CHARACTERIZING WET SLAB AND GLIDE SLAB AVALANCHE OCCURRENCE ALONG THE GOING-TO-THE-SUN ROAD, GLACIER NATIONAL PARK, MONTANA, USA

Erich H. Peitzsch[1*], Jordy Hendrikx[2], Daniel B. Fagre[1], and Blase Reardon[3]

[1] U.S. Geological Survey, Northern Rocky Mountain Science Center, West Glacier, Montana, USA.
[2] National Institute of Water and Atmospheric Research Ltd (NIWA), Christchurch, New Zealand.
[3] Sawtooth National Forest Avalanche Center, Ketchum, Idaho, USA.

Wet slab and glide slab snow avalanches are dangerous and yet can be particularly difficult to predict. Both wet slab and glide slab avalanches are thought to depend upon free water moving through the snowpack but are driven by different processes. In Glacier National Park, Montana, both types of avalanches can occur in the same year and affect the Going-to-the-Sun Road (GTSR).

Both wet slab and glide slab avalanches along the GTSR from 2003-2010 are investigated. Meteorological data from two high-elevation weather stations and one SNOTEL site are used in conjunction with an avalanche database and snowpit profiles. These data were used to characterize years when only glide slab avalanches occurred and those years when both glide slab and wet slab avalanches occurred.

Results of 168 glide slab and 57 wet slab avalanches along the GTSR suggest both types of avalanche occurrence depend on sustained warming periods with intense solar radiation (or rain on snow) to produce free water in the snowpack. Differences in temperature and net radiation metrics between wet slab and glide slab avalanches emerge as one moves from one day to seven days prior to avalanche occurrence. On average, a more rapid warming precedes wet slab avalanche occurrence. Glide slab and wet slab avalanches require a similar amount of net radiation. Wet slab avalanches do not occur every year, while glide slab avalanches occur annually. These results aim to enhance understanding of the required meteorological conditions for wet slab and glide slab avalanches and aid in improved wet snow avalanche forecasting.

1. INTRODUCTION

In the USA most avalanche fatalities occur due to dry slab avalanches. However, wet snow avalanches, including both wet slab and glide slab avalanches, are also dangerous and can be particularly difficult to predict because they are relatively poorly understood (Kattelmann, 1984; Reardon and Lundy, 2004; Reardon et al. 2006; Baggi and Schweizer, 2008). Though most scientific literature addresses dry snow avalanches, nearly one in ten (9 percent) U.S. avalanche fatalities since 1950 have resulted from wet snow avalanches (WWAN, 2006).

Wet snow avalanches impact recreationists, transportation corridors, and ski areas. In some ski areas, poorly understood wet snow avalanches often create more difficulty for the ski patrol than better-understood dry snow avalanches because of unpredictability (Savage, 2010).The mechanical properties of wet snow make both wet slab and glide slab avalanches difficult to control with explosives (Clarke and McClung, 1999; Jones, 2004; Steiner, 2006; Simenhois, 2010). While wet slab avalanches occur in all snow climate types, glide slab avalanches 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). With the anticipated increase of global mean temperatures due to climate change there are likely to be changes to the regional distribution of avalanches and a higher frequency of wet snow and glide slab avalanches. As snow may be precipitated at warmer temperatures, rain-on-snow events might become more frequent, and the snowpack itself might trend toward a generally warmer and wetter one.

The mechanism driving wet slab avalanches contrasts with that of dry slab avalanches. Wet slab avalanches depend upon the introduction of liquid water in the snowpack thus changing the shear strength and decreasing slope stability, whereas dry slab avalanches typically occur because of an increase in shear stress (Kattelmann, 1984). Conway and Raymond (1993) showed that the introduction of free water in the snowpack causes melting and disintegration

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[*] *Corresponding author address:* Erich Peitzsch, USGS Northern Rocky Mountain Science Center, West Glacier, MT, 59936;
tel: 406-888-7925; fax: 406-888-7923;
email: epeitzsch@usgs.gov

of bonds between snow grains thus affecting slope stability. Bond disintegration occurs because of lateral spreading along a boundary such as a capillary barrier or ice layer. They also observed increased vertical strain during periods of water infiltration through a horizontal snowpack. Thus, it is possible that as grains metamorphose due to the presence of water on a slope this vertical strain leads to slope instability.

Glide is the process during which the snow cover on a slope slips downhill along the interface with the underlying ground (Jones, 2004). When glide rates vary on a slope, a tensile fracture, commonly called a glide crack, forms upslope of the area of faster glide where stresses are concentrated (Clarke and McClung, 1999; LaChapelle, 2001; Jones, 2004). Full-depth avalanches often follow the formation of a glide crack (Figure 1). Such glide slab 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).

Figure 1: Full depth glide slab avalanche on Heavens Peak, Glacier National Park, 15 June 2010.

Glide slab avalanches are more often a concern for operational avalanche forecasting programs particularly highway and railroad 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, 2004; Stimberis and Rubin, 2004; Simenhois, 2010).

Forecasting wet slab and glide slab avalanches relies on local experience and monitoring of local meteorological conditions (Jones, 2004). While the physical failure processes differ between wet slab and glide slab avalanches, both types of avalanches are dependent upon free water flowing either through the snowpack or at the ground-snow interface, which is driven by meteorological parameters. Thus, improving our understanding of wet slab and glide slab avalanches will aid in wet avalanche forecasting. By, examining certain meteorological parameters prior to and during avalanche release we hope to provide a more thorough understanding for forecasting these types of avalanches. The primary objective of this study was to examine measureable relationships between surface air temperature, net radiation, and incoming solar radiation, and wet slab and glide slab avalanche occurrence. Also, another objective was to determine whether there exists a difference in these meteorological parameters, between days prior to wet slab avalanches and days prior to glide slab avalanches. If a significant difference exists, then characterizing each parameter for each type of avalanche will aid in forecasting for these two types of avalanches.

2. STUDY AREA AND METHODS

2.1 Location

Wet slab and 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 (GTSR) (Reardon and Lundy, 2004). This two-lane, 80-kilometer road traverses the park, crossing the Continental Divide at Logan Pass (2026 m a.s.l.). The Park closes a 56 km section of the road each winter due to inclement weather, heavy snowfall, and avalanche hazards. Since 2003, GNP and the U.S. Geological Survey (USGS) have partnered to provide an operational forecasting program for the annual spring opening of the GTSR. Forecasters from the program maintain two automated weather stations and record weather data and snow and avalanche observations in a database developed specifically for the site. The avalanches recorded in this database comprise a rare, multi-year dataset of natural wet snow avalanches from a well-instrumented drainage.

The study area was comprised of the slopes visible from the GTSR west of the Continental Divide (Figure 2). These slopes were located in the headwaters of McDonald Creek upstream of Avalanche Creek, an area of 24,761 ha. The lowest point in the study area lies at 1036m a. s. l. and the surrounding peaks reach 2915m. McDonald Valley is the major drainage in the park west of the Continental Divide, and Logan Pass is both the high point of the GTSR and the lowest point in the Continental Divide in the drainage.

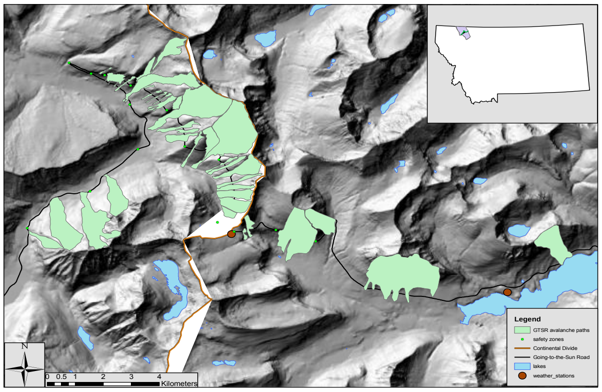

Figure 2: Overview of study area - avalanches along the GTSR corridor, Glacier National Park, MT.

2.2. Climate and Weather

The snow avalanche climate of the study area exhibits a generally maritime precipitation regime accompanied by continental temperature characteristics (Reardon et al., 2006; Mock and Birkeland, 2000). The contrasting precipitation and temperature regimes are due to the study area's position astride the Continental Divide, which allows both Pacific and continental air masses to influence the area's weather. Snowfall and rain amounts during the spring tend be light, unless winter weather patterns persist into spring, leading to dramatically wet and stormy weather. Though the peak Snow Water Equivalent (SWE) typically occurs the last week in April (1970-2010, Flattop SNOTEL, 1810m a.s.l.), the snowpack is at its most variable during the spring (Klasner and Fagre, 2000).

3. DATA AND METHODS

3.1 Avalanche Data

The source for wet and glide slab avalanche observations and measurements was the database created for the GTSR avalanche forecasting program (Reardon and Lundy, 2004). From the database, we selected all natural avalanches identified as wet slab and glide slab avalanches. The database yielded 57 wet slab and 168 distinct glide avalanches from eight seasons (2003-2010). These 168 glide avalanche events occurred on 76 distinct days, that are referred to as an avalanche day. The database also included 57 distinct wet slab avalanche events that occurred on 22 distinct days. In total, 225 distinct avalanche events on 93 avalanche days were observed. On 5 avalanche days both wet slab and glide slab avalanches were observed. Records included date of occurrence and destructive class for all 225 avalanches, as well as start zone elevation for 221 of the 225 avalanches. Vertical fall was available for 200 of the 225 avalanches, and start zone aspect was recorded for 222 of the 225 avalanches. The database did not include data describing slope angle of the avalanche start zones nor an explicit identification of whether snowmelt or rain triggered the avalanches.

The database consisted 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). Though direct measurements were taken when possible, most avalanche parameters were estimated in the field and later verified using photographs and topographic maps. All data were collected and recorded by a total of 4 observers over the 8 years. Field observations were collected during operational hours, typically weekdays from 0700 to 1500. Snow removal and forecasting operations began the first week of April and continued generally through the early part of June.

Several factors complicated field observations. One was the fact that observations were collected opportunistically, as part of an operational forecasting program, rather than systematically, as might be expected in pre-designed study. Thus, there are few observations from weekends. Avalanches that occurred on weekends were assigned to one of the two weekend days according to apparent age of the debris and crowns when observed on subsequent workdays. A second was the large size of the study area. Many avalanche sites were inaccessible or not visible until snow removal permitted travel to slopes above the upper reaches of the GTSR. Pre-season overflights of the study area provided a baseline for observations in 2004 and 2006. In all eight 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. Finally, a change in observers may have also added error due to individual subjectivity in identifying and classifying avalanches. We conclude the database contained the majority of the wet and glide slab avalanches that occurred in the study area each spring.

3.2 Meteorological Data

Meteorological data were collected at two automated weather stations (AWS) and one SNOTEL site. The 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 wet and glide avalanches included in this study. The Kipp and Zonen CNR1 Net Radiometer is located at this station. The station was installed in December, 2003 and operated during the 2004-2007, and 2009-2010 seasons. A second AWS was located at Logan Pass Visitor Center at an elevation of 2035m a. s. l. and operated during all eight seasons with a suite of sensors similar to GWWX. Logan Pass is a broad, low-angle bench at tree line. At both stations, temperature measurements were made at sixty-second intervals and reported as hourly averages and daily minimum and maximum values. Occasional data gaps occurred at both stations due to instrument and power problems.

3.3 Data Analysis

The quality of the meteorological and avalanche data was verified through visual methods as well as filtering out outliers based on parameters from nearby meteorological stations. Daily means for each parameter were calculated by averaging hourly temperatures to daily. Maximum and minimum daily data were tabulated from the hourly data as well. Moving averages for minimum, maximum, and mean temperatures and net radiation values were calculated for one, three, five, and seven days prior to and including every wet slab and glide slab avalanche day. The distribution of the moving average data were tested for normality using a Shapiro-Wilk test of normality (Shapiro and Wilk, 1965). Because the data exhibited a largely non-normal distribution, a Wilcoxon rank sum test was then performed on each of the one, three, five, and seven days prior-moving averages for all temperature and net radiation metrics comparing wet slab avalanches against glide slab avalanches (Wilcoxon, 1945).

We were also interested in the rate of change in both the temperature and radiation metrics for the days prior to an avalanche day. To examine this rate of change, we plotted each of the metric values for the prior three and seven days, as well as for the avalanche day in question (e.g. for the seven day maximum temperature plot we plotted the eight values of daily maximum temperature). A linear trend line was then applied to these four (three days prior plus the avalanche day) or eight (seven days prior plus the avalanche day) values and the slope of this line was extracted. This process was then repeated for all the temperature and net radiation metrics (i.e. maximum, minimum and mean).

We then selected the glide slab avalanche days and generated summary statistics of the gradient values for this group. The summary statistics of the gradient values include the count, mean, maximum and minimum values. We repeated this for the wet slab avalanche days. These summary values for the gradients of the wet slab and glide slab avalanche days were then compared.

4. RESULTS

The average day of wet slab avalanche occurrence was April 21 and the average day of glide slab avalanche occurrence was May 3.

4.1 Temperature

The comparison of temperature averages from one, three, five, and seven days prior to (and including the day of) each avalanche day show similar patterns between wet slab and glide slab avalanche days (Table 1). None of the differences in temperature medians between wet slab and glide slab avalanches are significant at the $p<0.05$ level (Figure 3). However, when considered at a $p<0.1$ level, maximum temperature differs between wet slab and glide slab avalanches.

Table 1: Comparison of moving averages for min. max., and mean net radiation (W/m^2) and temperature (°C) for one, three, five, and seven days prior to each avalanche day.

Comparison of Moving Averages								
Days Prior to Avalanche	**Net Radiation (W/m^2)**	**Median Wet Slab Net Radiation (W/m^2)**	**Median Glide Slab Net Radiation (W/m^2)**	*p-value*	**Temperature (˚C)**	**Median Wet Slab Temp. (˚C)**	**Median Glide Slab Temp. (˚C)**	*p-value*
1	**min.**	-79.50	-78.80	1.000	**min.**	1.15	1.20	0.705
	max.	220.40	271.30	0.832	**max.**	8.05	7.30	0.743
	mean	19.00	25.90	1.000	**mean**	4.85	4.00	0.852
3								
	min.	-97.00	-82.00	0.720	**min.**	-1.90	0.05	0.313
	max.	174.80	226.70	0.185	**max.**	6.00	6.05	0.341
	mean	10.50	22.55	0.160	**mean**	1.70	2.95	0.387
5								
	min.	-89.80	-80.55	0.839	**min.**	-1.70	-0.65	0.201
	max.	122.00	213.55	0.175	**max.**	3.60	5.15	0.189
	mean	5.80	22.20	0.156	**mean**	1.20	2.20	0.207
7								
	min.	-79.90	-78.75	0.988	**min.**	-2.35	-1.40	0.215
	max.	120.00	206.05	0.083	**max.**	3.30	4.90	0.092
	mean	6.60	20.70	0.115	**mean**	0.25	1.50	0.178

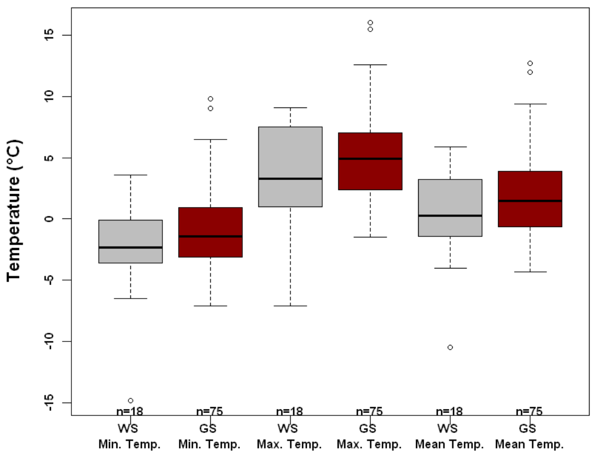

Figure 3: Boxplots displaying minimum, maximum, and mean temperatures (°C) for seven days prior to and including avalanche days for wet slab (WS) and glide slab (GS) avalanches. Thick black lines indicate median, boxes interquartile range, whiskers extend to the 0.05 and 0.95 quantiles, and the circles indicate outliers.

The median of mean temperatures for both wet slab and glide slab avalanches from seven days prior remains above freezing, while the median of minimum temperatures actually drops below freezing level. Maximum temperatures range from below freezing to well above 15°C.

The slope trend of temperatures from three and seven days prior to the avalanche day were compared between wet slab and glide slab avalanches. For both wet slab and glide slab avalanches the slope of the minimum, maximum, and mean temperature trends were similar for both three and seven days prior to avalanche events ($p<0.05$) (Figure 4 and Table 2).

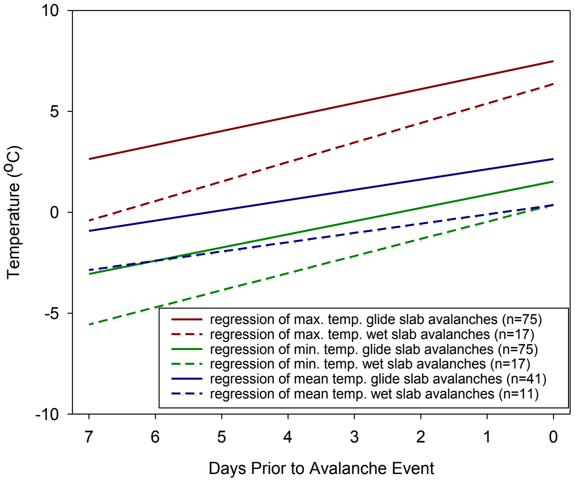

Figure 4: Linear regression of temperature trends (°C) from seven days prior to wet slab and glide slab avalanche events. The solid color lines indicate glide slabs and the dashed color lines indicate wet slabs.

Table 2: Average slope for minimum, maximum and mean temperatures (°C) and net radiation values (min., max., mean) from three and seven days prior to avalanche events.

Comparison of Mean Slope							
Metric		**3 Days Prior**			**7 Days Prior**		
		WS	**GS**	***p-value***	**WS**	**GS**	***p-value***
Temperature (˚C)	**min.**	1.06	0.49	0.3249	0.89	0.67	0.454
	max.	1.19	0.72	0.5465	1.01	0.70	0.322
	mean	1.25	0.82	0.433	0.60	0.53	0.899
Net Radiation (W/m^2)	**min.**	-8.94	-5.21	0.349	-5.21	0.69	0.0249
	max.	13.32	11.91	0.973	12.26	10.73	1
	mean	0.78	3.76	0.287	0.65	2.73	0.1392

4.2 Net Radiation

Similar to the temperature patterns, the comparison of net radiation averages from one, three, five, and seven days prior to (and including the day of) each avalanche day show no significant difference between wet slab and glide slab avalanche days at the $p<0.05$ level (Table 1 and Figure 5). However, a difference for maximum net radiation parameters occurs seven days prior to the avalanche event between wet slab and glide slab avalanches at the $p<0.1$ level.

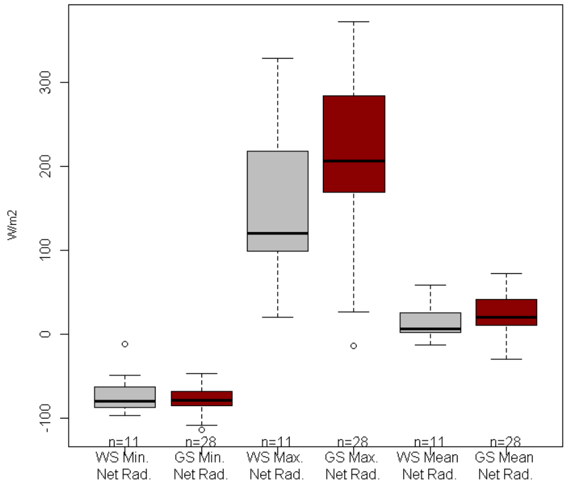

Figure 5: Boxplots displaying minimum, maximum, and mean net radiation (W/m^2) values for seven days prior to and including avalanche days for wet slab (WS) and glide slab (GS) avalanches. Thick black lines indicate median, boxes interquartile range, whiskers extend to the 0.05 and 0.95 quantiles, and the circles indicate outliers.

The range for both minimum and mean net radiation for both wet slab and glide slab avalanches from seven days prior is relatively narrow when compared to the range of maximum net radiation values. Maximum net radiation values range from just above zero to well over 300 W/m^2.

The slope trend of net radiation values from three and seven days prior to the avalanche day were compared between wet slab and glide slab avalanches. There is no statistically significant difference in slope trend for glide slab and wet slab avalanches except for minimum net radiation trends seven days prior ($p<0.05$) (Table 2 and Figure 6). In this instance, on average, wet slab avalanches exhibit a negative trend in minimum net radiation values seven days prior to avalanche occurrence.

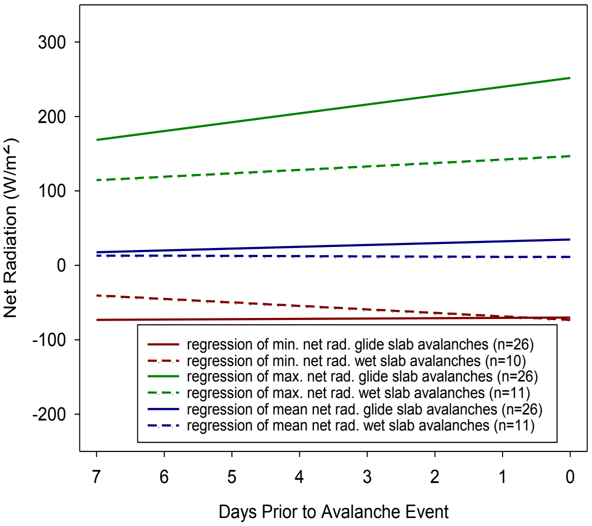

Figure 6: Linear regression of net radiation trends (W/m^2) from seven days prior to wet slab and glide slab avalanche events. The solid color lines indicate glide slabs and the dashed color lines indicate wet slabs.

5. DISCUSSION

The database is a collection of observations of avalanche activity, which, by nature, is a dynamic phenomenon. Observations of avalanche activity were limited by visibility and access to upper portions of the GTSR early in the season. Thus, the database is an opportunistic collection of data. The slope trend analysis has used the data for all avalanche days (and the three or seven days prior) for both avalanche types. Further refinement of the slope trend analysis may well need to consider excluding slope values with very poor linear correlations, or test other trend line fits. This would provide a more robust assessment of rates of change in the selected metrics, but will also reduce the sample size further. The discussion below provides a summary for the temperature and net radiation analyses.

5.1 Temperature

The temperature averages of days prior to avalanches for wet slab avalanches did not differ significantly from glide slab avalanches as they moved further out from the avalanche day except for maximum temperature. This suggests that the meteorological processes driving wet slab avalanches versus glide slab avalanches are similar, yet wet slab avalanches may occur at lower maximum temperatures. However, a larger dataset may exhibit differences not found in this dataset. Thus, monitoring meteorological parameters from the beginning of a warming period rather than a few days into it is critical for forecasting wet and glide slab avalanches.

Similar to the median temperature metrics there is no significant difference ($p < 0.05$) between temperature trends of wet slab and glide slab avalanches. Both types of avalanches exhibit similar slope trends in temperature from three and seven days prior to avalanche occurrence. Because of this result we cannot suggest that either avalanche type requires a more rapid warming than the other. However, it appears that an increase in temperature increases water movement through the snowpack leading to both wet slab and glide slab avalanches. Because snowpack properties were not investigated in this paper, it is not possible to attribute wet slab avalanche occurrence to either temperature or snowpack conditions. However, we obviously anticipate that snowpack stratigraphy is an important factor (Reardon and Lundy, 2004; Baggi and Schweizer, 2009). The combination of temperature and snowpack conditions leading to wet slab avalanche cycles may be attributed to the first rapid warming of the season that brings the snowpack to an isothermal state. Baggi and Schweizer (2009) found that the days immediately after the snowpack has reached an isothermal state were the most critical for wet slab avalanche release. Glide slab avalanches also involve water movement through the snowpack, but the critical interaction exists at the ground-snow interface. Water always exits the snowpack through the bottom at some given time during the melt season. Thus, temperature patterns are similar for both types of avalanches prior to avalanche occurrence.

Thresholds of temperature trends (i.e. – number of degree changes in a given day (or number of days) for wet slab avalanches) were not investigated for this paper, yet this metric may prove useful when investigating temperature patterns involved with wet slab avalanches. Overall, it appears that temperature may be a useful indicator in forecasting both wet and glide slab avalanches in terms of warming, but may have limitations in forecasting whether wet slab or glide slab avalanches will occur.

5.2 Net Radiation

The difference for each “days prior” net radiation values between wet slab and glide slab avalanches was not significantly different. This is interesting because we might expect glide slab avalanches to have higher net radiation values prior to avalanche occurrence because of the later average date of occurrence (May 5) than wet slab avalanches (April 21).

The large range of maximum net radiation values when compared to minimum and mean values for both wet slab and glide slab avalanches is interesting. This suggests that both types of avalanches can occur with both low and high maximum values of net radiation. Thus, using net radiation as an indicator of whether wet or glide slab avalanches will occur may be inadequate.

The slope trend in net radiation values seven days prior to wet slab and glide slab avalanche release suggests that patterns for this metric are similar for both wet slab and glide slab avalanche occurrence except for minimum net radiation trends. Wet slab avalanches exhibit a negative slope trend in minimum net radiation values. This difference may be attributed to positive net radiation values only immediately before wet slab occurrence or it may be due to a small sample size (n=11). A larger dataset may provide clearer results. A more detailed analysis of both temperature and net radiation rates of change are necessary for any substantial conclusions to be made.

However, small increases in net radiation trends prior to wet slab avalanche occurrence is similar to other studies that show no significant difference in radiation values between wet slab avalanche days and non-avalanche days (Baggi and Schweizer, 2009). Thus, based on this limited analysis it appears when forecasting for glide slab avalanches, net radiation trends may not be useful when discerning between wet slab or glide slab avalanche occurrence. A much more robust statistical analysis of the net radiation data should be undertaken before any such conclusions can be stated with any statistical confidence.

6. CONCLUSIONS

This paper details a cursory investigation into temperature and net radiation characteristics between glide slab avalanches and wet slab avalanches. The database for these avalanches consists of wet snow avalanche data from 168 glide slab avalanches and 57 wet slab avalanches, but contains only eight years of avalanche and weather data. Thus, when comparing only avalanche days of each type of avalanche, the sample size decreases markedly to 93 total days. This is the major limitation of this database using the simple analysis completed thus far, but also makes us reluctant to reduce the sample size further by applying additional more stringent restrictions on our analysis data.

However, a few characteristics and interesting pieces of information can be gleaned from the analysis. Temperature may be a useful meteorological parameter for forecasting both wet and glide slab avalanches. Increases in temperature lead to water movement in the snowpack thus increasing the probability of wet slab or glide slab avalanches. In this dataset net radiation may be useful when forecasting both types of avalanches, yet using the trend of net radiation alone may be more difficult when trying to determine if either wet slab or glide slab avalanches will occur.

Further work on this database would include refinement and extension of the weather data analysis and investigating more variables including snowpack conditions, such as depth, structure, and snow water equivalence (SWE). This would provide a more complete and robust understanding of the processes of wet slab and glide slab avalanches and how meteorological variables interact with certain snowpack structures. This would require a more robust statistical analysis as well. The analysis of the database thus far prevents any strong conclusions at this time and further work is necessary. Wet snow avalanches are still poorly understood and any insight into this phenomenon is useful for wet snow avalanche forecasting.

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DISCLAIMER

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