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Interactive comment on "Characterizing the nature and variability of avalanche hazard in western Canada" *by* Bret Shandro and Pascal Haegeli

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Overall this is a very good paper, I suggest publication with some minor revisions. The authors have a unique avalanche dataset in W Canada to study their objectives on snow avalanche characteristic very closely. Methods are robust and results are very well described, including the SOM (Self-organizing maps), and figures in the most part are very good.

We would like to thank Dr. Mock for his positive assessment of our manuscript and his constructive suggestions.

Figures and tables a bit numerous, more so than the average manuscript, they are useful and present a lot of information, but I wonder how perhaps some can

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be condensed. It is hard for me to comment further at this point. Maybe more information can be added to Supplemental material online.

We agree with the reviewer that this study includes a lot of figures, but we but we find it difficult to present the richness of the data and the results in a more concise way. However, to address the reviewer's concerns and to reduce the figure and table overload in the main manuscript, we decided to move the SOM error figure and the prevalence anomaly figures (Fig. 7, 8 &10) into supplemental material. To provide readers with a reference interpreting the variability within the prevalence values directly out of the bar charts, we added and additional bar representing mean prevalence values on the very left of Fig. 6 & 9.

Below are some comments.

1. **The authors are correct on the top of p. 3 noting the little research on specifying the nature of avalanches (loose wet slabs, etc.) as well as avalanche safety aspects within the context of broad climate types. The authors should note that Mock and Birkeland (2000) and some of their subsequent papers did note the role of short-term weather conditions within days to a few weeks (particularly as driven by synoptic patterns) on faceted crystals etc., so Mock and Birkeland did not simply just rely on the 3 main climate specifications. Thus assertions on interseasonal variability are not too surprising (bottom p. 26). The authors on p. 27, should strike out the limitation of Mock and Birkeland on ignoring the sequences of weather events, as they acknowledged the importance of studying shorter weather timescales.**

We acknowledge that the Mock and Birkeland (2000) include December snowpack temperature gradient to account for faceting of the entire early-season snowpack, a process common in continental snow and avalanche climates. In our opinion, this still represents an average condition since the average December temperature gradient applies to the entire snowpack and the resulting weak snowpack foundation typically persists for the entire season. This seems to be distinctly different from the more short-term fluctuations in weather conditions that are the primary drivers for direct action avalanches and the formation of persistent weaknesses, such as surface hoar layers.

We did not intend to say that Mock and Birkeland (2000) did not acknowledge that the effect of short-term weather fluctuations on avalanche activity, but rather that the existing avalanche and snow climate definitions do not take them into account. To clarify our intent and more accurately represent the contribution and perspective of Mock and Birkeland (2000), we made the following changes to our manuscript:

- P. 3 - Lines 10-17: Described the limitation of the snow climate classification more explicitly and included a brief description of Mock and Birkeland's (2000) additional trend analysis.

The newly developed algorithm allowed Mock and Birkeland (2000) to examine spatial and interseasonal variabilities in snow and avalanche climate characteristics in the western United States and explore the potential effects of El Nino Southern Oscillation, the **Pacific-North American Pattern** and the Pacific Decadal Oscillation on avalanche conditions. **While their seasonal snow climate classifications showed whether winters associated with different phases of these climate oscillations were more continental or more maritime as a whole, it did not provide more detailed insight about the nature of avalanche hazard during those winters. However, their temporal trend analysis of seasonal avalanche indices at select sites with reliable long-term avalanche activity records in the central Rocky Mountains showed some interesting relationship between the magnitude of avalanche activity and climate oscillations.**

- P. 3 - Line 23: Added Mock and Birkeland (2000) as an additional reference highlighting the importance of short-term weather fluctuations on avalanche activity.

. . . seasonally summarized weather observations only have limited connections to the factors driving daily avalanche hazard. Instead, avalanche hazard is determined by short-term weather fluctuations and particular sequences of weather events that dominate over general climate effects (Gruber et al., 2004; **Mock and Birkeland, 2000**).

- P. 25 - Lines 8-15: We slightly reworded the section to better highlight that we refer to the snow climate classification algorithm and not to the entire study by Mock and Birkeland (2000).

These results highlight that examining the seasonal prevalence of typical hazard situations can offer a more insightful perspective on the avalanche hazard conditions of a winter than the **snow climate classification algorithm of** Mock and Birkeland (2000). **While the classification schema considers early season faceting, a common situation in continental snow climates that affects the nature of avalanche hazard for the entire rest of a season**, it is limited because avalanches and their particular character are the result of specific sequences of weather events and not the average weather conditions of a winter.

2. **The authors should note Fitzharris' older Rogers Pass work. Though old, it's the most comprehensive long-term avalanche record in W Canada dating back to the 19th century and has been studied extensively in its climate context.**

We agree with Dr. Mock, that work of Fitzharris (1987) should be mentioned in this study and we apologize for the oversight. We have added citations to this study in several locations in the manuscript including:

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- On page 2 line 13 & 32
- On page 28 line 10.

3. **p. 12, Table 1. On the SOM hazard situations (which is a very good research approach), I assume that avalanche control is not a factor in creating any of these?, and that the data set is truly unique with regards to avalanche control (which the authors describe later in the period that is usually a problem with avalanche data sets).**
4. **Section 5.2.2. Again I assume spatial variability of hazard situations are not impacted by aspects of avalanche control? This includes the high prevalence of deep persistence slabs in the alpine and treeline of the Central Rocky Mountain region.**

This assumption is correct. The uniqueness of our dataset is that avalanche problem characterizations included in the bulletins a) represent assessments for the uncontrolled backcountry (i.e., not affected by changes in avalanche control practices), and b) are spatially a larger-scale assessment than the more point-location perspective that avalanche observations of transportation corridors offer. To better highlight these features of our dataset, we added additional explanations in several locations in the manuscript including:

- On page 4 line 23

The resulting dataset of avalanche problem assessments for **uncontrolled backcountry areas** across large areas of western Canada offers new opportunities . . . .

- On page 4 line 23

The core information presented in Canadian avalanche bulletins consists of a characterization of avalanche problems **in uncontrolled backcountry areas** according to the CMAH . . .

- On page 6 line 8

The combined dataset from Avalanche Canada and Parks Canada consists of . . . forecast regions that **comprehensively cover the main mountain ranges in western Canada** (Tables S1 & S2).

5. **Biggest thing missing in the analyses, and the logical next step would be to have a synoptic meteorological/climate component to relating with the appropriate hazard situations (ex. storm & wind slab events, spatial variability of hazard situations etc.), and if available, some snow pit data analyses. This should stress timeframes shorter than ENSO/seasonal, given the avalanche hazard situation findings. The large-scale meteorological analyses and forecast model simulations in some part, with recognition on non-weather factors etc. may provide additional forecast value to help in terms of probability, and perhaps explain some additional differences in seasons as presented in Figures 6-8 (Seasonal prevalence of typical hazard situations). This can be stressed a bit strongly briefly in a few places in the paper.**

We completely agree with Dr. Mock that the logical next step is to explore climate affects on avalanche hazard by correlating the hazard variability mentioned in this study with climate variability. While our study actually examined some of these relationships and identified some interesting correlations, we decided that including all results in a single manuscript would be too overwhelming. Hence, the present manuscript focuses on the method for identifying hazard patterns, while a second manuscript (currently in preparation and soon to be submitted to NHESS) will focus on the relationship with climate oscillations.

6. **Conclusion: the authors on p. 28 correctly point out the issues and difficulty in long term avalanche datasets and practices, and applications in the backcountry. They seem a bit too negative on long-term studies overall, and this should just be brief mention and be more constructive/complimentary, as long-term approaches are often studied differently with those issues in mind. That includes dendrochronological studies, which have very good value on probability of events, etc. Here, citing the Fitzharris studies show the value and perhaps an example of looking at things at a longer timeframe, and merging different interdisciplinary approaches.**

We completely agree Dr. Mock that studies using long-term avalanche records (e.g., Dixon et al., 1999; Fitzharris, 1987; Hebertson and Jenkins, 2003; Keylock, 2003; McClung, 2013; Reardon et al., 2008; Thumlert et al., 2014; Bellaire et al., 2016; Castebrunet et al., 2012; Jamieson et al., 2017; Laternser and Schneebeli, 2002; Lazar and Williams, 2008; Sinickas et al., 2016) have provided many useful results and have inspired creative research examining the problem of characterising avalanche hazard variability. We believe that the various approaches offer perspectives with different strengths and weaknesses and that all perspectives are necessary to develop a comprehensive understanding. To clarify our position, we have reworded parts of the conclusion on page 26.

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