Responses to Referee #1

GENERAL COMMENT

We thank Referee #1 for their constructive review and helpful comments. We appreciate the encouraging comments about the use of public avalanche bulletin data and the analysis of avalanche problem type information, as well as the suggestions for alternate analysis approaches. Please see below for our detailed responses to specific comments and suggestions from Referee #1. Additions to the manuscript are included in our responses in quotes. In the revised manuscript, the edits are marked with the number of the Referee comment.

RESPONSES TO SPECIFIC COMMENTS

1.1 Limited length of study period

Referee Comment:

Their avalanche data cover 2012-2019, clearly limited for climate research use on what the authors were doing. They stated limitations but it mostly comes at the end and not early in the paper.

Author Response:

We completely agree with the Referee's concern about the relatively short study period. To account for this issue, we employed a 'conservative' analysis approach, and we were careful not to overinterpret our results. To address the Referee's concern, we included for following additional sentence at the beginning of section 3.3 (Statistical analysis) to alert the reader of this limitation of our study right up front.

"While a 10-year dataset is relatively short for a climatological study, our analysis approach aims to maximize the value of the available data to provide meaningful insight into the relationship between the combined Pacific-centered atmospheric-ocean oscillations and the AO and the nature of avalanche hazard in western Canada at the regional scale."

1.2. Concerns about statistical analysis

Referee Comment:

Given this limitation of a 10 year dataset, I am critical on the use of correlations and other statistics given the sample size for confidence intervals, significance and other things. It would be better throughout to focus on the visualization (as they do in Figure 3 very well).

Author Response:

As mentioned in our response to comment 1.1, we believe that our chosen 'conservative' statistical approach is appropriate, and the resulting insights are meaningful within the existing constraints. To maximize the value of our short data set and avoid over-interpretation we focused on regional patterns, considered both the statistical significance and the magnitude of the observed associations in our discussion, and related the results to physical processes responsible for the observed associations.

The correlation analyses included in our study primarily serve to illustrate the nature of the available dataset and justify our choices for the analysis. In other words, the correlation coefficients for the atmospheric oscillations presented in Section 3.2 (Information on atmosphere-ocean oscillations) aim to show the similarities of the oscillation indices during our study period (as further highlighter in Fig. 3) and are not intended to characterize the general relationship among the oscillations. Hence, we believe that our approach was justified, and we did not make any modification to the manuscript.

As pointed out by Referee #2, the regression analysis approach and subsequence post-hoc tests employed in our study take sample size into account. Hence, the results presented are statistically significant given the limitations of the dataset.

1.3 Relevance of PNA and AO

Referee Comment:

The teleconnection indices such as PNA mostly reflect very broad patterns (probably explain at most about 60 percent of the variance in western Canada), as these specific well known teleconnections really focus on centres of action of circulation centers at very large scales. Also, the AO impact is really more farther north and more North Atlantic centered.

Author Response:

We agree with the reviewer that the atmosphere-ocean oscillations reflect broad patterns and general trends. Our selection in oscillations in the present study was based on a) what was examined in existing snow and avalanche climatology studies, and b) oscillations whose effect on the winter weather in Western Canada has been studied. Please see our response to Referee comments 2.1 and 2.3 for our improved descriptions of the AO and PO

1.4 Autocorrelation issues

Referee Comment:

The PDO and to some degree the AO suffers from the autocorrelation issues that can extend for several years (see Deser et al article in J of Climate that debates the clarity of the PDO), and this is quite problematic when connecting results with a 10 year avalanche data set.

Author Response:

We appreciate that the Referee has made us aware of additional relevant PDO literature. In response to this comment, we included Newman et al (2016) as an additional reference in our general discussion of the PDO.

We understand that the monthly indices of atmospheric oscillations like the PDO or AO exhibit considerable autocorrelations. For example, Newman et al. (2016) points out that the year-to-year PDO autocorrelation is over 0.45 in later winter and spring. However, since the seasonal snowpack largely melts out every summer, and the snowpack structures relevant for avalanches emerge each winter independently from the previous winter, it is not necessary to use an autoregressive model approach for the present analysis. We added the following new paragraph in Section 3.3 (Statistical analysis) to explain this situation to the reader.

"It is well known that the indices of atmospheric oscillations like the PDO or AO exhibit considerable autocorrelations. Newman et al. (2016), for example, points out that the year-to-year PDO correlation is over 0.45 in late winter and spring. However, since the seasonal snowpack in Western Canada largely melts out every summer, and the snowpack structures relevant for avalanches emerge each winter independently of the previous winter, it is not necessary to use an autoregressive model approach for the present analysis."

Newman, M., Alexander, M. A., Ault, T. R., Cobb, K. M., Deser, C., Di Lorenzo, E., Mantua, N. J., Miller, A. J., Minobe, S., Nakamura, H., Schneider, N., Vimont, D. J., Phillips, A. S., Scott, J. D., and Smith, C. A.: The Pacific Decadal Oscillation, Revisited, J. Climate, 29, 4399-4427, 10.1175/jcli-d-15-0508.1, 2016.

1.5 Averaging of teleconnection indices

Referee Comment:

On Line 229. I don't like the idea of averaging the teleconnection indices since they have some intercorrelation with one another, plus with the PDO's autocorrelation and seem confusing/artificial in meaning.

Author Response:

Due to the high correlation of the Pacific-centered oscillations within our study period, a regression analysis that includes each of the oscillations (ENSO, PDO, PNA) as separate parameters would not be able to properly isolate their effects. Furthermore, we would be pushing what is reasonable given our relatively short study period. Since there are many similarities in the effects of the Pacific-centered oscillations on the winter weather in Western Canada, averaging their indices for the present analysis seems reasonable. In our opinion, the intercorrelations mentioned by the Referee, the shared correlations to some common underlying process, seems to further justify the averaging of the indices. However, to address this concern, we added the following two new sentences in the limitation paragraph of the new discussion section:

"The associations between PO and avalanche hazard presented in this study represented the combined effect of the Pacific-centered atmosphere-ocean oscillations. Isolating the effect of ENSO, PDO and PNA would require a considerably longer time series of avalanche hazard assessments, which are currently not available."

Also see our response to Referee comment 1.4 for our discussion of the concerns around autocorrelation issues.

1.6 Synoptic classification

Referee Comment:

It might be more conducive to employ synoptic classifications more keen to western Canada, such as work done by Ian McKendry and his group. The McKendry synoptic work also may relate much more to how weather is connected to some of the important snowpack processes. Another suggestion is to perhaps the authors devised their own index from circulation data from grid points off the BC coast to reflect more specific aspects of the Pacific subtropical high, low pressure off the coast, etc.

Author Response:

We appreciate the suggestions of alternative analysis approaches for our dataset. While we understand the potential benefits of the suggested approaches, the objective of this study was to examine the relationship between avalanche hazard in western Canada and well-established indices of the most dominant atmosphere-ocean oscillations affecting the regional weather conditions. This choice was made to build on existing research and to explore the possibilities for producing seasonal avalanche predictions from existing seasonal forecasts of climate conditions (as highlighted by Referee #2). We will keep the Referee's suggestions in mind for future research.

1.7 Introduction to avalanche topic for The Cryosphere readership.

Referee Comment:

The paper is clearly a detailed snow avalanche paper. In the beginning of the paper, it should have a paragraph to appeal more to the broad The Cryosphere readership and why avalanches are significant in Cryosphere studies overall.

Author Response:

Avalanche safety research seems a well-established topic in TC. However, to better introduce the topic to the TC readership, we added the following sentences at the beginning of the introduction describing the societal impact of avalanche hazard.

"Snow avalanches are an inherent natural hazard in mountainous regions that receive substantial amounts of seasonal snow. In these regions, snow avalanches can threaten communities, transportation corridors, critical infrastructure (e.g., hydroelectric dams, transmission and communication lines, pipelines) and resource extraction operations. In Western countries, most people killed in avalanches are recreationists pursuing winter mountain activities such as backcountry skiing, mountain snowmobile riding and out-of-bounds skiing."

1.8 Misspellings

Referee Comment:

On Line 39. Arctic is misspelled.

Author Response:

Thank you for pointing out this typo. We have fixed the spelling.

Responses to Referee #2

GENERAL COMMENT

We thank Referee #2 for their constructive review and helpful comments. We appreciate the encouraging comments about the quality of our study and its contribution to the scientific literature. Please see below for our detailed responses to specific comments and suggestions from Referee #2. Additions to the manuscript are included in our responses in quotes. In the revised manuscript, the edits are marked with the number of the Referee comment.

RESPONSES TO SPECIFIC COMMENTS

2.1 Addition information on AO impacts in mountain of Western Canada

Referee Comment:

Some additional referencing for AO impacts in the mountains of western Canada could be helpful. The impacts of Pacific-centered circulation patterns are very well-studied there, but the AO less so. Off the top of my head I can think of four additional examples that could be useful to cite here for additional support. Vincent et al. (2015) mapped out statistically significant temperature and precipitation teleconnections for much of Alberta and British Columbia to the NAO, which is closely related to the AO. Other examples I'm aware of in the region are framed in terms of hydroclimatic teleconnections to the AO specifically: Gobena et al. (2013), Fleming and Dahlke (2014), and Fleming et al. (2016).

Author Response:

We appreciate Referee #2 highlighting the additional relevant literature to us. After reviewing the suggested papers, we included the following additional sentences in our initial description of the AO.

"Gobena et al. (2013), who studied the effect of AO on stream flows in the Columbia River Basin of Southeastern BC, only identified effects during negative AO anomalies with cooler than average temperatures during December, January and March, and below-average precipitation during winter and spring. Vincent et al. (2015), on the other hand, noted a positive association of winter temperatures in Northern BC with the North Atlantic Oscillation, a close relative to the AO (Fleming and Dahlke, 2014). They did not find a significant signal in winter precipitation."

While the other papers do discuss the effect of AO on weather in British Columbia, their descriptions are more focused on summer patterns and seem therefore less relevant.

After reading about the non-monotonic response patterns in the suggested papers, we also included references to them in our discussion of the non-existing relationship between PO and the prevalence of persistent slab avalanche problems. References were included in both Sections 4.1 (Response to Pacific-centered oscillations) and the limitation paragraph of the new discussion section.

Fleming, S. W., and Dahlke, H. E.: Modulation of linear and nonlinear hydroclimatic dynamics by mountain glaciers in Canada and Norway: Results from information-theoretic polynomial selection, Can. Water Resour. J., 39, 324-341, 10.1080/07011784.2014.942164, 2014.

Gobena, A. K., Weber, F. A., and Fleming, S. W.: The Role of Large-Scale Climate Modes in Regional Streamflow Variability and Implications for Water Supply Forecasting: A Case Study of the Canadian Columbia River Basin, Atmos. Ocean, 51, 380-391, 10.1080/07055900.2012.759899, 2013.

Vincent, L. A., Zhang, X., Brown, R. D., Feng, Y., Mekis, E., Milewska, E. J., Wan, H., and Wang, X. L.: Observed Trends in Canada's Climate and Influence of Low-Frequency Variability Modes, J. Climate, 28, 4545-4560, 10.1175/jcli-d-14-00697.1, 2015.

2.2. Concerns about serially correlated observations

Referee Comment:

While the small sample size (n=10) in time is of concern when studying associations between interannual climate variability and avalanche impacts, these concerns are mitigated by the use of statistical significance tests as an objective basis for ascertaining the presence of associations, as these of course account for sample size. This was done in the study, but the catch here is that the effective sample size might be reduced by serially correlated observations. If such a lack of independence exists, it can be handled in the statistical modeling, but I didn't see any mention of it in the paper. This procedural detail ought to be addressed.

Author Response:

This concern was also raised by Referee #1. Please see Referee Comment 1.4 for our response.

2.3 Description of PO impacts

Referee Comment:

The wording of lines 365-373 require some fine-tuning. The description of PO impacts provided in this passage is accurate for southern British Columbia, but there is a spatial dipole between ENSO/PDO teleconnections in southern BC and the Pacific Northwest vs. those in northwestern British Columbia and southern Alaska. See the article by Fleming and Whitfield (2010) already cited in the article.

Author Response:

After reviewing the article of Fleming and Whitfield (2010) again, we expanded our description of the impact of PO on the weather in British Columbia both in Section 2.1 (Atmosphere-ocean oscillation affecting weather in western Canada) and Section 4.1 (Response to Pacific-centered oscillation).

We added the following sentence to Section 2.1:

"Fleming and Whitfield (2010) highlight that the positive temperature signal of El Niño is weaker in northern BC, and while El Niño tends to bring drier conditions to the southern part of BC, it produces wetter conditions along the northern coast."

The edited version of the relevant paragraph in Section 4.1 now reads (additional underlined):

"These observations are consistent with the existing understanding of the effect of PO on the winter weather in <u>the southern parts</u> of BC and the Pacific Northwest as the warmer temperatures experienced during the positive phase (Shabbar and Khandekar, 1996; Shabbar and Bonsal, 2004; Bonsal et al., 2001) generally result in a shallower and less hazardous snowpack at lower elevations. The observed pattern is also consistent with the results of Lute and Abatzoglou (2014), who showed that La Niña winters in the Pacific Northwest are generally associated with above normal snow water equivalents that result from both more snowfall days and more extreme snow fall events compared to El Niño winters, and the

studies of Brown and Goodison (1996) and Moore and McKendry (1996) who showed that the positive phases of both ENSO and PNA are associated with reduced snow cover western Canada. Hence, our prevalence values for alpine/treeline Storm slab avalanche problems exhibit the expected negative association with PO at higher elevations (Figure 4 and 5). Consistent with the previous research, our regression analysis indicates a homogeneous effect of PO across the study area (i.e., no significant interaction effect), but the magnitude of the estimated difference over the observed PO index is most pronounced in the Rocky Mountains. While Fleming and Whitfield (2010) point out that the northern coast of BC and Alaska exhibits an inverse response pattern for precipitation with the warm ENSO phase bringing wetter winter and spring conditions, this deviation would only affect the Coast North region of our study area."

Responses to Editor

RESPONSES TO SPECIFIC COMMENTS

3.1 Conclusions too long

Editor Comment:

The Conclusions are somewhat lengthy and I recommend you consider, during the revision process, to move some paragraphs into a Discussion section.

Author Response:

In response to this comment we split the original results and discussion section into two separate sections. The revised results section now focuses on the presentation of the results of the beta regression models. The new discussion section includes a concise summary of the results that contains additional big-picture interpretations (previously included in conclusion section) and a detailed analysis of the limitations of the study.