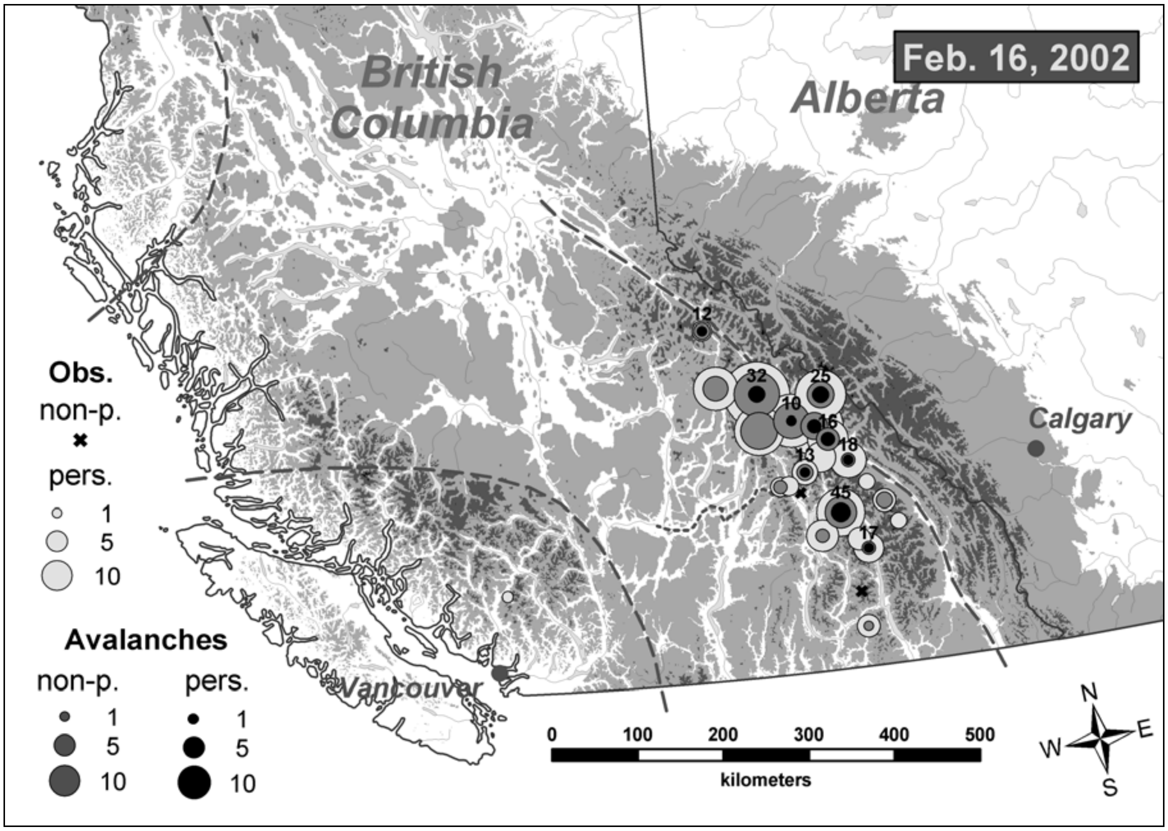


Figure 5.9:
Spatial extent of February 16, 2002 surface hoar weak layer. Symbols and labels same as in Figure 5.4.

Mountain range in the central Columbia Mountains. The spatial pattern of observed avalanche activity is clearly more homogeneous and denser than in the case of the faceted layers. The average activity period of this surface hoar layer is approximately three weeks, which is in agreement with results of previous studies (Hägeli and McClung, 2003 [Chapter 3]).

In total, 36 persistent surface hoar layers from six winter seasons were examined in this study [see Appendix E for details]. Depending on the region, two to four active surface hoar layers were observed every season. The spatial and temporal patterns described above were common and can be regarded as fairly typical for surface hoar layers in the region.

c) Pure crust interfaces

During the season of 2001/2002 only one persistent pure crust interface was observed in the entire study area (Figure 5.10). The snowpack comments in the InfoEx did not contain more specific information about the crust. However, the lack of rain, the high temperature recorded prior to March 26 and the subsequent temperature drop at Mount Fidelity (Figure 5.7) suggest that it is a melt-freeze crust. This type of crust is typically found under spring conditions. Observed avalanche activity only occurred during the first ten days after burial and was, therefore, not considered to be persistent by the definition used here. However, the interface was still observed more than ten days after burial in central parts of the Columbia Mountains. Similar to the avalanche activity pattern on weakness of faceted grains, the spatial pattern is inhomogeneous and less dense than in the case of surface hoar layers. This pattern was confirmed by other crust interfaces examined in this analysis [see Appendix E].

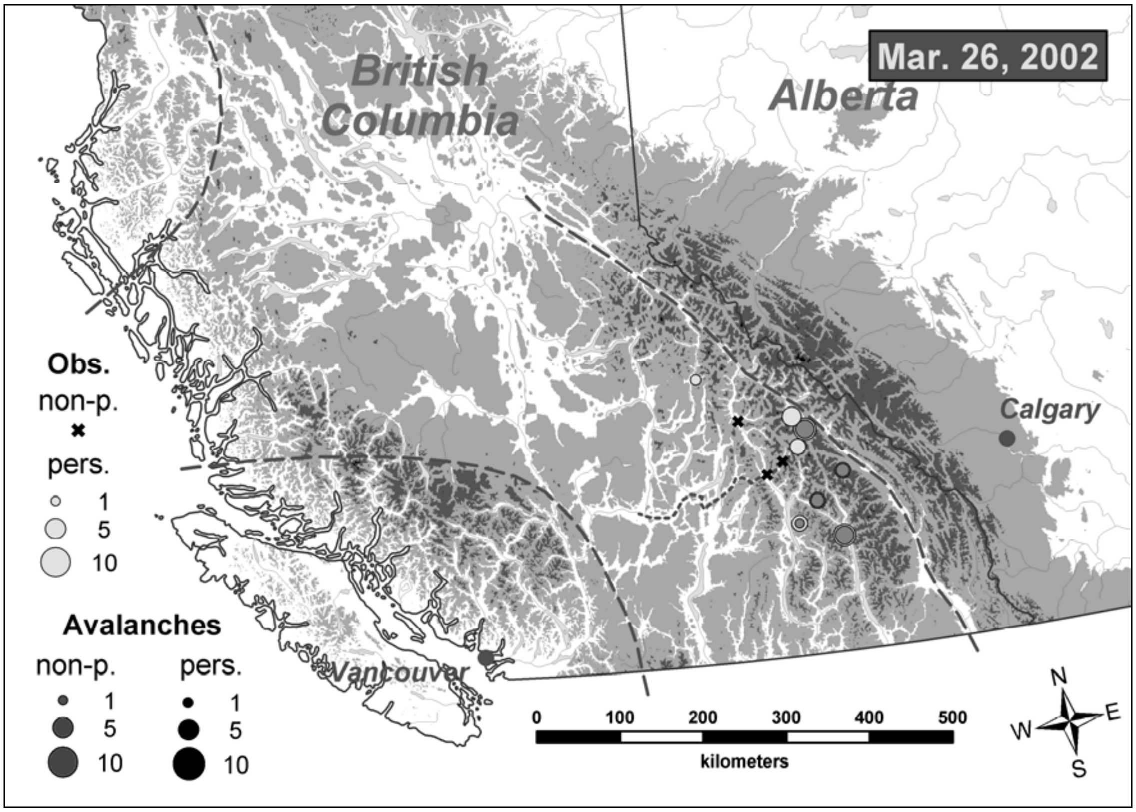


Figure 5.10:
Spatial extent of March 26, 2002 crust interface. Symbols and labels same as in Figure 5.4.

d) Summary

In total the analysis in this paper included 56 persistent weaknesses, 10 weak layers of faceted grains, 36 surface hoar layers and 10 pure crust interfaces. The maps presented above illustrate example patterns of the three main types of persistent snowpack weaknesses and their related avalanche activity. The patterns shown are the result of complex interactions of numerous processes that act over a wide range of different spatial and temporal scales before and after burial (Hägeli and McClung, in press [Chapter 2]). For example, even though the February 16 surface hoar layer was observed across the entire Columbia Mountains, the persistent avalanche activity was limited to eastern parts of the northern and the central section of the Southern Columbia Mountains. This pattern might have been caused by enhanced surface hoar growth and/or a more persistence-promoting sequence of snowfalls after burial in these areas. Similarly, the lack of avalanche activity on the November 16 facet-crust combination in the Southern Coast Mountains was probably caused by the subsequent rain event on November 18 (Figure 5.7), which resulted in the more prominent November 19 weak layer for this area. The limitations of the data prevent a quantitative analysis of these hypotheses.

Similarly, scale characteristics of underlying processes might also be responsible for the differences in avalanche activity patterns among various types of weaknesses. For the data analyzed, the observed persistent avalanche activity on surface hoar layers is generally concentrated in a core region, while layers of faceted crystals and pure crust interfaces exhibit a more variable activity pattern. This additional spatial pattern of faceted and crust layers might be related to the high spatial variability of the precipitation process. While the necessary conditions for surface hoar formation (clear and calm weather; moisture source) can generally be widespread, large-scale phenomena, the precipitation process exhibits many more small-scale variabilities (see, e.g., Gupta and Waymire, 1990; Foufoula-Georgiou and Venugopal, 2000).

5.4.3 Avalanche Winter Regimes

The spatial patterns of snowpack weaknesses and their related avalanche activity presented in the last section were used to create seasonal maps that show the distribution and frequency of the three main weakness types across Western Canada. These patterns are considerably influenced by the pattern of the recording operations (Hägeli and McClung, in press [Chapter 2]). In areas with only a few stations reporting, such as the southeastern part of the Columbia Mountains (Figure 5.2), it was not possible to reliably draw the contour lines of number of observed persistent weaknesses. Again, we use the season of 2001/2002 as an example to discuss the main characteristics observed [see Appendix F for Figures of other seasons].

Persistent weaknesses are generally widespread and observed across the entire study area (Figure 5.5). While the number of layers with faceted crystals is 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 generally exhibits more surface hoar interfaces 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 position of maximum occurrence of surface hoar weak layers is reasonably stationary during the seasons examined in this study. The maps of the different seasons show that the number of surface hoar weak layers generally drops from west to east and toward the northern and southern parts of the Columbia Mountains. The Rocky Mountains can also be divided into 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 Rockies. However, the division cannot be demonstrated conclusively with the data at hand.

Figure 5.11 presents the frequency and spatial character of areas of persistent avalanche activity for the winter season of 2001/2002 [see Appendix F for Figures of other seasons]. While persistent weaknesses are generally widespread, the regions where weaknesses lead to persistent avalanche activity are considerably smaller. However, the avalanche activity patterns observed during the different seasons generally confirm the division of the study area discussed above.

The analysis of the spatial patterns of persistent weaknesses and related avalanche activity presented suggests that the study area can be divided into seven different regions. Each of these regions exhibits different average snowpack weakness and avalanche activity characteristics. The limited number of winters analyzed in this study prevents an accurate delineation of the different regions. Instead, seven central locations were chosen to represent the different regions (Table 5.1, Figures 5.5 and 5.11). For each of these representative

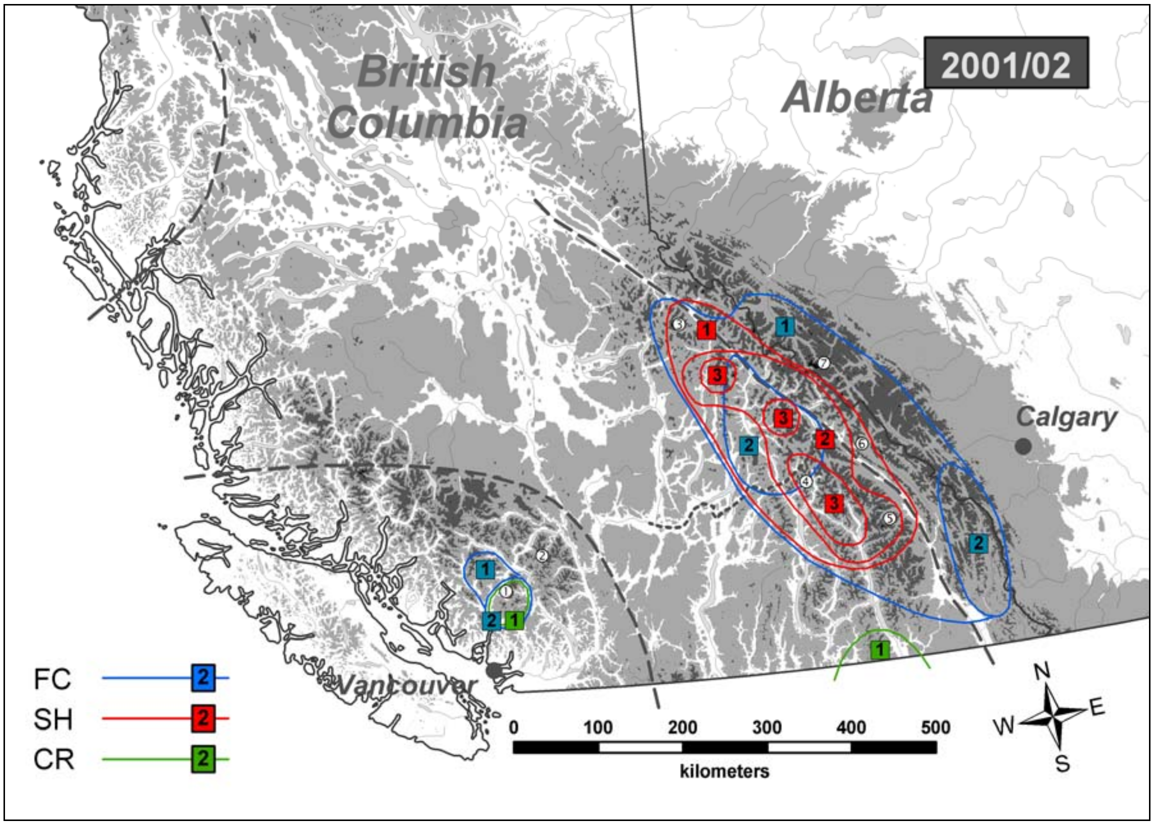


Figure 5.11:
Contour map showing the number of areas of persistent weaknesses with observed avalanche activityduring the winter season of 2001/2002. Legend and labels are the same as in Figure 5.5.

Table 5.1:
Description of representative locations for different regions of similar snowpack weakness and avalanche characteristics

Num.	Representative Location	Description of Region
1	Whistler Area	Western section of Southern Coast Mountains
2	Duffy Lake	Eastern section of Southern Coast Mountains
3	Eastern Cariboo Mountains	Northeastern part of Columbia Mountains
4	Central Selkirk Mountains	Western section of central Columbia Mountains
5	Eastern Purcell Mountains	Southeastern part of Columbia Mountains
6	Yoho NP Area	Central Rocky Mountains west of continental divide
7	Columbia Icefield	Central Rocky Mountains along and east of continental divide

Locations are indicated in Figures 5.5 and 5.11.

locations idealized snow profiles for each season were constructed that show number and sequence of persistent weaknesses in their respective region (Figure 5.12).

Climatological profiles were created to identify the average conditions for the different regions. Early season faceted layers were observed in all areas and occasional pure crust layers occurred predominantly in the Coast Range and the central Selkirk Mountains. The most significant observation in these climatological profiles is that the number of surface hoar layers can be used as a distinguishing factor between the different regions (Figure 5.12). The central Selkirk Mountains clearly experience the highest number of active and inactive surface hoar layers. On average, there are no significant surface hoar layers observed on the eastern slopes of the Rocky Mountains and the Coast Mountains experience only experience the occasional surface hoar weakness. In addition to this variation in the west-east direction, the observations also show a decrease in the number of persistent surface hoar layers towards the north and south within the Columbia Mountains. These observations are clear indicators that with respect to avalanche activity, the transitional Columbia Mountains have very distinct characteristics that go beyond a simple combination of maritime and continental influences. These results are in agreement with the preliminary study of Gruber and others (in press [Chapter 4]).

Climatological snow profiles can also be used to compare the observed sequence of snowpack weaknesses of individual winters to the climatological average characteristics. Winters that are very similar to the climatological average are 1999/2000 and 2001/2002. Both these seasons were classified as average winters by the snow climate classification scheme (Figure 5.6). 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 [Chapter 3]), which showed that these events primarily occur during the early months of the winter season. The season 1997/1998, which was also classified as a regular snow climate winter, was characterized by the absence of an active

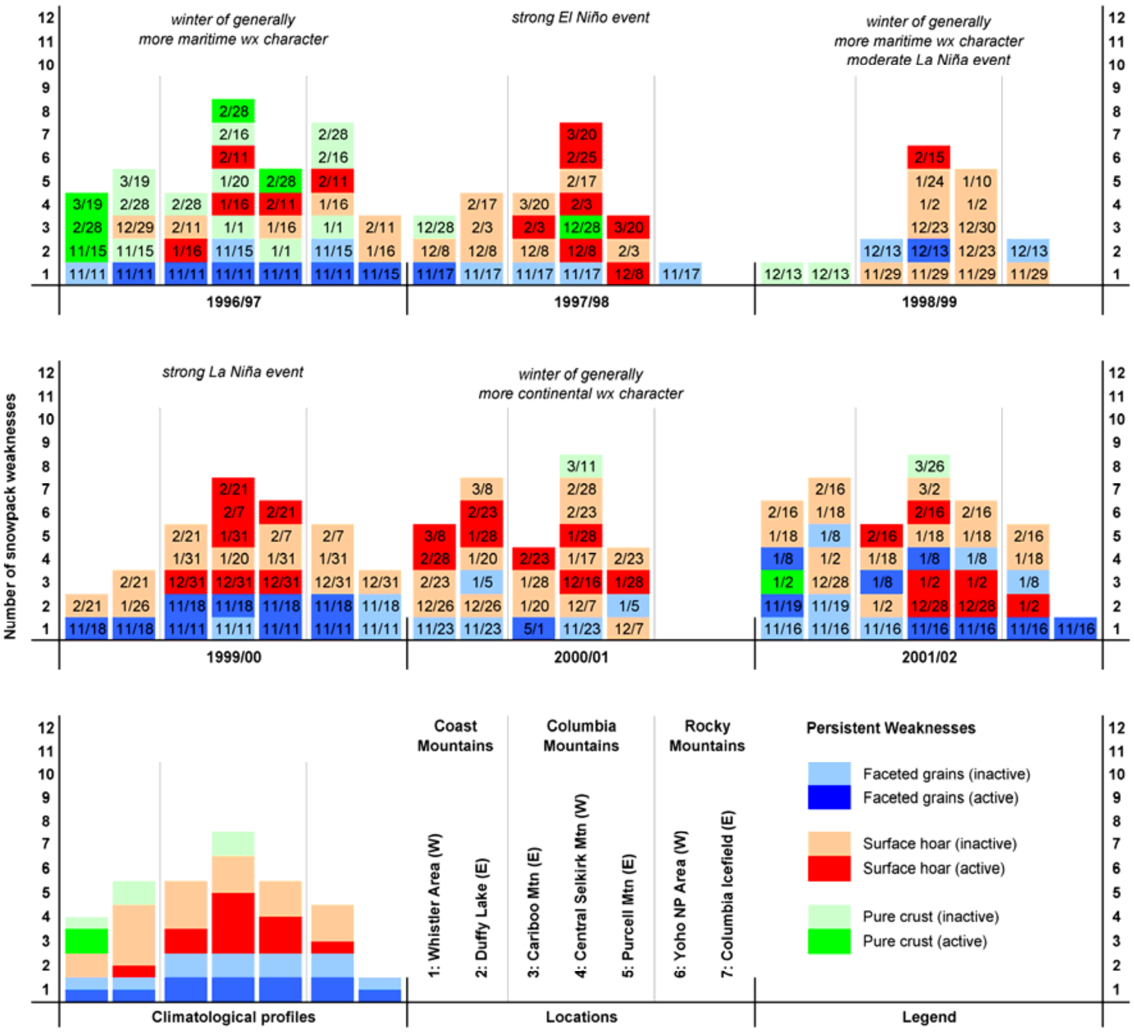


Figure 5.12:
Idealized snow profiles showing the frequency and sequence of active and inactive persistent weaknesses in different avalanche regime areas for the seasons 1996/1997 to 2001/2002. The labels show the burial date of the respective weakness. The bottom left panel presents tentative climatological profiles for the different avalanche winter regimes.

early season weak layer of faceted grains. These three winters together show 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 1996/1997 and 1998/1999. The first season was dominated by the November 11 facet-crust combination, a small number of surface hoar layers and numerous crust interfaces during the main winter months. The 1998/1999 winter, on the other hand, 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, 2000/2001, 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.

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 artefact of the reporting system, since depth hoar layers cannot easily be associated to specific burial dates. A rough analysis of avalanche bed surface types (within storm snow, old interface or ground; CAA, 2002) shows a significantly higher percentage of ground avalanches in the Rocky Mountains than in other areas (Figure 5.13), which might be interpreted as a potential increase in depth hoar avalanches. This interpretation supports the theory of the observation bias.

The analysis of the different winters shows 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. The results also show considerable, consistent variability within the traditional snow climate regions of the main mountain ranges. This emphasizes the conclusion that the snow climate classification is inadequate for capturing the characteristics relevant for describing the avalanche activity of a region effectively.

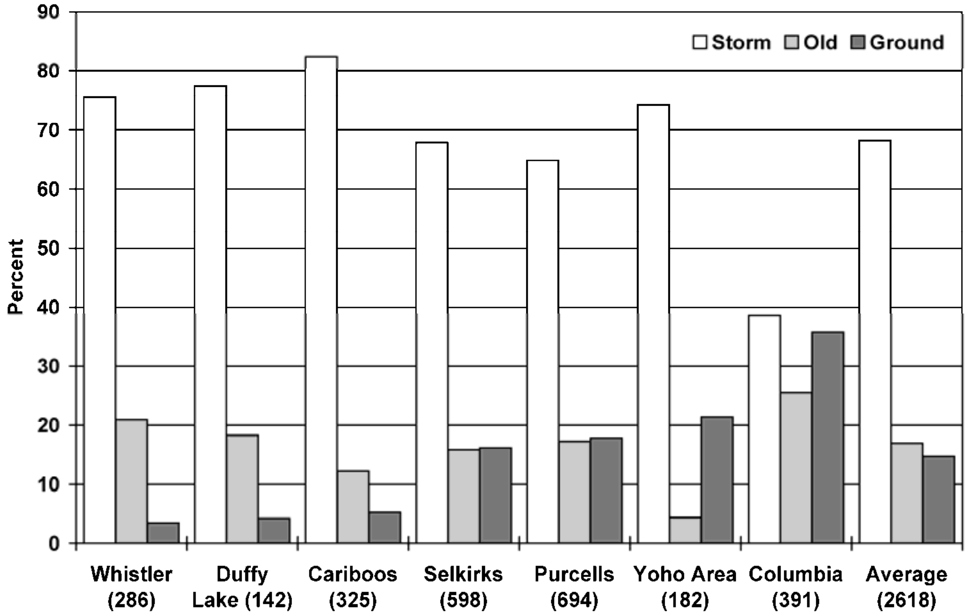


Figure 5.13:
Percentage of avalanche observations with bed surfaces within recent storm snow, on old interfaces and ground avalanches whenever recorded (only 6% of all avalanche records, seasons 1991/1992 to 2001/2002). Number in parentheses indicates number of avalanche observations with bed surface information.

Similar to the snow climate classification, there is no apparent relationship between ENSO and the observed seasonal patterns of persistent snowpack weaknesses (Figure 5.12). Recent research, however, has shown that ENSO and PDO have distinct influences on mean winter temperature variability (Bonsal and others, 2001) as well as the frequency and duration of winter temperature extremes over Western Canada (Shabbar and Bonsal, 2004). Other studies, such as Moore and others (2003) demonstrate that there are relationships between moisture transport anomalies and ENSO events over the North Pacific and Western North America. These results are encouraging. However, more seasons with reliable snowpack data are necessary to conclusively examine the importance of atmospheric oscillations on persistent snowpack weaknesses.

We suggest the term ‘avalanche winter regime’ as a new classification that describes the local characteristics of the expected avalanche activity. This classification should contain detailed information about the characteristics of expected avalanches 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 avalanches on persistent weaknesses (Table 5.2).

The snowpack weakness characteristics of the other regions (Table 5.1) show intermediate properties that can be interpreted as combinations of these three regimes. The climatological snow profiles (Figure 5.12) show that these regimes can vary from season to season, similar to snow climate characteristics. While there is no east-west shift of the climatological pattern during more maritime winters, the only continental winter does show a shift of the maximum number of surface hoar layers towards the Coast Mountains. We suspect that the main reason for the absence of these weaknesses in the Rocky Mountains is the very low humidity. Even a maritime influence cannot provide enough moisture to create persistent surface hoar weaknesses in this region.

Table 5.2:
Description of snowpack weakness characteristics of different avalanche winter regimes

Num	Avalanche winter regime area	Number of persistent weaknesses	Dominant persistent weaknesses
1	Whistler Area	3-4	Several pure crust interfaces
4	Central Selkirk Mtn	7	One facet-crust weak layer Several surface hoar weak layers
7	Columbia Icefield	1	One weak layer of faceted grains (potentially depth hoar)

Locations are indicated in Figures 5.5 and 5.11.

5.5 Conclusions and Outlook

The goal of this study was to identify a new avalanche winter classification that addresses aspects that are directly relevant for avalanche forecasting. The meteorological character of a winter including the sequence of events that produce persistent snowpack weaknesses is a significant feature in backcountry avalanche forecasting. This information is not formally included in any existing snow and avalanche climate classifications. Hence, they can only be of limited used for forecasting purposes.

The snow climate classification scheme of Mock and Birkeland (Mock and Birkeland, 2000) provided a good tool for characterizing average winter weather conditions across the study area. The overall classification agreed with existing assessments of the snow climate of the three main mountain ranges (e.g., McClung and Schaerer, 1993). Despite considerable spatial variability, the method allowed the identification of winters that showed homogeneous deviations from the climatological average conditions across the entire study area. Within the twenty-one winters covered by the study, five had a more continental character while three had more maritime influenced weather. Overall, the results agreed with the expectations and confirmed the general results presented by Gruber and others (in press [Chapter 4]). However, due to the significant variability observed within a mountain range and the fact that one local event can completely change the climate classification of a winter, we suggest that the snow climate classification should not be applied below the mountain range scale and that a number of weather stations should be used for the classification of a mountain range.

The focus of the study was the analysis of persistent snowpack weaknesses. The three main weaknesses are layers of faceted grain, surface hoar layers and pure crust layers. While all three types of weaknesses are generally widespread, avalanche activity related to each weakness type has distinct spatial characteristics. These observations clearly confirm the hierarchical concepts suggested by Hägeli and McClung (in press [Chapter 2]), where avalanche activity patterns are presented as the result of the interaction of the spatial patterns of all contributing processes at different scales. In the present study, we were only able to examine patterns at the largest scale, which are dominated by the sequence of large-scale weather events throughout an individual season. These large-scale patterns are overlain by a range of variabilities with smaller scale characteristics, such as aspect and elevation range patterns (see e.g., Hägeli and McClung, 2003 [Chapter 3]). These smaller scale variabilities could not be resolved with the dataset at hand.

Seasonal maps showing the distribution and frequencies of different snowpack weaknesses and their related avalanche activity across the study area revealed that patterns vary considerably depending on the weather character of the particular winter. However, even though the number of winters with reliable data is limited, it was possible to determine climatologically persistent patterns. The number of surface hoar weak layers emerged as the main distinguishing variable between different areas. The fact that the highest number of weak layers is found in the Columbia Mountains confirms the results of the preliminary weak layer study of Gruber and others (in press [Chapter 4]).

The analysis of idealized snow profiles revealed considerable differences in snowpack weakness composition between winters, even if classified similarly by the scheme of Mock and Birkeland (2000). Most dramatic are the differences in layer composition between the maritime seasons 1996/1997 and 1998/1999. In the same way, Whistler and Mount Fidelity (Central Selkirk Mountains) also exhibit considerably different weak layer characteristics, even though their snow climate classification was comparable.

In summary, the study shows that avalanche-relevant snowpack structures can be highly variable under similarly classified average winter weather conditions. The results confirmed that the existing snow climate classification is only of limited use to describe the resulting avalanche characteristics. To be truly useful for avalanche forecasting, a classification system has to include information about significant local snowpack weaknesses. An ‘avalanche winter regime’ was suggested as a classification system that specifically addresses local avalanche activity characteristics. The analysis of persistent weaknesses revealed three distinct snowpack weakness compositions for Western Canada. Numerous regions within the study area exhibit intermediate snowpack weakness characteristics.

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 and include more relevant parameters. In addition, more high-elevation meteorological observation sites are necessary to characterize the local sequence of weather events better and to conclusively explain the observed large-scale avalanche activity patterns. Meteorological indicators, such as the clear-night-cold-day index used in Gruber and others (in press [Chapter 4]) or the potential for facet-crust combinations of rain-on-snow events (Hägeli and McClung, 2003 [Chapter 3]) might provide means to identify and describe different avalanche winter regimes. Such indicators might also provide better means for examining the influence of atmospheric oscillations on the distribution of 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 (see Hägeli and McClung, in press [Chapter 2]), which will lead to improved quality and delivery of large-scale avalanche forecast products, such as the public avalanche bulletins or industrial information exchanges, such as the InfoEx.

5.6 References

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CHAPTER 6

CONCLUSIONS

Information about existing persistent snowpack weaknesses including their trigger potential and characteristics of related avalanches are crucial for backcountry avalanche forecasting. Including detailed information about these weaknesses, however, adds considerable complexity to the forecasting task. While avalanches occurring within new snow can be linked to individual storms, avalanches on persistent weaknesses are the result of a longer and more complex process. Avalanches are caused by the interaction of numerous factors that act over wide ranges of different spatial and temporal scales. While avalanche practitioners, such as mountain guides, have developed successful strategies to deal with the multi-scale characteristics of the avalanche phenomenon, this complexity has yet to be explicitly incorporated into formalized avalanche forecasting approaches. The goal of this research was to examine the scale characteristics of avalanches on persistent snowpack weaknesses in the context of backcountry avalanche forecasting. The following sections summarize the main conclusions of the research presented in this thesis. The chapter concludes with an outlook for future research possibilities.

6.1 Scaling and Scale Issues

The relationship between the scale of input parameters and the scale of the resulting output is a crucial aspect of a forecast approach. Chapter 2 (Hägeli and McClung, in press) presented a framework for conceptualizing the interactions of different factors that contribute to avalanches at a variety of scales based on hierarchy theory (Ahl and Allen, 1996). The two-dimensional framework consists of a temporal hierarchy with seven levels representing the main groups of contributing factors. Within each of these levels there is an embedded spatial hierarchy.

Observed avalanche activity exhibits spatial patterns that can be viewed as the result of the combination of spatial patterns of factors contributing to avalanches. The short discussion about scale characteristics of the main contributing factors presented in Chapter 2 (Hägeli and McClung, in press) suggested that the spatial patterns of avalanche activity can exhibit spatial variabilities on a wide range of scales. In an ideal world, it would be necessary to include information from all factors at a specific scale to produce a valid forecast at that scale. In reality, however, it is often not possible to obtain data at the required scale and scaling becomes necessary. While avalanche professionals have developed intuitive skills that enable them to use information across scales, scaling of information has to be incorporated explicitly into formalized forecasting models. To ensure the resulting model output is still relevant, the scaling has to be process-oriented and incorporate information of the new scale. An example of scaling in avalanche forecasting models is the combination of large-scale weather data and small-scale avalanche observations in the nearest neighbour method (see, e.g., Buser and others, 1987; McClung and Tweedy, 1994). The historic avalanche observations used in these models indirectly contain small-scale information of all contributing factors. This justifies the usage of the model on the avalanche path scale, even though the operational input parameters are mainly synoptic scale weather observations.

The hierarchy framework presented in Chapter 2 provides a reference system for the discussion of scale and scale issues in avalanche forecasting and may facilitate the design of future monitoring networks and forecast models.

6.2 Scale Characteristics of Avalanche Activity on Persistent Snowpack Weaknesses

In order to incorporate information about persistent snowpack weaknesses properly into future forecasting models, it is necessary to know more about their scale characteristics. Chapter 3 (Hägeli and McClung, 2003) and Chapter 5 examined the spatial and temporal characteristics of persistent snowpack weaknesses in Western Canada. The following questions were addressed in detail: 1) What are the most important types of persistent weaknesses? 2) What are the temporal avalanche activity characteristics of the different weakness types? and 3) What are the different spatial activity patterns?

The avalanche datasets used to examine these questions are the SNOWBASE data of Canadian Mountain Holidays (CMH) in Chapter 3 (Hägeli and McClung, 2003) and the InfoEx data of the Canadian Avalanche Association (CAA) in Chapter 5. In both chapters, it was pointed out that avalanche datasets are inherently incomplete (see also Laternser and Schneebeli, 2002), which imposes significant limitations on data analysis and interpretation. As a consequence, geostatistical methods were not applicable, forcing mainly descriptive analyses

The analyses identified three main types of persistent snowpack weaknesses in Western Canada. Weak layers of faceted grains including facet-crust combinations and surface hoar layers were clearly identified as the two main types. Pure crust interfaces, a third weakness type, is considerably less important that the previous two types.

Chapter 3 (Hägeli and McClung, 2003) mainly focused on the temporal activity patterns of the two main types of weaknesses. The SNOWBASE data were used to examine the temporal avalanche activity patterns of 31 different weaknesses observed in the Columbia Mountains (see Appendix B). The study showed that, in this region, significant weaknesses of faceted grains most often appear as facet-crust combinations. They frequently form during the early season after rain-on-snow events and their related persistent avalanche activity is intermittent and generally persists throughout the entire season. Surface hoar layers, on the other hand, typically exhibit one to three distinct avalanche cycles soon after burial and the activity generally decreases after three to four weeks.

Chapter 5 focused on the spatial patterns of persistent snowpack weaknesses and related avalanche activity. Based on the InfoEx dataset, 56 individual weaknesses were examined (see Appendix E). The analysis showed that significant persistent weaknesses are generally widespread and observed across considerable portions of the study area (Western Alberta and British Columbia). Their areas of related persistent avalanche activity are, however, usually significantly smaller and the different weakness types generally exhibit distinct activity patterns. While the avalanche activity on facet-crust weakness is generally more widespread but heterogeneous, the activity on surface hoar layers is usually more concentrated in a core area. Pure crust interfaces show patterns similar to the ones exhibited by facet-crust combinations. These differences in spatial activity patterns were explained with the different scale characteristics of the related main formation processes. While precipitation processes exhibit significant small-scale variabilities (Foufoula-Georgiou and Venugopal, 2000), the conditions necessary for the formation of surface hoar (clear and calm weather, nearby moisture source) are generally more homogenous and widespread.

In addition to the large-scale spatial patterns summarized above, avalanche activity on persistent weaknesses also exhibits numerous embedded, smaller-scale variabilities. Chapter 3 (Hägeli and McClung, 2003) briefly touched on some of these patterns. For example, surface hoar weaknesses on northern aspects are often observed together with weak pure crust interfaces on south-facing slopes. This pattern is clearly the result of solar radiation, which melts the developing surface hoar crystals on sunny aspects during the daytime. Another similar example is the observation that the persistent avalanches on surface hoar layers in the Columbia Mountains are often concentrated in a narrow elevation band around treeline (see also Schweizer and others, 1996).

The observations presented show that avalanche activity exhibits a variety of spatial and temporal patterns depending on the main contributing factors. The identified patterns help to confirm the idea of overlying patterns presented in Chapter 2 (Hägeli and McClung, in press).

6.3 Avalanche Winter Regimes

The three snow climate types, namely maritime, continental and transitional (McClung and Schaerer, 1993) are well established and have been used in many studies to describe the local characteristics of the snowpack and the resulting avalanche activity. The classification scheme of Mock and Birkeland (2000) was applied to the Columbia Mountains in Chapter 3 (Hägeli and McClung, 2003) and more widely across Western Canada in Chapter 5. The analyses confirmed the existing characterisations of the three main mountain ranges: the maritime Southern Coast Mountains, the continental Rocky Mountains and the transitional Columbia Mountains. Chapter 4 (Gruber and others, in press) examined the climatological large-scale patterns of resulting snow instability, which confirmed the existing perception of the snow climate regions with the Coast Mountains having the most stable and the Rocky Mountains the least stable snowpack.

The snow climate classification of Mock and Birkeland (2000) focuses mainly on average meteorological conditions and can only give rough descriptions of expected avalanche activity. The classification is therefore only of limited use for avalanche forecasting purposes. It is the comprehensive character of a winter including the sequence of events that produce persistent weaknesses that is of crucial importance for backcountry avalanche forecasting. An ‘avalanche winter regime’ was suggested as a new term that can be used to specifically describe the avalanche characteristics observed in an area during a winter season. The description of an avalanche winter regime should include information about the dominant persistent weaknesses and discuss the characteristics of the related avalanche activity.

The analysis presented in Chapter 3 (Hägeli and McClung, 2003) showed that depending on the character of the winter, persistent weaknesses are responsible for up to 40% of the recorded avalanche activity in the Columbia Mountains. The quality of the InfoEx dataset did not allow a similar analysis for the other mountain ranges.

In Chapter 5, the avalanche activity on relevant snowpack weaknesses was examined across Western Canada in relation to existing snow climate classifications for six different winters (see Appendix F). While facet-crust combinations are generally observed across the entire study area, the number of persistent surface hoar layers emerged as the main distinguishing factor among different regions. The maximum number of surface hoar layers was generally found on the western side of the central Columbia Mountains. The fact that this maximum was found in a region of a transitional snow climate clearly deviates from the traditional snow climate type definition and shows that the observed avalanche characteristics in this area are clearly more than a simple combination of maritime and continental influences. Similarly, an analysis of different winters showed that the local composition of persistent weaknesses can be significantly different, even among winters of similar average winter weather. Both of these results clearly justify the definition of the ‘avalanche winter regime’ as a new term to describe the local avalanche characteristics.

Based on persistent weaknesses examined in Chapter 5, three main avalanche winter regimes can be identified for the study area. The avalanche winter regime in the Whistler area is characterized by a low number of persistent weaknesses. The most dominant weaknesses are pure crusts and facet-crust combinations. The Selkirk Mountain regime exhibits the largest number of persistent weaknesses. Typically, there are one or two facet-crust combinations and several surface hoar layers observed in this area. The avalanche winter regime on the eastern side of the Rocky Mountain displays the lowest number of persistent weaknesses. As pointed out in Chapter 5, this result might be caused mainly by an observational bias. The other locations presented in the analysis exhibit intermediate avalanche winter regime characteristics.

Chapter 5 contains only a preliminary definition of avalanche winter regimes in Western Canada, due to the limited number of winters with reliable avalanche observations. A more detailed avalanche winter regime classification system should allow a more process-oriented division of Western Canada into regions of similar avalanche characteristics. Meteorological indicators, as proposed in Chapter 4 (Gruber and others, in press), might provide means to identify and describe some aspects of the different regimes. This research may lead to improvements in large-scale forecasting programs, the quality and delivery of public avalanche bulletins and the structure of the industrial information exchange.

6.4 Outlook

This thesis has addressed numerous aspects of backcountry avalanche forecasting. A hierarchical framework was proposed for discussing scaling and scale issues in avalanche forecasting, the scale characteristics of persistent snowpack weaknesses were examined and the term ‘avalanche winter regime’ was suggested for describing the characteristics of a given winter relevant to avalanche forecasting. All results presented in this thesis are only small steps in the effort of improving backcountry avalanche forecasting methods.

While the hierarchical framework presents a reference system for discussing scale issues in avalanche forecasting, the scaling problem is still largely unsolved. To make the most use of forecast models for avalanche professionals it is necessary to address in detail the scale issue of inter- and extrapolation of information. Output from larger-scale models, such as the Safran-Crocus-MÉPRA model chain (Durand and others, 1999), has to be down-scaled in a useful manner, while point simulations, such as the Swiss SNOWPACK model (Lehning and others, 1999), have to be extrapolated to the neighbouring terrain. Without addressing this issue of scale adequately, these modeling efforts will be only of limited use for applied avalanche forecasting. More field research is needed to examine the spatial characteristics of relevant measurements taken and to determine their optimal use for forecast purposes. Numerous studies have addressed variabilities at the small scale (Jamieson, 1995; Landry, 2002; Pielmeier, 2003). While Chapter 3 (Hägeli and McClung, 2003), 4 (Gruber and others, in press) and 5 examined the large-scale characteristics of avalanches, more knowledge is necessary at the intermediate scale of individual drainages and small mountain ranges. The only existing studies at the intermediate scale are the works of Birkeland (1997) and Kronholm (2004).

Elevation and aspect are often used to describe spatial patterns in forecast models and avalanche advisories (see, e.g., Safran-Crocus-MÉPRA output in Durand and others, 1999). While this description of patterns is relatively easy to incorporate into models, research on decision-making of helicopter-ski guides (Grimsdottir, 2004) has shown that smaller-scale terrain characteristics are often considered to be equally important for the forecasting process. Future studies should examine whether there are more effective terrain classifications to express spatial patterns in avalanche forecasts.

Chapters 3 (Hägeli and McClung, 2003) and Chapter 5 emphasized the importance of information about snowpack weaknesses for backcountry avalanche forecasting at all scales. Both studies focused mainly on the large-scale characteristics of weak layers, but also showed that there exists a full spectrum of variabilities. This raises the question of how snow profile and weakness information can be included effectively in forecast models at different scales. Existing snow profile interpretation methods (see Schweizer and Wiesinger, 2001; Schweizer and Jamieson, 2003) assign snow stability ratings to observed snow profile characteristics. Such an interpretation dramatically reduces the information content and important information about snowpack weaknesses is lost in the process. Other methods classify the snow profile type (de Quervain and Meister, 1987) or identify and rank significant weaknesses in an observed profile, such as the expert system presented by McClung (1995). More research is necessary to find methods to effectively generalize observed snow profile information to minimize the effect of unwanted small-scale influences, while, at the same time, preserve important information about relevant snowpack weaknesses. Avalanche professionals often draw idealized snow profiles to conceptualize the general conditions based on numerous observations of the day. This complex process includes aspects of interpolation and up-scaling. It may be beneficial to examine and potentially formalize this process for modeling and visualization purposes.

In Chapter 5, 'avalanche winter regimes' were suggested as a classification scheme for describing the character of an avalanche winter. The analysis revealed the existence of three main types of avalanche winter regimes in Western Canada, but the limited number of winters with reliable avalanche observations allowed only a preliminary description of their characteristics. The surface hoar dominance observed in the Columbia Mountains might be a peculiarity of the area. More studies are necessary to confirm the regime types found and describe them in more detail. More high-quality meteorological data are necessary to design more sophisticated indicator variables. In addition, studies in other geographic areas are needed to generalize the regime types found in Canada. As an example, the San Juan Mountains in southwestern Colorado might be another geographic area of high interest for such a study due to the local importance of near-surface faceting (LaChapelle and Armstrong, 1976; Birkeland, 1998) for the formation of persistent weaknesses. The research resented encourages a process-oriented classification scheme for the description of local avalanche characteristics that can provide relevant local information to avalanche professionals.

More research is necessary to examine the effect of atmospheric oscillations, such as El Niño–Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO) or the Pacific Decadal Oscillation (PDO), on avalanche winter regimes and snow stability. While the effects of ENSO on temperature (e.g., Bonsal and others, 2001; Shabbar and Bonsal, 2004) and precipitation (e.g., Moore and others, 2003) patterns in Western North America have been shown separately, the effects on avalanche winter regimes and snow stability have not been studied. Due to the limited number of winters with reliable data, the results presented in Chapter 5 can only be viewed as being preliminary. More reliable snowpack data are necessary to examine the effects of atmospheric oscillations on avalanche winter regimes and snow stability in detail.

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