Natural glide avalanches present a regular but relatively unpredictable hazard to snow removal operations during the annual Spring opening of the Going-to-the-Sun Road (GTTSR) in Glacier National Park (Reardon and Lundy, 2004). As such, records of natural glide avalanches that occur during the Spring opening are included in the database created for the GTTSR avalanche forecasting program (Reardon and Lundy, 2004). These observations formed the source data for this study.

The study area was comprised of the slopes visible from the GTTSR (Figure 2) west of the Continental Divide and upstream of Avalanche Creek, an area of roughly 24,000 ha. The lowest point in the study area lies at 1036m a.s.l. and the surrounding peaks reach 2915m. Many rock layers in the area dip distinctly to the east and the overlying glacial till has slipped or eroded away, exposing bedrock faces (Alt and Hyndman, 1973). Many other slopes in the valley are covered with bear grass (*Xerophyllum tenax*), a perennial evergreen herb with grass-like leaves that grows in clumps on dry, open sites.

The snow avalanche climate of the study area exhibits a generally Coastal precipitation regime accompanied by Continental temperature characteristics (Reardon et al., 2006; Mock and Birkeland, 2000) as a result of its position astride the Continental Divide. Though the peak Snow Water Equivalent (SWE) typically occurs the last week in April (1970-2008, Flattop SNOTEL, 1810m a.s.l.), the snowpack is at its most variable during the spring (Klasner and Fagre, 2000). Peak SWE totals can vary by more than 50% and the date of peak SWE has occurred as early as March 27 and as late as May 27.

Because of the site’s mid-hemisphere latitude (48° 40’ N), insolation increases in both intensity and duration as the snow removal season progresses. Data from weather stations in the study area show 13 hours of radiation in the westerly-facing start zones in early April and 17 hours by early June. The average monthly radiation is $7.95 \times 10^8$ j/m$^2$ in July (Finklin, 1986).

The database for the GTTSR forecasting program consists of field observations and measurements of snow conditions, avalanche occurrence and weather conditions collected and recorded using standard methods and nomenclature (Greene et al, 2004). Some avalanche occurrence parameters were estimated in the field and later verified using photographs and topographic maps. From the database, we selected all natural avalanches identified as glide avalanches and for which notes and/or photographs indicated a full-depth avalanche occurred following formation of a glide crack. These events resulted in both a visible bed surface of bare ground and debris that flowed over a stauchwall before continuing downslope over the snow surface. The database yielded 152 distinct glide avalanches from six seasons (2003-2008). Records included date of occurrence and destructive class for all 152 glide avalanches, as well as start zone elevation, vertical fall and estimated crown depth and width for a majority of the recorded avalanches. The database did not include data describing slope angle of the glide avalanche start zones nor an explicit identification of whether snowmelt or rain triggered the glide avalanches.

The database contained the majority of the glide avalanches that occurred in the study area each spring, despite several constraints. Observations were made during operational hours, so glide avalanches that occurred on weekend were assigned to one of the two weekend days according to apparent age of the debris and crowns when observed on subsequent workdays. Many avalanche sites were inaccessible or not visible until snow removal permitted travel to slopes above the upper reaches of the GTTSR. Pre-season overflights of the study area provided a baseline for observations in 2004 and 2006. In all six seasons, most slopes within the study area were visible by the second week of April. The exception was the south-westerly facing slopes...
between Haystack Butte and Logan Pass, which were visible by late April or early May each season. Despite the constraints, observations occurred most days and included most of the study area on any given day.

Meteorological data were collected at one SNOTEL station and two automated weather stations (AWS) within the study area. Precipitation and temperature were measured at Flattop Mountain SNOTEL at 1810m a. s. l. The station is located below the summit of a broad plateau between the two major mountain ranges in GNP. It is operated by the Natural Resource Conservation Service (NRCS) and is part of the SNOTEL network. It provided daily maximum, minimum and mean air temperatures, SWE and height-of-snow measurements, as well as some hourly measurements of the same parameters (http://www.wcc.nrcs.usda.gov/snotel/snotel.pl?sitenum=482&state=mt).

One automated station, Garden Wall Weather Station (GWWX), sits atop a southwest-facing slope at 2240m a. s. l. just west of the Garden Wall, a rock spine that forms the Continental Divide. The station was situated within 10km of most of the glide avalanches included in this study. GWWX was outfitted with a full complement of standard meteorological sensors, except precipitation sensors due to the site’s windy exposure. A second AWS was located at Logan Pass Visitor Center at an elevation of 2035m a. s. l. and operated with a suite of sensors similar to GWWX. Logan Pass is a broad, low-angle bench at treeline. Windy conditions again prevent the collection of precipitation data. At both stations, temperature measurements were made at sixty-second intervals and reported as hourly averages and daily minimum and maximum values. Data from both stations was available for the 2004-6 seasons, as well as from Logan Pass for the 2003 season.

A total of 152 glide avalanches were observed during the 2003-2008 seasons. The results suggest that a typical glide avalanche for the six seasons was destructive class 2, with a start zone elevation of 2230m, a vertical fall of 250m, and a crown depth over 2m, that occurred roughly a week after the SWE peak in late April. Some interannual variability is apparent, however, particularly for those parameters describing timing and number of glide avalanches each season.

A summary of the meteorological characteristics of the six seasons showed more variability than the physical characteristics of the observed glide avalanches. The largest variability was associated with snowpack characteristics; the maximum SWE varied by +22% from the mean and date of maximum SWE had a range of 29 days. The date of the maximum daily air temperature at Flattop SNOTEL was also highly variable, coming as early as day 122 (2004) and as late as day 147 (2003).

For two of the five seasons (2004 and 2006), the number of glide avalanches observed in a day had modest but significant (p<0.05) correlations with nearly all of the same day air temperature variables (Table 3). Significant Pearson correlation coefficient values ranged from 0.303 to 0.469. The one variable in this group that did not have a significant correlation was daily minimum temperature at Flattop SNOTEL during the 2004 season. For the remaining seasons (2005, 2007, 2008), there were no significant correlations between the number of observed glide avalanches in a day and any of the air temperature variables measured at the three weather stations.

For the seasons in which data was available from all three stations, the correlation strength varied between the weather stations, with the air temperature variables at GWWX generally having the strongest correlation with the number of observed glide avalanches and Flattop SNOTEL typically having the weakest. At all three stations mean daily air temperatures tended to have higher correlations with the number of observed glide avalanches than daily maximum or minimum temperatures, though there was some variability from year to year.

We attribute some of the results to the influence of local terrain and seasonal weather. The consistency in the physical characteristics of the observed glide avalanches over the three seasons is partly due to the fact that many of the same slopes released as full-depth glide avalanches each season. These annual slides – the “repeat offenders” – typically occurred on northeasterly facing slopes with exposed bedrock as the substrate, while the slopes with occasional glide avalanches often had bear grass substrates. A change in observers after the 2006 season may account for some differences in the number and timing of glide avalanches in the following seasons, though there were very real differences in snowpack in those seasons as well.

Terrain influences may contribute to the inconsistent results amongst the temperature variables in different years. For instance, Flattop SNOTEL is located on a broad bench that is subject to nighttime inversions, especially during the periods of sustained high pressure that bring the warmest temperatures to the study area. This
characteristic may explain why daily minimum temperature at Flattop was the only temperature variable in 2004 that did not significantly correlate with number of observed.

The chaotic and dynamic nature of the processes that create glide avalanches is underscored by the modest correlations between air temperature variables as well as the inconsistent results from season to season underscore. They also suggest that air temperature is an indirect cause of glide avalanche release, and that primary problem in forecasting glide avalanches is the current inability to measure the direct causes for their release, namely the amount and distribution of water at the ground-snow interface.

REFERENCES


