ABSTRACT: Sea surface temperatures and sea-level pressures in the Pacific and Arctic oceans have been shown to affect weather patterns in western Canada, thus they can affect the snow avalanche activity. Major oscillations of sea-surface temperature and sea-level pressure have been shown to exist on the 2 to 15 year time-scales. In this paper, avalanche data from over 17,800 avalanches recorded from six different roadways in western Canada were analyzed with respect to several of these oscillations. We studied the El Niño Southern Oscillation, Pacific Decadal Oscillation, Arctic Oscillation, Pacific / North American Pattern, and the North Atlantic Oscillation. Larger and more frequent avalanche activity was found during the Pacific Decadal Oscillation negative phase and during the El Niño Southern Oscillation negative phase (La Niña) for avalanches classified as dry. Conversely, avalanches classified as wet increased during the Pacific Decadal Oscillation positive phase and during the El Niño Southern Oscillation positive phase (El Niño). The Arctic Oscillation correlated positively with all wet and dry avalanche activity (not significant). Understanding the relationship between avalanche activity in western Canada and these oscillations provides some advanced prediction of general avalanche climate which is helpful for planning avalanche hazard mitigation programs. Finally, global climate change is likely to affect these climate oscillations; thus, the relationship between avalanche activity and these climate oscillations provides some insight into how avalanche activity could be affected by climate change.


1. INTRODUCTION
This preliminary analysis explores the effect of several large-scale ocean-atmosphere oscillations on avalanche activity in western Canada.

The most actively researched and studied oscillation, the El Niño Southern Oscillation (ENSO), has been shown to affect global weather patterns (Philander, 1989). The negative phase of ENSO has been shown to increase snowfall (Smith and O'Brien, 2001) and avalanche activity (McClung, 2013) in western Canada. Note, for this study we used the Multivariate El Niño Index (MEI) (Wolter and Timlin, 2011).

The Pacific Decadal Oscillation (PDO) affects western Canada weather similarly to MEI in that the negative phase brings cooler weather and increased snowfall (Mantua and Hare, 2002). The Arctic Oscillation (AO) is defined as non-seasonal sea level pressure variations north of 20 deg latitude. The negative phase affects western Canada by pushing the jet stream north into Alaska and thus directing storm tracks away from southwestern BC. The negative phase creates a “blocking high” or “Omega block”, whereas the positive phase creates more of a “zonal flow” pattern (Thomson and Wallace, 1998).

The North Atlantic Oscillation (NAO) is a climatic phenomenon in the North Atlantic Ocean that mostly affects storm tracks across the North Atlantic. The NAO is closely related to the AO (Bjerknes, 1964), therefore we included it in this analysis. The Pacific North American Pattern consists of anomalies in geopotential height fields typically between 500 – 700 mb. It is strongly influenced by MEI and affects western Canada climate similarly in that the positive phase brings warmer weather, higher winter precipitation, and higher air pressures (Leathers et al., 1991).

To date, few studies have been conducted on the influence of these large-scale climate oscillations on avalanche activity in western Canada. McClung (2013) showed more snow, more avalanches, and a higher percentage of dry avalanches than wet
avalanches during the negative phase of ENSO. Bellaire (2013) showed data from Roger’s Pass, a mountainous highway corridor in western Canada, indicating an increasing frequency of avalanche activity with the negative phase of PDO and ENSO. He also recognized that PDO and ENSO have greater effects on avalanche activity when they are in phase. Mock and Birkeland (2000) showed data from several sites in the central Rocky Mountains of USA that indicated relationships between the snow avalanche climate and both the PNA and the PDO.

The oscillations investigated here are actively researched and forecasted, thus understanding the connection to avalanche activity yields potential for advanced prediction of avalanche hazard in western Canada.

2. METHODS

We used a dataset of observed avalanches from the British Columbia Ministry of Transportation and Infrastructure (BCMOTI) for six highway passes. Approximately 17,800 slab avalanches from 30 years were analyzed. By definition, larger avalanches have higher destructive potential, thus larger avalanches are more hazardous than smaller ones. To account for this, the observed avalanches were modified by size (Table 1), loosely based on the vulnerability work of Jameson and Jones (2012). An avalanche activity index was created by summing all the modified avalanche observations for each year.

Yearly indices for all the oscillations were created by averaging monthly values. The yearly oscillation indices were then related to the yearly avalanche activity using Spearman rank correlations.

Figure 1: Boxplots of the MEI for wet (top) and dry (bottom) avalanche activity. The negative, positive, and neutral classifications were based on \( \frac{1}{2} \) a standard deviation of the index. Boxes span the interquartile range. Whiskers extend to the data point closest to 1.5 times the interquartile range. Open circles indicate outliers.

Figure 2: Boxplots of the AO for all (top) and dry (bottom) avalanche activity. Classifications and boxplots as in Figure 1.
Table 2 shows the correlations with significance levels.

Table 1: Modification of avalanche sizes

<table>
<thead>
<tr>
<th>Size</th>
<th>Modification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0.01</td>
</tr>
<tr>
<td>3</td>
<td>0.2</td>
</tr>
<tr>
<td>4</td>
<td>0.5</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
</tr>
</tbody>
</table>

3. RESULTS

PDO and MEI showed a significant increase in dry avalanche activity during their negative (cool) phases, whereas the positives phases produced non significant increases in wet avalanche activity. Interestingly, PDO and MEI correlated significantly with each other.

The AO showed non-significant increases in avalanche activity for both wet and dry. Surprisingly the PNA showed no significant correlation with avalanche activity. The NAO showed a significant correlation with wet avalanche activity.

An additive combination of all the indices showed significant relations with avalanche activity. More dry avalanches were found when the combined index was negative and more wet avalanche activity was found when the combined index was positive.

Figures 1 – 4 show boxplots of the important correlations.

![Boxplots of the PDO for wet (top) and dry (bottom) avalanche activity. Classifications and boxplots as in Figure 1.](image1)

![Boxplots of the combined index for dry (top) and wet (bottom) avalanche activity. Classifications and boxplots as in Figure 1.](image2)
4. DISCUSSION

The results of the preliminary analysis presented here confirm some relationship between avalanche activity and large-scale climate oscillations on a year-to-year scale. This is promising as forecasted values of these indices are readily available. Thus, the opportunity for advanced prediction of avalanche activity is available. However, what is not clear is the actual effect on avalanche risk. The negative phases of MEI and PDO may create winters with higher precipitation from consistent storms that lead to more predictable storm instabilities, but few deep weaknesses in the snow cover. Thus, the increased avalanche activity observed may not actually be more hazardous. Conversely, the lower dry avalanche activity observed with the positive phases of PDO and MEI may result from dry spells that create persistent weaknesses in the snow cover. These weaknesses may create more hazardous avalanche conditions overall despite fewer avalanches. We recommend a more involved analysis of how the climate oscillations affect avalanche character (Atkins, 2004). Such a study would provide more accurate description of how the climate oscillations contribute to avalanche risk.

Another limitation of this study is the yearly time scale. The lag time between changing indices and the weather patterns in western Canada is not known. If El Niño (negative MEI) conditions develop, how long until the weather patterns across western Canada are influenced, thus affecting avalanche patterns? The indices studied here involved different climatic phenomena, thus the lag times will be different for each oscillation. An analysis with daily or monthly data is required to assess the lag times for each individual oscillation. A lag time analysis would likely lead to better correlations between avalanching and the oscillations. Finally, global climate change is likely to affect the climate oscillations and this is a very active meteorological research topic. Thus, if the link between avalanche risk and the climate oscillations can be established, the opportunity to predict how avalanche risk is likely to change with a changing global climate may be possible.

5. ACKNOWLEDGEMENTS

We would like to thank NSERC, Parks Canada, HeliCat Canada, the Canadian Avalanche Association, Mike Wiegele Helicopter Skiing, Canada West Ski Areas Association, Backcountry Lodges of British Columbia Association, the Association of Canadian Mountain Guides, Teck Mining Company, the Canadian Ski Guide Association, Backcountry Access, the B.C. Ministry of Transportation and Infrastructure Avalanche and Weather Programs, the Canadian Avalanche Foundation, and TECTERRA for their support of ASARC. Last, but not least, Scott Thumlert would like to thank the Alberta Scholarship program for financial support from the Queen Elizabeth II scholarship.
6. REFERENCES


