USING TREE RINGS TO COMPARE COLORADO'S 2019 AVALANCHE CYCLE TO PREVIOUS LARGE AVALANCHE CYCLES

Erich H. Peitzsch[1*], Ethan M. Greene[2], Jason Konigsberg[2], Gregory T. Pederson[1], Justin T. Martin[1], Nickolas Kichas[3], Daniel K. Stahle[1], Adrien Favillier[4], Nicolas Eckert[5], Karl W. Birkeland[6], Kelly Elder[7]

[1]U.S. Geological Survey, Northern Rocky Mountain Science Center, West Glacier, Montana, United States
[2]Colorado Avalanche Information Center, Leadville, Colorado, United States
[3]Montana State University, Bozeman, Montana, United States
[4]Climate Change Impacts and Risks in the Anthropocene, Institute for Environmental Sciences, University of Geneva, Geneva, Switzerland
[5]Univ. Grenoble Alpes, INRAE, CNRS, IRD, Grenoble INP, IGE, Grenoble, France
[6]Birkeland Snow and Avalanche Scientific, Bozeman, Montana, United States
[7]U.S.D.A. Forest Service Rocky Mountain Research Station, Fort Collins, Colorado, United States

ABSTRACT: Large magnitude avalanches (size ≥D3) impact settlements, transportation corridors, and public safety worldwide. In Colorado, United States, avalanches have killed more people than any other natural hazard since 1950. In March 2019, a historically large magnitude avalanche cycle occurred throughout the entire mountainous portion of Colorado resulting in more than 1000 reported avalanches during a 2-week period. Nearly 200 of these avalanches were size D4 or larger with at least three D5 avalanches. The extensive number of downed trees from this avalanche cycle allowed us to collect 1188 cross-sections and cores from 1023 unique trees within 24 avalanche paths across the state. We recorded 4135 growth disturbances in these samples. These data comprise the largest known avalanche tree-ring dataset in the world. We employed a strategic nested sampling design to account for scale by including several individual avalanche paths within a given drainage to create sub-regions and then sampled six major sub-regions (counties) throughout the greater region (state). We identified 76 avalanche years within 24 individual avalanche paths from 1698 to 2020. Large magnitude empirical avalanche event frequency varied across paths and sub-regions. Our results indicate the most widespread avalanche cycle in our study area prior to 2019 occurred in 1899, where 12 avalanche paths show evidence of large magnitude avalanche activity. Historical records also highlight 1899 as a year with widespread and large magnitude avalanche activity. These results indicate the avalanche cycle of March 2019 was of similar magnitude. Understanding the spatial extent and return frequency of large magnitude avalanche cycles across multiple spatial scales, from individual paths to an entire state, helps avalanche forecasters improve their products and mitigation strategies and assists infrastructure planners when designing and planning in avalanche terrain.

KEYWORDS: Large magnitude avalanche, Dendrochronology, Colorado.

1. INTRODUCTION

Large magnitude avalanches impact settlements, transportation corridors, and public safety worldwide. In Colorado, United States, avalanches have killed more people than any other natural hazard since 1950. In March 2019, a historically large magnitude avalanche cycle occurred throughout the entire state. In late October and early November of 2018, Colorado received abundant early-season snow. An extended dry period followed, and faceted crystals (depth hoar) developed at the base of the snowpack. In early 2019, snow depth increased to average and above-average levels across the state.

Following mainly small storms throughout January and February, a series of warm and wet Pacific storms brought heavy snowfall to many parts of Colorado in early March. Over 14 inches of snow water equivalent (SWE) accumulated across the wettest areas of Colorado with six to 12 inches across most other areas. Throughout the season the depth hoar layer gained strength and was less of a concern prior to this storm. However, the snowfall during this early March storm cycle eventually reached the critical weak layer strength limit, resulting in the largest avalanche cycle throughout Colorado in recent memory.

The Colorado Avalanche Information Center (CAIC) recorded over 200 avalanches size D4 or larger during the early March cycle. For reference, the CAIC only recorded 25 D4 or larger avalanches over the previous nine winters. The March 2019 avalanche cycle impacted transportation and commerce across the state. Avalanches buried several vehicles along State Highway 91 and forced closures

---

* *Corresponding author address:*
Erich Peitzsch, U.S. Geological Survey, Northern Rocky Mountain Science Center,
West Glacier, MT, USA;
email: epeitzsch@usgs.gov

along Interstate 70 and U.S. Highway 550, and the latter was closed for 18 days. In early March 23 people were caught in avalanches, killing two and severely injuring four others. Avalanches damaged powerlines in at least five counties and impacted 10 other structures. The CAIC found no historical evidence of an avalanche cycle as destructive and widespread as the March 2019 cycle through observational records, historical publications, and interviews with longtime avalanche workers.

Our objective in this study was to place the March 2019 avalanche cycle in historical context using tree-ring data to reconstruct a chronology of large magnitude avalanches within each avalanche path and across the state. Here, we define large magnitude avalanches as avalanches of size D3 or greater (Greene et al., 2022). Avalanches can cause mechanical damage to a tree in its path and result in a growth response within the tree ring for that year (Stoffel et al., 2010), and subsequent years as the tree responds to the disturbance. Using tree-ring data allows us to develop an annual time series of avalanches in areas with few or no observational records and provides an opportunity to extend avalanche records back in time beyond existing observational records. As such, we aimed to answer the question: How does the March 2019 avalanche cycle in Colorado compare to previous widespread large magnitude avalanche cycles throughout the region?

2. METHODS

2.1 *Study Site*

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). Cold-season snowfall ranges from 247 to 811 cm with a 30-year (1981-2010) mean of 450 cm (Marraccini et al., 2014) throughout our study area. The starting zone elevation of avalanche paths sampled in our study ranged from 3500 to 4100 m (a.s.l.) with a median elevation of approximately 3800 m. Most of the avalanche path start zones in our study are in either alpine or subalpine zones with tracks and runout zones that descend into forested terrain below tree line.

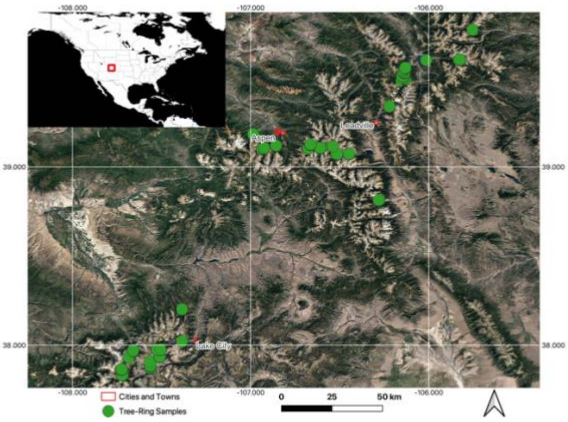

Figure 1: Overview map of the study area. The inset map (upper left) shows the study area as a red rectangle on the continental scale. Green dots represent tree-ring samples. Note that the sample symbols overlap given the scale of the study area. Red polygons represent nearby towns in Colorado for reference. Map data ©2015 Google.

2.2 *Avalanche Year Reconstruction*

We used established dendrochronological methods to reconstruct an avalanche chronology from tree-ring data in each avalanche path (Favillier et al., 2017; Peitzsch et al., 2021; Stokes and Smiley, 1996). We collected 13 to 68 samples in each path throughout 24 avalanche paths in six counties throughout Colorado. We mainly collected cross sections from dead and downed trees in the runout zone and along the trim line of each avalanche path (see Peitzsch et al. (2021) for a full description of sample collection methods). After sanding each sample, we assessed the cross-dating calendar year accuracy of each sample by statistically verifying measured tree rings with cores taken outside the avalanche path and from pre-existing regional tree-ring chronologies.

We implemented a multi-step process to reconstruct avalanche years by 1) classifying the quality of each tree-ring growth response (Reardon et al., 2008), 2) using a threshold for avalanche years based on the number of trees alive in that year and the number of growth responses, and 3) creating a weighted index based on growth response quality (Favillier et al., 2017; Favillier et al., 2018; Peitzsch et al., 2021). We then calculated empirical event frequencies for each avalanche path, and reconstructed an avalanche chronology for the entire region using a hierarchical Bayesian modeling approach for regional tree-ring derived avalanche chronologies developed by Favillier et al. (2023). We define empirical event frequency as the length of time between reconstructed avalanche years. We use this term instead of return intervals because the underlying process is non-stationary. In other words, external factors like climate change and the decreasing sample size further back in time impact return period analysis.

2.3 Comparison with Historical Observational Records

Historical avalanche observations in Colorado, specifically the central and northern mountains of the state, extend back to the mid-19th century (Martinelli and Leaf, 1999). We qualitatively compared our tree-ring derived avalanche chronology for three regions in Colorado (north, central, and south) to public and professional observations from the CAIC database and avalanches documented by Martinelli and Leaf (1999). We chose the period from 1980 to 2019 to maximize quality observations from the historical dataset and leverage the highest temporal resolution of climate data for future avalanche-climate analysis. We further limited the observational record used for comparison to only those observations for which confidence in the assessment of destructiveness and spatial distribution was high. Avalanche observations from these sources have become more robust in recent years, and this initial validation for the entire chronology provides some measure of how well the tree-ring reconstruction captures avalanche activity.

3. RESULTS

3.1 Demographics

The extensive number of downed trees from this avalanche cycle allowed us to collect 1188 cross sections and cores from 1023 unique trees within 24 avalanche paths across the state. This resulted in 4135 growth disturbances. We classified over 30 percent of the growth responses as C_1 (highest quality), and the mean age of sampled trees was 127 years (Figure 2a and b). Most samples were spruce with some pine and fir (Figure 2c).

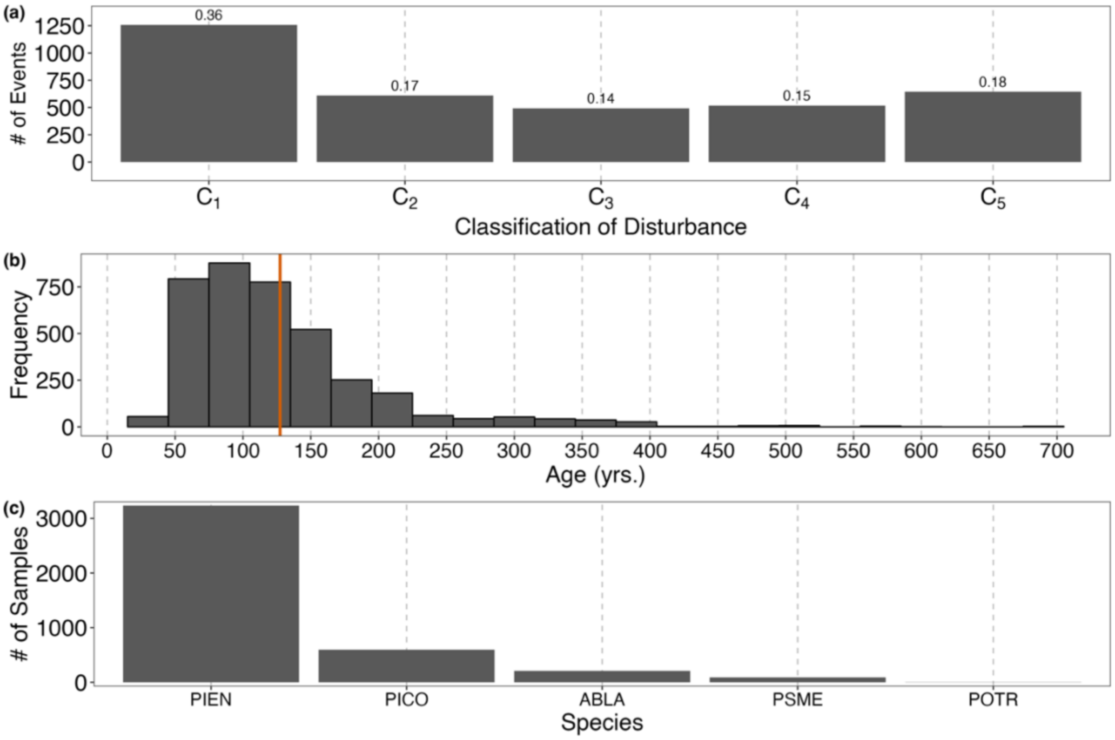

Figure 2: Column plots of (a) number of classification of responses with proportion values on top of each column ranging from C1 (highest quality) to C5 (lowest quality) events, (b) sample age (red line represents mean age), and (c) collected species. For the species, PIEN is Picea engelmannii (Engelmann spruce), PICO is Pinus contorta (lodgepole pine), ABLA is Abies lasciocarpa (subalpine fir), PSME is Pseudotsuga menziesii (Douglas-fir).

3.2 Reconstructed Avalanche Years and Event Frequency

We reconstructed avalanche years for each avalanche path and identified 2019 as a large magnitude avalanche year in 23 out of 24 avalanche paths in our dataset (Figure 3). The year with the second most number of avalanche paths exhibiting large magnitude avalanche activity is 1899 (n=12). Historical observations also highlight 1899 as a year with widespread large magnitude avalanche activity across the state.

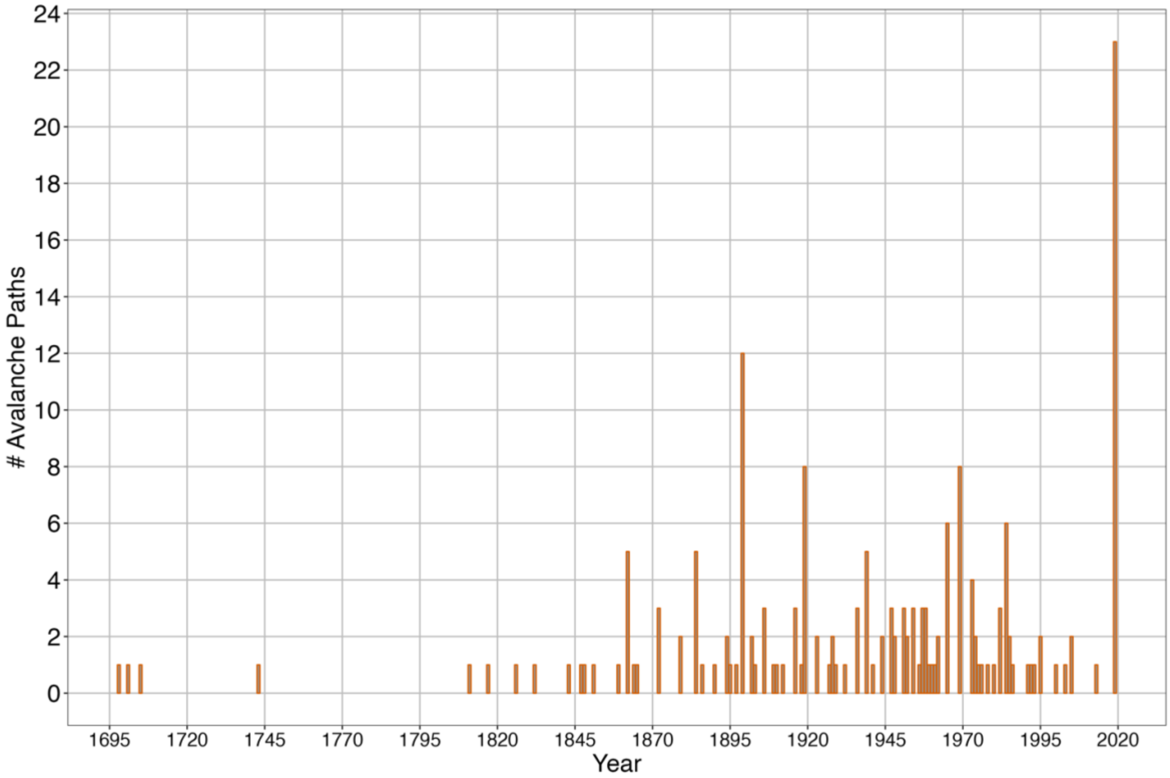

Figure 3: The number of avalanche paths exhibiting large magnitude avalanche activity in each year.

We calculated the empirical event frequency of large magnitude avalanche activity in each avalanche path. The event frequency is a measure of avalanche recurrence from the tree ring reconstructed record and is not a reflection of median (or average) return intervals between two successive events. The lack of recording data (i.e. trees) further back in time precludes us from calculating precise return intervals. Everett B (EVB) exhibits the largest median empirical event frequency (62 years) of large magnitude avalanches in any avalanche path in our reconstructed dataset (Figure 4). Sievers (SVS) exhibits the most frequent event recurrence (4 years). The five avalanche paths in Pitkin County had the most similar median event frequency (range of 4 to 8 years) of any of the six counties. Note that counties are administrative boundaries within a state but are also useful in grouping avalanche paths with similar geographic characteristics.

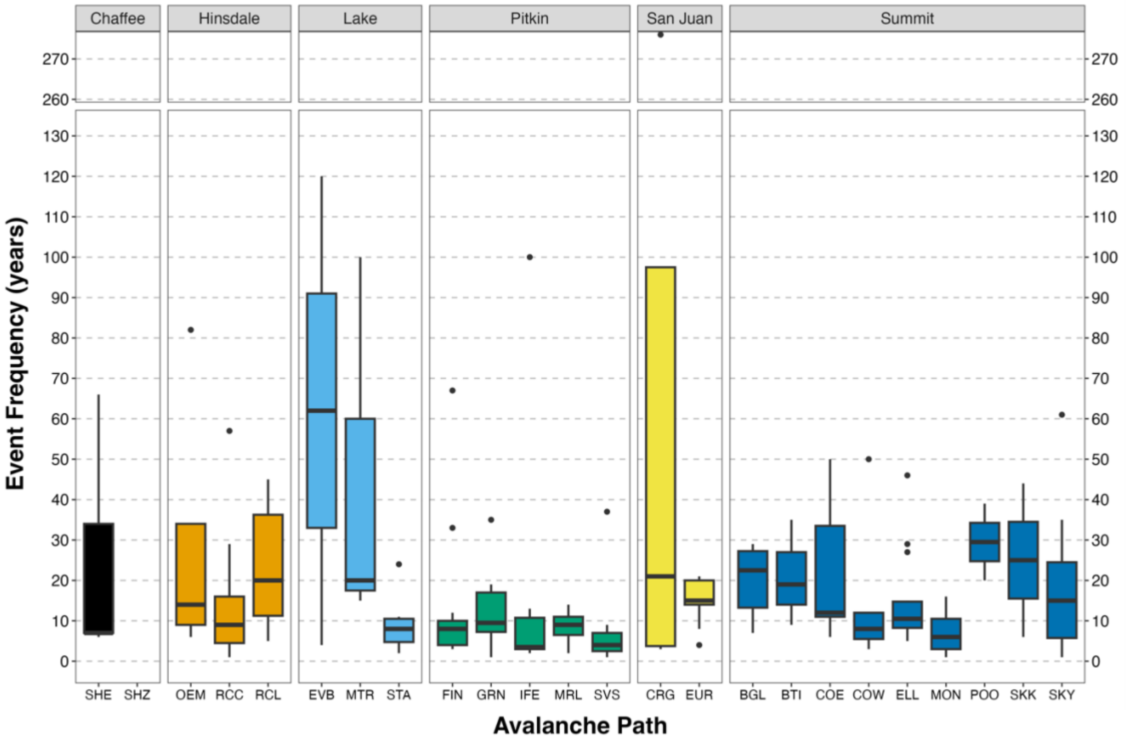

Figure 4: Boxplots of return intervals for individual avalanche paths in each county: The labels at the top represent county names. Note that SHZ has no return interval due to an insufficient number of avalanche years reconstructed from tree rings.

3.3 Regional Avalanche Years

We compared our tree-ring reconstructed avalanche chronology to historical observations from 1980 to 2019. The individual paths in our study site did not necessarily align with paths in the observational dataset, and older avalanche observations often lacked specific avalanche path name and location. Therefore, we grouped individual paths into three climatically similar sub-regions: north, central, and south. The north zone represents all the paths in Summit County. The central zone consists of all paths from Lake, Chaffee, and Pitkin Counties, and the south zone consists of all paths from Hinsdale and San Juan Counties. The best agreement between our reconstructed avalanche chronology and the observational record exists in the central and south sub-regions. Six and four avalanche years align in both datasets for the central and south sub-regions, respectively. In both sub-regions, we found two years in our reconstructed record without associated observational evidence, and one year in the observational record not identified in the tree-ring record. In the north sub-region, we found three years in the reconstructed chronology not identified in the observational record, and vice-versa. Comparing observed and tree-ring reconstructed avalanche years further back in time requires further analysis.

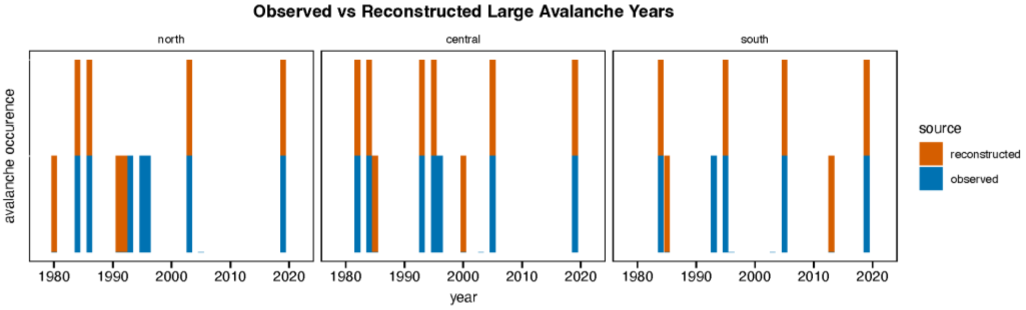

Figure 5: Comparison of avalanche years 1980-2019. The three boxes represent avalanche paths in three sub-regions within Colorado: north, central, and south. The red (reconstructed large magnitude avalanche year) and blue (historically observed large magnitude avalanche year) bars represent the presence of an avalanche year from each dataset (source). The presence of two bars for a given year indicates avalanche year identified in both datasets.

We used a hierarchical Bayesian modeling approach to quantify the probability of a year with widespread large magnitude avalanche activity across the state from 1800 to 2019. Large confidence intervals further back in time represent greater uncertainty due to a decreasing tree-ring sample size (Figure 6). Preliminary results indicate a general decreasing trend in avalanche probability from 1900 to 2019, and 1899 and 2019 have the greatest mean probability in this chronology.

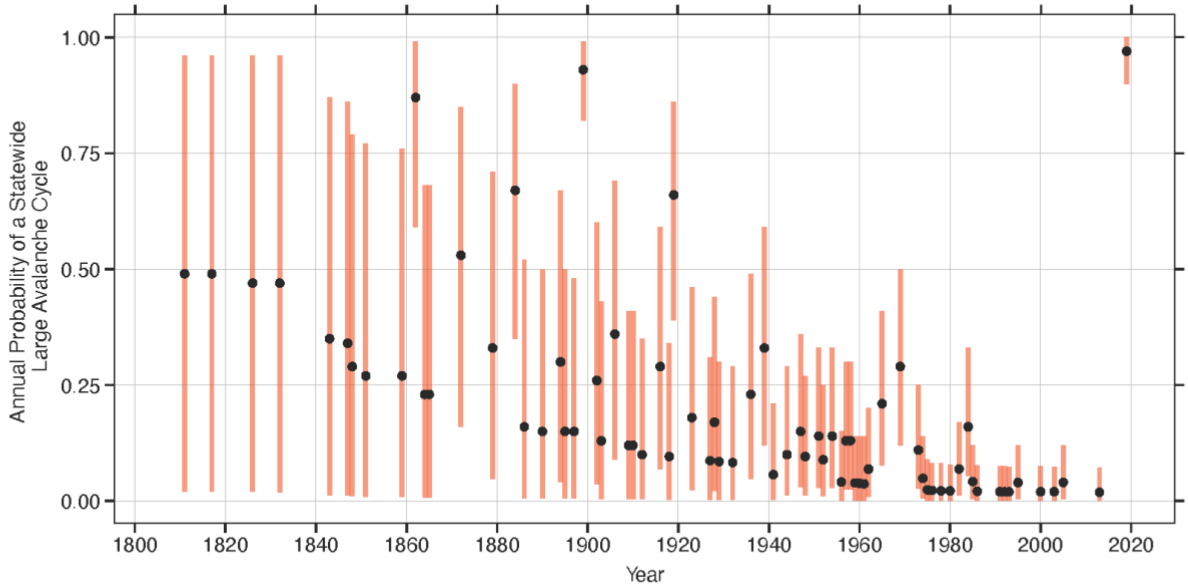

Figure 6: Annual probability of each year being a year with large magnitude avalanche activity. The black dots represent the mean probability for that year and the salmon-colored vertical lines are the 95% confidence intervals of probability for each year.

4. DISCUSSION

We collected over 1188 tree-ring samples and reconstructed an avalanche chronology in 24 avalanche paths in Colorado from 1698 to 2019. We classified over half of our growth responses (i.e., avalanche signals in the tree rings) as C1 and C2 quality responses indicating high-quality signals for avalanche year reconstruction in each path. All avalanche tree ring studies are susceptible to a decreasing sample size further back in time (Corona et al., 2012), but we accounted for this by sampling cross-sections in numerous paths with adequate sample size and tree age.

Our analysis of event frequency indicates variability of large magnitude avalanche reoccurrence both within and across counties. Similar median return intervals between the paths within Pitkin County suggest large magnitude avalanches occur on a more frequent basis in this group than any other group. We will examine potential drivers of this intra- and inter-county variability in future analysis, but previous research suggests a combination of geomorphic differences (Peitzsch et al., 2021), micro-climate effects (Součková et al., 2022), and snowpack differences related to aspect (Gratton et al., 2020) contribute to large magnitude avalanche return intervals within a given path. Another potential contributor to return interval variability is decreasing sample size back in time. For example, the 270-year maximum event frequency in CRG is possible, but the smaller maximum return intervals in paths within San Juan and neighboring Hinsdale County suggest this large return interval may be due to a lack of recording trees in CRG during that time interval. Specifically, the lack of recording trees overestimates recurrence intervals.

When we compared our reconstructed avalanche chronology to recent avalanche observations in three sub-regions, we found decent agreement in two of three sub-regions. Sources of error in both datasets contribute to disagreement (Corona et al., 2012; Reardon et al., 2008). While all our paths were easily accessible by road, it is possible that avalanche activity in several of the more remote paths (i.e., those accessed by dirt road) were not observed and reported in the observational database. This accounts for avalanche years present in the tree-ring chronology but not in the observational record. Conversely, the successive damage and removal of trees from events sized D2 or greater impacts the future potential to record subsequent events of similar magnitude in each avalanche path. In other words, if a large magnitude avalanche removes a large swath of trees in one year, then there are fewer trees available to record a slightly smaller magnitude avalanche in subsequent years. This explains the presence of an avalanche year in the observational record, but not a corresponding record in the reconstructed chronology. Additionally, it is possible that a large magnitude avalanche cycle occurred in the sub-region, but not in the specific paths we sampled (Peitzsch et al., 2021). We will quantify the probability of capturing a regional large magnitude avalanche cycle with our dataset in future work.

In our study, we found a decreasing probability of statewide large magnitude avalanche activity from 1900 to 2019. The number of paths exhibiting an avalanche signal combined with our statistical modeling approach suggests that 2019 was probably as large, if not larger, than the avalanche cycle from 1899. Therefore, a plausible empirical return period of an avalanche cycle of this scale and magnitude is approximately 100-120 years. Additionally, Martinelli and Leaf (1999) provided evidence of widespread avalanche occurrence in 1899. Subsequent widespread large magnitude avalanche cycles occurred between 1899 and 2019, but our results and supporting historical records suggest that 1899 and 2019 were widespread large magnitude avalanche years that stand out from other years in our dataset.

5. CONCLUSION

In March 2019, a historically large magnitude avalanche cycle occurred throughout the entire state of Colorado. The Colorado Avalanche Information Center (CAIC) recorded over 1000 avalanches during a 2-week period. Of these avalanches, 200 were classified as size D4 or larger. We used a large tree-ring dataset to reconstruct an avalanche chronology for each individual avalanche path, three major sub-regions, and the entire state. We found substantial variability in event frequency within each path but decent agreement with observational records in recent years when we aggregated to a sub-regional scale. At the statewide scale, we found the March 2019 avalanche cycle to be as large or larger than the widespread avalanche cycle in 1899, indicating an approximately 100-year or greater avalanche cycle. Understanding the spatial extent and return frequency of large magnitude avalanche cycles across multiple spatial scales helps avalanche forecasters improve their products and mitigation strategies and assists infrastructure planners when designing and planning in avalanche terrain.

DISCLAIMER

ACKNOWLEDGEMENT

We thank Michael Bartley, Mathew Cecil, Mike Cooperstein, Dylan Craaybeek, Jeff Davis, Ryan Zarter, Ron Simenhois, Mike Floyd, Dylan Elder, Rebecca Hodgetts, Matt Huber, Coleman Kane, Brian Lazar, Spencer Logan, Meave McCormick, Lisa Morgan, Chase Quant, Rocky Spencer, Eric McCue, and Banning Starr for their assistance in the field.

REFERENCES

Corona, C., Lopez Saez, J., Stoffel, M., Bonnefoy, M., Richard, D., Astrade, L., and Berger, F.: How much of the real avalanche activity can be captured with tree rings? An evaluation of classic dendrogeomorphic approaches and comparison with historical archives, Cold Regions Science and Technology, doi: 10.1016/j.coldregions.2012.01.003, 2012. 2012.

Favillier, A., Guillet, S., Lopez-Saez, J., Giacona, F., Eckert, N., Zenhäusern, G., Peiry, J. L., Stoffel, M., and Corona, C.: Identifying and interpreting regional signals in tree-ring based reconstructions of snow avalanche activity in the Goms valley (Swiss Alps), Quaternary Science Reviews, 307, 2023.

Favillier, A., Guillet, S., Morel, P., Corona, C., Lopez Saez, J., Eckert, N., Ballesteros Cánovas, J. A., Peiry, J.-L., and Stoffel, M.: Disentangling the impacts of exogenous disturbances on forest stands to assess multi-centennial tree-ring reconstructions of avalanche activity in the upper Goms Valley (Canton of Valais, Switzerland), Quaternary Geochronology, 42, 89-104, 2017.

Favillier, A., Guillet, S., Trappmann, D., Morel, P., Lopez-Saez, J., Eckert, N., Zenhäusern, G., Peiry, J.-L., Stoffel, M., and Corona, C.: Spatio-temporal maps of past avalanche events derived from tree-ring analysis: A case study in the Zermatt valley (Valais, Switzerland), Cold Regions Science and Technology, 154, 9-22, 2018.

Gratton, M., Germain, D., and Boucher, É.: Meteorological triggering scenarios of tree-ring-based snow avalanche occurrence on scree slopes in a maritime climate, Eastern Canada, Physical Geography, doi: 10.1080/02723646.2019.1573622, 2020. 1-18, 2020.

Greene, E., Birkeland, K. W., Elder, K., McCammon, I., Staples, M., Sharaf, D., Trautman, S., and Wagner, W.: Snow, weather, and avalanches: Observation guidelines for avalanche programs in the United States (4th ed), American Avalanche Association, Denver, CO, 2022.

Marraccini, B. J., Lazar, B., and Greene, E.: Climate-scale maps of cold-season precipitation in the mountainous areas of Colorado for operational forecasting applications, In: Ed. Haegeli, P. , Proceedings of the 2014 International Snow Science Workshop, Banff, Alberta, Canada, 29 Sep. - 3 Oct. 20214. 461-464., 2014. 2014.

Martinelli, M. and Leaf, C. F.: Historic Avalanches in the Northern Front Range and the Central and Northern Mountains

of Colorado, United States Department of Agriculture Forest Service, General Technical Report RMRS-GTR-38. September 1999., 1999.

Mock, C. J. and Birkeland, K. W.: Snow Avalanche Climatology of the Western United States Mountain Ranges, Bulletin of the American Meteorological Society, 81, 2367-2392, 2000.

Peitzsch, E. H., Hendrikx, J., Stahle, D. K., Pederson, G. T., Birkeland, K. W., and Fagre, D. B.: A regional spatiotemporal analysis of large magnitude snow avalanches using tree rings, Natural Hazards and Earth System Sciences, 21, 533-557, 2021.

Reardon, B. A., Pederson, G. T., Caruso, C. J., and Fagre, D. B.: Spatial reconstructions and comparisons of historic snow avalanche frequency and extent using tree rings in Glacier National Park, Montana, U.S.A., Arctic, Antarctic, and Alpine Research, 40, 148-160, 2008.

Součková, M., Juras, R., Dytrt, K., Moravec, V., Blöcher, J. R., and Hanel, M.: What weather variables are important for wet and slab avalanches under a changing climate in a low-altitude mountain range in Czechia?, Natural Hazards and Earth System Sciences, 22, 3501-3525, 2022.

Stoffel, M., Bollschweiler, M., Butler, D. R., and Luckman, B. H. (Eds.): Tree Rings and Natural Hazards - A State of the Art, Springer Science and Business Media, 2010.

Stokes, M. A. and Smiley, T. L.: An Introduction to Tree-Ring Dating, The University of Arizona Press, Tucson, 1996.