DEEP SLAB INSTABILITY: LOADING, TEMPERATURE, AND SETTLEMENT RATE THRESHOLDS RELATED TO FAILURE – PART II

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ABSTRACT: Deep slab avalanches, which tend to be large and destructive, remain a challenge to accurately forecast. Using 42 seasons of historical data from Jackson Hole Mountain Resort and the Bridger-Teton National Forest Avalanche Center, we see evidence for multiple mechanisms that can lead to deep slab failure, including: 1) loading rates and duration, 2) temperature increase, and 3) settlement rates. We analyze case studies of historic deep slab cycles that independently demonstrate each of the three mechanisms, and show that any single cycle can be highly unique with regard to snowpack structure and a combination of trigger mechanisms. In previous work, loading rates and multi-day temperature change have both been recognized as important variables. Although settlement rates are driven by trends in loading and/or air temperature, we propose that settlement rates can be a valuable additional forecasting tool when included in an overall multivariate approach. To provide initial constraints on settlement thresholds we report statistics from the historical record including settlement rates during storm periods, 'background' rates during drought periods, and rates for days with deep slab events. In addition, we report loading thresholds of multi-day cumulative precipitation that correspond to deep slab events. These results will help inform further work assessing the physical processes leading to failure, and will enable more accurate forecasting of deep slab cycles.

KEYWORDS: deep slab, persistent slab, settlement, loading, avalanche forecasting

1. INTRODUCTION

Deep slab avalanches can be highly destructive and dangerous, and are challenging to accurately forecast. In this study we use 42 seasons of data from the Bridger-Teton National Forest Avalanche Center (BTAC) in northwest Wyoming to analyze thresholds in weather and snowpack variables that correspond to deep slab events.

Previous analysis of the BTAC dataset showed that deep slab events are larger, harder, and tend to occur more frequently in December and January. These events also display a large variation in frequency of occurrence by season (Comey and McCollister, 2008). Here, we utilize data from 1974 through 2016 to examine 1,180 deep slab events with focus on loading rates, loading duration, temperature change and settlement rates.

Precipitation, wind and temperature are commonly cited as important contributing factors to deep slab instability and failure (e.g. Schweizer et al., 2003; Savage, 2006; Conlan et al., 2014), with many studies using statistical analysis to rank relative importance of variables (e.g. Jamieson et al., 2001; Baggi and Schweizer, 2009; Marienthal et al., 2015). Here, we present case studies of historic deep slab cycles that demonstrate dominance of either loading (precipitation and wind) or temperature change as trigger mechanisms.

In addition, we present a preliminary analysis of the potential role of snow settlement rates, which have received limited previous study as an indicator of instability. Although snow settlement is a secondary process that is driven by changes in loading and air temperature, we suggest that settlement rate observations can be a valuable addition to a forecaster’s ability to assess hazard, particularly in low or no-precipitation days immediately following storm events. Using the historic BTAC database, we report thresholds in loading and settlement rates that correspond to deep slab events.

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2. METHODS

We utilize historic measurements (1974-2016) from four study plot locations at the Jackson Hole Mountain Resort (JHMR): Mid-Mountain Plot (2,493 m), Raymer Plot (2,853 m), Rendezvous Bowl Plot (2,920 m), and the Summit wind station (3,185 m). The JHMR and the BTAC forecast area represent an intermountain climate zone (Mock and Birkeland, 2000) dominated by dry-snow avalanches (Comey and McCollister, 2008).

Historic daily (24-hr) measurements used in this study include:

- minimum and maximum air temperature
- total wind kilometers
- height of new snow
- water equivalent of new snow (SWE)
- height of snowpack

Using the previous day snowpack height (HS_{prev}), the current day snowpack height (HS_{curr}), and height of 24-hr new snow (HN24) we calculate daily settlement rates as:

$$settlement = (HS_{prev} + HN24) - HS_{curr} \qquad (1)$$

The JHMR study plots are nearly flat sites, such that settlement calculations represent the compressive, vertical component of deformation. However, deformation in an inclined snowpack is known as 'creep', having both shear and vertical components (McClung and Schaerer, 2006). In our discussion of snowpack deformation and the effects on stability in alpine terrain, we use settlement measurements as a proxy for snowpack creep.

We calculate 24-hr new snow density as a dimensionless ratio following standard methods (Greene et al., 2010). In addition, we calculate cumulative SWE totals by summing data for previous 3-day, 5-day, 7-day, and 10-day moving windows.

Avalanche events are recorded throughout the historical record, which include natural and artificial triggers at JHMR and in the backcountry. Deep slab events are selected with crown depths of 1.12 meters (44 inches) or greater. We note that the timing of avalanche events in the historical record can be biased by the inability to observe or access terrain during storms (potentially delayed recording of events), and control-released avalanches will tend to correspond to periods when ski patrol are able to access the mountain.

3. RESULTS AND DISCUSSION

3.1 Loading rate thresholds

Loading due to new snow precipitation and wind is commonly associated with deep slab cycles in the historical record. To quantify thresholds in SWE totals that statistically correspond to deep slab failure, we queried the database for cumulative SWE totals for days with deep slab events (Figure 1, Table 1). There is high variability in the amount of SWE loading that corresponds to failure for any single event, however we expect the median values for each SWE window to represent general thresholds for a snowpack with a persistent weak layer.

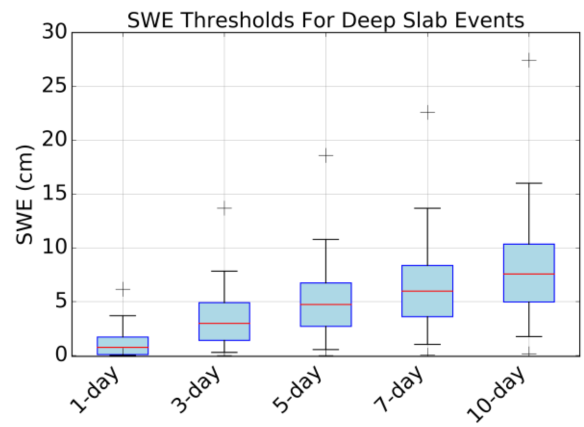

Figure 1. Distribution of cumulative SWE totals for days with deep slab events (N=501). Boxes span the 1st and 3rd quartiles, whiskers extend to the 5th and 95th percentiles, and crosses indicate minimum and maximum points. Red lines are median values reported in Table 1.

Table 1: Median values for SWE thresholds (cm) corresponding to days with deep slab events (N=501).

Cumulative window length	*Median SWE (cm)*
1-day	0.7
3-day	3.0
5-day	4.7
7-day	6.0
10-day	7.6

3.2 Loading case study

The 1997-98 season represents a loading-dominated deep slab cycle, with air temperatures remaining mostly steady and well below freezing throughout the cycle (Figure 2). At the end of November 1997, snow depths were relatively shallow with 74 cm (29 in) at Mid Mountain and 99 cm (39 in) at Rendezvous Bowl. December was mostly dry with three extended drought periods resulting in widespread faceting of the snowpack and development of a surface crust. Total snowfall for December at Mid Mountain was only 84 cm (33 in) (56% of normal for December), with end of month snow depths of 89 cm (35 in) at Mid Mountain and 73 cm (29 in) at Rendezvous Bowl.

A major storm cycle began on January 2 and continued through the end of the month, with total January snowfall at Mid Mountain of 348 cm (137 in) (165% of normal for January). A deep slab cycle began on January 8 with a single recorded event. Despite multiday SWE totals slightly below statistical threshold values (Figure 1), rapid loading and high settlement rates corresponded with multiple deep slab events. On January 9, a ski patroller at JHMR triggered a 1.52 m (5 ft) slide down to the basal facets with a 0.45 kg (1 lb) hand charge. Natural events were widespread in the backcountry, with 7 recorded events on January 9 only representing a portion of the regional deep slab events.

Deep slab events at JHMR and in the backcountry persisted with continued rapid loading and significant increases in the density of new snow. Several major events with 1.83 m (6 ft) crown depths occurred over a 5-day period. On January 12, the largest class V event ever observed on the East Ridge of Rendezvous Bowl was triggered with explosives. On January 14, a grooming machine triggered a deep slab at the top of Laramie Bowl with debris running the length of the bowl. On January 16, a 0.9 kg (2 lb) air blast triggered a deep slab event on the Hanging Rock path after being previously air-blasted every day of the storm cycle.

An additional defining feature of this case study is the distinct lack of deep slab events after January 18. This period is accompanied by continued loading in late January with high winds and a major secondary peak in settlement rates. The lack of deep slab events is likely due to new precipitation loads falling below thresholds necessary for failure. New snow densities averaging 10-15% during the deep slab cycle decreased to 5-7% after January 18. The change in loading regimes is also seen with cumulative 5-, 7-, and 10-day SWE totals, which peak and decline towards the end of the deep slab cycle. Strengthening of the slab could also play a role in the close of the cycle.

This bimodal behavior is not unique in the historical record: a similar pattern occurred in December 2000 where continued loading of lighter density snow immediately following a major deep slab cycle failed to produce additional deep slab events.

3.3 Air temperature case studies

Although less common than loading-dominated cycles in the historical record, increases in air temperature (usually over multiple days) can also be a dominate mechanism for initiation of deep slab activity.

During the winter of 1995-96, widespread deep slab activity occurred in late January at all aspects and elevations, running on a late December drought surface (Figure 3). This represents a loading-dominated cycle similar to the January 1998 cycle, with air temperatures remaining below -7° C (20° F). The January 1996 cycle included 46 recorded deep slab events and crown depths up to 3.66 m (12 ft) in the Wyoming Range.

The cycle came to a close after February 1, but was then reactivated with an additional storm accompanied by a significant multiday temperature increase occurring over February 4-6. Although 24-hr new snow totals were relatively moderate (maximum of ~25 cm (10 in) on Feb. 7), high winds and a 23° C (41° F) increase in minimum temperatures to near-freezing levels at Mid Mountain created high-density slabs overlying the existing January snowpack, resulting in 9 additional recorded deep slab events.

Similar temperature-dominated cycles can be found throughout the historical record. Beginning February 11, 1981, temperatures at all elevations increased to near-freezing levels over two days and remained warm for an additional 7 days. 24-hr new snow totals over the 7-day period never exceeded 13 cm (5 in), multiday SWE totals and settlement rates remained relatively low and steady, and 24-hr wind totals at the Summit did not exceed 1030 km. However, the week-long warm period re-activated a late-December rain crust producing 9 events with 1.5–2.4 m (5-8 ft) crowns.

During December 27-29, 2008, minimum and maximum 24-hr temperatures increased 10.6° C (19° F) at mid elevations (Raymer Plot), with the increase in minimum temperature occurring over a

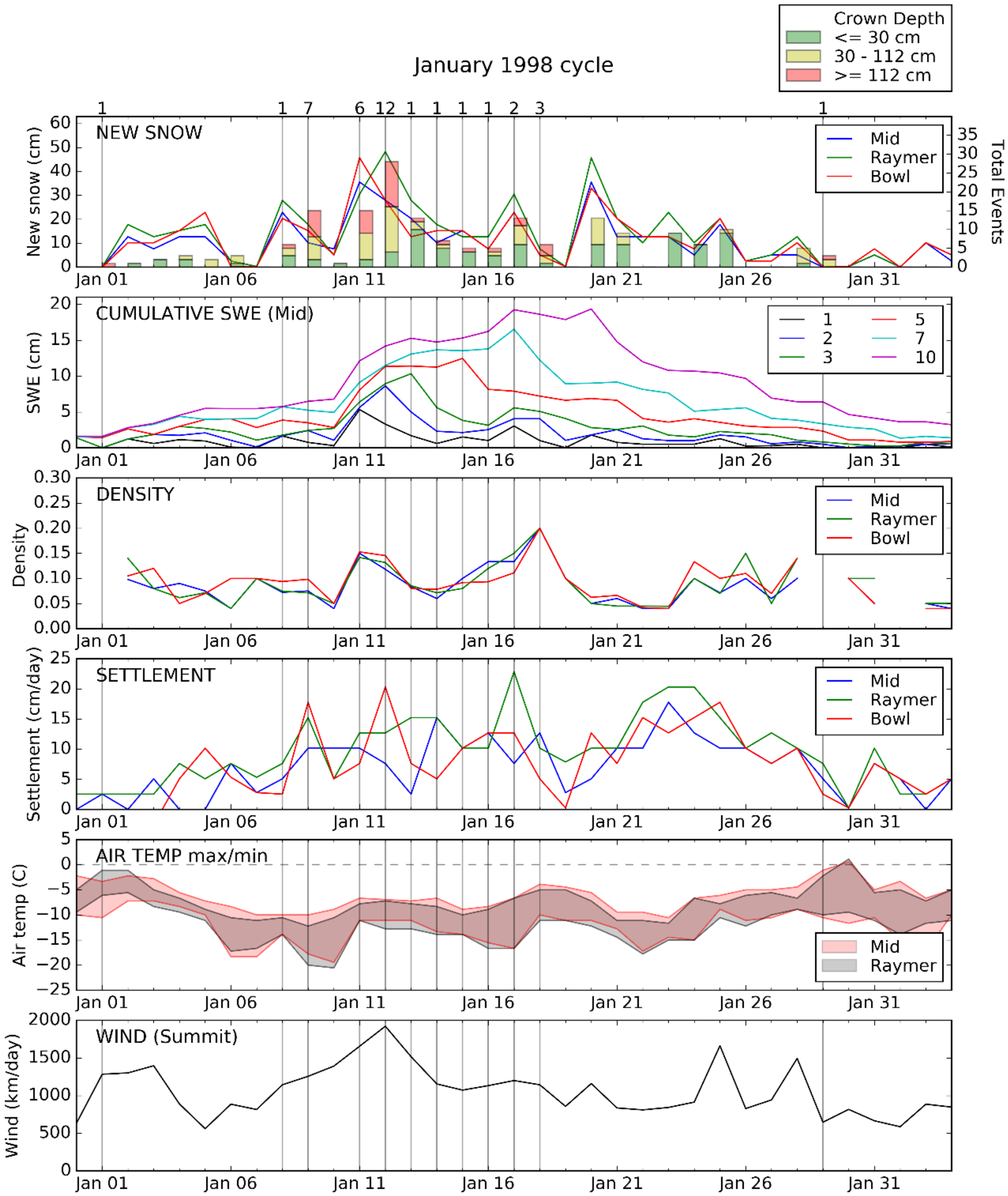

Figure 2. Snow and weather data from a major deep slab avalanche cycle in January 1998, representing a loading-dominated cycle. Avalanche events are shown in the first panel (2nd y-axis) with color coding corresponding to crown depth. The number of deep slab events for each day (red bars) are indicated along the top of the first panel, with corresponding vertical lines extending through all panels for reference.

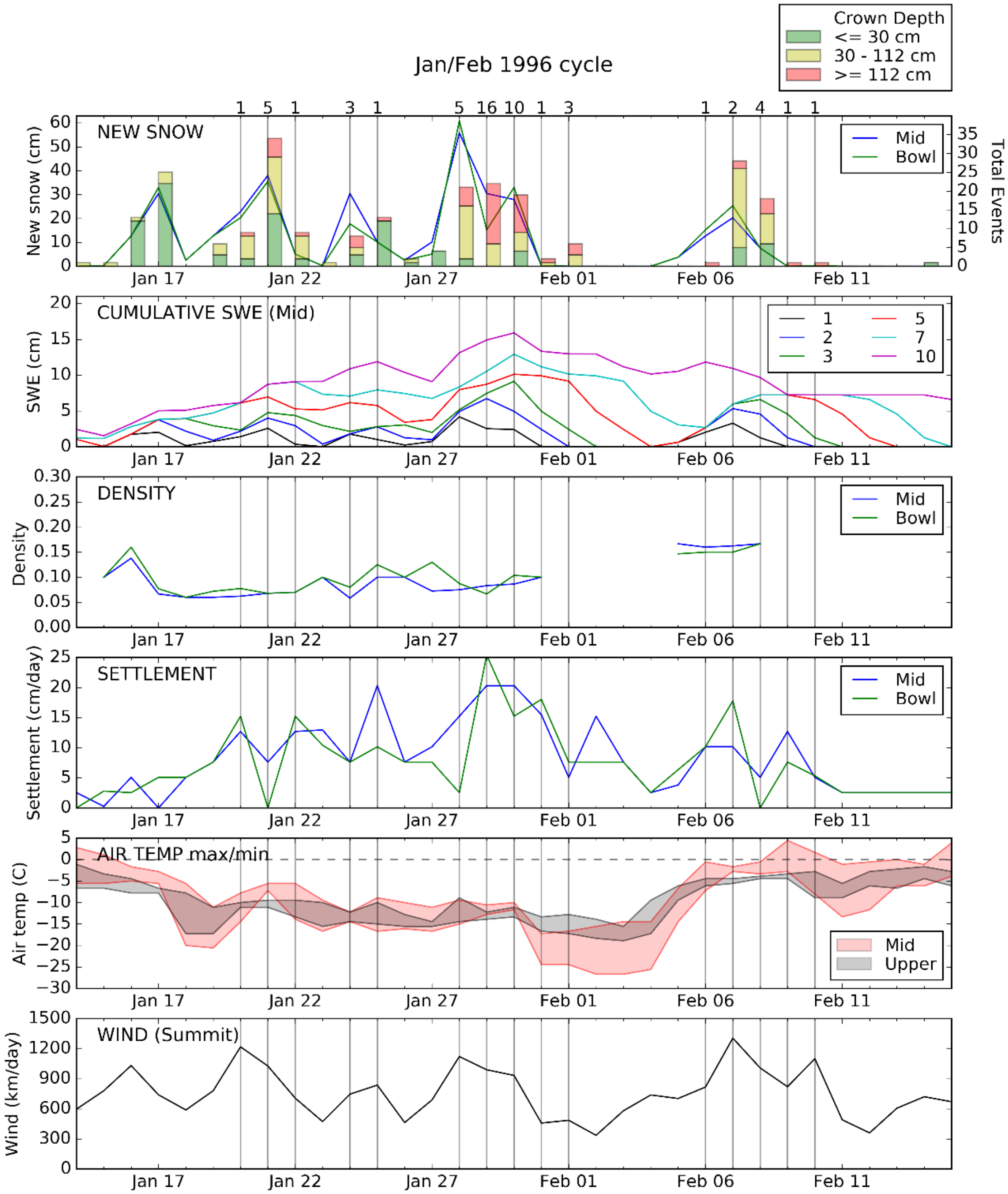

Figure 3. Snow and weather data from a major deep slab avalanche cycle in January and February 1996. The second cycle occurring in early February was characterized by significant increases in air temperature that reactivated deep slab events on a December drought surface. Avalanche events are shown in the first panel (2nd y-axis) with color coding corresponding to crown depth. The number of deep slab events for each day (red bars) are indicated along the top of the first panel, with corresponding vertical lines extending through all panels for reference.

single day. An artificially-triggered deep slab event on the Headwall of the JHMR occurred the morning of the 29th, damaging a structure and burying multiple patrollers. This event was also associated with significant loading, coinciding with peaks in 1-day to 10-day SWE totals, and failing on a November rain crust.

3.4 *Settlement rate thresholds*

For settlement rate observations to be a potentially useful forecasting tool, it is necessary to constrain the range of rates throughout the historical record. Here, we analyze daily settlement rates over 42 seasons to characterize the range of rates that are typical of storm periods and of drought periods.

We use 3-day cumulative SWE totals of 2.54 cm (1.0 in) or greater to define storm periods, and 3-day cumulative SWE totals of 0.13 cm (0.05 in) or less to define drought periods or 'background' settlement rates. Thresholds in 3-day cumulative SWE totals are used instead of 24-hr totals in an attempt to capture settlement rates for days with no precipitation in the middle of storm periods, or immediately following the end of a storm period that often retain elevated settlement, and should be included in the storm period statistics.

We find that storm periods have a median settlement of 7.6 cm/day (3.0 in/day) (N=1107), and drought periods have a median settlement of 2.5 cm/day (1.0 in/day) (N=1659). Although the highest settlement rate measured is 43.2 cm/day (17.0 in/day), we treat this as an outlier and calculate a representative maximum storm settlement rate of 25.8 cm/day (10.2 in/day) using the mean of the highest 30 rates on record. In addition, the median settlement rate of all data (N=6839) is 2.8 cm/day (1.1 in/day), reflecting the dominance of lower rates in the overall record. (Figure 4; Table 2).

Table 2: Median values for settlement rates (cm/day) corresponding to storm and drought periods. 'Storm Max' is the mean of the highest 30 rates.

Period	*Settlement rate (cm/day)*
Storm	7.6
Storm Max	25.8
Drought	2.5
All data	2.8

To characterize settlement rates that correspond with deep slab failure, we queried the historical database for settlement rate values for days with deep slab events (Fig. 5). The median rate for all study plot locations is 7.6 cm/day (3.0 in/day), matching the median storm settlement rate.

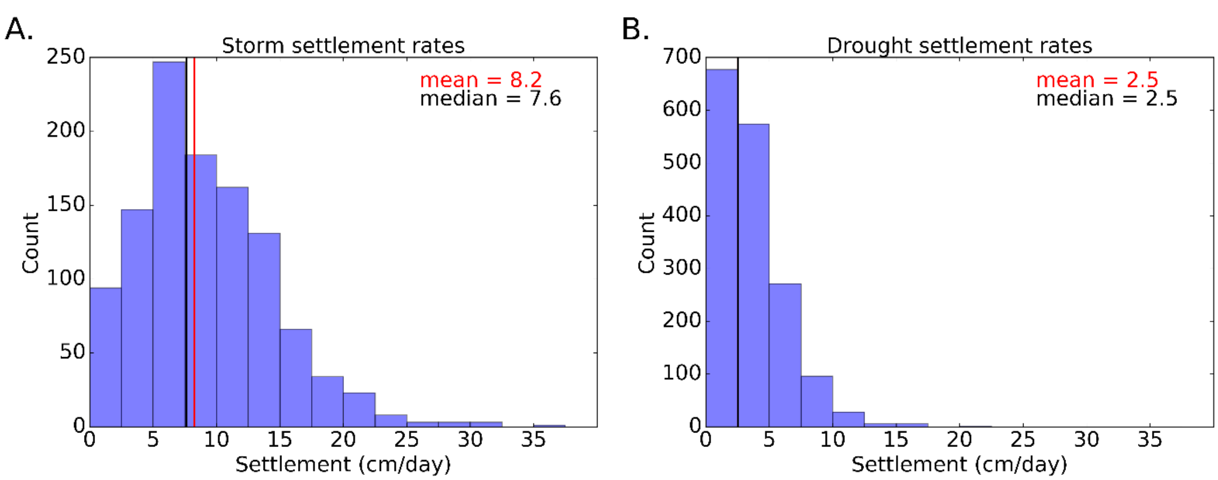

Figure 4. Distribution of settlement rates (cm/day) for storm periods (A) and drought periods (B) at the Mid Mountain study plot. Storm periods are defined by cumulative 3-day SWE totals of 2.54 cm (1.0 in) or greater, and drought periods are defined by cumulative 3-day SWE totals of 0.13 cm (0.05 in) or less.

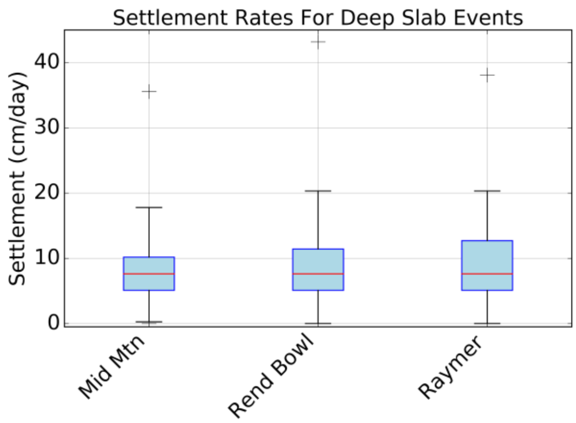

Figure 5. Distribution of settlement rates corresponding to days with deep slab events (Mid Mountain Plot, N=499; Rendezvous Bowl Plot, N=497; Raymer Plot, N=298). Boxplot dimensions are the same as described in Figure 1.

3.5 Settlement rate case studies

In historic deep slab cycles it is common to find 1-2 day periods immediately following multiday storm periods with sustained elevated settlement rates. There can be little to no new precipitation and no significant increases in wind speed or air temperature, yet deep slab events can continue over these periods.

Although this combination of conditions can be found throughout the historical record, classic examples of these events occurred in late December and early January, 1981-82. After a prolonged period of nearly constant daily new snow totals throughout December 1981, 30 cm (12 in) of new snow with 1.65 cm (0.65 in) SWE accompanied a warming trend during December 29-30. This scenario resulted in a 2.4 m (8 ft) deep slab event on Cody Bowl (just south of the JHMR boundaries). Weather conditions were mostly clear the following day (Dec. 31st), with only 9.7 cm (3.8 in) new snow containing 0.6 cm (0.25 in) SWE received in the previous 24 hrs. Air temperature and wind speed showed decreasing trends while settlement rates increased to nearly 20 cm/day (7.9 in/day) at Mid Mountain. These conditions coincided with a ~1.8 m (6 ft) deep slab event on the east face of the Grand Teton.

Similarly, after a multiday storm period, clear sky conditions on January 6, 1982 accompanied 24-hr new snow totals of only ~10 cm (4 in). Although there were decreasing trends in multiday SWE totals, air temperature, and wind speed, rapidly increasing settlement rates coincided with two significant deep slab events with 1.8-2.4 m (6-8 ft) crowns.

3.6 Settlement rate and deep slab instability

The long term effect of snow settlement is an increase in snow stability through increases in density, hardness, and strength (McClung and Schaerer, 2006). However, high settlement rates over shorter time scales (hours to days) may be a mechanism contributing to instability and failure. Because increased settlement often coincides with and results from increased loading and/or temperature increase, it is not a primary forcing of instability. However, sustained or increased settlement in days following new snow loads represents a physical mechanism causing deformation of the snowpack separate from the processes of active loading or temperature change.

Whereas loading can directly force instability by addition of mass to weak layers, settlement is highly dependent on snow density, snow structure, grain type, grain bonding, and snow temperature. A combination of viscous and elastic deformation translates through the snowpack to increased strain rates and shear stress at weak layers (Wilson et al., 1999; Schweizer and Jamieson, 2010), promoting ductile failure that can lead to sudden brittle failure propagation.

We suggest observations of settlement rates as a proxy for creep rates that can be useful as an additional tool for avalanche hazard forecasting. Our statistical results (Fig. 4, Figure 5; Table 2) can act as baselines for expected ranges of settlement. For example, rates rapidly increasing to above ~8 cm/day (3 in/day) could be an indication of instability during a deep slab cycle, whereas multiple days of sustained rates of 2.5 cm/day (1.0 in/day) or less could indicate the close of the deep slab cycle and overall stable conditions.

4. CONCLUSIONS

Assessing hazard during deep slab cycles in the northwest Wyoming climate and terrain setting requires knowledge of a broad set of variables. These include pre-existing snowpack structure, and the precise timing of precipitation, wind and air temperature trends during storm cycles. Our analysis demonstrates that forecasting with emphasis on any single trigger mechanism is not a reliable approach. This is in support of previous work that identifies high false alarm ratios when using threshold values of single variables (Schweizer et al., 2009; Tracz, 2012).

Analysis of 42 seasons of historical records from the Bridger-Teton National Forest Avalanche Center shows that both loading rates and air temperature trends can dominate as failure mechanisms during deep slab cycles. To quantify loading thresholds, we have identified multiday cumulative SWE totals that correspond to deep slab events.

In addition, we propose settlement rate observations as a proxy for snowpack creep and an additional indicator of instability. In particular, we find that increased settlement rates (typically > 8 cm/day (3.0 in/day)) can be used as an indicator of sustained hazard during days with no or low precipitation following storm events, and that multiple days of low settlement rates (typically ~2.5 cm/day (1.0 in/day)) can indicate that snowpack conditions may be gaining stability. Settlement rates are driven by trends in multiday cumulative SWE totals and/or air temperature trends, yet can act as a valuable additional forecasting tool when included in an overall multivariate approach to hazard assessment.

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