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Meteorological variables to aid forecasting deep slab avalanches on persistent weak layers

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ABSTRACT

Deep slab avalanches are particularly challenging to forecast. These avalanches are difficult to trigger, yet when they release they tend to propagate far and can result in large and destructive avalanches. We utilized a 44-year record of avalanche control and meteorological data from Bridger Bowl ski area in southwest Montana to test the usefulness of meteorological variables for predicting seasons and days with deep slab avalanches. We defined deep slab avalanches as those that failed on persistent weak layers deeper than 0.9 m, and that occurred after February 1st. Previous studies often used meteorological variables from days prior to avalanches, but we also considered meteorological variables over the early months of the season. We used classification trees and random forests for our analyses. Our results showed seasons with either dry or wet deep slabs on persistent weak layers typically had less precipitation from November through January than seasons without deep slabs on persistent weak layers. Days with deep slab avalanches on persistent weak layers often had warmer minimum 24-hour air temperatures, and more precipitation over the prior seven days, than days without deep slabs on persistent weak layers. Days with deep wet slab avalanches on persistent weak layers were typically preceded by three days of above freezing air temperatures. Seasonal and daily meteorological variables were found useful to aid forecasting dry and wet deep slab avalanches on persistent weak layers, and should be used in combination with continuous observation of the snowpack and avalanche activity.

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1. Introduction

Forecasting deep slab avalanches on persistent weak layers becomes an increasingly challenging task as the winter snowpack deepens. Avalanches that fail on a particular weak layer often become less common the longer the weak layer is buried, but when they do occur they are typically larger and more destructive than other avalanches (Comey and McCollister, 2008; Tracz, 2012). In contrast to avalanches that fail on recently buried persistent weak layers and new snow instabilities, deep slab avalanches on persistent weak layers are seldom accompanied by strong evidence that suggests instability (LaChapelle and Atwater, 1961). After certain weak layers form (e.g., depth hoar), they endure frequent changes between weakening due to strong temperature gradients and strengthening due to weak temperature gradients or pressure from snow accumulating above the weak layer (Bradley and Bowles, 1967). Avalanches on recently buried weak layers are common during and after most storms, which lends strong evidence towards predicting their timing (e.g., Davis et al., 1999). Deep slab avalanches are commonly triggered during and shortly after storms, but it is difficult to differentiate between storms that will trigger a deep slab avalanche and storms that will not (e.g., Conlan et al., 2014). Various studies have explored the difference in meteorological conditions prior to days with deep slab avalanches compared to conditions prior to days without deep slab avalanches (e.g., Conlan et al., 2014; Jamieson et al., 2001). However, few have considered the meteorological conditions during weak layer formation over the early months of seasons with deep slab avalanches compared to those meteorological conditions during seasons without deep slab avalanches. We examined the meteorological conditions during weak layer formation in November, December, and January of each season, as well as the meteorological conditions over days prior to deep slab avalanches on persistent weak layers at Bridger Bowl ski area in southwest Montana.

In a study by Davis et al. (1999), meteorological conditions during weak layer formation were considered by including the starting snow depth of the year in models created to forecast avalanche days and size. They found starting snow depth of the year to be significant in explaining the daily sum of avalanche size and maximum avalanche size. Jamieson et al. (2001) compared meteorological conditions during persistent weak layer formation between two regions where the same weak layer developed, but only one region had extensive avalanche

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activity on this layer. They suggested that persistent weak layer formation can be predicted based on air temperature, snowfall, and precipitation measurements from a suitable weather station.

A variety of definitions have been used for deep slab avalanches in order to study meteorological variables associated with them. Jamieson et al. (2001) focused on avalanches that failed on a buried facet-crust weak layer throughout one season. They found that prior meteorological conditions associated with avalanches on this layer were cumulative precipitation up to 19 days and air temperature change over 4–5 days. Savage (2006) found a weak correlation between prior cumulative precipitation and deep slab avalanches, which were defined by average crown depths deeper than 1.2 m. However, all deep slab avalanches that he studied had wind transport on at least one of four prior days, and 55% of deep slab avalanches occurred when four out of five prior days had wind transport (Savage pers. comm., 2014). Furthermore, small explosive charges were more common triggers than larger explosive charges (Savage, 2006).

Schweizer et al. (2009) found large avalanches (i.e., those running past a given point on an avalanche path) on one path in Switzerland to be most strongly associated with substantial loading over 3–5 days prior to avalanche release and slight increases in air temperature over the prior 24 h. They noted that seasonally dependent variables associated with these avalanches were a weak snowpack base and a snow depth deeper than the terrain roughness. Tracz (2012) examined meteorological conditions prior to naturally triggered avalanches with crown depths greater than 0.8 m. He found prior precipitation up to 12 days, changes in air temperature up to six days, and hours of above freezing temperatures over a period up to 12 days to be associated with these avalanches. Similarly, Conlan et al. (2014) found hard-to-forecast avalanches, defined as avalanches that fail on a weak layer some time after the initial cycle of avalanches on that weak layer, to be associated with precipitation and warming air temperatures. They showed precipitation amounts prior to hard-to-forecast avalanches were not much greater than precipitation amounts that did not precede these avalanches, and warming also commonly accompanied most snowstorms in their region of study. This resulted in high false alarm rates when using these variables to predict hard-to-forecast avalanches (Conlan et al., 2014).

Our study included both dry and wet deep slab avalanches on persistent weak layers. In general, dry slab avalanches are the result of stress being added to the snowpack more quickly than increases in snowpack strength, while wet slab avalanches are the result of a decrease in strength of the snowpack that allows it to succumb to existing, and sometimes added, stresses (Tremper, 2008). The addition of free water to the snowpack is a primary contributing factor to the initiation of wet slabs (Baggi and Schweizer, 2009; Kattelmann, 1984; Peitzsch et al., 2012; Reardon and Lundy, 2004). Previous research has used measurements of SWE loss or snow settlement, and sustained warming, which suggest the introduction of water to the snowpack, to forecast wet slabs (Baggi and Schweizer, 2009; Peitzsch et al., 2012). Baggi and Schweizer (2009) effectively used the presence of capillary barriers (a significant difference in grain size between adjacent layers that may impede vertical water flow through the snowpack), increased load on a weakened snowpack, and days since the snowpack went isothermal to forecast wet slabs in Davos, Switzerland. Previous research has also described situations when added stress preceded wet slab avalanche initiation, in conjunction with a decrease in snowpack strength (e.g., Baggi and Schweizer, 2009; Marienthal et al., 2012). Reardon and Lundy (2004) described a snowpack structure for wet slab avalanches that included a weak basal layer. While non-basal weak layers have been observed as failure planes for wet slabs (e.g., Conway and Raymond, 1993), they are less frequently an issue in ski area settings due to the frequent disturbance of the snowpack (Kattelmann, 1984).

We used classification trees and random forests to find meteorological variables that were associated with deep slab avalanches on persistent weak layers late in the season. Classification trees are a popular statistical tool for avalanche forecasting and research (e.g., Baggi and Schweizer, 2009; Davis et al., 1999; Hendrikx et al., 2005, 2014). They typically have comparable correct classification rates (70–86% when cross-validated) to traditional statistical forecasting methods such as discriminant analysis and nearest neighbors (e.g., McClung and Tweedy, 1994). Although classification trees have had minimal improvement in operational forecasting accuracy, they have many benefits. They are useful for both prediction and explanation, and they are usually easier to interpret by end users than other statistical methods (Davis et al., 1999; Hendrikx et al., 2005).

Random forests are a bootstrapping method that iteratively grows a given number of classification trees while withholding random subsets of data, which are used to assess model performance and parameter importance (Breiman, 2001). Random forests have been used for avalanche research on spatial variability (Guy and Birkeland, 2013) and forecasting wet slab avalanches (Mitterer and Schweizer, 2013).

For this analysis we defined deep slab avalanches as those that failed on persistent weak layers deeper than 0.9 m, and that occurred between February 1st and the end of the operational season (early April). Avalanche records often did not specify the weak layer type for each event. So, in order to imply if avalanches slid on a persistent weak layer we used other characteristics that are commonly recorded with avalanches. We grew classification trees and random forests from two datasets to examine both seasonal and daily meteorological variables that preceded deep slab avalanches on persistent weak layers at Bridger Bowl ski area in Montana. We used variables that represent meteorological conditions during weak layer development to separate seasons with and seasons without deep slabs on persistent weak layers. In addition, we used meteorological variables up to seven days prior to deep slab avalanches on persistent weak layers to differentiate between days with and days without deep slabs on persistent weak layers.

2. Methods

2.1. Deep slab avalanches on persistent weak layers

We defined deep slab avalanches that failed on persistent weak layers from 44 seasons (1968–2013) of avalanche occurrence records at Bridger Bowl (the 1995–96 season was omitted due to missing data). Each season roughly spanned from November to April, with exact start and end dates varying. Ski patrollers at Bridger Bowl recorded all avalanches that were triggered by explosives as well as all in-bounds avalanches larger than or equal to relative size (R-size) two (Greene et al., 2010). Ski patrol often, but not always, recorded large and visible avalanches that occurred adjacent to the ski area due to natural or human triggers. Standards used to record observed avalanches previously followed guidelines of the West Wide Avalanche Network (WWAN), and recently evolved towards recording standards set forth by Greene et al. (2010). These standards did not typically require weak layer type and other weak layer properties to be recorded, so we used other avalanche characteristics to determine if an avalanche was a deep slab on a persistent weak layer.

Avalanche characteristics that we used in this study were recorded with most observations and include: date, type of trigger, avalanche type, R-size, crown depth, and bed surface (i.e., layers involved) (Greene et al., 2010). Deep slabs become more difficult to forecast the longer a persistent weak layer has been buried (e.g., Conlan et al., 2014), so we restricted our study to avalanches that occurred after February 1st. If an avalanche after February 1st was recorded with bed surface as “ground” (or layers involved as “all”), then we considered it to have been a deep slab on depth hoar (or basal facets), because this is a common persistent weak layer near the ground in the intermountain snow climate of Bridger Bowl (Mock and Birkeland, 2000).

Observers did not always record the bed surface as the ground for avalanches on deep persistent weak layers. Avalanches that failed in depth hoar might have failed on the upper boundary of the layer or

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