RELEASE OF AVALANCHES ON PERSISTENT WEAK LAYERS IN RELATION TO LOADING EVENTS IN COLORADO, USA

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ABSTRACT: Avalanches breaking on persistent weak layers such as surface hoar, faceted grains, or depth hoar account for most fatal avalanche accidents in Colorado, USA. These avalanches are also the hardest for avalanche forecasters to assess and describe to the public. Avalanche seasons may contain periods with no snowfall, infrequent avalanche activity, and few signs of unstable snow, but snow profiles still show a troubling structure with the propensity for crack propagation.

We examined avalanches on persistent weak layers recorded by the Colorado Avalanche Information Center from 2011 to 2018. We used snowfall and wind data recorded at automated weather stations to determine 24-hour snowfall, 24-hour wind speeds, and cumulative snowfall over several days. From the data we were able to determine when avalanches released in relation to loading events. This analysis provides insight in to the probability distribution of avalanches on persistent weak layers. Using “days since a loading event” and “days without snowfall” can provide important guidance to avalanche professionals forecasting avalanche danger, and communicating risk to the public.

KEYWORDS: loading, persistent weak layer, avalanche forecasting, weather

1. INTRODUCTION

Colorado is a classic example of a Continental snow climate (Mock and Birkeland, 2000). The high elevation of the Rocky Mountains in Colorado leads to relatively cold winter temperatures, which cause faceting of the snowpack and extensive weak layer development. Of 45 avalanche fatalities in Colorado from 2011 to 2018, 39 (87%) can be attributed to avalanches breaking on persistent weak layers (CAIC 2018).

As storms move through Colorado, avalanche activity on buried weak layers increases. During dry periods, avalanche activity on persistent weak layers tails off and becomes more sporadic. The release of avalanches on buried persistent weak layers seems to decrease as dry weather continues and time elapses following a storm or loading event. Although we observe these patterns of decreasing avalanche activity on persistent weak layers following loading events, there is little documentation or published research that shows the temporal decline of avalanche activity.

Previous studies have included many different weather variables that may contribute to avalanche release. In contrast, our study focused solely on snowpack loading. Evidence supporting the importance of loading of the snowpack in avalanche release has been published in many studies since the early days of avalanche forecasting. Avalanche forecasting pioneer Monty Atwater recognized the importance of precipitation and wind loading in his ten contributory factors for avalanche hazard evaluation (1954). Birkeland and van Herwijinen (2016) showed that artificially loading a test column resulted in a decrease in critical crack length and increases in crack propagation speed in a propagation saw test.

Knowing that loading events increase the probability of avalanches on a persistent weak layer, we examined a large data set of weather events and avalanche occurrence. Our goal was to determine if there was a period following a weather-related loading event when an avalanche on a persistent weak layer becomes unlikely.

2. DATA AND METHODS

2.1 Study location

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We examined avalanches and weather in Colorado for the years 2011 to 2018. The Colorado Avalanche Information Center (CAIC) issues forecasts of avalanche danger for backcountry recreation for ten regional forecast zones. These ten zones include approximately 65,000 km^2. The area of each forecast zone varies from about 3,900 km^2 to about 11,700 km^2. Weather patterns can vary significantly from zone to zone, as does avalanche activity. For example in the winter of 2018, areas of Northern Colorado received 750 cm of snow while areas of Southern Colorado received less than 350 cm.

The backcountry forecast zones used in this study can be up to 218 km from end to end resulting in distinct weather variations within each zone. To account for these smaller scale weather variations, we divided each zone further to group avalanches around a nearby weather station. After dividing the zones further, we wound up with 19 zones to analyze avalanches and loading events.

2.2 Avalanche data

The CAIC maintains a database of avalanche occurrence within the Colorado mountains. During Avalanche Years 2011 to 2018 there were a total of 21,571 avalanches recorded. We selected events where the avalanche released on the ground or an old snow layer. From this set we removed wet-snow avalanches, keeping only the events that released in dry snow. We also removed all of the avalanches triggered with explosives, keeping only natural and human-triggered avalanches. We were left with 1,802 events that fit the avalanches we wanted to examine; a dry-snow avalanche that released on a persistent weak layer and was triggered by a natural-loading event or a person participating in winter recreation.

The 1,802 avalanches identified for this study were sorted by subzones within the forecast zone to account for possible weather and snowpack differences and allow for comparison to nearby automated weather stations. In four of our ten forecast zones, avalanche data was sparse so we excluded those zones from this study and focused on the six more data-rich zones.

2.3 Weather data and loading events

For this study we identified three kinds of loading events:

1. a 24-hour period in which snowfall totaled four or more inches.
2. consecutive days of snowfall totaling six or more inches.
3. a day with three consecutive hours of wind speeds between 32 km/h to 64 km/h (20 to 40 mph) and snowfall of at least 4 inches on the previous day.

We used snowfall data from the National Resource Conservation Service (NRCS) automated SNOTEL sites. SNOTEL sites are typically near or below treeline in Colorado. They are good places to measure snow but are located well below the start zone of large avalanche paths. The lower elevation of these sites explains the relatively low snowfall amounts we used to define a loading event day.

SNOTEL sites measure snow height (HS) at various intervals. NRCS staff provides quality-controlled daily readings to account for sensor errors (NRCS 2014). We used the daily readings, and calculated 24-hr snowfall from the difference in daily readings.

Wind data was measured at automated sites operated by ski areas, research sites, and Colorado Department of Transportation sites. Wind data was evaluated on an hourly basis. Our criteria for a loading event based on wind loading was defined by three consecutive hours of wind speeds between 32 km/h to 64 km/h (20 to 40 mph). However, not all days matching this wind speed criteria were defined as a loading event day. We also attempted to discern if there was snow available for transport during times of sufficient transport speeds. Therefore, in addition to the wind speed criteria being met, there also must have been snowfall the previous day.

2.4 Comparing avalanche data and loading events

After identifying all the loading event days for each subzone, we recorded how many days a loading event preceded each persistent weak layer avalanche. The amount of avalanches and days since a precipitation loading event is our first dataset. The second dataset includes wind loading days. This shows the amount of days an avalanche occurred after a precipitation or wind loading event.

For our third dataset, we looked at days without any measurable snowfall at each SNOTEL site and avalanche activity during these dry periods. The amount of days without any measurable snowfall were counted until an avalanche occurred. For example, a SNOTEL site showed an increase of four inches on Saturday and three inches on Sunday followed by no recorded snowfall Monday through Wednesday. An avalanche released on Thursday so this avalanche occurred after three days without snowfall.

3. RESULTS

3.1 Avalanche release following a precipitation loading event

With loading events resulting from snowfall only, we found that 55% of avalanches on persistent weak layers occurred within three days of a snowfall event and 74% of persistent weak layer avalanches released within seven days of a snowfall event (Figure 1). That is 1,326 avalanches out of the 1,802 avalanches studied occurring within seven days of a snowfall loading event.

3.2 Avalanche release following a precipitation loading or wind loading event

When evaluating wind loading events in addition to snowfall events, we found that 64% of persistent weak layer avalanches occurred within three days of a precipitation or wind loading event and 80% within seven days (Figure 2). Because wind data was a less complete data record, there were only 1435 avalanches for which we could calculate the days since a wind loading or snowfall event.

3.3 Avalanche release and days without snowfall

During dry periods we saw a drastic decrease in avalanche activity. A dry period is defined as a day or stretch of days with no measurable snowfall. After just three days with zero snowfall, 84% of persistent weak layer avalanches that will occur, have occurred. After seven dry days, 93% of persistent weak layer avalanches that will occur have occurred (Figure 3). It is not rare in Colorado to see long periods of extended dry weather, sometimes lasting 10 days or longer. The results of the data analysis show that the occurrence of avalanches following 10 days of dry weather are in fact uncommon with only 18 out of 1,802 persistent weak layer avalanches occurring after 10 days of zero snowfall.

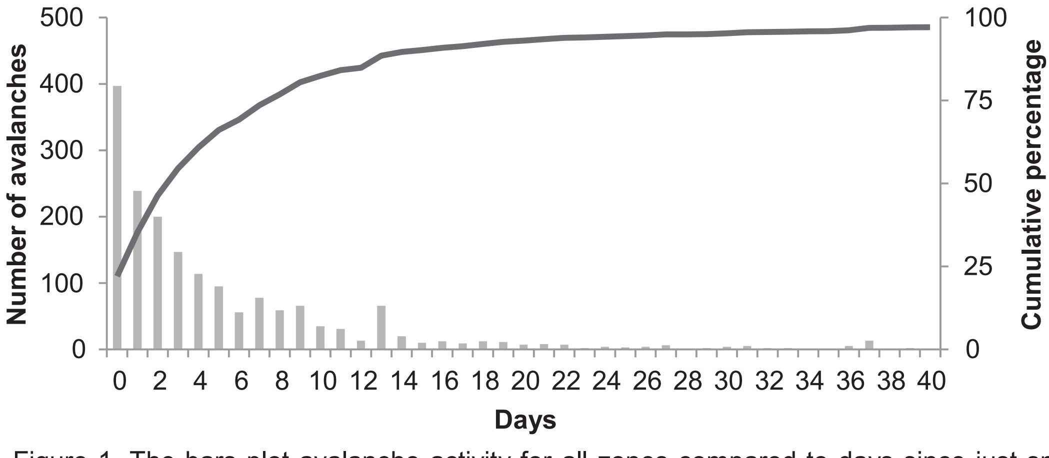

Figure 1. The bars plot avalanche activity for all zones compared to days since just snowfall loading. The curve shows the cumulative percentage of avalanche activity.

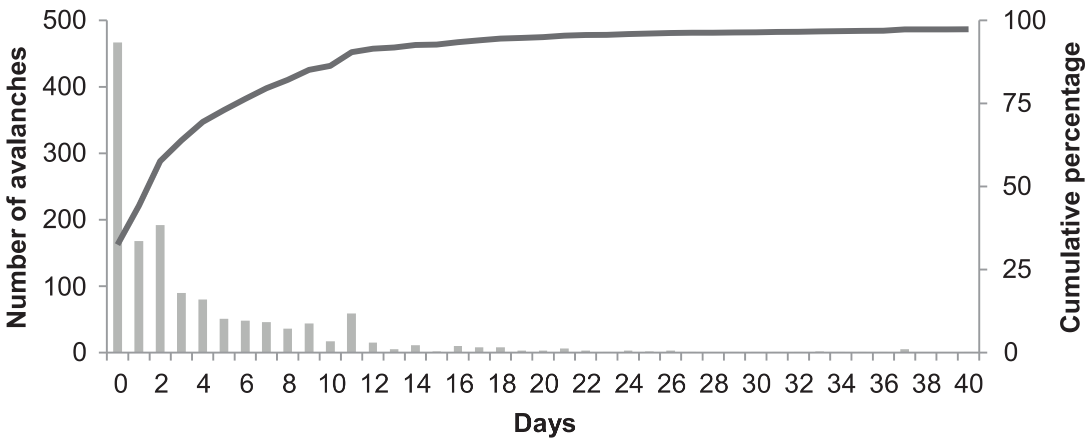

Figure 2. The bars plot avalanche activity for all zones compared to days since snowfall or wind loading. The curve shows the cumulative percentage of avalanche activity.

4. DISCUSSION AND CONCLUSIONS

We know intuitively that avalanches are more likely to release after a snowfall or wind-loading event. This study is a first attempt to look at the decline in avalanche occurrence on persistent weak layers following a loading event. It does not provide a quantitative forecasting tool, but does provide insight on temporal patterns gleamed from a large dataset.

The results of this study are consistent with our collective knowledge of how avalanche cycles on persistent weak layers develop and progress. Avalanche activity is highest immediately following snowfall or wind-loading events. Avalanche activity can continue for many days after a precipitation or wind-loading event, though there is a precipitous decline in avalanche activity after a few days. We found that 13% of the avalanches in our dataset released more than 10 days after what we defined as a loading event.

Only 1% of avalanches released after more than 10 days with no measureable snowfall. The difference between the rate at which avalanche activity tails off when comparing “days since a loading event” and “days without snowfall” may be explained by incremental loading or small snowfall amounts. In Colorado, significant avalanche events have been observed with small amounts of loading and no other notable weather changes. This is purely anecdotal evidence and is a topic for future study.

A key component in determining avalanche danger for a backcountry avalanche forecast is trying to predict the likelihood that an avalanche

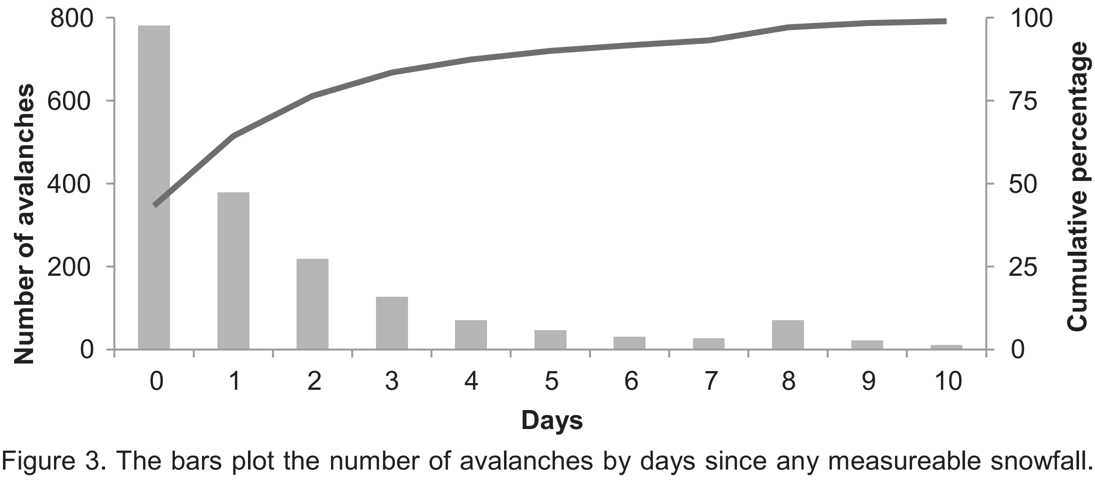

Figure 3. The bars plot the number of avalanches by days since any measureable snowfall. The curve shows the cumulative percentage of avalanche activity.

will release. In some weather patterns, especially long dry periods, it is difficult to forecast the likelihood of avalanches releasing on a particular day without knowing the probability of avalanche release given similar weather conditions and a similar snowpack. The data shows that avalanches after many days without snowfall may fall into the "unlikely" category and a Low (1 of 5) danger when evaluating likelihood. On the other hand, if small snowfall amounts continue, the likelihood of avalanche release may remain at "possible" and a Moderate (2 of 5) danger for as long as snowfall continues.

The results of the data analysis in this study may prove useful to avalanche forecast centers as a guide to avalanche probability following loading events.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the rest of our forecast team. Many CAIC forecasters were involved in discussions to help guide this study and assisted in the collection of data.

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