PATTERNS OF GLIDE AVALANCHE RELEASE: INSIGHTS FROM 23 YEARS OF OBSERVATIONS ALONG THE GOING-TO-THE-SUN ROAD, MONTANA, USA

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ABSTRACT: Glide avalanches pose a notable hazard during annual spring snow removal operations along the Going-to-the-Sun Road (GTSR) in Glacier National Park (GNP), USA. Glide cracks consistently form on specific slopes near and above the GTSR. Some glide crack locations produce glide avalanches most years (known as repeater paths), whereas others are less predictable and either release or melt in place. Previous studies of glide avalanches have focused on different meteorological, snowpack, and terrain parameters that influence glide release. The timing of glide avalanche release remains difficult to predict, which can be a challenge. To the authors' knowledge, no previous work has approached the issue of timing by comparing the chronological release order of glide paths within an operation. To address this, we examine the release order of repeater paths along the GTSR and investigate different topographical factors that may influence release timing. To investigate the timing of glide avalanche release, we analyzed a dataset of annually recorded glide avalanches from 2003 to 2025 along the GTSR from mid-March to June. We identified 359 glide avalanches with starting zones covering all aspects between 1,600 and 2,700 meters, and performed analysis on topographic factors including elevation, aspect, slope angle, and bed surface. Additionally, we assessed the likelihood and sequence of the release of seven repeater paths. Seven repeater paths along the GTSR generate glide avalanches nearly every year (65–100% of the study period), with two paths (Peak 7774 and Peak 7850) releasing first in over half of the years observed (p-value < 0.01). These paths have been informally recognized as "indicator paths," though this distinction has not been quantified until now. Identifying factors that drive the timing of glide avalanches using a days-scale operational signal can support the safeguarding of infrastructure and personnel. By examining release order and related variables, this study provides practical insights to inform operations managing glide avalanche hazards. Our methods may help forecasters pinpoint indicator paths and potentially recognize the onset of glide avalanche cycles, offering a framework for other operations.

KEYWORDS: avalanche forecasting, glide avalanches, indicator path.

1. INTRODUCTION

Glide avalanches are full depth avalanches that involve the entire snowpack gliding, or slipping, downhill along the ground-snow interface (Jones, 2004). They are typically preceded by full-depth glide cracks, which open when glide rates vary on a slope. The time between glide crack formation and glide avalanche release is highly variable, from seconds to months (Birkeland, 2025; Fees et al., 2024; Mitterer and Schweizer, 2012), and some cracks never release, instead calving off in pieces or melting out as spring progresses (Reardon et al., 2006).

Because glide avalanches involve the downslope movement of the entire snowpack, they can be exceptionally large and destructive (Jones, 2004). As a result, these avalanches are a hazard in numerous operational settings, including highways, ski areas, and the backcountry (Johnston-Bloom et al., 2016). Common dry-snow mitigation techniques, such as explosives, are often ineffective at triggering glide avalanches, and forecasting glide avalanche timing remains challenging (Johnston-Bloom et al., 2016; Reardon and Lundy, 2004; Simenhois and Birkeland, 2010; Stimberis and Rubin, 2009). Recent work suggests that rising global temperatures may contribute to increases in wet snow avalanches in general (Mayer et al., 2024), and glide avalanches in particular (Dillon et al., 2025; Heuberger et al., 2024).

Researchers have investigated glide avalanches using a variety of approaches. Numerous studies have examined the meteorological and snowpack conditions associated with glide release (Heuberger et al., 2024; Peitzsch et al., 2012; Resch et al., 2023; Simenhois and Birkeland, 2010). Others have focused on terrain characteristics, highlighting the importance of slope angle and the "glide factor," a metric that combines ground

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https://doi.org/10.15788/1790098947

substrate and aspect (Peitzsch et al., 2015). Advances in remote sensing have further improved understanding by enabling snow depth measurements in otherwise inaccessible terrain (Dillon et al., 2025; Peitzsch et al., 2016). Similarly, time-lapse photography has proven valuable for documenting the evolution of glide cracks and precisely identifying the timing of glide avalanche release (Fees et al., 2024; Hendrikx et al., 2012; van Herwijnen and Simenhois, 2012). Despite these advances, accurately forecasting the release of glide avalanches remains a challenge and a holistic approach using several techniques may improve forecasting of the timing of glide avalanches (Humstad et al., 2016).

This uncertainty in glide avalanche timing is a concern along the Going-to-the-Sun Road (GTSR) in Glacier National Park, Montana, USA, where glide avalanches threaten personnel, equipment, and recreationists during spring snow removal operations (Peitzsch et al., 2026). Glide cracks consistently form on specific slopes above and around the road corridor, and forecasters have noted that some paths tend to produce glide avalanches nearly every year (Reardon et al., 2008; Reardon and Lundy, 2004). We refer to these paths as “repeater paths.” In other locations, glide cracks are more variable, releasing in some seasons and melting out in others. Research along the GTSR has enhanced our understanding of glide avalanches. For example, Peitzsch et al. (2012) identified key air temperature and snow settlement thresholds that can aid forecasters in anticipating days that may drive glide and wet slab activity. Still, the precise timing (hours or days depending on operations) of glide avalanche release remains difficult to predict.

This uncertainty occurs each spring as forecasters anticipate the timing of glide avalanches that can hit the road, affecting plowing operations and worker and visitor safety. When a glide avalanche cycle begins, a few repeater paths that are visible from the GTSR, but do not impact the road, tend to release first. Forecasters sometimes refer to these as “indicator paths,” though this designation has never been rigorously investigated (Hutchinson et al., 2016). Indicator paths are generally defined as paths that release at the onset of periods of high avalanche activity and may therefore offer predictive value (Schweizer et al., 2012). Prior research on indicator paths is limited and has primarily focused on winter avalanche cycles rather than springtime events. Judson (1983) found that indicator paths have little diagnostic value, and Schweizer et al. (2012) concluded that although indicator paths can be useful predictors, forecasting avalanches solely by observing indicator paths is not possible or recommended. Ultimately, avalanche activity can still occur even when an indicator path has not released (Judson, 1983; Schweizer et al., 2012).

To our knowledge, no previous work has applied an indicator path framework to glide avalanches. Because the location of glide avalanches is repetitive and generally predictable, potential indicator paths along the GTSR are readily identifiable. A 23-year dataset provides a comprehensive record of glide activity, allowing us to investigate whether the chronological order of glide releases can provide helpful insight for forecasting. In this study, we examine whether paths that anecdotally release early might function as indicator paths. We also examine patterns in glide avalanche release order and analyze topographic variables. Ultimately, we aim to determine whether a better understanding of chronological release order and associated terrain variables can improve glide avalanche forecasting along the GTSR.

2. METHODS

2.1 Study Area and Data

The Going-to-the-Sun Road (GTSR) in Glacier National Park (GNP) is located in northwest Montana, USA. This 80-kilometer two-lane road is the primary traffic corridor that connects the east and west entrances of GNP. Each winter season, 56 km of the GTSR is closed to vehicle traffic due to frequent snowfall, harsh weather, and avalanche hazards (Peitzsch et al., 2010b). Snow plowing operations to re-open the GTSR start in April.

All glide paths in this study area are located on the west side of the Continental Divide in the McDonald Valley (Figure 1), which exhibits an intermountain snow climate (Finklin, 1986; Mock and Birkeland, 2000). The road’s elevation ranges from 1,025 meters at Avalanche Creek to 2,026 meters at Logan Pass (Dillon et al., 2025), and slopes along the GTSR can harbor a variety of avalanche problems. The most common avalanches in the spring are wet snow avalanches, as they are associated with increases in air temperature, increased incoming solar radiation, and liquid water in the snowpack (Reardon et al., 2006).

We used a publicly available dataset of avalanche occurrence observations recorded by GNP and U.S. Geological Survey (USGS) avalanche forecasters from 2003 to 2025 (Peitzsch et al., 2026) according to standards outlined in Snow, Weather, and Avalanche Guidelines (American Avalanche Association, 2022). The dataset includes basic information (date, time, avalanche path and subpath names, avalanche type, and size) together with start zone terrain attributes (elevation, aspect, slope angle, and bed surface).

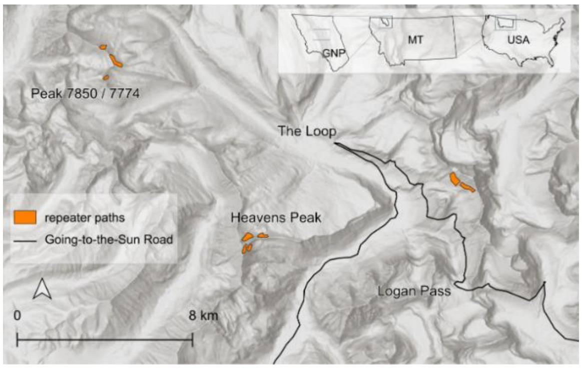

Figure 1: The study area in Glacier National Park, Montana, USA, with glide avalanche repeater paths highlighted in orange (polygons drawn by Peitzsch et al. (2015) and refined by the authors). Hillshade basemap from Esri World Hillshade (Esri, 2026). Country and state boundaries from Natural Earth (www.naturalearthdata.com). Glacier National Park boundary from U.S. National Park Service (NPS, 2026).

2.2 Data Processing

First, we selected avalanche types coded as glide avalanches with a bed surface of ground (“G”). We narrowed this subset further to avalanche paths consistently visible from the GTSR that had recorded a release more than once over the period of record. This resulted in a dataset of 359 avalanches. Additionally, we standardized avalanche path and sub path names for consistency.

We conducted quality control to establish consistent spatial references of repeater path start zones. We overlaid polygons digitized by Peitzsch et al. (2015) on high-resolution Google Earth imagery (Google LLC, 2024) and compared them with photographs to refine the polygons in QGIS (QGIS Development Team, 2025). We derived terrain attributes using a 10-m digital elevation model (DEM), and calculated zonal statistics for elevation (m), slope (°), and aspect (°). Distributions of observational terrain attributes were similar to those of the modeled polygons, and we omitted observations with errors. We infilled missing observational data with modeled median values.

We classified ground surface values using aspect and a glide factor index as per Margreth (2007). All start zones met the criteria of a similar ground class (Class 4), so we divided them into Beargrass, Rock Slab, and Mixed Scree based on ground class definitions from Margreth (2007). Separate from ground class, we added a binary variable indicating the presence of a cliff edge below a glide start zone (1 = present, 0 = absent). We determined ground class as well as cliff edge presence using high-resolution imagery and expert knowledge.

2.2 Data Limitations

We acknowledge various sources of error in the dataset. Observations were collected opportunistically as part of an operational forecasting program rather than systematically (Peitzsch et al., 2010a). Forecasters typically collect field observations from 0700 to 1500 during operational hours (Monday-Thursday). As such, they assign glide avalanches that occurred on weekends to one of the three days (Friday through Sunday) according to apparent age of debris and crowns when observed on subsequent workdays (Peitzsch et al., 2010a; Reardon et al., 2008). Prolonged periods of clouds, rain, and heavy snow limit the ability to view terrain, meaning forecasters often must estimate the timing of avalanche release. As a result, multiple avalanches may be recorded on the same day, even if those avalanches did not actually release on the same day. Our dataset consists of observations by 18 individuals from 2003 to 2026 with operational overlap between observers. Despite the overlap, a change in observers may have also added error due to individual subjectivity in identifying and classifying avalanches (Peitzsch et al., 2010a). Notably, glide avalanche records do not distinguish between a partial release involving calved-off pieces of a glide crack or a full release involving the entire snowpack beneath the glide crack (Figure 2). We treated a partial release as a release for this study.

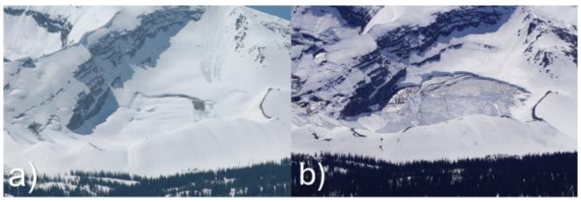

Figure 2: The avalanche occurrence dataset considers a glide avalanche as either: a) a partial release with a calved-off piece or pieces of a glide crack, or b) a full release involving the entire snowpack beneath the glide crack. These photos show possible differences in glide avalanche records for the Heavens Peak Remnant Glacier path, one of the repeater paths in our study. Photograph a: U.S. Geological Survey, 2006. Photograph b: U.S. Geological Survey, 2025.

Most avalanche data consist of field estimates verified using photographs and topographic maps, though direct measurements are taken when possible (Reardon et al., 2006). We used GIS-based quality control to identify and remove erroneous observation estimates of elevation, slope, and aspect. The GIS-derived start zone polygons are approximations, and the 10-m DEM can introduce small discrepancies in terrain metrics due to spatial resolution.

2.3 Data Analysis

We defined the first glide avalanche of each year as the earliest recorded day of the year of any glide avalanche observation. When multiple paths released on this day, we treated all tied paths as the first release of that year. We note when ties are excluded from an analysis.

First, we examined a subset of “repeater” paths (n=7 with 318 avalanches), defined as those that released in 15-23 years (65-100%) of the 23-year record. To determine whether a consistent release order existed among these seven repeater paths, we performed a Pairwise Spearman correlation of release ranks between all pairs of years. For each pair of years, this test compares the release ranks of paths, providing a correlation coefficient for every pair of years in the dataset (Spearman, 1904).

We calculated how often each repeater path released first. We then identified repeater paths that consistently released first and calculated how often at least one of these paths produced the first glide avalanche of the season. To expand on this empirical analysis, we fit a Plackett-Luce model to the glide release data using the PlackettLuce package in R (version 4.6.0) (R Core Team, 2026; Turner et al., 2020). This model provides a worth parameter for each path, which represents the probability of a path releasing first relative to the other paths in the model, and assesses the statistical significance of worth parameters using z-tests. The Plackett-Luce model accommodates for ties and partial rankings, meaning it accounts for years in which not every path releases, and years in which multiple paths tie for first (Turner et al., 2020).

We also expanded our analysis beyond the repeater paths (n=7) to all glide avalanche paths in the dataset (n=12 with 359 avalanches) to identify whether any non-repeater paths might serve as indicators. Similar to our repeater path analysis, we calculated how often each path released first, and identified groups of paths that, together, most consistently produced the first glide avalanche of the season.

We then separated the 12 glide paths into two categories: those located above the GTSR with potential to impact it (“road-impacting”), and those visible from the road but not located above it (“non-impacting”). We note that road-impacting paths do not always hit the road; they simply have the potential to. Additionally, we identified and investigated yearly patterns in road-impacting and non-impacting release order.

To examine whether terrain parameters are associated with the timing of glide avalanches, we performed a Partitioning Around Medoids (PAM) cluster analysis with Gower distance on repeater path observations (Rousseeuw, 1987). PAM with Gower identifies clusters using real observations, rather than averages, by calculating how similar each observation is from another, while accommodating the different variables in our data (Gower, 1971; Kaufman and Rousseeuw, 1990). We selected the optimal numbers of clusters based on the silhouette score (Rousseeuw, 1987). We ran the analysis on the first recorded release of each path per year. If there were multiple glide releases within a path on the day of the path’s first release, we included all releases. After performing cluster analysis, we examined the median day of year (DOY) of release associated with each cluster to determine whether any clusters were typically earlier or later releasers.

We also created groupings of repeater paths that release early most and least consistently. We then compared terrain parameters, including elevation, slope angle, circular mean aspect, cliff edge presence, and ground surface type, between the two groups.

3. RESULTS AND DISCUSSION

3.1 Release Order

The seven repeater paths do not release in a statistically reliable order from year to year over the 23-year record. A Pairwise Spearman correlation of release ranks across years showed high variability, emphasizing a lack of a strong, consistent release order of these paths. Every one of the repeaters has released first or tied for first in at least one year of the record (Figure 3). In fact, ties for first between repeater paths occurred in 9 of 23 years (39%), with up to four paths releasing first in the same year. We include ties in percentages of years released first for each repeater path, and so these percentages add up to well over 100%.

We found notable patterns in first glide activity in groups of paths. Peak 7850 and Peak 7774 most frequently produced the first glide avalanche of the season. One or both paths released first in 16 of 23 years (70%). In five of those years, however, they tied for first with another repeater path, so we cannot easily identify one of these paths as an “indicator” for the others. If we examine the three paths where glide avalanches most commonly release first by including Heavens Peak East Ridge in this subset of possible indicators, a more distinct pattern emerges. In 17 of 23 years (74%), the first repeater to release was exclusively Peak 7774, Peak 7850, or Heavens Peak East Ridge, and no other repeater paths tied with these paths for first. The Plackett-Luce model confirmed these empirical findings, showing that Peak 7774 (worth = 0.390) and Peak 7850 (worth = 0.383) had the highest estimated probabilities of releasing first (p value < 0.001), followed by Heavens Peak East Ridge (worth = 0.140) (p value < 0.01).

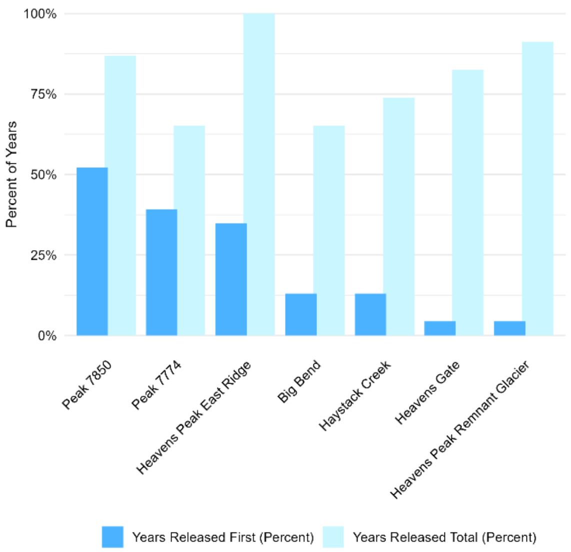

Figure 3: Percentage of years released total vs percentage of years released first (2003-2025) for repeater paths. This graph includes ties for first, meaning that when multiple paths release first in a year, they are all considered first. Thus, percentages of years released first between paths add up to more than 100%.

The results of the Plackett-Luce model represent theoretical probabilities under the assumption that all paths release every year with no ties. Over our 23-year study period, this was not usually the case. Thus, the model provides statistical support for the overall pattern, but the basic percentages are more immediately operationally applicable. Nonetheless, examining the repeater paths identified three potential indicator paths that may signal the beginning of a glide avalanche cycle. These results are operationally encouraging because none of these paths impact the GTSR. Thus, when they release first, they can help forecasters anticipate other releases that may threaten plowing operations. However, though these paths may have helped forecasters predict the onset of a glide cycle among repeater paths in 17 of the years on record, a different path released first in six of those years.

Expanding our analysis to all twelve paths in the dataset showed that eleven of these paths had produced the first glide avalanche of the year at least once. Peak 7850, Peak 7774, and Heavens Peak East Ridge remained among the most frequent first glides, but another path emerged as a potential indicator. SBRC, a low elevation path located above the GTSR, recorded a release in six years, and released first in three of those years. Avalanches in SBRC impact the GTSR, whereas avalanches in the other potential indicators do not affect the road. In 16 of the 23 years (70% of the study period), the first glide avalanche of the year was either SBRC or one of the three previously identified paths (Peak 7850, Peak 7774, and Heavens Peak East Ridge), with no other paths tying for first. This finding provides quantitative insight into a few of the glide paths that release first more often than others. At the same time, it highlights the difficulties of determining a reliable and predictable chronological order of glide release along the GTSR.

In 70% of years, a non-impacting path produced the first glide of the season, suggesting that non-impacting paths could serve as a warning for forecasters before road-impacting paths release and potentially affect operations. However, in the remaining 30% of years, a road-impacting path released first or tied for first. Thus, we cannot assume a non-impacting path will provide a warning for road-impacting glides. Regardless, a comparison of road-impacting and non-impacting paths revealed another interesting pattern.

A closer examination of yearly data from a road-impacting versus non-impacting perspective revealed a striking temporal pattern (Figure 4). From 2003-2018, the first glide of the year impacted the road only once (6% of the time). Then, from 2019-2025, the first glide of the year impacted the road every year but 2024 (86% of the time). When we examine repeater paths only, rather than all glide paths in the analysis, this pattern remains. From 2003-2018, the first repeater of the year did not impact the road (0% of the time) but from 2019-2025, the first repeater of the year impacted the road more than half of the years (57% of the time). This suggests a shift in recorded glide activity occurred around 2019.

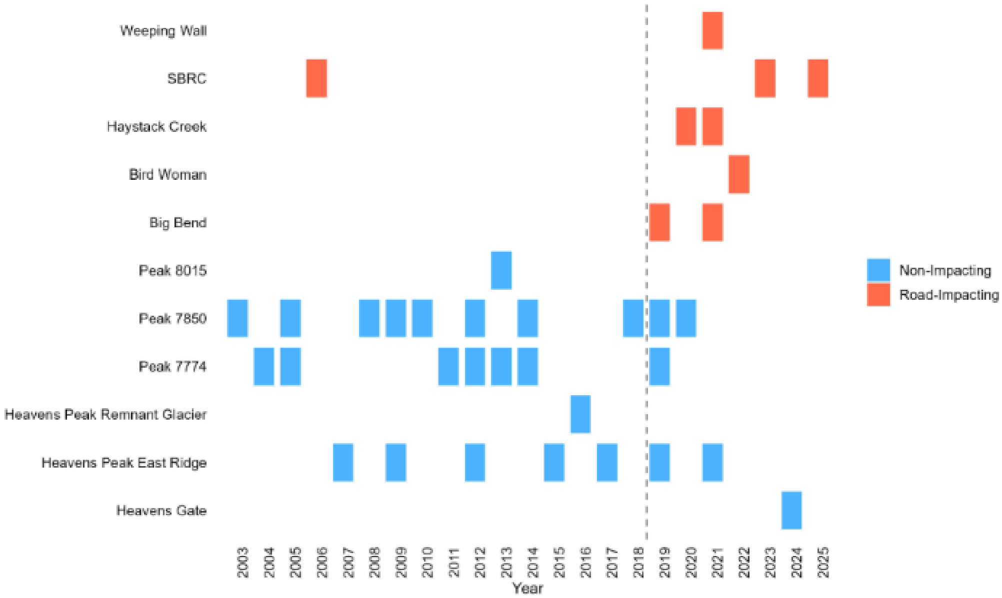

Figure 4: First-releasing glide path by year (2003-2025), distinguishing between road-impacting and non-impacting paths. The vertically oriented dotted line separates 2018 and 2019, which is when we noticed a shift in the first glide of the year impacting the GTSR. Prior to 2019, the first glide of the year usually did not impact the road. This provided forecasters with a more reliable indicator of the beginning of a glide cycle, but since 2019, this pattern appears to be changing. We have been unable to identify any drivers of this pattern shift.

We were unable to identify a clear driver of this temporal shift in our preliminary analysis. It may reflect dataset limitations, such as changes in the frequency of observation of some paths or changes in observers over time. With changing weather and climate conditions, past research suggests glide avalanche activity may change (Mayer et al., 2024). However, there is no identifiable trend towards earlier or later first glide releases over the 2003-2025 period, and high year-to-year variability exists in the data (Figure 5). The median DOY of first release over the study period is 111, or April 21 on a non-leap year. We also examined temperature data from a nearby automated weather station (Flattop SNOTEL, 1,914 m) and found no statistically significant differences in temperature (temp.) over these two periods (minimum temp. $p = 0.06$; mean temp. $p = 0.76$; maximum temp. $p = 0.37$) (USDA Natural Resources Conservation Service, 2003-2025). Future investigation into the potential drivers of this temporal shift could build on previous studies that have investigated the meteorological and snowpack conditions associated with glide avalanche release (Heuberger et al., 2024; Peitzsch et al., 2012; Resch et al., 2023; Simenhois and Birkeland, 2010).

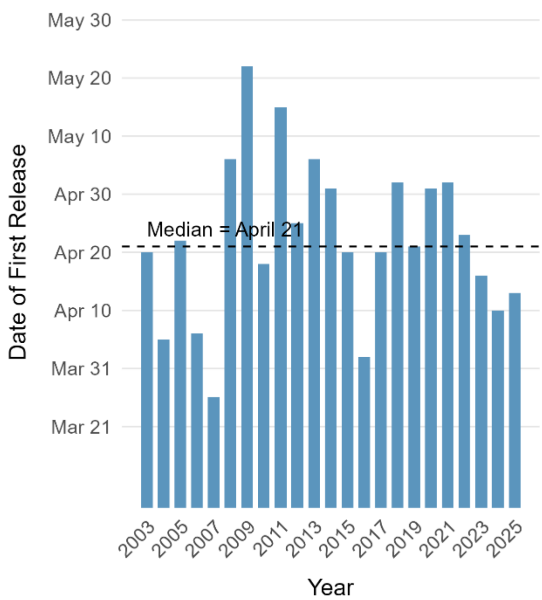

Figure 5: Date of first glide avalanche release by year (2003–2025). Bars represent the earliest recorded release day of year (DOY) across all paths each year. The dashed line indicates the median DOY of first release. Date labels reference a non-leap year and will be offset by one day for leap years. We identified no clear trend in first glide release timing over the study period.

3.2 Terrain

The cluster analysis of repeater paths, using the first recorded release(s) of each path in each year (n = 93), grouped observations into three clusters (k = 3) with a silhouette score of 0.632. This means most observations fit reasonably well into their assigned cluster, but some overlap exists between the clusters. Although the three clusters sorted repeater paths into groups with similar terrain parameters, the median first DOY of each cluster did not differ substantially.

Release timing was similar across clusters, with up to five days difference in median release DOY. Notably, cluster analysis grouped paths together that we had previously identified as more consistent early and late releasers. Peak 7774, Peak 7850, Heavens Gate, and Heavens Peak Remnant Glacier were all clustered together. Peak 7774 and Peak 7850 each released first in 60% of the years that each of these paths released, whereas Heavens Peak Remnant Glacier and Heavens Gate released first in only 5% of their release years. This suggests that paths with similar terrain characteristics do not necessarily release in similar patterns, and that internal glide mechanics may be a more influential driver of glide avalanche timing and release (Fees et al., 2024). Further, release DOY is not equivalent to release order—DOY may vary between seasons depending on weather and snowpack characteristics. A path might consistently release first but release on different DOYs each season. To more directly address whether terrain drives release order, we compared terrain characteristics between the two repeater paths that most consistently released first and the two paths that most consistently released last.

We compared Peak 7774 and Peak 7850 (each first in 60% of their release years) with Heavens Gate and Heavens Peak Remnant Glacier (each first in 5% of their release years). Mean and median elevation and slope angle differ minimally between early and late paths (less than 70 m and 3 degrees, respectively). Early paths have a circular mean aspect of 84 degrees (east facing), and late paths have a circular mean aspect of 59.6 degrees (northeast facing). Neither Peak 7850 nor Peak 7774 have cliff edges, but 50% of late path releases have cliff edges.

With only two paths in each group, we cannot distinguish path-specific characteristics from those associated with release order. The subtle terrain differences observed in this analysis may reflect individual paths rather than a broader pattern. For more conclusive results, we would need to be able to identify more consistent early and late paths. Overall, this comparison reinforces the conclusion that terrain parameters do not predict glide avalanche release order or timing along the GTSR.

4. CONCLUSIONS

Our study utilized a novel approach to glide avalanche forecasting along the GTSR, examining 23 years of data to identify potential indicator paths and terrain characteristics associated with glide avalanche release timing. Ultimately, our results highlight both the utility and the limitations of an indicator path approach to glide avalanche forecasting. We identified general patterns that may support operations, but we found high year-to-year variability in glide avalanche release order. No single repeater path reliably released before other repeater paths, and terrain characteristics did not strongly predict release timing or release order. However, we identified a small subset of paths, among both repeater paths and all paths, that released first more consistently than others. This finding has practical value for forecasters. We also identified a temporal pattern of activity in glide avalanche paths that impact the GTSR compared to those that do not, which may be operationally helpful in the future.

Our findings are consistent with previous research that shows the difficulty of forecasting glide avalanches and of using indicator paths in general for avalanche forecasting. As Schweizer et al. (2012) noted, “if one would rely on the indicator path, many avalanche situations would be missed.” Our results reinforce this sentiment of caution. When forecasting for avalanches that threaten personnel and equipment along the GTSR, a single forecasting approach is insufficient. As such, the insight we gained by examining 23 years of glide avalanche data along the GTSR can be used in conjunction with other forecasting tools and approaches. This study investigates a new approach for predicting glide avalanches, emphasizing the complexity of these avalanches and how further research could enhance our understanding.

DISCLAIMER

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

ACKNOWLEDGEMENTS

We would like to share our appreciation for the NPS and USGS avalanche forecasters and employees who contributed their insight and observations to the avalanche database over the years. This work was supported by the U.S. Geological Survey Ecosystems Land Change Science Program.

This research employed a variety of AI tools: generative AI for manuscript editing, and AI-assisted coding for data processing. All AI-generated outputs, including text, code, and analytical results, were reviewed, validated, and, where necessary, modified by the authors to ensure scientific rigor, integrity, accuracy, and compliance with USGS standards.

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