BIG AVALANCHES IN A CHANGING CLIMATE: USING TREE-RING DERIVED AVALANCHE CHRONOLOGIES TO EXAMINE AVALANCHE FREQUENCY ACROSS MULTIPLE CLIMATE TYPES

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ABSTRACT: Large-magnitude snow avalanches pose a hazard to humans and infrastructure worldwide. Analyzing the spatiotemporal behavior of avalanches and the contributory climate factors is important for understanding historical variability in climate-avalanche relationships as well as improving avalanche forecasting. This study uses established dendrochronological methods to develop long-term regional avalanche chronologies for three different climate types: high-latitude maritime climate of southeast Alaska, intermountain climate of the northern Rocky Mountains, and continental climate of Colorado.

In the maritime study area, we collected 434 cross sections throughout six avalanche paths near Juneau, Alaska. This resulted in 2706 identified avalanche growth disturbances between year 1720 and 2018 Common Era (CE), which allowed us to reconstruct 82 years with large magnitude avalanche activity across three sub-regions. By combining this tree-ring derived avalanche dataset with a suite of climate and atmospheric variables and applying a generalized linear model to fit a binomial regression, we found February and March precipitation and the Oceanic Niño Index (ONI) were significant predictors of large magnitude avalanche activity in the southeast Alaska study area.

In the intermountain climate study area, tree-rings from 647 trees exhibited 2134 avalanche-related growth disturbances in the northern Rocky Mountains of northwest Montana from 1867 to 2019. The data show that the amount of snowpack across the northern Rocky Mountain region is directly related to avalanche probability. Coincident with warming and regional snowpack reductions, a decline of ~ 14% (~ 2% per decade) in overall large magnitude avalanche probability is apparent through the period 1950–2017 CE.

In the continental climate of Colorado, we sampled 24 avalanche paths throughout the state and collected 1188 total samples with 4135 identified growth disturbances from 1698 to 2019. Preliminary results suggest years with large magnitude avalanche activity across the sub-regions of this study area are generally characterized by stormy winters with above average snowpack development but that early and late winter temperature and precipitation also play an important role in large avalanche activity.

Characterizing historical climate-avalanche relationships across different climate types provides a broad baseline for understanding potential future changes in avalanche activity. Overall, this work helps forecasters and planners better understand the influence of climate on large magnitude avalanche frequency, and how potential changes in avalanche character and occurrence will affect their operations in the context of a warming climate.

KEYWORDS: Climate, Large Magnitude Avalanches, Dendrochronology.

1. INTRODUCTION

Understanding avalanche frequency and contributory climate and weather factors helps us understand how climate change may affect avalanche activity and its associated societal impacts. Weather directly influences snowpack structure and avalanche activity on daily to seasonal time

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scales, while climate setting (e.g., coastal, continental) controls prevailing weather conditions over the long term that can influence the general nature of avalanche activity in an area. Meanwhile, climate variability and change serve as background influences on snowpack characteristics over time that drive long-term patterns in avalanche activity (Armstrong and Armstrong, 1987; Mock and Birkeland, 2000; Mock et al., 2016) or prevalent avalanche problem type (Haegeli et al., 2021).

Recent research examined the effects of climate change on avalanche frequency, magnitude, and trends. Several studies found decreases in large-magnitude avalanche activity due primarily to decreasing snowpack, particularly at lower elevations (Eckert et al., 2013; Giacona et al., 2021; Peitzsch et al., 2021b). However, changes in avalanche frequency due to climate change are regionally dependent, and a changing climate can also cause increases in wet snow avalanche activity (Ballesteros-Canovas et al., 2018; Pielmeier et al., 2013).

The relationship between long-term avalanche frequency patterns and large-scale climate is complex and often difficult to disentangle from short-term synoptic weather events. Studies examining climate-avalanche relationships require long-term avalanche and climate data. However, in the western United States, complete long-term avalanche records are sparse or non-existent. Dendrochronological studies are a common method of reconstructing past avalanche activity and have been used in a wide variety of snow climates (Ballesteros-Canovas et al., 2018; Favillier et al., 2018; Hebertson and Jenkins, 2003; Martin and Germain, 2016; Peitzsch et al., 2021a; Pop et al., 2018). We used established dendrochronological methods to develop long-term regional avalanche chronologies for three different climate types: high-latitude maritime climate of southeast Alaska, intermountain climate of the northern Rocky Mountains, and continental climate of Colorado. The objective of this study was to describe the relationship between large-magnitude avalanche frequencies and contributory climate factors in these three climate types.

2. METHODS

2.1 Study Areas

We collected tree-ring samples in three distinct avalanche-climate types in southeast Alaska, northwest Montana, and Colorado (Figure 1). Our study area near Juneau, Alaska, consisted of six individual avalanche paths in the Coast Mountains of southeastern Alaska (Beck et al., 2018). The six paths comprised pairs of avalanche paths in three distinct subregions within the same general maritime climate type (Peitzsch et al., 2023). Mean monthly temperatures range from −2 to 14°C and mean annual precipitation is 1,400 mm in Juneau. The avalanche paths in this study extend from sea level to 1000 m above sea level (a.s.l.) and include a variety of aspects.

In the northern Rocky Mountains, we sampled a network of 12 avalanche paths in northwest Montana, (Peitzsch et al., 2021a). Northwest Montana is classified as both coastal transition and intermountain avalanche climates. Avalanche paths within the study site range from approximately 1100 to 2700 m in elevation and cover all aspects except true north. The mean annual precipitation across the starting zone elevation of the avalanche paths is 1693 mm.

Our study site in Colorado consists of 24 avalanche paths distributed throughout the state. The winter climate in Colorado’s mountains is characterized by cold temperatures and low relative humidity resulting in a continental avalanche climate (Mock and Birkeland, 2000). An important climate-impacting feature is the Continental Divide, which runs north to south through Colorado. Areas west of the Continental Divide accumulate larger amounts of snowfall. The lee side of the Continental Divide is much drier and windier. In the paths sampled, cold-season snowfall ranges from 247 to 811 cm with a median of 450 cm (Marraccini et al., 2014). Avalanche paths sampled in this study have start zones that sit at elevations ranging from approximately 3500 m above sea level to 4000+ m above sea level. Of the 24 paths sampled, the median start zone elevation is approximately 3800 m. Most of the avalanche path start zones are in either alpine or sub-alpine climatic zones with tracks and runout zones that descend into forested terrain.

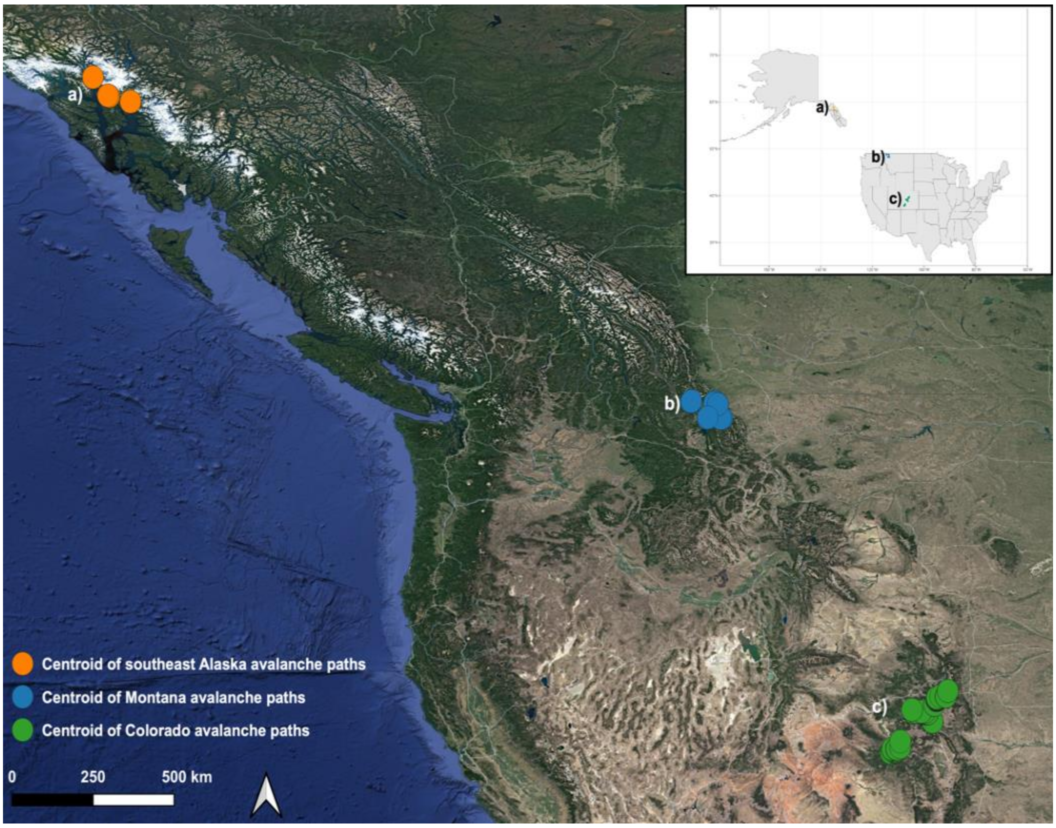

Figure 1: Overview map of three study regions in the United States – (a) southeast Alaska, (b) northern Rocky Mountains, and (c) Colorado. The colored circles indicate the centroid of each individual avalanche path within each region. Map data ©2015 Google.

2.2 *Dendrochronology Techniques*

Throughout the three major regions, we sampled 11-149 cross sections and cores per avalanche path. We collected three types of samples: (1) cross sections from dead trees, (2) cross sections from the dead leaders of avalanche-damaged but still living trees, and (3) cores from living trees. We predominantly used cross sections for a more robust analysis as events can potentially be missed or incorrectly identified in cores (Peitzsch et al., 2021a). We analyzed samples for signs of traumatic impact events likely caused by snow avalanches and reconstructed an avalanche chronology for each individual avalanche path using a multi-step process that accounts for signal quality, sample size of trees alive in a given year, and other external factors impacting tree growth like climate and insect outbreaks (Favillier et al., 2017). See Peitzsch et al. (2021a) and (Peitzsch et al., 2023) for a full description of methods.

2.3 *Statistical Techniques*

For each region, we completed different analytical procedures based on dataset quality, sample size, and availability of climate data. For southeast Alaska, we completed a univariate analysis of contributory climate and atmospheric variables between large magnitude avalanche (LMA) years and non-avalanche (non-LMA) years. We then used those variables with significant differences between LMA and non-LMA years as input variables to a generalized linear model where we fit a binomial regression predicting a binary outcome (LMA or no LMA) from our continuous predictor variables. See Peitzsch et al. (2023) for a full description of the analysis workflow and techniques.

For the northern Rocky Mountain and Colorado dataset, we conducted a similar univariate analysis to examine differences in LMA and non-LMA years. We then completed a principal component analysis to group similar predictor variables together and used the leading principal components as predictors in a generalized linear autoregressive moving average model. Using this model, we estimated LMA year probability from 1950-2017 in the northern Rocky Mountains. We then completed a trend analysis on the probability of a LMA year through the period of record. See Peitzsch et al. (2021b) for a full description of methods.

3. RESULTS

Here, we report only a portion of the results from this work. For full results of the study in southeast Alaska see Peitzsch et al. (2023) and for complete results in the northern Rocky Mountains study region see Peitzsch et al. (2021b).

3.1 Maritime Climate of Southeast Alaska

Using a generalized linear model to fit a binomial regression allowed us to predict a binary outcome (LMA or no LMA) from our continuous independent variables. Results of the generalized linear model indicate Oceanic Niño Index (ONI), February precipitation, and March precipitation to be significant predictors of years associated with regional LMAs. Specifically, large magnitude avalanche activity was correlated with winters having elevated February and March precipitation and neutral or negative (cold) ONI values, while years not characterized by large magnitude avalanches occurred more frequently during warm winters (positive ONI values).

We implemented a supervised probability range when assessing the probability of a given year being one associated with LMAs or not (Figure 2a). In other words, when we classify outcome probabilities above 0.60 as confident it is a large magnitude year and below 0.25 as confident it is a non-LMA year model, the model performance improves to 83 and 85%, respectively (Figure 2b). The model performs poorly when the probability of outcome is between 0.25 and 0.60 (undecided) with a designated threshold of 0.5 (>0.5 = correct and <0.5 = incorrect) and an accuracy of 56%.

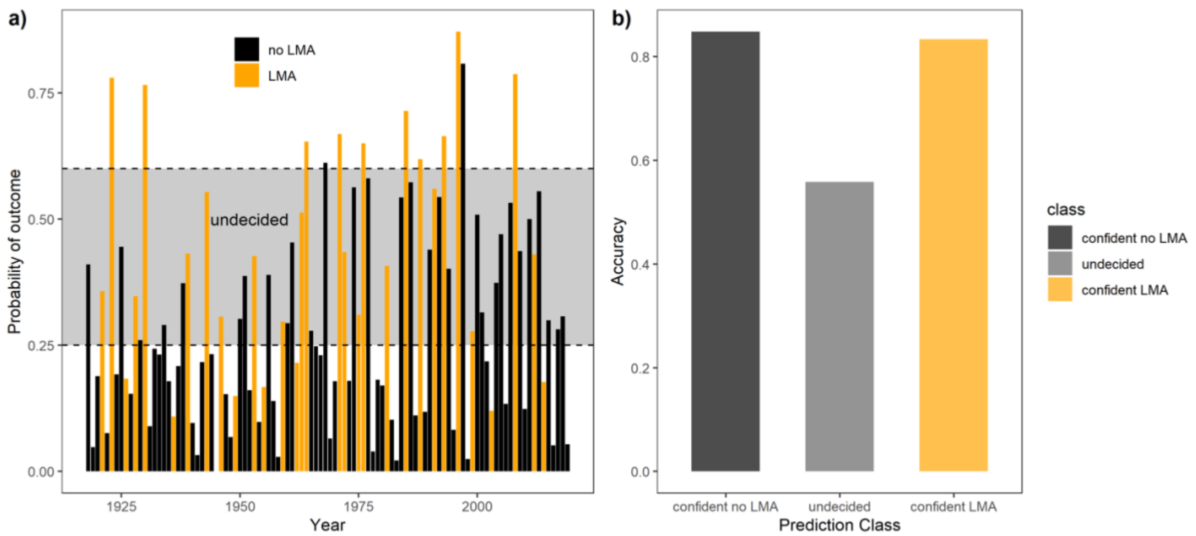

Figure 2: (a) Predictions (probabilities) of the model containing Oceanic Niño Index, February precipitation, and March precipitation for each year. Observed outcomes are presented as the color of the bar (black = no LMA, yellow = LMA) in each year. The gray shaded area represents the range of probabilities between 0.25 and 0.60 and are classified as “undecided.” We classify areas above this shaded area (0.61–1.00) as “confident LMA” and areas below (<0.25) as “confident no LMA.” (b) Accuracy values for each classified region of probability.

3.2 Intermountain Climate of Northern Rocky Mountains

The generalized linear autoregressive moving average model estimates avalanche probability using a 6-year moving average term, determined by autocorrelation and partial autocorrelation plots, and the snowpack (principal component (PC) 1), winter temperature (PC2), and early spring precipitation (PC6) as significant predictor variables. Decreases in snowpack and warming temperatures combine to drive a general downward trend in LMA year probability from 1950 to 2017 (Figures 3a and b). However, increases in spring precipitation also drive a small proportion of LMA years in our dataset.

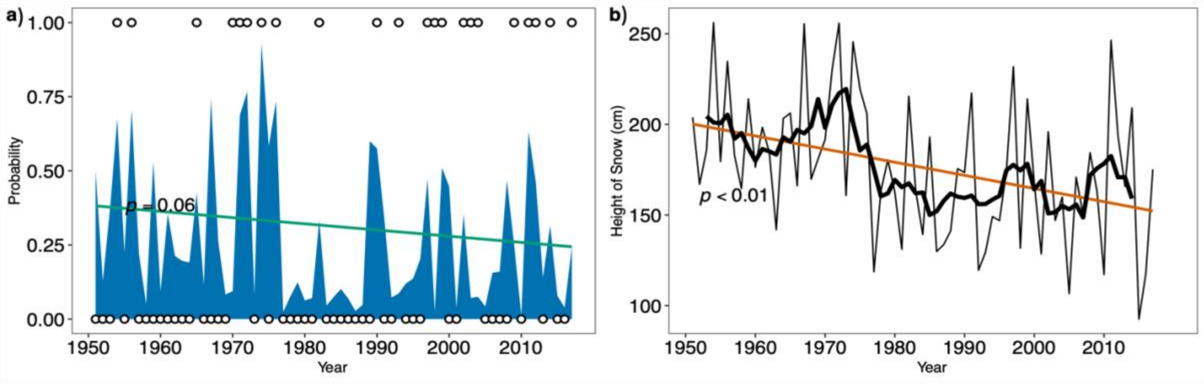

Figure 3: (a) Probability of an avalanche year in blue (white circles; 1 = observed avalanche year, 0 = observed non-avalanche year) using the generalized linear autoregressive moving average model. The green line represents a generalized linear model trend. (b) Time series of maximum snow depth (HSmax) (cm) (a major contributor to and function of the first principal component (PC1)) during the period of record. The red line represents a generalized linear model trend. The p-value of < 0.01suggests a decreasing trend. The black line denotes a 6-year moving average to the time series.

3.3 Continental Climate of Colorado

A preliminary and simple comparison of climate and atmospheric variables between LMA years and non-LMA years throughout the entire state of Colorado reveals significant differences in several variables (Figure 4a). On average, avalanche years have greater values in total winter (November through March) precipitation, March precipitation, maximum snow water equivalent (SWE) and maximum height of snow (HS). On the other hand, non-avalanche years, on average, have greater 500-mb geopotential heights in November and March, maximum temperature in March and November, and minimum temperature in November. We also demonstrate that LMAs occur during years with above average SWE twice as frequently as years with below average SWE (Figure 4b).

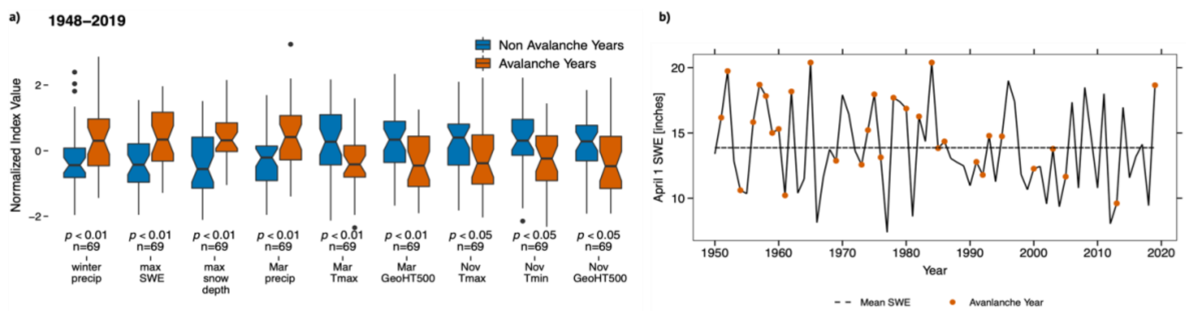

Figure 4: (a) Boxplots showing the distribution of normalized climate and atmospheric values between LMA years and non-LMA years. The horizontal black line represents the median value, the box shows the interquartile range (middle 50% of the data), the vertical lines (whiskers) represent 1.5 Interquartile Range (IQR), and the dots represent maximum and minimum. (b) Time series of April 1 snow water equivalent (SWE) representing average annual snowpack development from SNOTEL stations within the Colorado study region. The horizontal black line represents the mean SWE throughout the period of record, and the red dots indicate large magnitude avalanche years.

4. DISCUSSION

We used avalanche damage events recorded in tree-ring samples from avalanche paths in three different climates to derive a regional large magnitude avalanche chronology for each region. Our results illustrate that specific seasonal climate and atmospheric circulation variables contribute to years with common large magnitude avalanche events across each region. In southeast Alaska, our results suggest that late-winter (February and March) precipitation is the primary driver of LMA activity in this region. However, the relationship with ONI also indicates that there is an interaction with winter temperature, which is significantly warmer in southeast Alaska during the positive phase of the ONI (Fleming and Whitfield, 2010). Therefore, small changes in winter temperature associated with shifts in the state of the ONI can change the form of precipitation (liquid vs. solid) during winter months. A large percentage change in the odds of LMA activity in southeast Alaska (48%) occurs with a single unit change in ONI, highlighting the substantial influence of temperature on precipitation type in February and March, which influences avalanche activity. Accordingly, we demonstrate that winters exhibiting El Niño conditions are associated with a lower proportion of years with LMA activity. This is consistent with the idea that, while precipitation is an important predictor of LMA years, temperature dictates the precipitation type (rain vs. snow) falling in the Coast Mountains of southeast Alaska.

Historically, in the northern Rocky Mountains, large magnitude regional avalanche years were characterized by winters with above average snowpack anomalies, whereas avalanche events of recent decades were increasingly driven by warmer temperatures and a shallow snowpack. Our data show that the amount of snowpack across the northern Rocky Mountains region is directly related to avalanche probability. Coincident with warming and regional snowpack reductions, a decline of approximately 14% (~2% per decade) in overall large magnitude avalanche probability is apparent through the study period 1950–2017. As continued climate warming drives further regional snowpack reductions in the northern Rocky Mountains study region, our results suggest an overall decrease in the probability of regional large magnitude avalanche frequency driven by large snowpack and storminess but a potential increase in large magnitude events driven by warming temperatures and spring precipitation.

Preliminary results examining avalanche-climate relationships in Colorado suggest LMA years tend to be characterized by winters with more precipitation, deeper snowpacks, and lower upper-atmospheric pressures (increased storminess), as represented by 500 mb levels, than years without LMAs. However, our results also demonstrate that LMAs can also occur during years with below average SWE. This indicates a complex relationship between snowpack, climate, and weather leading to several LMA cycle scenarios throughout the period of record in our study. For example, temperature in November is significantly lower in LMA years than non-LMA years. This suggests that cold early winters favor weak-layer development and create favorable conditions for LMAs in years where large late-winter storms (March precipitation) later impact the Colorado Rocky Mountains. This scenario can occur independently of total winter precipitation or snowfall and is one example of how LMAs can occur during below-average snowpack years.

By studying avalanche and climate relationships across three different climate types we gain a better understanding of the synoptic weather and atmospheric patterns that drive large-magnitude avalanche cycles across each region as well as how climate change influences avalanche behavior in each climate type. Future work could include quantitative comparisons of avalanche probability across climate regions to gain insight on how precipitation, snowpack, and temperature changes will influence future avalanche occurrence.

5. CONCLUSION

Characterizing historical climate-avalanche relationships across climate types provides a baseline for understanding potential future changes in avalanche activity. Overall, this work helps forecasters and planners better understand the influence of climate on large magnitude avalanche frequency and how potential changes in avalanche character and occurrence will affect their operations in the context of a warming climate.

DISCLAIMER

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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