SPATIAL AND TEMPORAL DISTRIBUTION OF AVALANCHE PROBLEM TYPES IN WESTERN CANADA: AN ANALYSIS OF THE WINTERS 2010-2016

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ABSTRACT: Not all avalanches are the same. Different combinations of snowpack structures and meteorological conditions create different types of avalanche problems with distinct risk scenarios. In North America, the Conceptual Model of Avalanche Hazard (CMAH) identifies nine distinct types of avalanche problems (also referred to as 'avalanche characters') Examples include 'persistent slab avalanche problems' or 'wind slab avalanche problems'. Having a detailed understanding of the prevalence and character of the avalanche problem types in different regions and during different winters can provide valuable information on the nature and variability of avalanche hazard conditions in western Canada. Since the CMAH was introduced into the production of public avalanche bulletins in Canada in 2010, the public bulletin datasets from Avalanche Canada and Parks Canada from 2010-2016 offers a unique opportunity for examining the character of avalanche hazard in western Canada more comprehensively. In this paper, we present a first quantitative analysis of this dataset with a focus on the prevalence and nature of the nine different avalanche problem types. Our results mainly confirm our experiential understanding of the role of the nine avalanche problem types in the different mountain ranges, different seasons, and their differences in nature. However, our analysis provides an important new perspective into the snow and avalanche climates of western Canada and builds the foundation for improving our understanding the components of the CMAH and the development of future decision aids for avalanche forecasters.

KEYWORDS: avalanche danger; avalanche forecasting; avalanche hazard; avalanche problems.

1. INTRODUCTION

Not all avalanches are the same. Different combinations of snowpack structures and meteorological conditions create different types of avalanche problems that have been linked to distinct risk treatment techniques (e.g. avalanche control, terrain selection, ski cutting) (Haegeli et al., 2010; Statham et al., under review).

The first study distinguishing between different of avalanche problems is Armstrong and Armstrong (1986). While incomplete avalanche records prevented the identification of significant patterns, their paper initiated the discussion about differences in the nature of avalanches and avalanche hazard (storm and non-storm) among the three traditional snow avalanche climates, maritime, continental and intermountain (also known as transitional).

The concept of avalanche character types was further developed by Atkins (2004), who highlighted its importance for avalanche risk management at commercial backcountry operations and improving communication of complex and subtleties of avalanche hazard in general. Atkins (2004) developed a tool, "avalanche characterization checklist", that linked types of avalanche with typical avalanche sizes and description of typical location features where these avalanches could be located.

The Conceptual model of Avalanche Hazard (CMAH) developed by Statham et al. (under review) further developed the ideas of Atkins and developed a comprehensive framework that describes the flow and key components of the avalanche hazard assessment process. The CMAH separates avalanche hazard into four main components: *what* is the types of the avalanche problem, *where* in the terrain can the problem be found, what is the *likelihood of triggering* an avalanche of the particular type, and what is the *expected size* of these potential avalanche (Statham et al., in review).

The concept of avalanche problem type is a central component of the CMAH as it provides an

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overarching filter that highlights in what terrain the different problems can most likely be found, what types of observations are most suitable for their assessment and how they are most effectively managed in the field. The CMAH defines nine different types of avalanche problem types:

- Storm slab avalanches
- Wind slab avalanches
- Persistent slab avalanches
- Deep persistent slab avalanches
- Wet slab avalanches
- Wet loose snow avalanches
- Dry loose snow avalanches
- Cornices
- Glide slab avalanches
  (later addition which is not included in the analysis presented in this paper)

For more details the definition and characteristics of the different avalanche problem types see Haegeli et al. (2010) and Statham et al. (under review).

Around the same time, public avalanche safety programs in Europe also introduced avalanche characterization into their public avalanche bulletins. Avalanche bulletins in Switzerland characterize four *typical avalanche situations,* (new snow, wind-transported snow, wet snow, and old snow) (Harvey et al., 2009). In Austria, Mair and Nairz (2010) identified ten *avalanche danger patterns* that are typically associated with avalanche accidents. Examples are early season surf hoar, rain, cold after warm or warm after cold, snowfall after cold spell, etc.

The CMAH has now become an essential part of the daily workflow of nearly all avalanche safety programs in Canada. To initially test the operational benefits of the CMAH, Haegeli (2008) developed an online wizard that guides avalanche safety operations through their assessment process according to the CMAH. The adoption and response was overwhelmingly positive and in 2011, Parks Canada formally implemented the CMAH into their production of public avalanche bulletins by integrating it into the newly developed the public avalanche forecasting software AvalX (Statham et al., 2012). In 2013, the CMAH was further integrated into the InfoEx (Haegeli et al., 2014), the daily exchange of observations and assessments among professional avalanche safety programs in Canada.

The use of the CMAH as the foundation of Canadian avalanche bulletins since 2010 provides a new opportunity for studying the nature of avalanche hazard in Canada. Having a detailed understanding of the prevalence and character of the avalanche problem types in different regions and winters provides a closer link to risk management practices that goes beyond the traditional snow climate definitions of maritime, continental and transitional.

The objective of this paper is to provide a first overview of the nature of the different avalanche problem types in western Canada. Using the public avalanche bulletin achieve from 2010-2016 for analysis. We a) examine the prevalence of avalanche problem types, and b) variations in likelihood of triggering and expected size of the individual avalanche problem types.

2. DATA

2.1 Study location

The three main mountain ranges of western Canada—the Coast, Columbia, and Rocky Mountains—are each characterized by a distinct set of snow and avalanche climate characteristics. The Coast Mountains in the west exhibit a maritime snow climate that is characterized by relatively warm temperatures, cloudier skies, and heavier snowfall resulting in fewer weak layers. Avalanche activity occur mostly during or immediately after a storm and the prevalence of warm temperatures promote rapid stabilization (McClung and Schaerer, 2006).

The Rocky Mountains in the east have a continental snow climate, which is characterized by colder temperatures, more clear skies, less snowfall, and relatively thin snowpack, which is conducive to the formation of depth hoar and persistent weak layers. Major avalanche activity is often associated with persistent structural weaknesses within the snowpack, which is distinctly different from the natural of avalanche activity in areas with maritime snow climates (McClung and Schaerer, 2006).

The Columbia Mountains, which are located between the Coast and the Rocky Mountains, exhibit a transitional snow climate with features typical of both, maritime and continental, snow climates. However, Haegeli and McClung (2007) show that the area also has distinct characteristics, such as the frequent presence of persistent surface hoar layers.

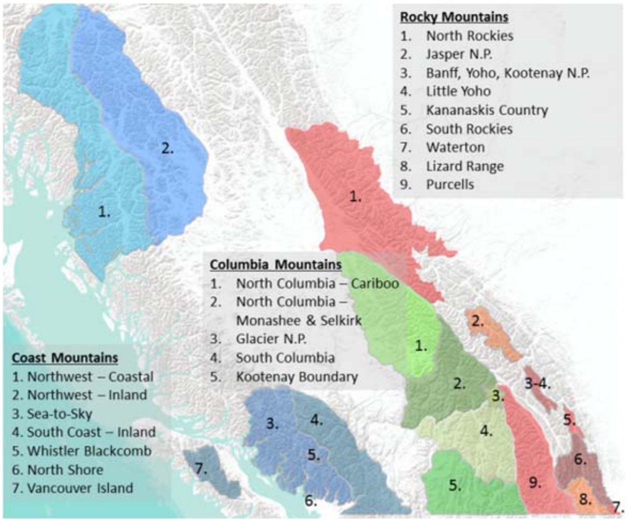


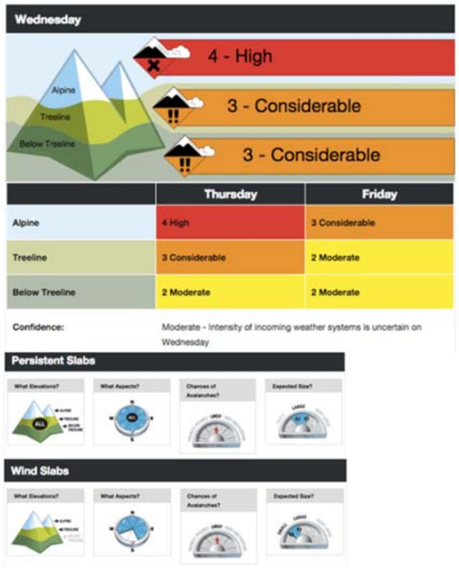
Fig. 1: Public avalanche bulletin forecast regions in western Canada.

2.2 *Data set*

The dataset for this study consists of archived daily public avalanche bulletins from Avalanche Canada (formally Canadian Avalanche Center) and Parks Canada from 2009/10 to 2015/16 and 2011/12 to 2015/16 respectively.

Avalanche Canada publishes daily avalanche bulletins for 22 forecast regions across all mountain ranges in western Canada and the Mountain Safety Program of Parks Canada publishes daily bulletins for five forecast regions (four in the Rocky Mountains and one in the Columbia Mountains) (Fig. 1).

The combined dataset from Avalanche Canada and Parks Canada consists of 12070 public avalanche bulletin records according to the CMAH for 27 different forecast regions. The bulletin records include 13678 avalanche problem assessments for the alpine, tree line, and below tree line elevation bands. An example of a Canadian public avalanche bulletin with avalanche problem information is shown in Fig. 2. Numerous forecast regions are only serviced with infrequent bulletins or bulletins of reduced content (North Shore, North Rockies, Bighorn Country, Vancouver Island, Whistler Blackcomb, and the Yukon forecast regions). To ensure a consistent dataset, we excluded the bulletins from these regions from the analysis dataset. The final dataset for statistical analysis consisted of 10651 public avalanche bulletin records spanning seven winters from 20 forecast regions aggregated into three main mountain ranges (Fig. 1).


Wednesday

Alpine 4 - High

Treeline 3 - Considerable

Below Treeline 3 - Considerable

	Thursday	Friday
Alpine	4 High	3 Considerable
Treeline	3 Considerable	2 Moderate
Below Treeline	2 Moderate	2 Moderate
Confidence:	Moderate - Intensity of incoming weather systems is uncertain on Wednesday	

Persistent Slabs

Wind Slabs

Fig. 2: Example of a public avalanche bulletin format for Avalanche Canada and Parks Canada.

3. METHODS

All data manipulations and statistical analysis presented in this paper were performed in R (R Core Team, 2015) and all statistical tests were evaluated at α = 0.05 significance level.

3.1 *Avalanche problem prevalence*

To provide an overview of the general nature and variability of avalanche hazard conditions in western Canada, we first explored the prevalence of avalanche problem types. We defined the avalanche problem prevalence as the percentage of avalanche bulletins that included avalanche problems of the particular type. To examine spatial and temporal variabilities we calculated separate prevalence values for individual forecast regions, elevation bands and winter seasons. To ensure that the overall summary statistics of prevalence are not dominated by forecast regions or seasons with larger number of bulletins, percentages for each season and each region were calculated first before they were aggregated into overall summary statistics.

We used Pearson's chi-squared tests to evaluate how the prevalence of each avalanche problem type differs among the following spatial and temporal scales:

- Elevation bands
- Three main mountain ranges
- Winter seasons

For the present paper, we limited our analyses on differences among mountain ranges and seasons to the alpine elevation band.

3.2 *Avalanche hazard characterization*

The CMAH visualizes the estimates of likelihood of triggering and destructive size of the identified avalanche problems combined in a single hazard chart (Fig. 3). While the center point of the squares for each avalanche problem represents their respective estimated typical value for likelihood of triggering and destructive size, the left/lower and right/upper limits represent the estimated minimum and maximum values to account for forecasted uncertainty and physically variability (Statham et al. in review).

While it is common practice in AvalX and InfoEx to display avalanche problems in the hazard chart as ellipses, Haegeli et al., (2012) suggest that hazard rectangles may be more appropriate since the maximum values of likelihood of triggering and destructive size (i.e., the top right corner of the hazard square) has the strongest influence on the hazard ratings. We therefore chose to represent avalanche problems as squares in our analysis.

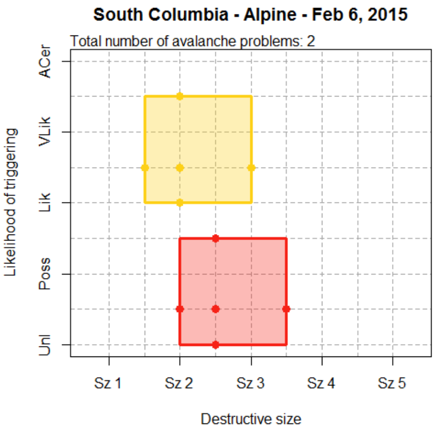


Fig. 3: Example of a hazard plot showing the hazard rectangle for a storm slab avalanche problem (yellow) and a persistent slab avalanche problem (red).

To examine differences in the general location of avalanche problem types on the hazard chart, we prepared summary hazard charts where each grid cell of the chart shows the counts or percentages of a particular type of avalanche problem squares covering it. To test for differences, we the cut the resulting two-dimensional distribution along the vertical axis (likelihood of triggering) and horizontal axis (destructive size) through the gird cell with the maximum count. To check for differences in median values and shape of distribution (i.e., wider or narrower) we applied the Wilcoxon rank-sum test and the Kolmogorov–Smirnov test respectively to the count values along these axes.

4. RESULTS & DISCUSSION

4.1 *Avalanche problem prevalence*

Wind slab avalanche problems emerge as the most prevalent (occurring in 63% of bulletins) when examining the prevalence of avalanche problems across all seasons and all regions (Fig. 4). They are followed by persistent slab avalanche problems (49%), storm slab avalanche problems (37%), cornices (24%), deep persistent slab avalanche problems (22%), loose wet snow avalanches (20%), loose dry snow avalanches (7%) and wet slab avalanche problems (2%).

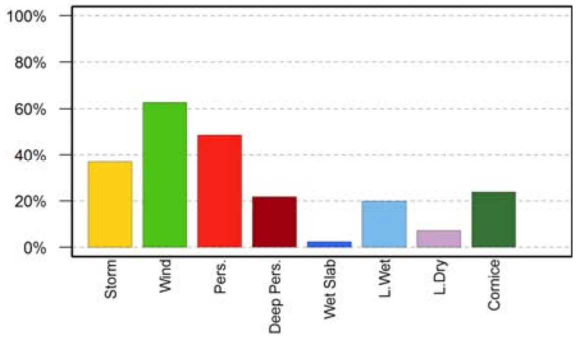


Fig. 4: Overall avalanche problem prevalence[1].

The results of the Pearson chi-squared comparisons for the prevalence of individual avalanche problem types among elevation bands revealed significant differences (p-value < 0.05) for all avalanche problem types. The most striking differences include (Fig. 5):

- Wind slab avalanche problems are most prevalent in the alpine and tree line (63% & 55%) while occurring in 5% of bulletins below tree line.
- Similarly, cornice problems occur most often in the alpine (24%), seldom at tree line (7%), and never below tree line (0%).

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[1] Abbreviations for avalanche problem types in Figures:
- Storm: Storm slab avalanche problems
- Wind: Wind slab avalanche problems
- Pers.: Persistent slab avalanche problems
- DPers.: Deep persistent avalanche problems
- WetS: Wet slab avalanche problems
- LWet: Loose wet avalanche problems
- LDry: Loose dry avalanche problems
- Corn: Cornice fall problems

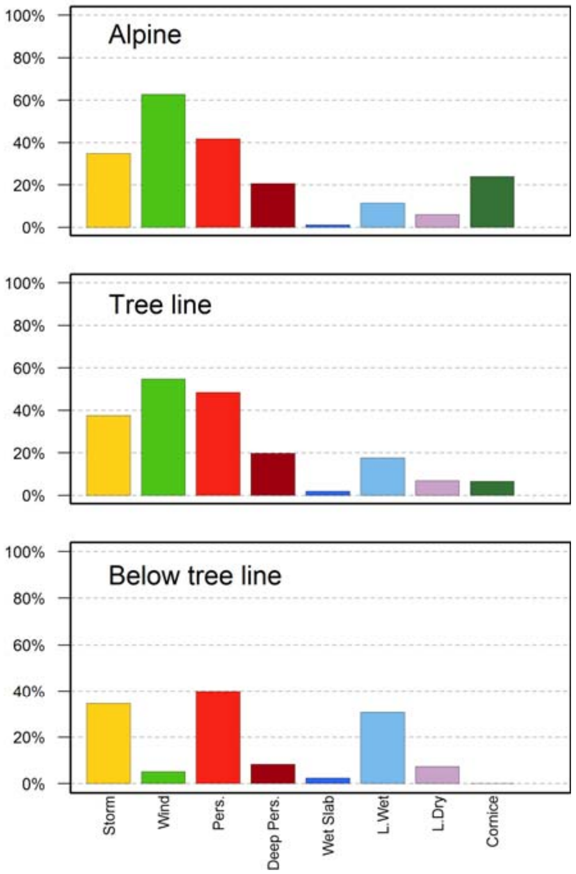

Fig. 5: Variability of prevalence in avalanche problem type by elevation bands.[1]

- Persistent slab avalanche problems occur more at tree line (48%), than in the alpine (42%) or below tree line (40%), while deep persistent slab avalanche problems occur more frequently in the alpine and tree line (21%, 20%) than below tree line (8%).
- Wet slab and loose wet avalanche problems increase as elevation decreases, from 1% and 12% in the alpine to 2% and 31% below tree line respectively.

Similar to the analysis by elevation bands, all the results of the Pearson chi-squared comparisons for the prevalence of individual avalanche problem types in the alpine elevation band among the main mountain ranges revealed significant differences ($p\text{-value} < 0.05$) for all avalanche problem types. For this comparison, the most striking differences include:

- Storm slab avalanche problems occur more in the Coast and Columbia mountain ranges (both 42%) than in the Rocky Mountains (26%).

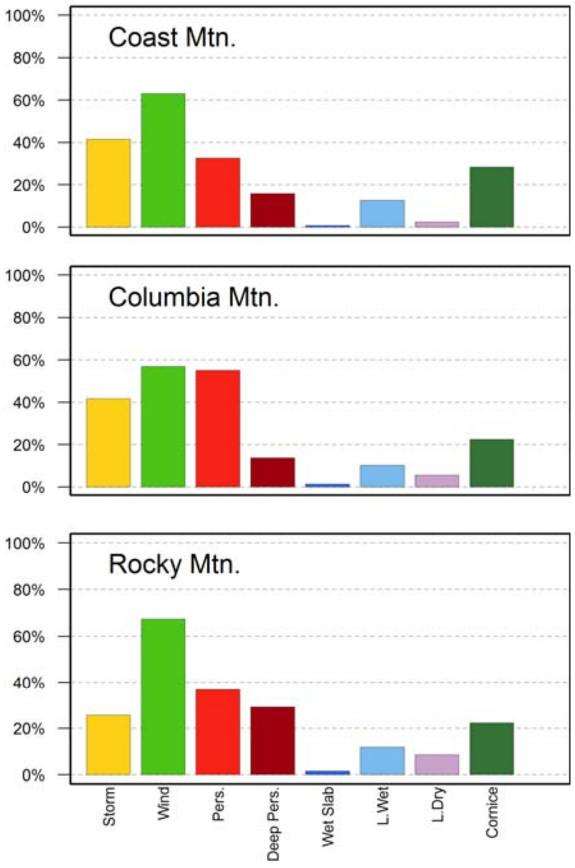

Fig. 6: Horizontal spatial variability of prevalence in avalanche problem type separated by general mountain range: Coast, Columbia, and Rocky Mountains.[1]

- Wind slab avalanche problems are most prevalent in the Rocky Mountains (67%), followed by the Coast Mountains (63%) and the Columbia Mountains (57%).
- Persistent slab avalanche problems are most prevalent in the Columbia Mountains (55%), less prevalent in the Coast and Rocky Mountains (33% and 37%) whereas deep persistent slab avalanche problems are most prevalent in the Rocky Mountains (29%), compared to Coast (16%) and Columbia Mountains (14%).
- Cornice problems occur more frequently in the Coast Mountains (28%) than the Columbia and Rocky Mountains (both 22%).

Examining the year-to-year variability in prevalence of individual avalanche problem types in the alpine elevation by general mountain range also reveals numerous interesting patterns. While all of the Pearson's chi-square tests for prevalence versus season revealed significant year-to-year

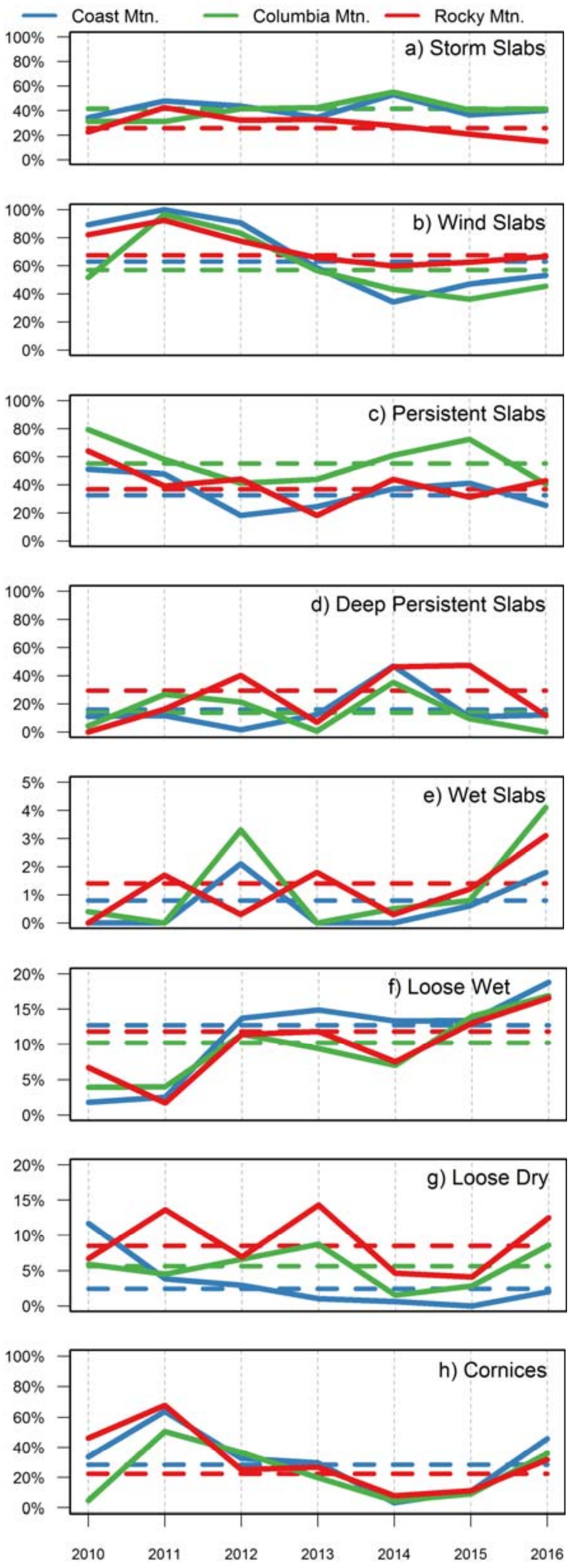

Fig. 7: Seasonal variability in the prevalence of individual avalanche problem types by mountain range. Dashed lines show averages. Note the different y-axis scale.

differences (p-value < 0.05), it is beyond the scope of this paper to describe all identified variabilities. Some of the most interesting observations include:

- In comparison to other avalanche problems, the prevalence of storm snow avalanche problems is relatively consistent throughout the study period (Fig. 7a).
- The seasonal prevalence of wind slab avalanche problems (Fig 7b) is highly variable with values ranging from 34% to 100%. The prevalence of winds slab problems in the Rocky Mountains exhibit less variability than the other mountain ranges. Winds slab problems were particularly prevalent during the 2010/11 winter season.
- The prevalence of persistent slab avalanche problems shows a similar degree of seasonal variability as wind slabs (Fig 7c). Particularly noteworthy are the winter seasons 2009/10 which saw above average prevalence of persistent slab avalanche problems in all mountain ranges and the winter season 2014/15 with an above average prevalence of persistent slab avalanche problems in the Columbia Mountains.
- The seasonal prevalence of deep persistent slab avalanche problems (Fig 7d) shows considerable variability. Of notice is that the prevalence of deep persistent slab avalanche problems was above average in the Rocky Mountains during the 2013/14 and 2014/15 winter season. This means that the combined prevalence of deep persistent and persistent slab avalanche problems was above average consistent with the above average prevalence of persistent slab avalanche problems in the Columbia Mountains during the 2014/15 seasons.
- Even though the average prevalence of wet slab avalanche problems is relatively low (Fig. 7e), we observe considerable seasonal variability.
- The seasonal variability in the prevalence of loose wet snow avalanches (Fig. 7f) is surprisingly similar among the three mountain ranges.
- Even though we have not yet explicitly tested for trends, there are visual indications of an increasing prevalence in wet slab and loose wet avalanche problems in all mountain ranges.

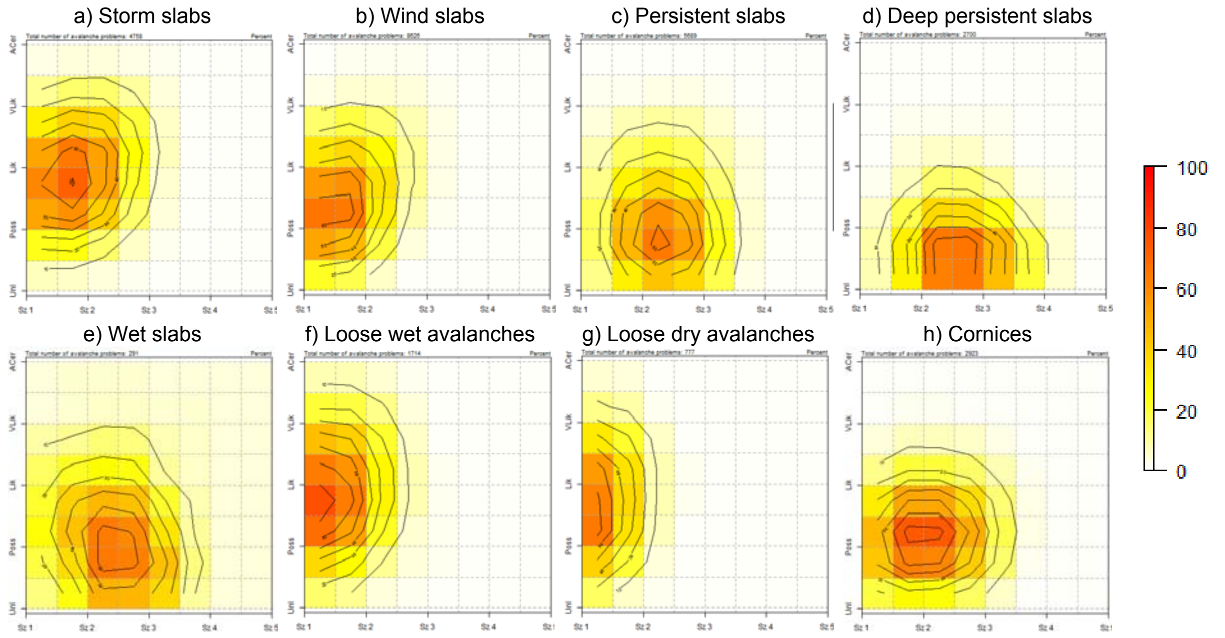

Fig. 8: Avalanche hazard summary chart for individual avalanche problem types in the alpine elevation band for all seasons and forecast regions. Shading of individual grid cells goes from white (0% of avalanche problem squares in this cell) to red (all avalanche problem squares in this cell). Contour lines at 10% intervals enhance the visibility of the spatial patterns.

- There is considerable seasonal variability in the prevalence of loose dry snow avalanches.
- Similar to the loose wet snow avalanche problems, the temporal pattern in the prevalence of cornices is surprisingly similar between the different mountain ranges.

4.2 *Characterizing Avalanche Hazard*

The visual examination of Fig. 8 and the results of the Wilcoxon rank-sum and Kolmogorov–Smirnov tests for comparing the distributions on the summary hazard chart between combinations of different avalanche problem types reveal significant differences between most types (p-value < 0.05) with a few notable similarities.

In general, storm slab avalanche problems exhibit the highest likelihood to triggering (peak at likely) and are expected to produce up to medium-sized avalanches (Fig. 8a). The chart for wind slab avalanche problems (Fig. 8b) shows that wind slab avalanche problems are typically associated with smaller avalanches that are less likely to be triggered. As expected, persistent and deep persistent slab avalanche problems, the likelihood of triggering is progressively decreasing while the expected avalanches are getting bigger (Fig. 8c & d).

The pattern observed for wet slab avalanche problems has great similarly with the pattern for persistent slab avalanche problems, with respect to both the distribution of likelihood of triggering and the distribution of destructive avalanche size. Furthermore, the distribution of likelihood of triggering is also not different from the distribution exhibited by wind slab avalanche problems.

Loose snow avalanches, both wet and dry, cover the widest range of likelihood of triggering, but are associated with the smaller avalanches, particularly loose dry avalanches. (Fig. 8f & g).

5. CONCLUSION

We present a first quantitative analysis of Canadian avalanche bulletin data that was produced according to the CMAH with a focus on the prevalence and nature of different avalanche problem types. The dataset provides a uniquely detailed and spatially comprehensive perspective for investigating the general nature and variability in avalanche hazard in western Canada. While limited by the relatively short time span of available bulletin data, seven seasons based on the CMAH, this study provides a meaningful first impression.

The results of the preliminary analysis presented in this paper mainly confirm our experiential understanding of the role of these avalanche problems in the different mountain ranges, different seasons, and their differences in nature, but having a systematic dataset on avalanche problems opens new opportunities for improving our understanding of avalanche hazard.

The methods presented in this paper can be further developed to quantitatively define and identify local avalanche winter regimes. This idea builds on the work of Haegeli and McClung (2007) who used avalanche activity and snowpack observations from the InfoEx to characterize individual winter seasons. The systematic and continuous nature of the bulletin CMAH dataset will allow for a much more rigorous characterization.

As the length of the bulletin CMAH dataset grows over time, it will able to contribute to a more in-depth and refined perspective on the traditional snow climate type definitions (maritime, continental and transitional) and provide an insightful perspective on intermediate and long-term trends in the nature of avalanche hazard in western Canada. This improved understanding could shed a better light on the influence of atmosphere-ocean oscillations (e.g., El Niño-Southern Oscillation, Pacific Decadal Oscillation) and long -term climate change on avalanche hazard in Canada. The primary advantages of using this type of dataset is that it circumvents the challenges of inherently incomplete avalanche activity datasets (Bellaire, Jamieson, Thumlert, Goodrich, & Statham, 2016; Sinickas, Jamieson, & Maes, 2015) and offers a more integrated and spatially more comprehensive perspective.

A better understanding of the components of the CMAH and their relationship will also improve the foundation for the development of evidence based decision aids that can assist avalanche forecasters assess conditions and assign avalanche hazard rating more effectively (see e.g., Haegeli, Falk and Klassen, 2012).

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