TIMING OF WET SNOW AVALANCHE ACTIVITY: AN ANALYSIS FROM GLACIER NATIONAL PARK, MONTANA, USA

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ABSTRACT: Wet snow avalanches pose a problem for annual spring road opening operations along the Going-to-the-Sun Road (GTSR) in Glacier National Park, Montana, USA. A suite of meteorological metrics and snow observations has been used to forecast for wet slab and glide avalanche activity. However, the timing of spring wet slab and glide avalanches is a difficult process to forecast and requires new capabilities.

For the 2011 and 2012 spring seasons we tested a previously developed classification tree model which had been trained on data from 2003-2010. For 2011, this model yielded a 91% predictive rate for avalanche days. For 2012, the model failed to capture any of the avalanche days observed. We then investigated these misclassified avalanche days in the 2012 season by comparing them to the misclassified days from the original dataset from which the model was trained. Results showed no significant difference in air temperature variables between this year and the original training data set for these misclassified days. This indicates that 2012 was characterized by avalanche days most similar to those that the model struggled with in the original training data.

The original classification tree model showed air temperature to be a significant variable in wet avalanche activity which implies that subsequent movement of meltwater through the snowpack is also important. To further understand the timing of water flow we installed two lysimeters in fall 2011 before snow accumulation. Water flow showed a moderate correlation with air temperature later in the season and no synchronous pattern associated with wet slab and glide avalanche activity. We also characterized snowpack structure as the snowpack transitioned from a dry to a wet snowpack throughout the spring. This helped to assess potential failure layers of wet snow avalanches and the timing of avalanches compared to water moving through the snowpack. These tools (classification tree model and lysimeter data), combined with standard meteorological and avalanche observations, proved useful to forecasters regarding the timing of wet snow avalanche activity along the GTSR.

1. INTRODUCTION

Wet slab and glide avalanches are hazardous and forecasting these types of avalanches is complex. Typically, wet slab avalanches require some type of weak layer within the snowpack, water production (via rain-on-snow or melt water), and the subsequent interaction of moving water through a specific snowpack structure (Kattelmann, 1984; Reardon and Lundy, 2004) . Glide avalanches occur at the ground-snow interface and also require the production and subsequent movement of water through the snowpack (Jones, 2004; Reardon et al., 2006; Stimberis and Rubin, 2011). Both types of avalanches affect operations and threaten worker safety along the Going-to-the-Sun Road (GTSR) in Glacier National Park (GNP), Montana, USA.

Currently, forecasting wet snow avalanches along the GTSR requires monitoring of meteorological conditions as well as knowledge of existing snowpack structure. Snowpack structure in the starting zones is sometimes difficult to assess in large starting zones along the GTSR due to lack of accessibility or safety concerns. Thus, representative slopes are used while accounting for large variability of snowpack structure in each path. For instance, some avalanche paths may have failed on the layer of concern at some point throughout the winter, but because access is limited in winter it is usually unknown whether or not an avalanche occurred or if that layer still exists.

The primary objective of this study was to determine the timing of wet slab and glide

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avalanche occurrence for the 2012 season by re-evaluating a previously devised and tested classification tree model of meteorological variables and wet slab and glide avalanche occurrence (Peitzsch et al., 2012). The classification tree model focused mostly on meteorological conditions and we also wanted to gain an understanding of snowpack characteristics during wet slab and glide events. Thus, a secondary objective was to examine water flow through the snowpack measured with two newly installed lysimeters and qualitatively describe water flow through the snowpack (using the lysimeter and visual observations), meteorological conditions, and avalanche occurrence. By assessing the effectiveness of the model and developing local parameters for spring snowpack characteristics and water flow through the snowpack, we hope to improve forecasting the timing of wet slab and glide avalanche occurrence along the GTSR. We also hope these methods will aid other forecasting operations that contend with wet snow avalanche hazards.

2. STUDY AREA

The study area was comprised of the slopes visible from the GTSR on both the east and west sides of the Continental Divide (Figure 1). The lowest point in the study area lies at 1036 m and the surrounding peaks reach 2915 m. The avalanche paths used in the dataset encompass all but due north aspects. The snow avalanche climate of the study area exhibits a generally maritime precipitation regime accompanied by continental temperature characteristics due to the position along the Continental Divide (Mock and Birkeland, 2000; Reardon and Lundy, 2004).

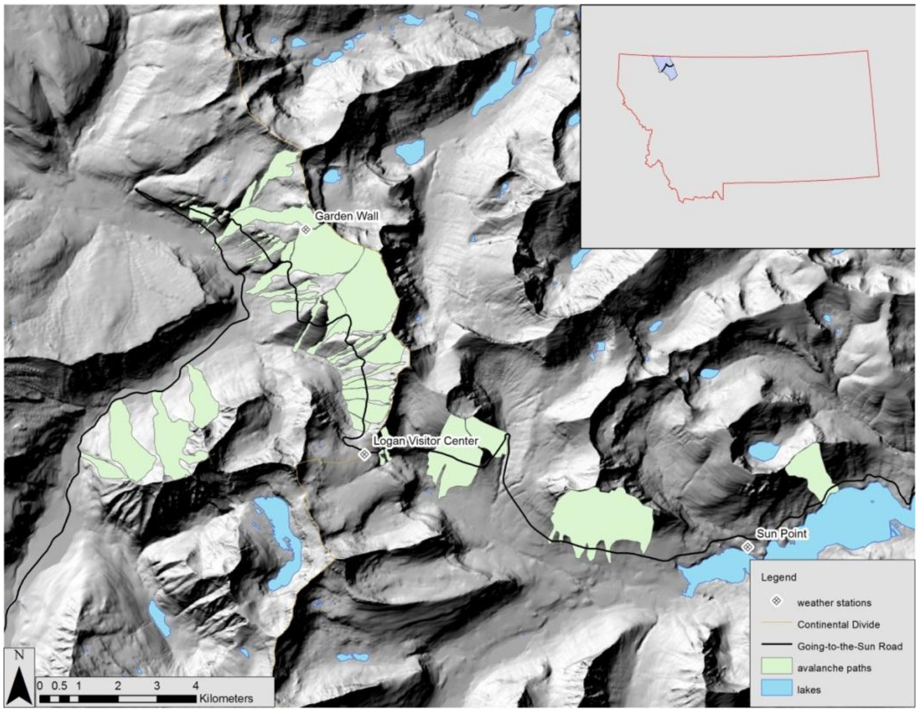

Figure 1: Location of study area - Going-to-the-Sun Road corridor, Glacier National Park, MT. Garden Wall and Logan Pass Visitor Center weather stations are labeled. Data used were from Garden Wall and Flattop SNOTEL (10 km NE of Garden Wall site).

3. DATA AND METHODS

3.1 Avalanche and Meteorological Data

Avalanche data were obtained from the U.S. Geological Survey/Glacier National Park Avalanche Program's Avalanche and Weather Database. Avalanche occurrence records commenced in spring 2003 and extend to spring 2012. Data were collected according to Greene et al. (2010) and Fierz et al. (2009). This database was used to develop and cross validate a classification tree model using meteorological and avalanche data from 2003-2010 and to test this model using 2011 data (Peitzsch et al., 2012). This study utilized 2012 data to test the model after another season of observations and data collection.

Meteorological data were collected at the Garden Wall Weather Station (GWWX) which is located at 2240 m on a small sub-ridge adjacent to two large starting zones (48°44’49.214” N, 113°44’26.23” W). Snow water equivalent (SWE), height-of-snow (HS), and rain measurements were measured at nearby (approximately 10 km NW of GWWX) Flattop Mountain SNOTEL (1810 m,(United States Department of Agriculture, 2012).

3.2 Data Collection and Analysis

Peitzsch et al. (2012) developed a classification tree model using eight seasons of avalanche and meteorological data from the GTSR. Their classification tree split the data on three nodes and found maximum air temperature (5.35 °C threshold), mean air temperature (1.65 °C threshold), and change in snow depth over 5 days (19.95 cm decrease) as the most efficient variables to discriminate between avalanche and non-avalanche days. They tested the model with data from the 2011 season and it proved effective in predicting 10 out of 11 avalanche days for that spring season. In this study, the model was tested once again with data from 2012 season using the same process as Peitzsch et al. (2012) to further determine its effectiveness. Misclassified avalanche days (days that the classification tree model predicted as non-avalanche days that were actually avalanche days) from 2012 were then compared to all misclassified avalanche days from 2003-2011. To examine potential causes of the poor performance of the classification tree model in 2012, a Mann-Whitney U-test was used to distinguish any differences between the 2012 misclassified avalanche days and the misclassified avalanche days from the original dataset that the classification tree was built upon (Wilcoxon, 1945). The variables tested were the three key splitting variables of maximum daily air temperature (°C), mean daily air temperature (°C), and change in snow depth (cm) five days prior to and including the day of avalanche occurrence.

In addition, to further understand water outflow, two lysimeters were installed at GWWX on a 30 degree slope in July 2011 before the accumulation of seasonal snowpack (Figure 2). Lysimeters for this study consisted of a metal tray 1m x 1m with a 10-cm lip on the bottom edge and a 5 cm lip around the other three edges. Water accumulated in the tray from the snowpack above and drained through plastic conduit to a tipping bucket located in an insulated paint bucket. The tipping buckets were wired to the datalogger at GWWX to allow for real-time observation. The amount of free water moving through the lysimeter was recorded hourly and summed to daily values (mm). Lysimeter measurements were then compared to air temperature and snow depth change. Unfortunately, communication and datalogger difficulties prevented one lysimeter from recording data.

Figure 2: Two lysimeters installed on a 30 degree slope adjacent to GWWX to record local water flow through the snowpack. This image was taken looking downhill.

Snowpit data were examined throughout the spring to visually determine the existence and depth of free water throughout the snowpack as well as weak layers and potential layers that may impede water (Baggi and Schweizer, 2009; Peitzsch, 2009). The moisture content (dry, moist, wet, very wet, slush) of each layer was observed and recorded and the entire snowpack was classified overall as dry, moist, transitional, or wet. We defined transitional as the time when the snowpack is both moist and wet. Classifying the bulk moisture property of the snowpack allowed a distinct classification of the snowpack development throughout the spring.

4. RESULTS

The classification tree model (Peitzsch et al., 2012) incorrectly classified all five avalanche days as non-avalanche days (0%). We randomly selected five non-avalanche days from 2012, and the classification tree model correctly classified three out of five days as non-avalanche days (60%). The misclassified avalanche days (days the model predicted as avalanche days that were non-avalanche days) from 2003-2011 were, on average, similar to misclassified avalanche days from 2012 with respect to daily air temperature (maximum and mean), but significantly different in a change in snow depth over five days (Table1).

Table 1: Mean and Maximum Daily Air Temperature and Change in Snow Depth for 2003-2011 and 2012 misclassified avalanche days using a Mann-Whitney U-test. Values in red are significantly different at the $p < 0.05$ level.

Metric	2003-2011 mean	2012 mean	*p*-value
Mean Daily Temperature (°C)	-0.87 (*n*=15)	-1.99 (*n*=5)	0.16
Maximum Daily Temperature (°C)	1.84 (*n*=15)	0.62 (*n*=5)	0.28
5-day Snow Depth Change (cm)	-2.70 (*n*=15)	-22.86 (*n*=5)	*0.016*

The lysimeter showed water (<0.3 mm) moving through the tipping bucket beginning 25 April 2012 (Figure 3). Between then and 21 May 2012 small amounts (<0.3 mm) were recorded on four separate days. On 22 May 2012, over 40 mm of water moved through the lysimeter. Another large outflow on 2-5 June 2012 occurred (324 mm total), and water outflow was fairly constant from that point forward during warming/melting periods. Water outflow from the lysimeter weakly correlated with synchronous (no lag) maximum and mean air temperature, and change in snow depth over five days ($r = 0.21$, $r = 0.18$, $r = -0.02$, respectively) from 1 April - June 15. Water outflow from 1 June to 15 June was moderately correlated with synchronous maximum air temperature and mean air temperature ($r = 0.57$ and $r = 0.60$, respectively).

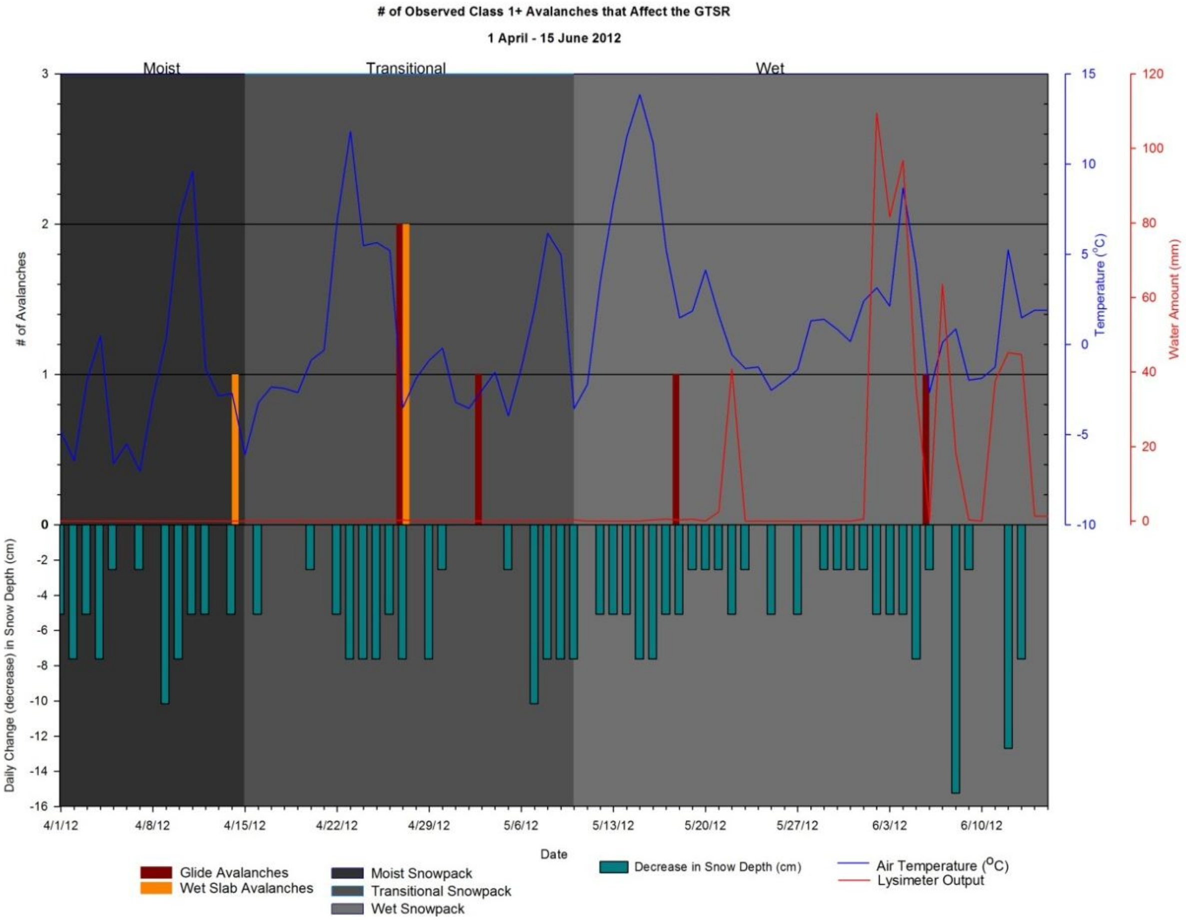

Figure 3: Observed avalanche occurrence (y-axis) is plotted with daily mean air temperature (blue line, 1st right y-axis) and daily outflow from a lysimeter (red line, 2nd offset y-axis). The observed bulk moisture content of the snowpack is displayed as three different shades of grey backgrounds that span the appropriate days. A daily decrease in snow depth is shown on the lower part of the graph (increases in snow depth not shown as only a decrease in snow depth was shown significant in the original classification tree model).

Snowpit observations near the starting zones commenced on 4 April 2012. Six days later the entire snowpack was moist to the ground/snow interface and the entire snowpack was isothermal around 0 °C (+/- 1.0). On this day approximately 30% of the snowpack (the top 66 cm) was classified as wet and the rest of the snowpack was moist. Various crusts existed within the top 1 meter and decomposing mixed faceted crystals (4c) were observed near the ground. Between 10 April and 10 May, the snowpack consisted of a mix of wet surface layers, melt-freeze crusts, and moist layers. By 10 May, the snowpack had transitioned to a wet snowpack throughout.

5. DISCUSSION

5.1. Classification tree testing

Classification tree methods have been used extensively in avalanche data analysis (Baggi and Schweizer, 2009; Davis et al., 1999; Hendrikx et al., 2005; Jones and Jamieson, 2001; Rosenthal, 2002; Schweizer and Jamieson, 2003). The development of the original classification tree model using data from the GTSR corridor was to improve a general understanding of wet slab and glide avalanches, but also to assist in an operational forecasting program along the GTSR. Thus, subsequent testing (or “hindcasting”) of the model with newer data (2012) further examines the effectiveness of the model for forecasting capabilities.

Peitzsch et al. (2012) found the model to be effective in predicting avalanche days outside of the training period when they tested it for the 2011 season. However, for the 2012 season, the model failed to predict days when avalanches occurred. Thus, we compared avalanche days from the original dataset that the model predicted as non-avalanche days to 2012 misclassified avalanche days to determine if any patterns existed. Our results showed no significant difference in air temperature metrics between missed avalanche days this year when compared to missed days from previous years. So this indicates that 2012 was characterized by avalanche days most similar to those that the model struggled with in the original training data. Maximum temperatures for both sets of data were well below the 5.35 °C threshold the classification tree model uses to discern avalanche and non-avalanche days. The mean temperature for both sets was also below the 1.65 °C mean temperature threshold in the model. This suggests that the model failed to capture avalanche days that do not occur under the more typical warm and sunny conditions on the GTSR. This can be attributed to the majority of avalanche days in the original dataset resulting from warming and subsequent melting events, and the missed avalanche days appear to be either rain-on-snow events or transition days (i.e. pattern change from warm, sunny conditions to cloudy, cool, and precipitation). Glide avalanches have been observed in many conditions ranging from warm and sunny conditions to cold with snowfall (Simenhois and Birkeland, 2010). Observations during the 2012 season show that all wet slab and glide avalanche days occurred immediately after a prolonged warming period (Figure 3). One such event in late April occurred during a rain event on the heels of a warming period. This also indicates there may be a discernible lag between warming periods and melting processes deeper in the snowpack that would be a factor in wet slab and glide avalanches. The results presented by Hendrikx et al. (2012) from analysis of a glide avalanche using a time-lapse camera on the GTSR concur with this assessment of a lag being necessary. Further examination into periods of lag between peak temperature of a warming period and avalanche activity will likely be useful.

Changes in snow depth over five days (including avalanche day) between 2003-2011 and 2012 were significantly different with days in 2012 having greater change in snow depth. However, the classification tree model classifies days using maximum and mean air temperature first. Thus, the days in 2012 were classified as non-avalanche days based on those metrics. The large changes in snow depth in 2012 (<-19.95) were present in four out of five days. This may be attributed to each warming/melting period immediately preceding the avalanche day.

Testing the classification tree model with 2012 data showed that the model was not effective in predicting avalanche days when air temperature was below the thresholds of the model. The model appears to be useful predicting avalanches during the more typical warming events but not avalanches that occur due to rain-on-snow events or events that lag behind the warm period. In part, this may be due to the lack of lysimeter data being present for the original training period. Thus, more work is necessary to calibrate the model to include such events.

5.2 Lysimeter/water flow and snowpack conditions

To examine the timing of water flow deeper in the snowpack we examined water output from a lysimeter installed at upper elevations adjacent to the starting zones. The lysimeter recorded very small amounts (<0.3 mm) in late April during the first wet slab and glide avalanche cycle (Figure 3). When examining lysimeter outflow amounts we concentrated on patterns more than actual amounts of water. Because this is only one slope and water movement through a stratified snowpack can be quite spatially and temporally variable, the actual water amount may or may not be representative. The small amounts of water recorded in late April may also be attributed to freezing of some portion of the lysimeter. While much care was taken to insulate the tipping bucket the drain on the lysimeter itself may have frozen and blocked water flow to the tipping bucket earlier in the season.

The moderate correlation with synchronous air temperature in the latter part of the spring (1 June - 15 June) during periods of notable outflow suggests that during warmer days in early June drainage channels are well established and water moves efficiently through the snowpack. This occurred when the snowpack was observed to be wet. It also suggests to some extent that as temperature rises so does water outflow through the snowpack later in the spring.

There appears to be no obvious pattern when examining synchronous avalanche activity and lysimeter outflow. Avalanches occurred during peaks in outflow in April, before and during peaks in outflow in late May, and after peaks in outflow in June (Figure 3). The last event was a result of a rain-on-snow event and was the last observed glide avalanche of the season. Thus, it appears that this water was already moving efficiently and abundantly through the snowpack to the ground/snow interface at the time of the glide avalanche.

Colbeck (1979) suggests that water flow through the snowpack on an inclined slope takes longer because water moves horizontally as well as vertically through a snowpack. On flat terrain water would reach the ground earlier than on a slope because of this mechanism. Conway et al. (2004) also observed this along the Milford Road in New Zealand. The lysimeters used in this study were on a 30 degree slope which was notably less than the approximately 40 degree slope of the adjacent starting zones. Thus, variability may be a factor when examining avalanche activity and lysimeter outflow. Because there was some evidence of water moving through the lysimeter either during or adjacent to all avalanche days in 2012, further work investigating water outflow and associated avalanche activity is necessary.

Classifying the bulk moisture properties through visual observation allows forecasters to track the development of a spring snowpack. While the transitional classification is not an established standard it is a useful descriptor for forecasters along the GTSR. For instance, layers near the surface can be wet or very wet and the snowpack near the ground that potentially harbors persistent weak layers can still be dry or moist. The lysimeter output began during the transitional period and increased markedly during the wet period. Interspersed crusts throughout and a layer of mixed facets near the bottom of the snowpack may have acted as layers that impeded vertical flow of water through the snowpack early in the spring. This illustrates the importance of such layers in the movement of water flow through the snowpack (Baggi and Schweizer, 2009; Peitzsch, 2009). Water appears to have flowed more easily to the ground once the snowpack became more homogenous and drainage channels were well established.

The lysimeter shows promise for use in operational forecasting along the GTSR. Conway et al.(2004) found a lysimeter as an effective tool in a forecasting operation as well. The pattern of increasing amounts of water moving through the lysimeter as the season progresses aids in determining the establishment of drainage channels. Thus, it helps to determine when deep wet slab activity may cease. However, since glide avalanches occur when water moves along the ground/snow interface, determining the end of a glide avalanche cycle is more difficult.

6. SUMMARY AND CONCLUSIONS

Forecasting wet slab and glide avalanches is difficult due to complex interactions of meteorological conditions, snowpack structure, and water flow through the snowpack. Our understanding of these types of avalanches is still fairly limited. In this study, we tested a previously tested classification tree model (created using data from the GTSR weather and avalanche database) with meteorological and avalanche data from spring 2012 along the GTSR corridor. We used this to assess the effectiveness of the model and to improve understanding of wet slab and glide avalanche occurrence. We also examined water flow through the snowpack measured with a lysimeter and examined the relationship between water flow through the snowpack, meteorological conditions, and avalanche occurrence.

Despite the previous success in 2011, the model performed poorly in predicting avalanche days in 2012. Comparing missed avalanche days from the original dataset showed that the missed events in 2012 were similar with respect to air temperature as those missed in the training dataset. Changes in snow depth were significantly different, illustrating the warming/melting periods preceding avalanche days in 2012. However, the model provided more insight to wet slab and glide avalanches by highlighting avalanche occurrence that occurred immediately after a warming event during cooler, cloudier conditions.

Lysimeter data showed a moderate correlation with synchronous air temperature, but no clear patterns associated with wet slab and glide avalanche activity. Care must be taken when using such a tool for operational forecasting due to variability of water flow because the lysimeter is merely one point on a slope. However, the lysimeter shows promise for future use after a few technical adjustments. This will also aid in comparing lysimeter outflow to general snowpack observations. Overall, these tools (the classification tree model and lysimeter) have provided some further insight to timing of wet slab and glide avalanches by illustrating the complexity of these types of avalanches. Further work investigating a lag between avalanche activity and meteorological conditions would aid in our understanding of these phenomena.

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DISCLAIMER

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

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