COMPARISON OF THE GLIDE ACTIVITY AT TWO DISTINCT REGIONS USING SWISS AND U.S. DATASETS

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ABSTRACT: Forecasting the timing of glide-snow avalanches still presents a challenge. Studies aiming for forecasting glide-snow avalanches usually employ statistical rather than physical approaches and often focus on a single geographical region. Several statistical approaches have shown promising results. Building on previous work, we employed various statistical models using data collected from two sites: Glacier National Park, Montana, USA, and the Dorfberg, Davos, Switzerland. We applied three different statistical methods, namely Random Forest Models, Binary Classification Trees, and a Multiple Linear Regression Model for analyzing contributing factors (predictors) for glide-snow avalanche events. For contributing factors we used meteorological parameters recorded at nearby weather stations. We focused on glide-snow avalanches driven by surface melt as opposed to melt initiating at the ground/snow interface. To compare model performance we used receiver operator characteristics. Although there are differences in the meteorological parameters that cause natural glide-snow avalanches at the two different locations, we also found similarities in the predictors of glide-snow avalanches across regions. Neither area showed glide release after a short-term change in environmental conditions. Results also suggest that a deeper snowpack takes more time to adjust to changes in air temperature. While we found strong similarities in predictors across sites, we did find some significant differences among predictors of glide activity. Our model showed that glide activity at the Dorfberg seemed independent of the snow depth, suggesting glide-snow avalanches can occur at any snow coverage. Conversely, glide-snow avalanches in Glacier National Park appeared to only occur above a certain snow depth, this snow-depth was related to glides-snow avalanche cycles in spring. Our models show similarities and differences across different regions and help to improve the understanding and forecasting of glide-snow avalanches.

KEYWORDS: glide-snow avalanche, forecasting, full-depth avalanches

1. INTRODUCTION

Snow gliding is a process where the entire snowpack is moving downslope (Humstad et al. 2016). This movement can result in a glide avalanche release. Because of variable glide velocities within the snowpack, so-called glide cracks may occur and can exist for months prior to the release of a glide-snow avalanche (McClung et al. 1994). Once the glide motion accelerates into an avalanche we call it a glide avalanche (Höller 2014). Although glide cracks are an indicator of a gliding snow mass, the timing of avalanche release is not easily predicted, and a visible glide crack is not a prerequisite for glide avalanche activity (Fees et al. 2023). Full-depth glide avalanches may also release under generally stable conditions without any additional loading (Clarke and McClung 1999). Glide avalanches mostly occur in the same area, constituting a considerable threat to local communities and infrastructures like the Dorfberg in Switzerland or the Going-to-the-Sun-Road in Montana (Dreier et al. 2016; Peitzsch et al. 2012). Although these areas are in distinct regions, they are both important for the local communities, e.g., due to the number of tourists they attract.

Important data like snow stratigraphy are often limited or non-existent. However, weather stations are often located in the vicinity (<1 km) of glide avalanche paths. These weather stations provide a way to assess the relationship between meteorological parameters and glide-snow avalanche activity. Understanding this relationship will improve forecasting and associated worker and public safety.

Several studies focused on forecasting glide-snow avalanches have employed statistical rather than physical approaches, often at a single site. Various statistical approaches have shown promising results (Peitzsch et al. 2012; Dreier et al. 2016). Building on this work, we employed various statistical models using data collected from two sites: Glacier National Park (GNP), Montana, United States, and Dorfberg, Davos, Switzerland. Due to limited data we focused

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on glide avalanches driven by surface melt as opposed to melt initiating at the ground/snow interface. We used meteorological parameters recorded at nearby weather stations as predictors and glide avalanches as the response to check if there is a relationship between the two. The goal of this study was to identify meteorological conditions associated with glide avalanche events to improve their forecasting.

2. METHODS

2.1 Surface melt vs ground/snow interface melt

It is generally assumed that glide events during spring are driven by surface melt, while glide avalanches during winter are initiated by melt at the ground/snow interface (Fees et al. 2023; Dreier et al. 2016; Clarke and McClung 1999). Thus, we split each winter season into two periods: a period with prevailing surface melt events (‘warm’) and a period with prevailing ground/snow interface melt (‘cold’). We visually selected the cutoff dates based on the day with the lowest air temperature before a general warming trend during spring. Based on these data we chose a cutoff date for each year and only focused on the ’warm’ glide avalanche regime. We then classified non-avalanche days (NADs) or avalanche days (ADs) after the cold/warm transition (Figure 1).

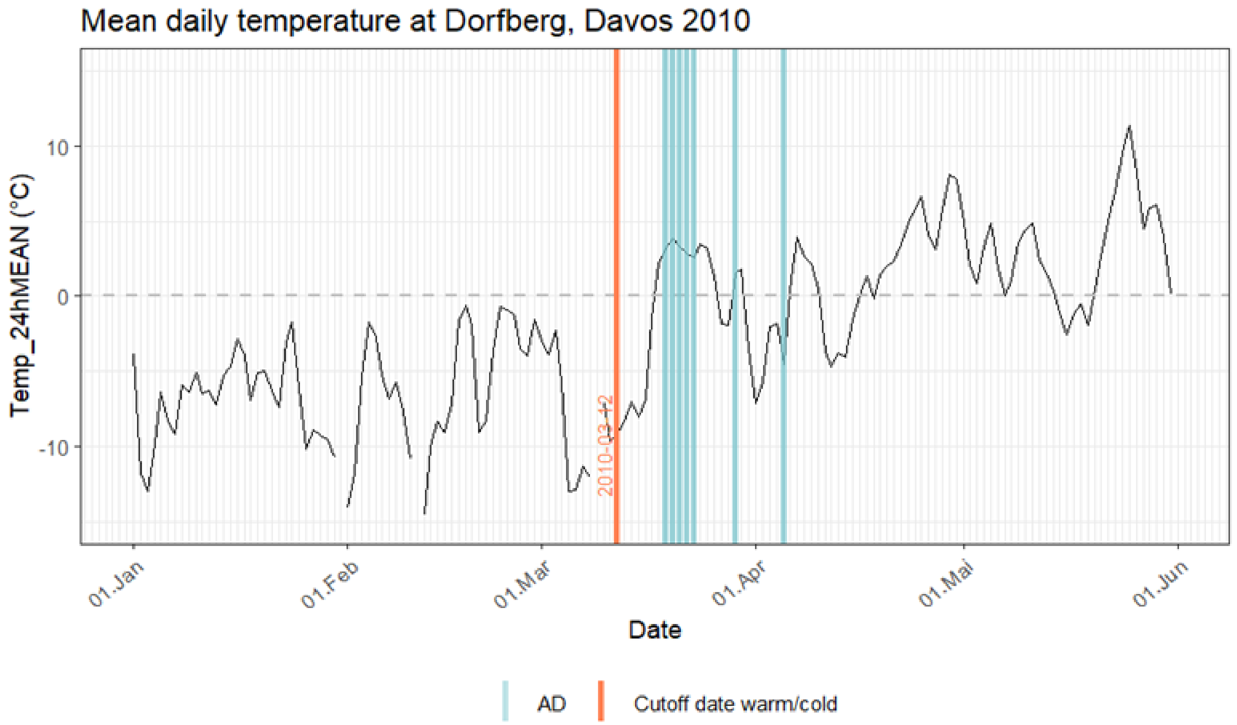

Figure 1: The mean daily air temperature and the avalanche days (ADs) of the year 2010 in Davos. The orange line indicates the cutoff date. We considered every AD before the cutoff date as an AD induced by melt at the ground/snow interface and all ADs after the cutoff date as ADs induced by surface melt.

.*2.2 Test and train data*

We split the dataset into training and test data. The training data were used to train the model, whereas the test data were used to test the trained model. We chose a random 80:20 split, where 80% of the available data were used to train the model and 20% were used to validate it.

2.3 Balancing the training data

Our dataset consisted of substantially more non-avalanche days than avalanche days (Figure 2). We used balancing techniques to minimize non-avalanche bias (Breiman 2001). We explored several

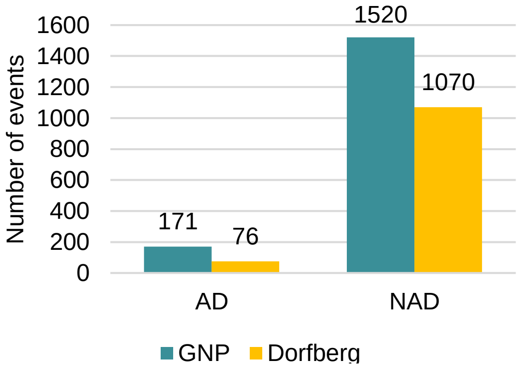

Figure 2: Number of avalanche days (AD) and non-avalanche days (NAD) at Glacier National Park and Dorfberg.

techniques, including over-, under-, both-, and rose-sampling (Lunardon et al. 2014).

2.4 Univariate statistical analysis

The significance of each parameter for ADs and NADs was analyzed using a univariate analysis. We visually inspected plots for every meteorological parameter to check for normal distributions, outliers, and measurement errors in the AD and NAD data. We removed outliers and measurement errors before we analyzed the data. We then performed a Wilcoxon Rank Sum Test (p-value cutoff = 0.05) to determine statistically significant differences between ADs and NADs.

2.5 Multivariable statistical analysis

We used multivariable statistical analysis tools to further investigate several parameters' influence on glide snow activity. This study implemented Multiple Linear Regressions (MLR), Binary Classification Trees (CART), and Random Forests (RF) to determine the most relevant meteorological parameters causing glide avalanches. We used the R packages caret (Kuhn 2008), rpart (Therneau et al. 2021), randomForest (Liaw and Wiener 2002), and glmnet (Friedman et al. 2010) to conduct the multivariate statistical analysis.

All models were optimized by implementing a five-fold cross-validation. During a five-fold cross-validation the training data are divided into five non-overlapping subsets, or "folds." The model is trained on four of these folds and is evaluated on the remaining fold. This process is repeated five times in which each fold is used for validation once. The results of each validation are then averaged to provide an overall estimate of the model's performance on the training data (Kuhn 2008).

3. RESULTS

3.1 Model Performance

At Dorfberg, the both-balanced Multiple Linear Regression (MLR) model exhibited the best performance, achieving an accuracy of 87%, a probability of detection (POD) of 87% and a probability of detection of non-events (PON) of 87%. At GNP, the under-balanced Random Forest (RF) model produced the most reliable results, with an accuracy of 75%, a POD of 71%, and a PON of 75%. The Dorfberg model notably outperformed the GNP model (Table 1).

Table 1: Performance parameters of the best-performing Dorfberg and GNP models.

Location	Parameter	Value
Dorfberg, Switzerland (MLR Model)	Accuracy	87%
	POD	87%
	PON	87%
GNP, USA (RF model)	Accuracy	75%
	POD	71%
	PON	75%

3.2 Variable Importance

At Dorfberg the most significant parameters were the 14-day air temperature difference (“Temp_14dDIF”), the mean air temperature over the preceding 7-days (“Temp_7dMEAN”) and the mean air temperature over the preceding 11-days (“Temp_11dMEAN”) (Figure 3). At GNP the most significant parameters were the snow depth (“SnowDepth”), the sum of preceding days with a mean daily air temperature above -5°C (“Days_above5neg”) and the mean air temperature over 11 days (“Temp_11dMEAN”) (Figure 4).

4. DISCUSSION AND CONCLUSION

We observed only minor differences in the parameters that contribute to glide avalanches at GNP and Dorfberg. Notably, the significance of these parameters varies greatly depending on the balancing method and modeling technique employed. This variability may be attributed to the strong correlation among parameters. Nevertheless, the significance of longer-term parameters can be observed across most of the models.

The glide activity at both locations does not exhibit an immediate response to short-term increases in air temperature. Instead, longer-term increases in air temperature serve as a reliable indicator for increased glide activity. The results suggest that more sustained warming is necessary for glide avalanche activity. Interestingly, in both locations, glide activity can increase even when the daily mean air temperatures are below 0°C. According to the models, a mean daily air temperature above -5°C is sufficient to cause a rise in glide activity in the warm glide regime.

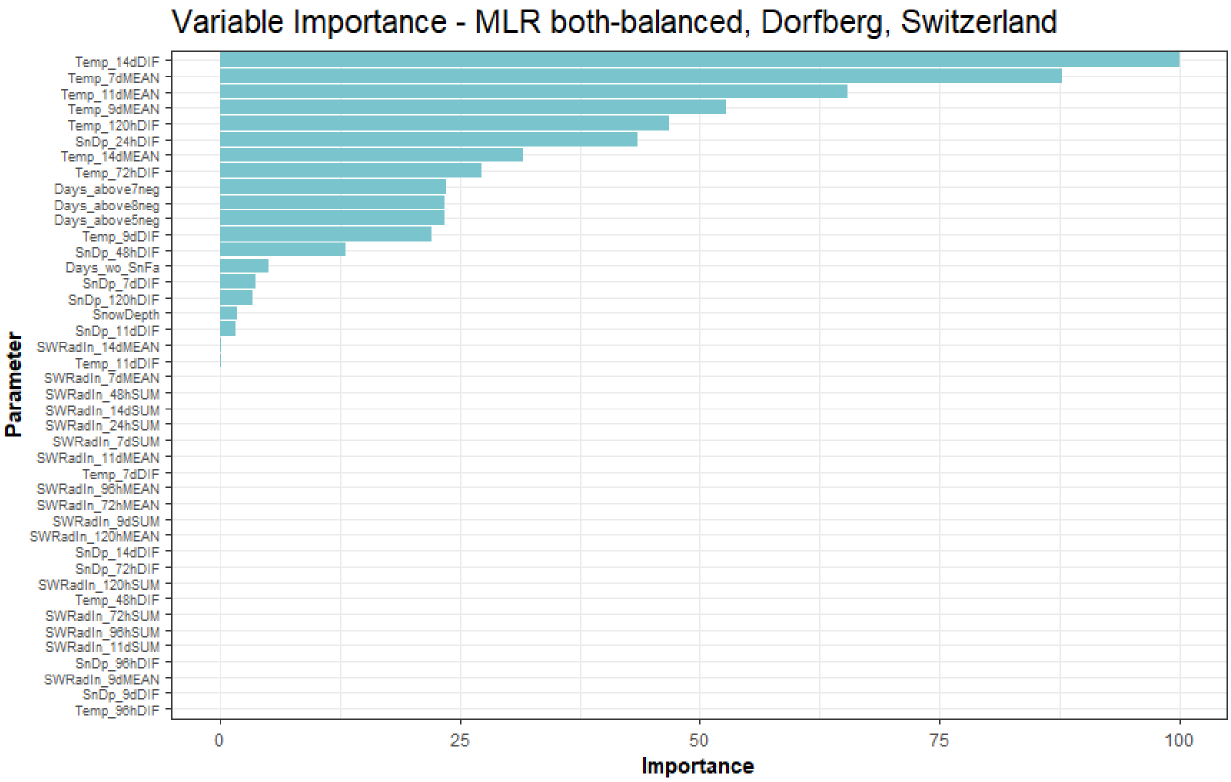

Figure 3: Variable importance of the best performing model MLR both-balanced. The most significant parameters were Temp_14dDIF, Temp_7dMEAN, Temp_11dMEAN.

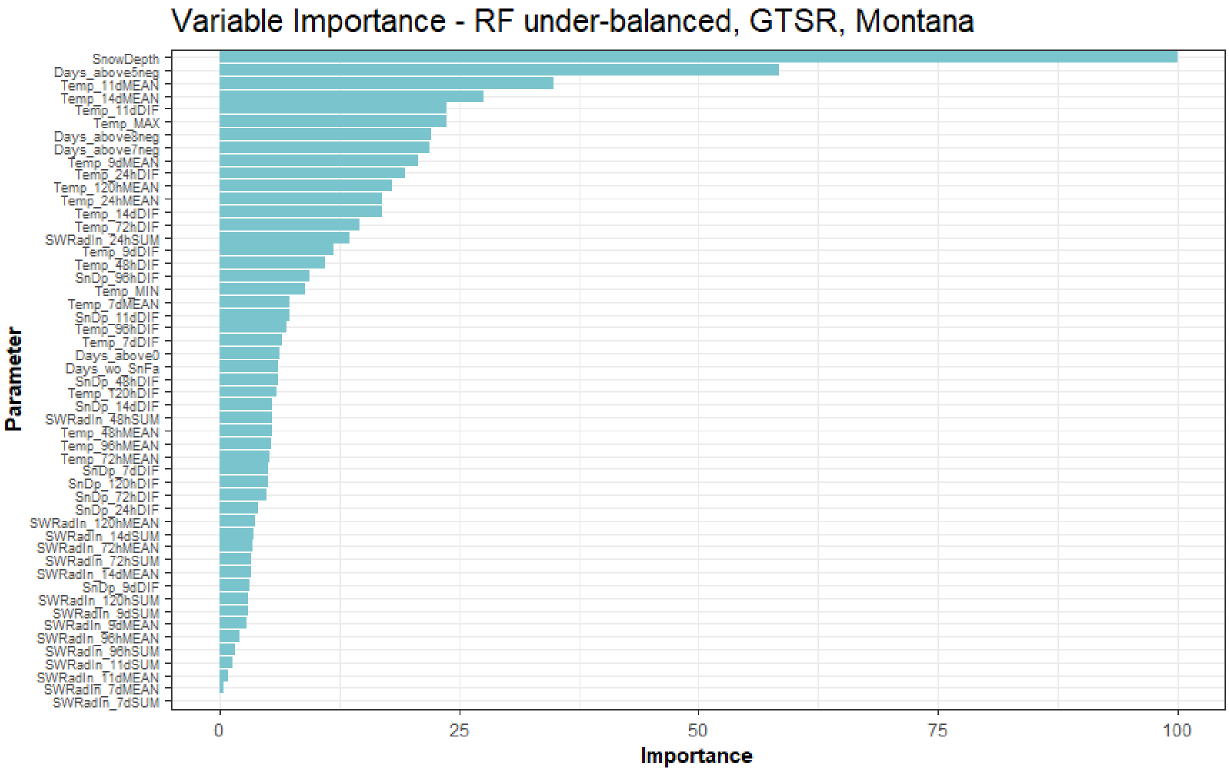

Figure 4: Variable importance of the best performing model RF under-balanced. The most important parameters were SnowDepth, Days_above5neg, and Temp_11dMEAN.

Snow depth shows distinctly different significance in models of the two locations. In GNP, snow depth is the most significant predictor of glide avalanche activity, with a threshold of 140 cm required for glide avalanche activity. In reality, this snow depth metric is merely a proxy for day-of-year timing rather than a physically based threshold as most of the glide activity in the observed dataset is from the spring when the snowpack is near maximum depth. Additionally, the snow depths considered in the GNP model are from a single weather station which does not capture the naturally occurring spatial variability of seasonal snow depths within the avalanche observation area. In contrast to the GNP model, glides-snow avalanche activity was independent of snow depth at Dorfberg, implying that glide-snow avalanches may occur at any depth.

Despite previous research identifying incoming shortwave parameters as significant indicators of glide avalanche activity, incoming shortwave radiation exhibited no significance at both Dorfberg and GNP in this study, suggesting minimal influence on glide activity. However, when considering all glide events at Dorfberg, including those before the spring season, longer-term incoming shortwave radiation parameters become significant. This finding indicates a shift in parameter significance at Dorfberg throughout the season.

Significant relationships with glide-snow avalanche activity were observed for the following parameters at both locations:

- Longer-term air temperature related parameters (“Temp_7dMEAN” at Dorfberg and “Temp_11dMEAN” at GNP),
- Multiple days of mean daily air temperature above -5°C (“Days_above5neg” at both).

It should be noted that the two datasets differ in terms of topography and observation quality. The Dorfberg site is well monitored, with avalanche activity being inferred from time-lapse images. However, it only covers a single slope at or below the tree line. The GNP data, on the other hand, is based on visual observations, covering a larger area with more varied topography, primarily situated above the tree line.

In general, the meteorological parameters favoring glide avalanches are very similar in both study areas. The primary difference lies in the length of time necessary for specific meteorological conditions, like air temperature, to influence glide avalanche activity. Despite this timing difference, the similarities in parameter significance suggest that statistical models based on simple meteorological parameters can enhance glide-snow avalanche forecasting, provided that long-term representative weather data and reliable avalanche observations are available. This study underscores the importance of having dependable weather stations and long-term avalanche observation programs. With larger datasets from diverse locations, we anticipate further improvements in statistical models, thus enhancing glide-snow avalanche forecasting.

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DISCLAIMER

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