NATURAL GLIDE SLAB AVALANCHES, GLACIER NATIONAL PARK, U.S.A.: A UNIQUE HAZARD AND FORECASTING CHALLENGE

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ABSTRACT: In a museum of avalanche phenomena, glide cracks and glide avalanches might be housed in the “strange but true” section. These oddities are uncommon in most snow climates and tend to be isolated to specific terrain features such as bedrock slabs. Many glide cracks never result in avalanches, and when they do, the wide range of time between crack formation and slab failure makes them highly unpredictable. Despite their relative rarity, glide cracks and glide avalanches pose a regular threat and complex forecasting challenge during the annual spring opening of the Going-to-the-Sun Road in Glacier National Park, U.S.A. During the 2006 season, a series of unusual glide cracks delayed snow removal operations by over a week and provided a unique opportunity to record detailed observations of glide avalanches and characterize their occurrence and associated weather conditions. Field observations were from snowpits, crown profiles and where possible, measurements of slab thickness, bed surface slope angle, substrate and other physical characteristics. Weather data were recorded at one SNOTEL site and two automated stations located from 0.6-10 km of observed glide slab avalanches. Nearly half (43%) of the 35 glide slab avalanches recorded were Class D2-2.5, with 15% Class D3-D3.5. The time between glide crack opening and failure ranged from 2 days to over six weeks, and the avalanches occurred in cycles associated with loss of snow water equivalent and spikes in temperature and radiation. We conclude with suggestions for further study.

KEYWORDS: Avalanche forecasting, natural avalanches, glide avalanches, Glacier National Park

1. INTRODUCTION

Glide is the process in which the snow cover on a slope slides downhill along the interface with the underlying ground (Jones, 2000). When glide rates vary on a slope, a tensile fracture, commonly called a glide crack, forms upslope of the area of faster glide (Clarke and McClung, 1999) where stresses are concentrated (Jones, 2000; LaChapelle, 2001). Full-depth avalanches often follow the formation of a glide crack (Figure 1). Such glide avalanches are unpredictable, however, because not all glide cracks culminate in avalanches (Tremper, 2001), and for those that do, the time between crack formation and avalanche release can vary widely, ranging from several hours (LaChapelle, 2001) to weeks or even months (McClung and Schaerer, 1993).

Jones (2000) reviewed glide processes and glide avalanches, relying heavily on a model developed by Clarke and McClung (1999). As presently understood, glide has three prerequisites: (1) an interface with little roughness, such as bare rock or grass, (2) a temperature of 0^oC at the interface, which allows liquid water to exist, and (3), a slope angle greater than 15^o. This combination reduces the effects of friction and


Figure 1: Full depth avalanches that occurred 10-14 days after formation of a glide crack. May 17, 2006, Heavens Peak. Glacier National Park, MT.

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increases the influence of liquid water at the snowpack/ ground interface. Water can separate the snow from the ground by covering small irregularities at their interface; smoother surfaces require a thinner film of water before separation and glide occur. The amount of liquid water present at the interface between the snowpack and the ground is thus understood to be the critical influence on glide rates and glide avalanches. Water may also contribute to glide avalanches by decreasing the viscosity of the slab, allowing it to flow over surface irregularities. The primary sources for this water are rain-on-snow events and snowmelt, which can occur at the surface due to short wave radiation or air temperature, or at the interface as a result of stored heat in the ground. Though glide rates have been measured at 1-40 mm/d, studies to date have not identified a threshold glide rate for initiation of glide avalanches, and it appears that an acceleration of glide rates is the critical component in the process.

Glide avalanches are generally considered a form of wet snow avalanche (Jones, 2000; Tremper, 2001). They tend to be more common in maritime snow climates, though they can occur in drier snow climates during mid-winter thaws or in the spring (LaChapelle, 2001; Tremper, 2001). Despite their destructive potential, fatalities resulting from glide avalanches are rare, with only one accident known to have occurred in recent years (Tremper, 2001b). Thus they are not a focus for backcountry recreationists or avalanche education.

Glide avalanches are more often a concern for operational avalanche forecasting programs, particularly highway programs, because they can occur repeatedly in the same paths, often annually and sometimes within the same season (Wilson et al, 1996; Clarke and McClung, 1999; Reardon and Lundy, 2005; Stimberis and Rubin, 2004). Forecasting for glide avalanches thus relies on experience with and monitoring of local meteorological conditions (Jones, 2000), despite several attempts to develop tools for monitoring glide and detecting glide avalanches (Wilson et al, 1996; Jones, 2000; Stimberis and Rubin, 2004).

Control methods are limited (Jones, 2001). Glide avalanches are difficult to control with explosives (Jones, 2000; Steiner, 2006) due to the mechanical properties of wet snow (Clarke and McClung, 1999) and the fact that glide avalanches are not usually triggered by increasing loads (Jones, 2000). Some operations have experimented with or proposed non-explosive methods of control, such as covering the snow surface with charcoal to melt the slab or introducing water into glide cracks by helicopter (Jones, 2000).

Natural glide slab avalanches occur regularly in the mountains of Glacier National Park (GNP), U.S.A. Some of these pose a threat during the annual spring opening of the Going-to-the-Sun Road (GTTSR) (Reardon and Lundy, 2004) This two-lane, 80-kilometer road traverses the park, crossing the Continental Divide at Logan Pass (2026m a.s.l.). The Park closes a 56km section of the road each winter due to inclement weather, heavy snowfall, and avalanche hazards. During the 2006 spring opening, glide cracks and natural glide avalanches were especially widespread; many of these threatened snow removal operations throughout the season and posed a complex forecasting challenge.

The 2006 glide avalanches also comprised a rare dataset of natural glide avalanches from a single season in two well-instrumented drainages. The objectives of this study were to (1) characterize the unique 2006 cycle with field-based observations made during forecasting, and (2) use these exploratory findings to suggest directions for additional study.

2. STUDY AREA

2.1 Location

The study area was comprised of the slopes visible from the GTTSR (Figure 2). These slopes were primarily located in the McDonald valley, the major drainage in the park west of the Continental Divide. Additional slopes were situated in the St. Mary Valley, the major drainage east of the divide. Logan Pass is both the high point of the GTTSR and the lowest point in the ridge shared by the two drainages. The study focused on slopes in the headwaters of the two valleys, areas of 24,761 ha and 3933 ha, respectively. Vertical relief was greatest in the McDonald Valley, where the lowest point in the study area lies at 1036m a.s.l. and the surrounding peaks reach 2915m. East of Logan Pass, vertical relief is reduced because the valley bottom sits over 300m higher. The mountains on both sides of the divide are composed of Precambrian sedimentary rock that was overthrust eastward 25-60km (Alt and Hyndman, 1973). In the McDonald Valley, many rock layers dip distinctly to the east and the overlying glacial till has eroded away, exposing bedrock faces.

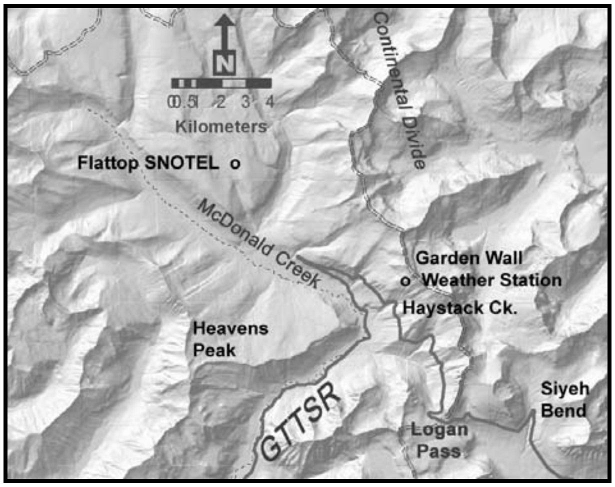

Figure 2: Shaded relief map showing the study area and locations named in text.

2.2. Climate and Weather

The snow avalanche climate of the study area exhibits both Coastal and Continental characteristics (Mock and Birkeland, 2000). Coastal characteristics include regular rain-on-snow events and abundant snowfall. Rain-on-snow events in GNP typically occur multiple times a winter, but rainfall amounts vary, exceeding 8mm many but not all winters. Average annual snowfall is estimated to exceed 1500cm in favored locations such as the upper McDonald valley (Finklin, 1986). A short-term (2000-2006) record of snow depths at Flattop Mountain SNOTEL station, located at 1920m a.s.l. in the headwaters of McDonald Creek, shows mean April 1 snow depth is 290cm. The mean April 1 SWE total at the station is 1130mm (1970-2004), above the threshold distinguishing the Coastal from Intermountain zone. April 1 SWE totals at the station do range widely, however, from 610-1768mm, indicating some years are markedly Coastal while a few tend towards Continental.

The generally Coastal precipitation regime is accompanied by temperatures typical of a Continental snow climate. The December-March mean temperature at Flattop SNOTEL is -8.1^{o}C (1982-2003), distinctly colder than the -3.5 to 7^{o}C range of an Intermountain snow climate. Despite the Continental-like temperatures, the December temperature gradient through the snowpack rarely approaches 10^{o}C/m due to high snow depths. Surface hoar and near-surface facets are the weak layers that typically develop during extended dry periods rather than depth hoar.

The contrasting precipitation and temperature regimes are due to the study area's position astride the Continental Divide. Both maritime and continental air masses influence the area's weather. Pacific weather systems dominate, bringing mild temperatures, low clouds and frequent snowfall. Arctic air-masses irregularly pour over the divide from the east, accompanied by clear skies, easterly winds and bitterly cold temperatures. The transition back to the dominant maritime regime can cause dramatic temperature changes of 25^{o}C in an hour as warm air overruns the Continental air, and this rapid warming, often accompanied by rain, can trigger widespread cycles of large, destructive avalanches.

The weather during the spring snow removal season is characterized by variability (Klasner and Fagre, 2000). As the transition to summer progresses, average 700-millibar heights increase and the storm track retreats northward, preventing strongly organized weather systems (Finklin, 1986). Precipitation tapers off, and the average peak SWE occurs April 27, with a range of a month. Snowfall and rain amounts during the spring tend be light, unless winter weather patterns persist into spring and then dramatically wet and stormy weather can occur.

Summer-like periods of fair weather typically occur each spring. These conditions occur when a ridge of high pressure pulls warm air into the region on a southwest flow. Under a strong ridge, they can persist for a week or more. Two notable features of this pattern are nighttime inversions and temperatures that peak gradually higher on successive days. Both features result in temperatures that are warmer in upper elevation start zones than at midslope.

The site's mid-hemisphere latitude (48^{o} 40' N) plays an important role in spring-time weather and avalanches. It makes for longer periods of ever-more intense insolation as the snow removal season progresses. The length of daylight doubles from late December to late June (8.2 to 16.2 hours); average monthly radiation increases 7.5 times in a similar period (1.05×10^{8} j/m^{2} in December to 7.95×10^{8} j/m^{2} in July) (Finklin, 1986). Data from weather stations in the study area show 13 hours of radiation in the start zones in early April and 17 hours by early June.

3. DATA AND METHODS

3.1 Glide Avalanche Data

We collected observations and measurements of natural glide avalanches in the study period as part of the avalanche forecasting program for the GTTSR (Reardon and Lundy, 2004). The data consist of field observations and measurements of snow conditions, avalanche occurrence and weather conditions collected and recorded using standard methods and nomenclature (American Avalanche Association, 2004). Though direct measurements were taken when possible, most avalanche data consists of estimates made in the field and verified using photographs and topographic maps.

Field observations were typically collected from 0700 to 1500, during operational hours. For this study, we defined the season as March 22, the first day of Spring, through May 31, when the last forecast of the season was issued. Helicopter overflights of the study area on March 23 provided a baseline for the season’s observations.

The primary purpose for making field observations was to create hazard forecasts, so data were collected opportunistically rather than systematically. Data collection was complicated by the large size of the study area. Many avalanche sites were inaccessible or even invisible until snow removal permitted travel to slopes above the upper reaches of the GTTSR. By the close of the season, however, most slopes within the study area were visible from the road. Despite the constraints, we were able to make almost-daily observations, and these included most of the study area on any given day. Based on these observations we believe we recorded nearly all the glide avalanches that occurred in the study area for the period.

3.2 Meteorological Data

Meteorological data were collected at two automated weather stations (AWS) and one SNOTEL site. The primary station was Garden Wall Weather Station (GWWX), which sits at 2240m a.s.l. just west of the the Garden Wall, a narrow spine of rock that forms the Continental Divide. The station was situated within 1km of many of the glide avalanches described 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 net radiometer was also installed at the station March 23 and operated through most of season. Data were not continuous throughout the study period due to power problems.

A second AWS was located at Logan Pass Visitor Center. A suite of sensors similar to GWWX was installed on the roof of the building. Windy conditions again prevented the collection of precipitation data. A pyranometer and a quantum sensor substituted for the net radiometer. At both stations, data from all sensors were recorded hourly and telemetered every 6-12 hours to the forecast office, where it was maintained.

Precipitation was measured at Flattop Mountain SNOTEL in the headwaters of the McDonald Valley. This site is operated by the Natural Resource Conservation Service (NRCS) and is part of the westwide SNOTEL network. Flattop provides daily air temperature, SWE and height-of-snow measurements, as well as some hourly measurements of the same parameters.

3.2 Analysis Methods

Past studies have shown 12-24hr lags between air temperatures and glide rates, even when instrumentation is directly adjacent to the slopes being investigated (Clarke and McClung, 1999). In addition, the constraints on data collection meant that glide avalanche occurrence in the study area was accurately reported at a daily resolution, though we did record exact times for those avalanches we witnessed. These considerations, along with the large size of the study area, led us to conduct our analysis at daily time steps for both glide avalanche occurrence and the weather parameters at each station.

4. RESULTS

4.1 2006 Season Glide Avalanche Characteristics

A total of 35 natural glide avalanches was recorded during the 2006 Spring opening. These occurred on 18 days of the 71 day season. The mean number of glide avalanches that occurred on days when avalanche were recorded was 1.8. The earliest glide avalanche recorded was March 22 and the latest was May 30, a range of 70 days that spanned the entire forecasting season. Additional glide avalanches occurred after observations ended May 31, almost entirely on high elevation slopes.

The size of the recorded avalanches ranged from D1 to D3.5, with a mean of 1.9 and a median of 2. Glide avalanche size showed a weak trend of increasing with elevation (Figure 3). Start zone elevations ranged from 1676m to 2637m, with a mean of 2150m. The observed avalanches had vertical falls of 61-1220m, with a mean of 293m. Slab thicknesses ranged from 0.25m to more than 6m and averaged 1.7m (n=25).

Estimated crown widths ranged from 10-155m, with a mean of 51m (n=25).

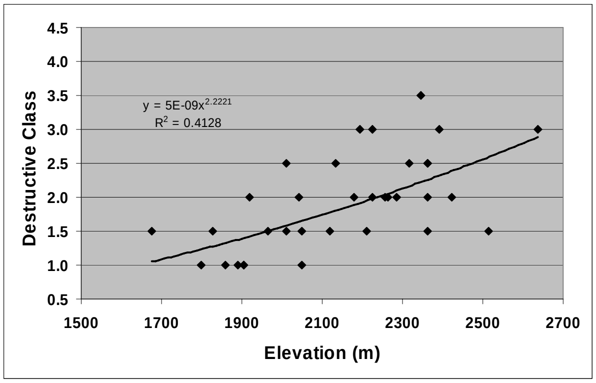

Figure 3: Scatterplot comparing glide avalanche Size (Destructive Class) vs. Elevation for 2006.

Glide avalanche size also showed some associations with date of occurrence. The glide avalanches were clustered into two main groups (Figure 4), those releasing at the end of April (April 19-30) and those releasing in mid-May (May 14-21). The mean size for the two clusters was similar (D2 vs. D1.8, respectively) but the avalanches in the first cluster were generally medium sized avalanches while the second included more small- and large-sized avalanches. Four of the five largest glide avalanches recorded during the season occurred after May 14.

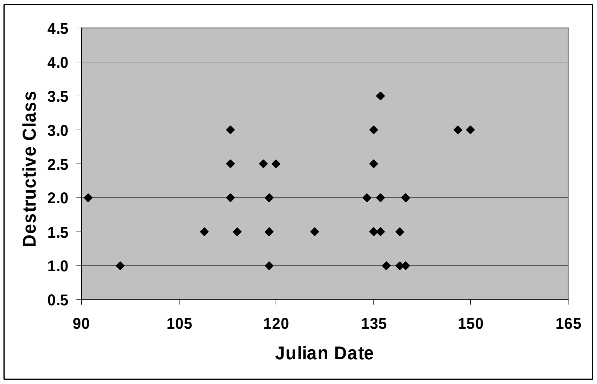

Figure 4: Scatterplot comparing glide avalanche Size (Destructive Class) vs. date of occurrence, 2006.

The starting zone aspects of the recorded glide avalanches were broadly distributed through all quadrants of the compass except northwest (Figure 5). The late-April cluster of glide avalanches occurred almost exclusively on easterly facing slopes (1-135 degrees). The mid-May cluster was more widely distributed through all aspects, though 41% (n=17) occurred on south through west facing slopes (180-270 degrees). The two early-season glide avalanches occurred on similar aspects.

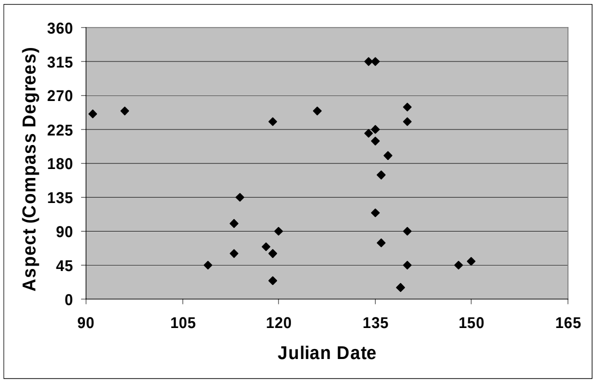

Figure 5: Scatterplot comparing starting zone aspect vs. date of occurrence, 2006.

Medium-sized glide avalanches (D1.5-2.5) occurred on nearly all aspects, while small avalanches (D1) were observed primarily on south- through west-facing slopes (Figure 6). No avalanches larger than D2.5 were observed on these slopes, but the full range of avalanche sizes (D1-3.5) occurred on north- through east-facing slopes. The large avalanches of the season (D3-3.5) occurred primarily on east-northeast facing slopes.

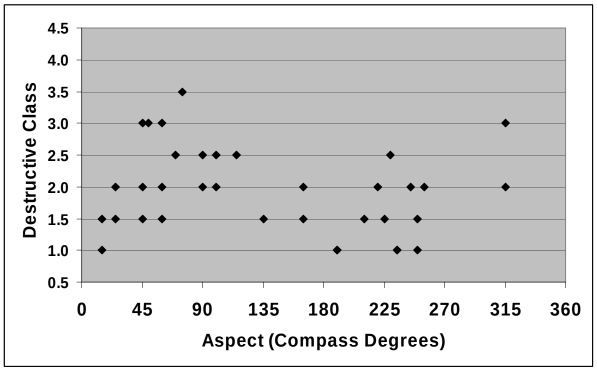

Figure 6: Scatterplot comparing starting zone aspect vs. glide avalanche size (Destructive Class) for 2006.

4.2 2006 Season Glide Avalanche and Weather Associations

SWE peaked at Flattop SNOTEL at 1293mm on April 18-19 (Figure 7), nine days earlier than the historic peak (1970-2006). The station recorded precipitation on 12 of the next 23 days, with the largest gain – 33mm – coming on

May 2. After May 12, however, Flattop recorded a gain in SWE on only one day.

Mean daily temperatures at the three stations ranged from -6.6°C to 15.9°C (Table 1). As expected the coldest values occurred earliest in the season, while the warmest values occurred at the end of the season. The values at the three stations generally tracked weather patterns simultaneously. Mean daily temperatures at all three stations were almost entirely below freezing prior to the date of peak snow accumulation (1293mm; April 18-19). After that date, mean daily temperatures generally remained above freezing, especially at Flattop SNOTEL, which recorded only two additional days with mean daily temperatures below freezing. After May 10, mean daily temperature remained above freezing at all three stations through the rest of the season.

Weather Station	Min. Daily Mean Temp (°C)	Max Daily Mean Temp (°C)	Avg. Mean Daily Temp (°C)
GWWX	-6.6 (3/26)	15.7 (5/16)	1.2
Logan VC	-5.6 (4/16)	15.8 (5/18)	1.7
Flattop	-3.1 (3/27)	12.9 (5/17, 18)	3.15

Table 1: Summary of mean daily air temperatures at the three weather stations in the study area for the period Mar. 22 – May 31, 2006. Dates values recorded given in parentheses.

A similar pattern was observed in the radiation data. Cumulative daily radiation values roughly doubled starting just before the peak snow accumulation. From Mar. 23-April 18, the average cumulative daily radiation was 3049w/m^2 at GWWX and 3584w/m^2 at Logan VC; for the remainder of the spring the averages were 5466w/m^2 and 5908w/m^2, increases of 79% and 65% respectively. At GWWX, the highest daily radiation value was recorded on May 2, while at Logan VC it was May 10.

Most glide avalanche activity was associated with the periods of SWE loss at Flattop, increasing air temperatures, and increasing solar radiation. A total of 89% (n=31) of the glide avalanches occurred after the peak snow accumulation for the season, nearly all in the two clusters noted in the earlier section. The first cluster (11 avalanches) occurred during the variable weather immediately after the SWE peak. The second cluster (15 avalanches) coincided with the most sustained period of SWE loss and temperature and radiation peaks.

5. DISCUSSION AND CONCLUSIONS

Some of the patterns of the 2006 glide avalanches may result from differences in bed surface conditions. Many of the easterly facing avalanches occurred on slopes with exposed bedrock surfaces, while many of the avalanches that occurred on south- through west-facing slopes occurred on grass-covered surfaces. We suspect infiltration reduces the amount of meltwater present at the snow/ ground interface on these slopes. Roughness on these slopes may also be more variable than on bedrock surfaces, making large avalanches less likely. Nonetheless, glide avalanches may be more common in the study area on north- through east-facing slopes because of snowpacks that are deeper and warmed more slowly than snowpacks on slopes more continuously exposed to the sun. A similar mechanism may result in the large avalanches that occur almost exclusively at upper elevation slopes in the study area. Further investigation, likely using glide avalanche data from previous seasons, is necessary to determine if these patterns are consistent over time.

Most glide avalanches occurred during or immediately following conditions that would be expected to increase meltwater production at the snow/ground interface, observational evidence of the model developed by Clarke and McClung (1999). Increasing insolation may play a large role in the step-like changes in temperature that were observed at the peak of the snowpack and mid-May. Investigation of glide avalanche data from other sites or previous seasons may help determine whether these patterns are similar each year. Further evidence is required to determine if there are direct correlations with rates of temperature change or actual temperature thresholds.

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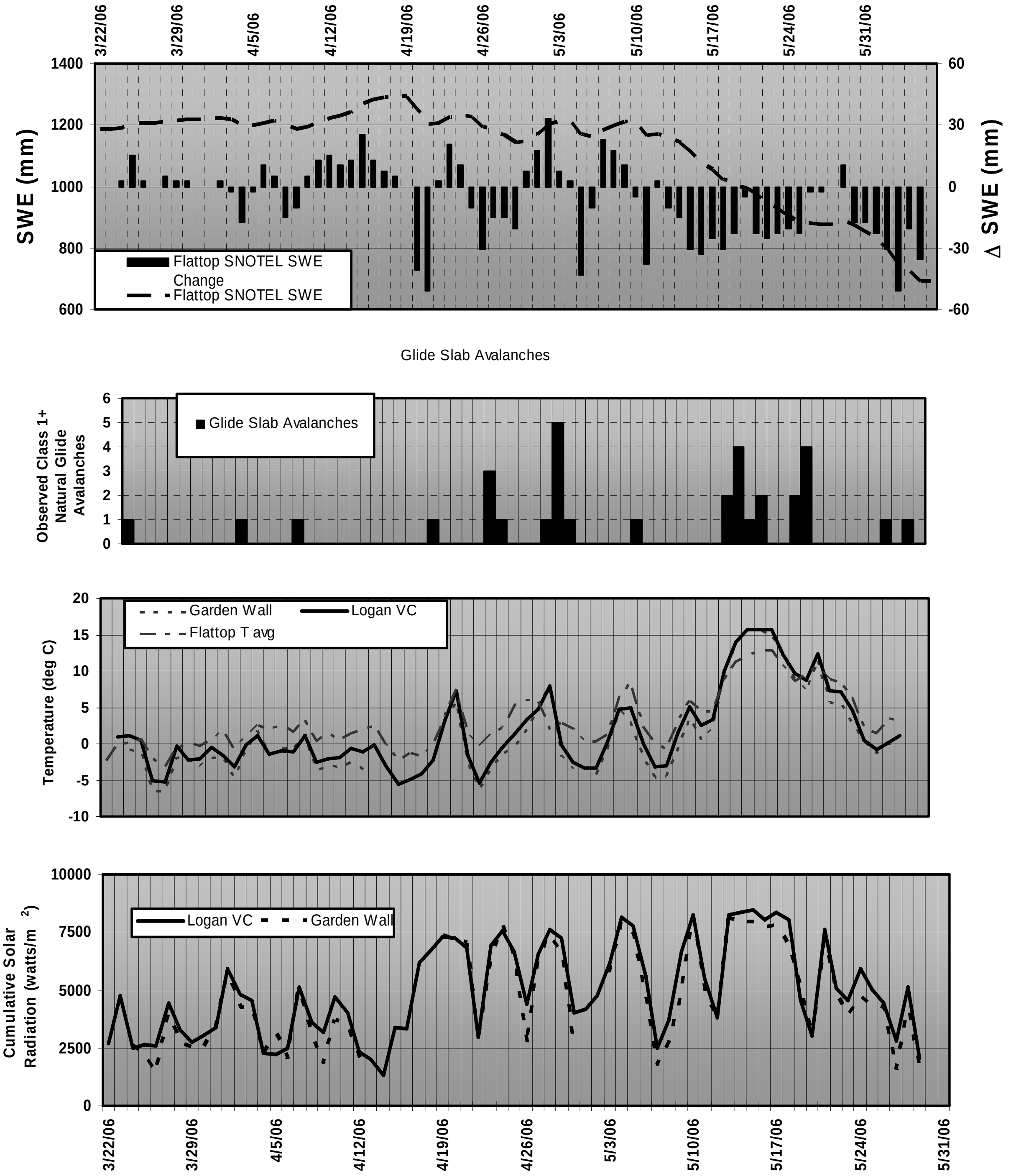

Figure 7: Weather parameters measured at Flattop Mountain SNOTEL and Garden Wall and Logan VC weather station, along with observed glide avalanches.

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