

## EFFECTS OF LARGE-SCALE ATMOSPHERE-OCEAN OSCILLATIONS ON THE NATURE OF AVALANCHE HAZARD IN WESTERN CANADA

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We present a new approach for gaining insight into the relationship between atmosphere-ocean oscillations and avalanche hazard in western Canada that uses information published in public avalanche bulletins. Our approach converts hazard assessments recorded according to the conceptual model of avalanche hazard into an avalanche winter characterization following Shandro and Haegeli (2018) and uses mixed effects models to identify response patterns in the prevalence of typical avalanche hazard situations. Even though our study period is short, the large-scale patterns emerging from our analysis agree reasonably well with the known impacts of the oscillations on winter weather in western Canada. However, we also find numerous smaller scale patterns that indicate that the effects on avalanche hazard are more complicated and regionally variable.

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**KEYWORDS:** El Niño-Southern Oscillation, Pacific Decadal Oscillation, Pacific North America Pattern, Arctic Oscillation, avalanche hazard, avalanche climate

## 1. INTRODUCTION

Avalanche hazard conditions continuously evolve over the course of a winter in response to the sequence of weather events. Much of the existing avalanche research is focused on examining the short-term effects of weather on avalanche conditions to improve operational avalanche forecasting. However, examining the relationship between longer-term variations in weather patterns and the nature of avalanche hazard can also offer valuable insight for the development of seasonal avalanche hazard forecasts and help improve our understanding of the effect of climate change on avalanche hazard.

The most prominent and well understood large-scale atmosphere-ocean oscillations affecting the winter weather patterns in western Canada, include El Niño-Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), the Pacific North American Pattern (PNA) and the Arctic Oscillation (AO). Interested readers are referred to Fleming et al. (2006), Shabbar and Bonsal (2004) or Stahl et al. (2006) for detailed descriptions.

Fitzharris (1987), McClung (2013) and Thumlert et al. (2014) have examined the relationship between avalanche hazard and these oscillations using avalanche observations from highway avalanche safety programs. In general, these studies found that the ENSO and PDO significantly correlate with overall avalanche activity and the ratio between dry and wet avalanches. While these studies offer valuable insight into the effect of these weather patterns on avalanche hazard, they have considerable limitations. Most importantly, the avalanche observations used to describe the nature of avalanche hazard in these studies (frequency of avalanches, ratio between dry and wet avalanches) only provide a very incomplete characterization of the challenges for avalanche risk management. The existing studies are also unable to provide a comprehensive perspective on the overall effect across western Canada since records from highway programs only offer limited point observations of the experienced avalanche conditions. In addition, it is difficult to conclusively attribute the observed patterns to changes in winter weather patterns since avalanche observation time series from highway operations are vulnerable to changes in avalanche control practices.

The information included in public avalanche bulletins offers a much more regional and richer perspective on the nature of the avalanche hazard than avalanche observations at point locations. While the qualitative nature of avalanche bulletin information has prevented its use in quantitative climate analyses in the past, the recent introduction of the conceptual model of avalanche hazard (CMAH; Statham et al.

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2018) as a structured foundation for producing public avalanche bulletins in Canada has opened new opportunities for the use of this data.

The objective of our study is to offer a new perspective on the effect of large-scale atmosphere-ocean oscillations on avalanche hazard in western Canada by using an approach that aims to overcome some of the shortcomings of existing studies. Our method takes advantage of information captured in CMAH-type avalanche hazard assessments included in daily public avalanche bulletins published by Avalanche Canada and Parks Canada and builds on avalanche winter characterization method recently introduced by Shandro and Haegeli (2018).

## 2. METHODS

### 2.1 *Avalanche hazard data*

We used public avalanche bulletins published by Avalanche Canada and Parks Canada during the winters of 2010 to 2018 (Dec. 1 to Apr. 15). The two agencies provide daily avalanche forecasts for all main mountain ranges in western Canada, which include the maritime Coast Mountains along the Pacific Coast in the west, the continental Rocky Mountains along the British Columbia-Alberta boarder in the east, and the Columbia Mountains that exhibit a transitional snow climate in between.

During the first two winters, the bulletin dataset is limited to six large forecast areas of Avalanche Canada (Fig. 1: 1-6: Northwest-BC, South Coast, North Columbia, South Columbia, Kootenay Boundary and South Rockies). In 2012, most of these regions were subdivided into subregions to provide recreationists with more location-specific hazard information. In the same season, Parks Canada implemented the use of the CMAH as the foundation for their avalanche bulletins. Hence, during the 2012 to 2018 winter seasons, our dataset consists of daily avalanche hazard analyses from 14 different forecast areas.

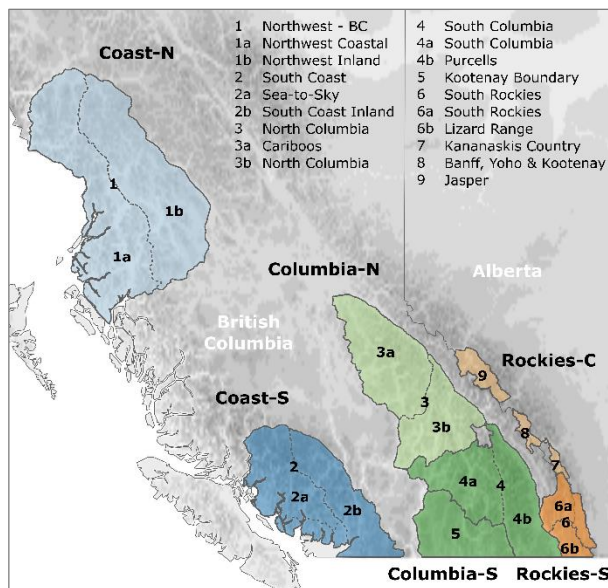


Fig. 1: Forecast areas and larger analysis regions.

To prepare the hazard assessments for analysis, we applied the method of Shandro and Haegeli (2018) to assign the daily avalanche hazard assessments of each elevation band (alpine, tree line and below tree line) to one of 13 typical avalanche hazard situations based on the included avalanche problems and their likelihood and destructive size characterization (Tbl. 1; see Shandro and Haegeli (2018) for detailed descriptions). Once the typical hazard situations were assigned, we calculated seasonal prevalence values (i.e., proportions) of each situation for each forecast area, elevation band and season. Hence, the nature of an avalanche winter in a forecast area is described by 13 prevalence values. The numeric nature of this seasonal characterization makes it suitable for statistical analysis. In addition to prevalence values for individual hazard situations, we also calculated combined prevalence values that included all hazard situations that included wind, storm, and persistent slab avalanche problems respectively.

Tbl. 1: Typical avalanche hazard situations (after Shandro and Haegeli, 2018) with median and maximum seasonal prevalence values.

Typical avalanche hazard situation	Seasonal prevalence values (median   max.)		
	Alpine	Tree line	Below tree line
No avalanche problem	0   8	4   19	34   83
Loose dry avalanches	2   24	2   21	1   17
Wind slabs	18   53	12   46	1   11
Storm slabs	7   49	7   49	12   42
Storm & wind slabs	1   47	1   40	0   12
Storm & persistent slabs	9   39	10   35	7   30
Storm & deep persistent slabs	2   29	1   29	0   15
Storm, wind & persistent slabs	0   26	0   30	0   3
Persistent slabs	1   32	3   36	15   51
Persistent slabs +	17   51	16   50	0   10
Deep persistent slabs	4   73	4   60	0   33
Loose wet & persistent slab	3   14	3   19	0   2
Spring-like	4   15	7   19	12   31

## 2.2 Atmosphere-ocean oscillation data

We used publicly available data from the National Oceanic and Atmospheric Administration (NOAA) for characterizing the various atmosphere-ocean oscillations. While various indices exist to describe the strength of ENSO, we used the Multivariate El Niño Index (MEI) described by Wolter and Timlin (2011). The intensity of the PDO is described with the PDO index (Mantua et al. 1997), the PNA is expressed with the PNA index (Zhao et al. 2013), and the AO index (Thompson and Wallace 1998) is used to describe the intensity of the AO.

For our analysis, we calculated seasonal indices for the strength of the individual atmosphere-climate oscillations by averaging their values of the winter months (Nov. to Apr.) for each winter between 2010 and 2018 (Fig. 2). Since the seasonal indices for the Pacific-centered atmosphere-ocean oscillations were highly correlated during our study period, it is impossible for the analysis to isolate their individual effects in a meaningful way. We therefore calculated a seasonal climate index for the combined strength of the Pacific-centered oscillations (POs) by averaging the ENSO, PDO and PNA indices (Fig. 2).

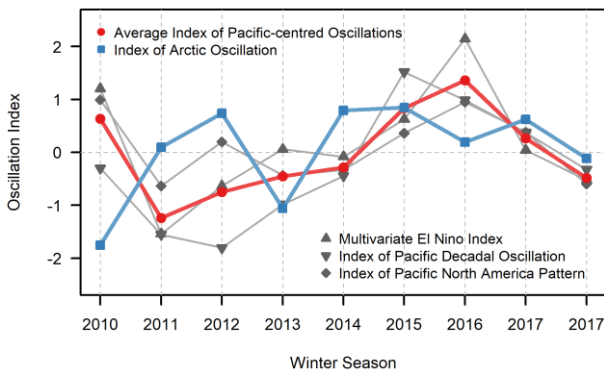


Fig. 2: Atmosphere-ocean oscillation indices.

## 2.3 Statistical analysis

For each hazard situation, we estimated two mixed effects models (MEM) that relate its seasonal prevalence values to the POs and AO indices. One model for the situation in the alpine/tree line elevation band and a second model for below tree line. MEMs are an extension of classic linear regression models that are better suited for the analysis of repeated measure and/or nested data that violate the independence of observation assumption required for classic linear regression. The output of a MEM consists of *fixed effects*, which describe the relationship between the dependent and independent variables for the overall dataset, and *random effects*, which describe the variability of these relationships among the groupings that exist within the dataset. Since our data consisted of repeated hazard situation prevalence values from individual forecast areas, we included a random effect for forecast area in our analysis. In addition, we

included a random effect for general region (Fig. 1; Coast-N, Coast-S, Columbia-N, Columbia-S, Rockies-C and Rockies-S) to account for the regional snow climates and spatial relationship of the forecast areas. Interested readers are referred to Harrison et al. (2018) for a brief introduction into MEM.

Since the prevalence values of hazard situations are proportions that are bound between 0 and 1 and considerably skewed towards lower values, we chose the flexible beta regression model (Cribari-Neto and Zeileis 2010; Smithson and Verkuilen 2006) with a logit link function for our analysis. The fixed and random effects from the beta regression can therefore be expressed as odds ratios (OR) by applying an exponential transformation to the parameter estimates. OR represent the relative increase in prevalence values per unit change in the atmosphere-ocean oscillation index.  $OR > 1$  indicate a positive relationship, while  $OR < 1$  represent negative associations.

We only considered parameter estimates to be insightful if their p-values were significant at the 5% level and their effect resulted in at least a 10% increase or decrease in the prevalence values of a hazard situation per unit of the oscillation index (i.e.,  $OR > 1.1$  or  $OR < 0.9$ ).

## 3. RESULTS & DISCUSSION

The following paragraphs provide a brief overview of the main results of our study. We focus our discussion on fixed slope estimates as they describe the effect of the atmosphere-ocean oscillations on the entire study area. A few examples of significant random slope estimates are included to illustrate regional variabilities. A manuscript that describes the results of our study in full detail is currently in preparation for a peer-reviewed journal.

### 3.1 Response to Pacific-centered oscillations

The results of our alpine/tree line models show that the alpine and tree line prevalence values of *No problems*, *Loose dry avalanches*, *Storm & deep persistent slabs*, and *Spring-like* hazard situations were unaffected by POs during our study period. *Persistent slab +* is the only hazard situation that emerged with a consistent significant relationship across the entire study area in the alpine/tree line elevation band. The OR of 0.82 (p-value = 0.04) indicates that *Persistent slab +* hazard situations were significantly more prevalent in western Canada during the negative phase of POs. None of the combined avalanche hazard situations exhibited a significant fixed effect.

Below tree line, our analysis revealed that the prevalence values of *Storm & wind slabs*, *Storm, wind & persistent slabs* and *Deep persistent slabs* hazard situations were unaffected by POs. However, there are four hazard situations that exhibit a consistent response pattern across the entire study area. While

the hazard situations of *Loose dry avalanches* (OR: 0.56; p-value = 0.02), *Storm & persistent slabs* (OR: 0.65; p-value < 0.01) and *Loose wet & persistent slabs* (OR: 0.78; p-value = 0.02) exhibit negative relationships with POs, *No problems* hazard situations (OR: 1.43; p-value = 0.03) show a positive relationship. Our analysis also showed that the combined prevalence of all hazard situations involving storm slab problems exhibits a negative relationship with POs below tree line (OR: 0.71; p-value < 0.01). However, the random slope estimates of this model indicate that this general pattern is superimposed with a significant regional pattern that makes the negative relationship even more pronounced in the Coast-N, Coast-S and Rockies-S regions, and weaker in the Columbias-S, Columbias-N and Rockies-C regions.

These large-scale responses in the nature of avalanche hazard across the entire study area can be explained reasonably well with the known temperature signal of the POs in western Canada. Since the temperatures below tree line are closer to the melting point, it seems reasonable that the below tree line response to POs is more pronounced than at tree line and above. The warmer temperatures and thinner snowpacks below tree line during the warmer phase of the POs promote stabilization and substantially reduce the presence of avalanche problems. Furthermore, the even more pronounced response of hazard situations with storm slab avalanche problems below tree line in the coastal regions is consistent with the conclusions of Stahl et al. (2006) who showed that the coastal regions of British Columbia experience a stronger ENSO temperature response than the interior ranges. The colder temperatures during the negative phase of the PO are more favorable for the development of persistent and deep persistent slab avalanche problems and the formation of dry loose avalanches at lower elevations. Additionally, the above average snowfall may produce thicker slabs and result in the higher prevalence of the more serious *Persistent slab* + hazard situations at higher elevations.

In addition to these large-scale responses, the random slope estimates of our analyses indicate numerous regionally specific responses. Some of these responses show clear east-west patterns, while others highlight differences between the southern and northern parts of our study area. For example, while the prevalence of *Persistent slab* hazard situations has a positive relationship with POs in the Columbia Mountains, the relationship is negative in the two coastal regions and the Rockies-S region. The prevalence of *Loose wet & persistent slab* hazard situations, on the other hand, has a positive relationship with PO in the Coast-S and Rockies-S regions, while the effect is negative in the Coast-N and Rockies-C regions and insignificant in the Columbia Mountains. These observations clearly highlight that in addition to the dominant general temperature signal of POs, these oscillations must also produce spatial and/or

temporal shifts in weather patterns that change the nature of avalanche hazard at the regional scale.

### 3.2 Response to Arctic oscillation

The results of the alpine/tree line models show that only the prevalence of the *Persistent slab* and *Spring-like* hazard situations were unaffected by the AO. Numerous hazard situations of the below tree line model were unaffected by the AO, where only the prevalence of *No problems*, *Storm & deep persistent slab*, and *Deep persistent slab* hazard situations seem to be impacted by the AO.

There are two hazard situations in the alpine/tree line models that only exhibit an overall effect of AO across the entire study area. The prevalence of *Loose dry avalanche* hazard situations shows a negative relationship with the AO (OR: 0.50; p-value < 0.01) and *Storm & deep persistent slab* hazard situations shows a positive relationship (OR: 1.82; p-value = 0.02). Below tree line, only the fixed effect for the *Deep persistent slab* hazard situation emerged as significant (OR: 1.32; p-value = 0.03).

The only model that emerged with both significant fixed and random slope estimates was for the combined prevalence values of all hazard situations including deep persistent hazard situations at tree line and above. The overall positive relationship (OR = 1.58; p-value = 0.05) is combined with a regional pattern that indicates that this relationship is significantly stronger in the Rockies-C region, while it is significantly weaker in the coastal regions.

Similar to results of the overall effect of POs, our analysis revealed numerous regional response patterns associated with AO. Some of the strongest observed regional patterns involve *Wind slab* and *Storm & wind slab* hazard situations. The prevalence values of both situations exhibit a positive relationship with AO in the coastal regions. The relationships are insignificant in Columbia Mountains except for the positive relationship between *Wind slab* hazard situation and AO in the Columbia-S region. The same relationship is negative in both Rocky Mountain regions and the *Storm & wind slab* situation exhibits a negative relationship in the more northerly Rockies-C region as well.

The observed patterns in hazard situation involving wind slab avalanche problems match reasonably well with the stronger westerly flows associated with the positive phase of the AO mentioned by Fleming et al. (2006) and Moore et al. (2009). The increased wind speeds might also be responsible for a decrease in the prevalence of loose dry avalanches across the entire study. However, our analysis also revealed numerous regional patterns that highlight that the response to AO is more complicated and the meteorological link between them is not as obvious.

## 4. CONCLUSION

We present a new approach for providing insight into the relationship between atmosphere-ocean oscillations and the seasonal character of avalanche hazard. Instead of using spatially sparse avalanche activity records from safety programs along transportation corridors, we used regional avalanche hazard assessments published in public avalanche bulletins from Avalanche Canada and Parks Canada.

The large-scale patterns emerging from our analysis agree reasonably well with the well-known impacts of POs and AO on winter weather in western Canada. However, we also find numerous smaller scale patterns that indicate that the effect of POs and AO on avalanche hazard is more complicated and regionally variable.

We believe that our approach offers a more insightful perspective on the impact of PO and AO on the nature of avalanche hazard in western Canada than previous research in this area. The use of structured avalanche hazard assessments from public avalanche bulletins circumvents some of the inherent limitations of using avalanche observations alone. We feel that the judgment process of avalanche forecasters, despite its potential flaws, adds considerable value to the insight gained from such climate analyses. Due to the consistency and substantial spatial coverage of avalanche bulletins in western Canada, our results also offer a much more comprehensive perspective of the response of avalanche hazard to atmosphere-ocean oscillations than what previous studies offered. In addition, the MEM regression approach can quantify the impact of the oscillations beyond just highlighting associations. Finally, the focus of the analysis on avalanche hazard situations (Shandro and Haegeli 2018) and avalanche problems (Statham et al. 2018) instead of avalanche observations alone makes the results more meaningful for avalanche risk management.

Despite these advantages, the short study period is a considerable shortcoming of our study. While this limits the generalizability of our results, we believe that our results clearly highlight the potential of our approach to improve our understanding of the effect of large-scale atmosphere-ocean oscillations on the nature of avalanche hazard in western Canada.

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## REFERENCES

- Cribari-Neto, F., and A. Zeileis, 2010: Beta Regression in R. *J of Stat Software*, **34**, 24.
- Fitzharris, B. B., 1987: A Climatology of Major Avalanche Winters in Western Canada. *Atmos-Ocean*, **25**, 115-136.
- Fleming, S. W., R. D. Moore, and G. K. C. Clarke, 2006: Glacier-mediated streamflow teleconnections to the Arctic Oscillation. *Intern J Climatol*, **26**, 619-636.
- Harrison, X. A., and Coauthors, 2018: A brief introduction to mixed effects modelling and multi-model inference in ecology. *PeerJ*, **6**, e4794.
- Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis, 1997: A Pacific Interdecadal Climate Oscillation with Impacts on Salmon Production. *Bull Amer Meteor Soc*, **78**, 1069-1079.
- McClung, D. M., 2013: The effects of El Niño and La Niña on snow and avalanche patterns in British Columbia, Canada, and central Chile. *J Glaciology*, **216**, 783-792.
- McClung, D. M., and P. A. Schaerer, 2006: *The Avalanche Handbook*. 3rd ed. The Mountaineers, 342 pp.
- Moore, R. D., and Coauthors, 2009: Glacier change in western North America: influences on hydrology, geomorphic hazards and water quality. *Hydrol Proc*, **23**, 42-61.
- Shabbar, A., and B. R. Bonsal, 2004: Associations between Low Frequency Variability Modes and Winter Temperature Extremes in Canada. *Atmos-Ocean*, **42**, 127-140.
- Shandro, B., and P. Haegeli, 2018: Characterizing the nature and variability of avalanche hazard in western Canada. *Nat Haz Earth Syst Sc*, **18**, 1141-1158.
- Smithson, M., and J. Verkuilen, 2006: A better lemon squeezer? Maximum-likelihood regression with beta-distributed dependent variables. *Psychol Methods*, **11**, 54.
- Stahl, K., R. D. Moore, and I. G. Mckendry, 2006: The role of synoptic-scale circulation in the linkage between large-scale ocean-atmosphere indices and winter surface climate in British Columbia, Canada. *Intern J Climatol*, **26**, 541-560.
- Statham, G., and Coauthors, 2018: A conceptual model of avalanche hazard. *Nat Hazards*, **90**, 663-691.
- Thompson, D. W. J., and J. M. Wallace, 1998: The Arctic oscillation signature in the wintertime geopotential height and temperature fields. *Geophys Res Letters*, **25**, 1297-1300.
- Thumlert, S., S. Bellaire, and J. B. Jamieson, 2014: Relating Avalanches to Large-Scale Ocean – Atmospheric Oscillations. *Proceedings of 2014 International Snow Science Workshop*, Banff, AB, 481-485.
- Wolter, K., and M. S. Timlin, 2011: El Niño/Southern Oscillation behaviour since 1871 as diagnosed in an extended multivariate ENSO index (MEI.ext). *Intern J Climatol*, **31**, 1074-1087.
- Zhao, H., K. Higuchi, J. Waller, H. Auld, and T. Mote, 2013: The impacts of the PNA and NAO on annual maximum snowpack over southern Canada during 1979-2009. *Intern J Climatol*, **33**, 388-395.