

Glide avalanche response to an extreme rain-on-snow event, Snoqualmie Pass, Washington, USA

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ABSTRACT: Rain-on-snow events trigger immediate and delayed avalanches as liquid water penetrates the snowpack. We present results from an extreme rain-on-snow event that triggered a glide avalanche near Snoqualmie Pass, Washington, U.S.A., located in the Cascade Mountains. Snoqualmie Pass recorded 463 cm of snowfall from 13-December 2008 through 06-January 2009. Temperatures were cold with periods of below normal snow water equivalencies. This period of snowfall and snowpack development was followed by a strong southwesterly flow of tropical origin that resulted in an extreme rain-on-snow event. Sensors at the study plot recorded 300 mm of precipitation over a 60-hour period. Flooding, slush flows, landslides, and avalanches resulted from this massive influx of precipitation. Snow heights decreased rapidly over the period with settlement rates approaching 8 cm/h. Liquid water infiltrated and flowed through the snow pack within a few hours of the arrival of rain, yet many of the major snowpack failures occurred 12 to 30 or more hours after the onset of rain and water outflow. A glide avalanche was recorded approximately 30 hours after the onset of rain and the establishment of drainage through the snowpack. Increasing glide rates correlate with periods of rapid snow settlement. During these periods, glide rates approached nearly 200 mm/h. Although glide and settlement rates increased during periods of intense precipitation, glide failure occurred some eight hours after peak precipitation and outflow.

KEYWORDS: glide avalanches, rain-on-snow, snow glide.

1 INTRODUCTION

Rain-on-snow is one of the major causes of winter snow avalanches in maritime climates (e.g., Conway et al., 1988; Conway and Raymond, 1993) and commonly triggers immediate and delayed avalanches as liquid water penetrates the snowpack. Rain-on-snow events are common in the Pacific Northwest (McCabe et al., 2007) and produce varying types of avalanches (Conway and Raymond, 1993; Clarke and McClung, 1999). Glide avalanches are unpredictable and due to evolving spatial distribution of liquid water in the snowpack accurate forecasting is difficult. Although glide avalanches triggered by rain-on-snow events are well documented (e.g., Lackinger, 1987; McClung et al., 1994; Clarke and McClung, 1999) it is still uncertain how the timing of liquid water penetration into the snowpack triggers glide avalanches.

In this paper, we present results from an extreme rain-on-snow event that triggered a full-depth glide avalanche near Snoqualmie Pass, Washington (Figure 1) and discuss the relations between the onset of rain-on-snow and full-release glide failure. Our goals are to

characterize avalanche processes and weather variables that influence the onset and eventual release of glide avalanches.

2 METHODS

2.1 Study area

The study area, Rockface, is located 2.5km north-northwest of Snoqualmie Pass, at an elevation of 1055m (Figure 1) in the central Cascade Mountains. The area has a maritime snow climate that is characterized by heavy winter snows and mild temperatures. Based on a 60-yr average, the annual winter snowfall at nearby Snoqualmie Pass (elev. 921 m) is 11 m, with nearly 2500 mm of precipitation annually.

Rockface has a northeast aspect and an average slope of 35° (Figure 1). The site is adjacent to the Alpental Ski Area, and though the start zone is located in a conditionally closed area, the historic runout is capable of reaching beginner ski trails (Figure 1). Avalanche control on Rockface has been largely unsuccessful, similar with other glide avalanche slopes (Jones, 2004).

2.2 Meteorological and snowpack observations

Meteorological and snowpack data come from the Washington State Department of Transportation (WSDOT) snow study site on Snoqualmie Pass (Figure 1). Both manual and automated observations are gathered from this site. Manual observations occur twice daily, at a

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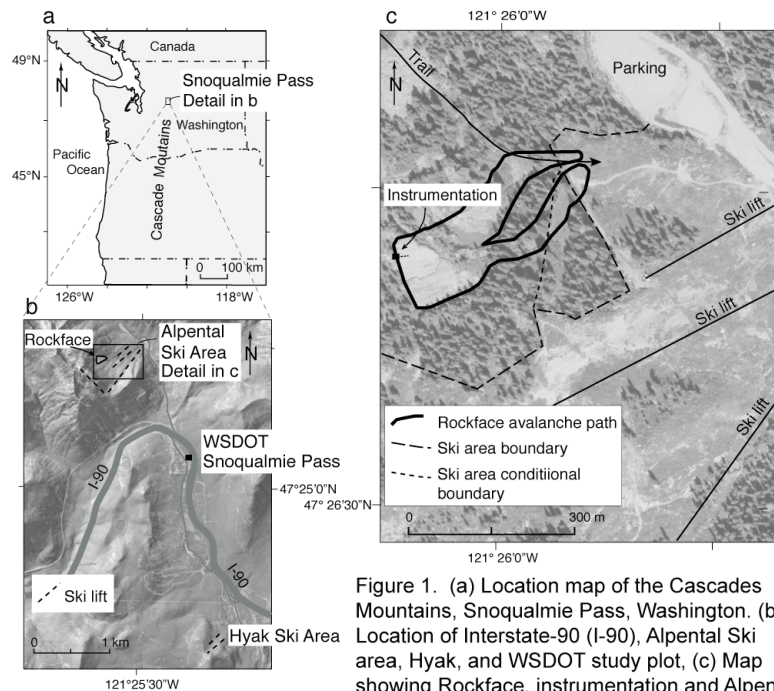


Figure 1. (a) Location map of the Cascades Mountains, Snoqualmie Pass, Washington. (b) Location of Interstate-90 (I-90), Alpentel Ski area, Hyak, and WSDOT study plot, (c) Map showing Rockface, instrumentation and Alpentel Ski area.

minimum. These observations include new and total snow (HN24, HS), snow density, and a snow stability profile. Instrumentation includes HN24 and HS collected with ultrasonic depth sensors, precipitation, air temperature, and relative humidity. Water outflow from the snowpack is measured with a lysimeter. In addition, glide data were collected at the Rockface site (Stimberis and Rubin, 2005 and 2008). In this paper, we concentrate on a 25-day period from 13-December 2008 to 06-January 2009 and focus on the 06-January to 07-January-2009 rain-on-snow event.

2.3 Early winter observations

The winter of 2008-2009 began in earnest on 13-December-2008 when a storm deposited 57 cm of snow (4.78 cm SWE) over a 36 h period. This storm was followed in quick succession by additional storms of varying intensity including 63 cm of snow (4.59 cm SWE) during one 24 h recording period. Over 460 cm of snow (46.52 cm SWE) were recorded over a 25-day period, between 13-December-2008 and 06-January-2009.

Temperatures were below average for the region between 13-Dec-2008 and 06-January-2009 with sub-freezing temperatures and snowfall reported down to sea level. Temperatures at the WSDOT study plot dropped as low as -18°C during this period, though low temperatures averaged about -10°C . Two brief periods of rain were recorded, though the events were short lived and did not penetrate the entire snow pack. Two thin crusts formed in the snowpack as a result of the brief rain events.

Temperature gradients within the snowpack were $\sim 2^{\circ}\text{C}/10\text{ cm}$. Overall, the snowpack was relatively cold and unconsolidated for a maritime region.

Avalanches and avalanche control occurred throughout the early-winter period. The WSDOT performed 14 highway avalanche control operations during late December to early January. Two avalanche fatalities occurred in the region as well (e.g., www.nwac.us).

2.4 January 2009 rain-on-snow event

By early January, weather forecasters at the National Weather Service (NWS) identified a strong Pacific storm system forming in the subtropical regions. These systems, referred to as a "Pineapple Express", can produce ample amounts of rain, warm temperatures, and flooding. By the evening of 4-January-2009 the storm system reached Washington State. The first 36 h produced 53 cm of snow (7.46 cm SWE). By the morning of 6-January-2009, the warm front, combined with a strong jet stream, reached the region and snow turned to rain. A rain-on-snow event was unfolding and NWS forecasters were expecting a record-setting event.

Avalanche paths near Snoqualmie Pass produced minor avalanche activity at the onset of rain. The WSDOT study plot snow lysimeter indicated that liquid water began to flow from the snowpack about three hours after the onset of rain. About 12 h after the onset of rain, WSDOT avalanche forecasters assumed the snowpack was beginning to stabilize and no avalanche control was scheduled. Previous work suggests

that avalanche release is rare after drainage through a snowpack has been established, even during continued rain (Conway and Raymond, 1993).

At 2300h PST, 15 h after the rain began and nearly 12 h after the lysimeter began recording water outflow from the snowpack, the first major avalanche occurred. This avalanche occurred after 91 mm of rain and 21 mm outflow from the snowpack. The avalanche path follows a streambed and produced a massive flow of snow, ice, rock, and trees that blocked the highway. The highway was closed to traffic and over the next few hours massive amounts of water began to inundate the highway. An additional slush avalanche was reported around 0200h PST on 07-January-2009, on the road to the Alpentel Ski Area (Figure 1).

At 0600h PST, 07-December-2009, nearly 24 hours after the rain began, another massive influx of snow, rocks, ice, and trees covered the highway in an area where avalanches are not well-documented. The WSDOT study plot had recorded 152 mm of rain and 43 mm outflow by this time. By 1100h PST, 07-January-2009, a landslide released at the Hyak Ski Area (Figure 2), destroying a house and the main chairlift. About 185 mm of rain and 55 mm of outflow were recorded by the time the Hyak slide occurred. The Hyak event occurred 24 h after first outflow of water was recorded by the lysimeter. At 1500h on 07-January-2009, a glide avalanche were recorded at Rockface after nearly 205 mm of rain and 60 mm of outflow was recorded. By the time the storm ended, the January 2009 rain-on-snow event was classified as an extreme event, with a return period in excess of 100 yrs (B. Bower, personal communication).

3 RESULTS

Air temperature, precipitation, snowpack drainage, and snow depth were collected in 15 min intervals at the WSDOT Snoqualmie Pass study plot (Figure 1). Glide rates on Rockface were collected in 30-sec intervals using a Celesco cable extension transducer (Stimberis and Rubin 2005). Since visibility was generally poor and flooding damaged the road to the Alpentel Ski Area (Figure 1), no physical observations of Rockface were made during the rain-on-snow event.

3.1 *Glide response to a rain-on-snow event*

Glide rates were minimal during the initial period of snowfall from 04-January to 05-January-2009. Over a 19 h period, 38 cm of snow fell (49 mm SWE) and <20 mm of

glide/creep were recorded. An additional 3.5 cm snow (19 mm SWE) was recorded over the next 12 h from 1200-2400h PST on 05-January. The increasing density of the snow likely contributed to glide/creep acceleration as the Rockface glide sensor recorded an additional 300 mm of movement during that 12h period (Figure 2). The HS experienced no net change during this period and temperatures averaged 0°C.

By 0800h PST on 06-January, snow had changed to rain. An additional 110 mm of glide/creep occurred between 0000h - 0800h PST on 06-January. Precipitation rates increased rapidly as the warm front moved over the area. Rainfall became heavy, averaging 7 mm/h and peaking at 12.5 mm/h over the next 24 h (0800h PST 06-January to 0800h PST 07-January). Air temperatures remained fairly consistent during the period with a general warming trend after the onset of rain, reaching a maximum of 5°C. Glide/creep motion remained low and consistent during 06-January, averaging 6mm/h with little variation in rate. The HS decreased about 16 cm during the 8 h period prior to the onset of rain. Glide changed by the end of 06-January and into the following day as glide rates accelerated and became increasingly erratic.

Precipitation rates of 7 mm/h on 07-January remained similar to the previous day, though there was a general decrease in intensity for a few hours prior to the glide avalanche. Outflow decreased during this period as well. Air temperatures decreased to a minimum of 2.5°C and averaged about 3.3°C prior to the avalanche. An additional 40 cm of snow settlement at an average rate of 2.7 cm/h occurred on 07-January before the glide avalanche released. Between the onset of rain and the glide avalanche on Rockface the WSDOT study plot recorded over 200 mm of precipitation and 60 mm of outflow. The HS decreased nearly 60 cm during that period as well. Over the 60 h rain-on-snow event, the HS would decrease more than 90 cm.

4 DISCUSSION

Rain-on-snow events occur most frequently during January in the Pacific Northwest (McCabe et al., 2007) and are responsible for avalanche release, initially triggering avalanches within minutes of rainfall (Conway and Raymond, 1993). Continued rainfall may trigger deeper avalanches over an extended period of time (Conway, 2005). During the January 2009 event a glide avalanche occurred over 32 h after the onset of rain.

Based on variations in glide/creep rate and acceleration over a 16 h period, we identified 7

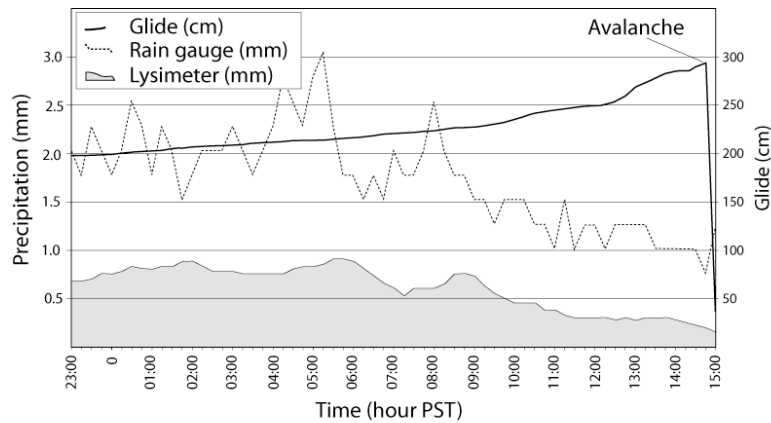


Figure 2. Overview of cumulative glide, temperature and outflow, 2300h PST 06-January-2009 to 1500h PST 07-January-2009. Rockface glide data are recorded every 30 sec. Air temperature, precipitation, and snow depth measurements are collected at 15 and 60 min. intervals. Lysimeter data are recorded every 5 min.

distinct glide subevents (Figure 3). The first subevent (subevent A) is characterized by a constant glide rate of ~ 28 mm/hr and lasted nearly 5 h. Subevent A marks the first prolonged period of snow glide on Rockface since the onset of rain. Here, the onset of glide correlates with the above freezing temperatures and the presence of liquid water at the snow/ground interface (Figure 2).

Subevent B marks the cessation of motion for about 45 min (Figure 3). During this pause, 8.1 mm of rain and 2.5 mm of outflow were recorded. Snow settlement increased from 1.1 to 3.6 cm/h during subevent B.

Subevent C is distinguished by erratic or stick-slip motion for over 4 h (Figure 3). Precipitation and water outflow slowly declined during this subevent (Figure 2). Similar fluctuating glide motion was observed in the Swiss Alps (in der Gand and Zupaničič, 1966). Air temperature decreases 1.6° C through the 4 h period. The end of subevent C marks the lowest air temperature recorded during remaining rain-on-snow event.

Subevent D is characterized by increasing glide rate of approximately 189 mm/h (Figure 3) and HS decreases about 14 cm at a rate of 4.6 cm/h. Air temperatures remain stable, averaging 3° C. Precipitation averages ~ 5 mm/h, beginning a relative lull before the next front reaches the area.

Similar temperature and precipitation trends continue into subevent E. Glide rates substantially increase during this subevent (Figure 3), with an average of nearly 190 mm/hr. Over 90 mm of glide occurs during one 7 min stretch, only to be followed by periods of limited glide. Snow settlement rates substantially decreased in the final 30 min of subevent E and closely correlate with a decline of glide rate.

Subevent F, a 15 min period, is defined by no glide motion or snow settlement (Figure 3). Average precipitation values are similar to the previous subevent, and air temperatures remain the same.

After the short pause of glide and snow settlement rates, subevent G is defined by a rapid acceleration of glide rate over a 30 min period before glide avalanche failure (Figure 3). Snow settlement substantially increased during the latter part of subevent G. Precipitation and outflow rates decrease to the lowest level during the 16 h glide event.

In the aftermath of the Rockface avalanche, precipitation rates and air temperatures increased gradually over the next 12 h. On 08-January, air temperatures began to cool and after several more hours the precipitation rates began to decline. No additional avalanches were reported in the Snoqualmie Pass area following the Rockface avalanche.

5 IMPLICATIONS FOR GLIDE FAILURE

The 32 h delay between the onset of rain and the avalanche at Rockface is similar to previous reports of delayed avalanches (Conway, 2005). The delay between the onset of rain and failure is perhaps due to the ground configuration of Rockface. A rock dihedral intersects the smooth rock surface and provides sufficient buttressing to support the snowpack along the lower flank of the avalanche path. Here, the snowpack is often characterized by extensive buckling and bulging prior to glide avalanche release. In addition, our study suggests that water outflow from the snowpack does not always accurately forecast full-release avalanches. Even during

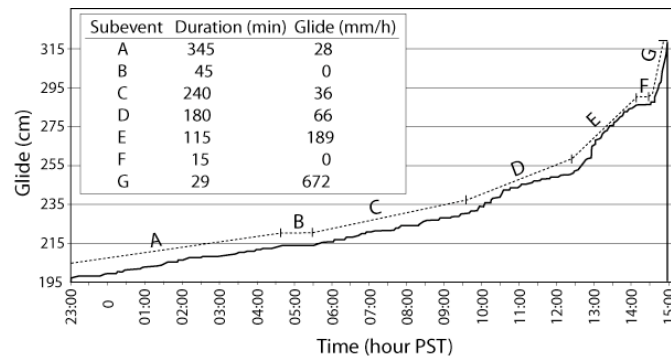


Figure 3. (a) Cumulative glide and subevents A-G between 06-January and 07-January 2009. Glide subevents are defined by changes in glide rate. Before full-release failure, glide rates average >670 mm/h.

periods of prolonged rain, delay between the onset of rain and failure might be longer than 32 h.

The interval between the onset of rain and failure raises important questions about the physical processes that control glide failure. Although the Rockface avalanche represents a single occurrence that was triggered by an extreme rain-on-snow event, our data suggest that an increase of snow settlement correlates with increased glide rates. Perhaps specific settlement rates could aid forecasting glide avalanches. Our data suggests that glide rates increased following periods of intense precipitation, at a time when both precipitation and outflow rates decreased. Finally, how did the structure of the snowpack affect the delayed avalanche response? Snowpack outflow occurred several hours after the onset of rain, yet the glide avalanche was delayed a substantial amount of time. A relatively unconsolidated snowpack may have required considerable settlement before the avalanche occurred.

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