TEMPORAL EVOLUTION OF SLAB AND WEAK LAYER PROPERTIES DURING THE TRANSITION FROM DRY TO WET SNOWPACK CONDITIONS

Josh Lipkowitz[1*], Erich Peitzsch[2,1], Jean Dixon[1], Marcus Kalb[4], Doug McCabe[3], Griffin Ditmar[3], and Christoph Mitterer[4]

[1] *Department of Earth Sciences, Montana State University, Bozeman, MT, USA*
[2] *U.S. Geological Survey, Northern Rocky Mountain Science Center, West Glacier, MT, USA*
[3] *Yellowstone Club Ski Patrol, Big Sky, MT, USA*
[4] *Avalanche Warning Service Tyrol, Innsbruck, Austria*

ABSTRACT: Wet-snow slab avalanches are destructive and may become more prevalent in a warming climate. This type of avalanche remains challenging to forecast because the underlying processes leading to wet-snow slab avalanche release are poorly understood. In this study, we examine the temporal evolution of weak layer and slab liquid water content (LWC), critical cut length, and propagation saw test (PST) results during the season's first critical melt period at our study site in the Madison Mountains of southwest Montana. We used snowpack profiles and in-situ weather station data to initialize and force the 1-D physics-based snow cover model SNOWPACK throughout the winter and spring seasons. We then used a high-resolution numerical weather model to force SNOWPACK simulations to forecast the onset of the transition from dry to wet conditions. From April 10-12, 2023, we conducted 67 PSTs, 1053 LWC measurements, 20 hardness profiles, and a full snow profile each morning and early evening. During the first two days of sampling, we observed a transition from low to high propagation propensity with decreasing cut lengths and increasing LWC. On Day 3, we observed consistently low propagation propensity, even as LWC levels remained elevated and comparable to the preceding period of high propagation propensity. This indicates that there is a point where the relationship we observed through the first two days between increasing LWC, increasing propagation propensity, and decreasing cut length no longer holds. Our results further suggest PST propagation mode may help pinpoint the onset, peak, and decline of wet-snow fracture propagation propensity.

KEYWORDS: Wet slab, liquid water content, PST

1. INTRODUCTION

Wet-snow avalanches are complex, destructive, challenging to predict, and may become more prevalent in a warming climate (Baggi and Schweizer, 2009; Ballesteros-Cánovas et al., 2018; Madore et al., 2022; Peitzsch et al., 2012, 2021). The underlying processes leading to wet-snow avalanche release remain poorly understood. Wet-snow avalanche formation depends on the complex interactions of a critical amount of water percolating through a specific snow stratigraphy resulting in a change of snowpack structure that leads to slope instability and avalanche release (Peitzsch et al., 2008; Reiweger and Mitterer, 2017; Schneebeli, 2004). Ponding of liquid water at a capillary barrier is a particularly important factor in the formation of wet-snow avalanches (Mitterer et al., 2011; Wever et al., 2016). Additionally, the first critical infiltration of liquid water into the snowpack in a given season often corresponds to wet snow avalanches (Conway and Raymond, 1993; Techel et al., 2011; Mitterer et al., 2013; Wever et al., 2016, 2018). Therefore, understanding the temporal change in snowpack properties is critical when assessing wet avalanche potential (Mitterer et al., 2016; Techel and Pielmeier, 2009). Previous research focused on meteorological conditions associated with wet-snow avalanche activity and liquid water moving through the snowpack (e.g., Baggi and Schweizer, 2009; Peitzsch et al., 2012; Wever et al., 2016), but few studies tracked the temporal change of snowpack properties over the duration of a melt event (Mitterer et al., 2011; Techel et al., 2011; Techel and Pielmeier, 2011).

Interactions between liquid water and snowpack structure are part of a complicated process that is non-linear, spatially variable, and constantly changing (Schneebeli, 2004; Techel and Pielmeier, 2011; Waldner et al., 2004). The complex nature of wet-snow avalanches and the difficulty of studying them in the field have led to the implementation of model-based approaches to wet-snow avalanche prediction (Mitterer and Schweizer, 2014; Hendrick et al., 2023).

Physics-based models such as the 1-D snow cover model SNOWPACK have been used to generate modeled stability indices based on:

* *Corresponding author address:*
Josh Lipkowitz, Department of Earth Sciences, Montana State University, Bozeman, MT 59715;
tel: +1 413-262-9837
email: joshua.lipkowitz@student.montana.edu

1) The ponding of liquid water at a capillary barrier (maximum local liquid water content (LWC)) (Wever et al., 2016), and
2) The bulk volumetric liquid water content as a proportion of the entire snowpack depth (LWC_{index}) (Mitterer et al., 2013).

These indices require a tradeoff between a higher probability of detection and lower false alarm rates depending on the threshold (Mitterer et al., 2016). Previous research confirms that elevated local or bulk LWC alone is insufficient for helping predict wet avalanche release (Bellaire et al., 2017; Wever et al., 2016; 2018). A better understanding of wet snow avalanche formation, specifically the mechanical properties of wet snow (Reiweger et al., 2016; Wever et al., 2016, 2018) and the temporal evolution of snowpack properties (Mitterer et al., 2016; Techel and Pielmeier, 2009), is necessary to improve wet-snow avalanche forecasting.

The objective of this study is to examine the temporal evolution of a specific set of snowpack properties as the snowpack undergoes the first critical melt event of the season. We define a first critical melt event as the period when SNOWPACK predicts LWC_{index} to increase above 0.3 (see Mitterer et al., 2016 for threshold) for the first time in the season and is forecast to continue to rise to 1. To achieve our objectives, we aim to answer the following questions:

1. How do liquid water content, critical cut length, and propagation mode change following the onset of the first critical melt event of the season?
2. Does crack propagation propensity change over time as weak layer and/or slab LWC change and if so, how?

2. DATA AND METHODS

2.1 Research Site

The field site is a south-facing slope located at the Yellowstone Club in the Madison Range of southwest Montana, United States (45.23016° N, -111.44227° W) (Figure 1). Our study site is within an intermountain avalanche climate (Mock and Birkeland, 2000) and the closest SNOTEL site (Lone Mountain, 2706 m) receives an annual median peak snow water equivalent (SWE) of 54.4 cm. The site has an approximate slope angle of 30-35 degrees and an elevation of 2750 meters.

At the beginning of the winter season, we installed an automated weather station (AWS) adjacent to our sample plot to measure air temperature, relative humidity, wind speed and direction, snow depth, and net longwave and shortwave radiation. We visited the study site weekly or biweekly throughout the winter to conduct a full manual snow profile and download the AWS data.

2.2 *Model Initiation and Forcing*

After conducting seven manual snow profiles throughout the season approximately bi-weekly, we ultimately chose a profile from March 7, 2023, to initialize SNOWPACK for our critical melt event forecasting. We chose this initiation date because of the proximity to potential forecasted melt events and the accuracy of our in-situ profile. Following an approach based on Bellaire et al. (2017), we forced SNOWPACK with our AWS data up until the melt event to provide us with a now-cast of the current snow cover. To determine when to begin our sampling protocol, we subsequently forced SNOWPACK with the 60-hour, 3 km National Centers for Environmental Prediction (NCEP) NAMNest numerical weather prediction (NWP) model to predict any future increases above our defined threshold values of LWC_{index}. We began our data collection when the LWC_{index} was forecast to increase above 0.3 for the first time.

2.3 *Data Collection*

Snow-pit data collection began on the morning of April 10, 2023. We completed a full snow profile each morning and at the end of the day. We measured LWC with the SLF Snow Sensor (FPGA Company) at 10 cm vertical increments in the pit sidewall and conducted a propagation saw test (PST) (American Avalanche Association, 2022) on a layer of depth hoar at 20 cm above the ground. The Yellowstone Club Ski Patrol recognized this layer as a persistent weak layer throughout the season on similar slopes. We used density values measured during our morning profile on April 10 to calibrate the Snow Sensor for LWC measurements. We completed a blade and hand hardness profile after every 3rd PST and collected LWC measurements on approximately 2 of 3 columns. After conducting a PST, we excavated a new side wall and continued moving across the slope, ensuring the sidewall was shaded. As the sun shifted overhead and began to illuminate the test wall, we moved up the slope approximately 2 m and worked our way back across the slope toward our starting point, to ensure a shaded test wall. We continued this protocol for 3 days, beginning at approximately 0845 each morning and concluded at approximately 1900 on Days 1 and 2 , and at approximately 1700 on Day 3 when PST results

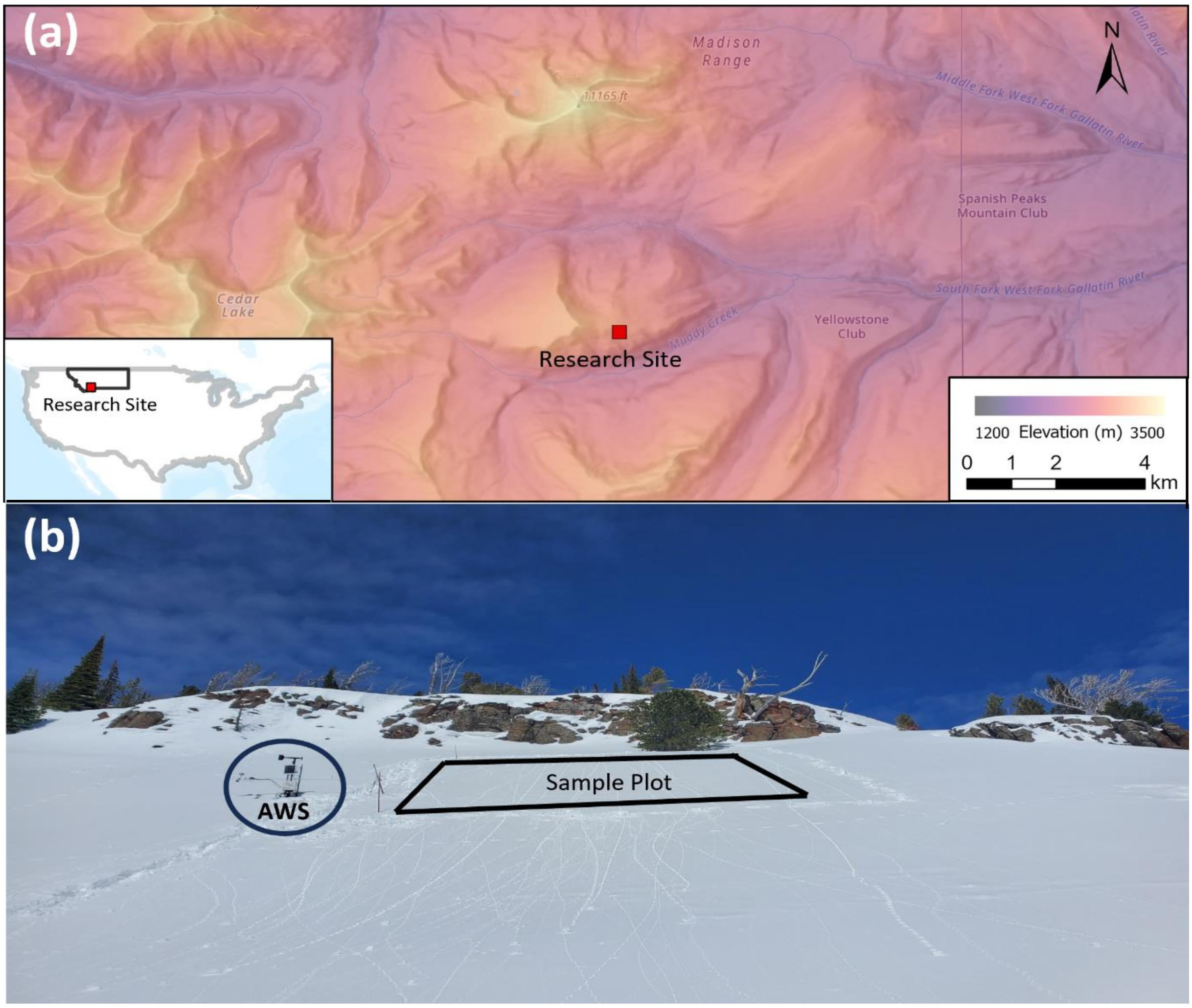

Figure 1: (a) Overview map of research site and surrounding area in the Madison Range of southwest Montana, USA. (b) Photograph of the research site. The site is located on the property of the Yellowstone Club on a south aspect at 2750 m with an approximate slope angle of 30-35 degrees. The black rectangle shows the location of the sample plot from April 10-12, 2023, and the black circle shows the location of the automated weather station (AWS).

became repetitive and the snowpack had fully metamorphosed into an isothermal state. Over the three days, we conducted 67 PSTs, 1053 LWC measurements as part of 39 full vertical LWC profiles, and 20 hardness profiles.

2.4 LWC Calculations

We identified the weak layer by classifying snow crystal type (American Avalanche Association, 2022), and we considered all layers above the weak layer as the slab. We calculated slab LWC from the median of LWC measurements from a given column taken between the surface and 25 cm above the ground. We calculated weak layer LWC from the median of LWC measurements from a given column taken between 0 and 20 cm above the ground. As LWC was always measured at a multiple of 5 cm above the ground, we have no recorded LWC measurements between 20 and 25 cm.

3. RESULTS

3.1 Season Summary

The Lone Mountain SNOTEL recorded a peak SWE of 66.3 cm for water year 2023; a 21.9% increase over the 1991-2020 climatological median. Monthly mean air temperature from October 2022 - April 2023 was 9.1% lower than the climatological mean for the same months between 1991-2020.

3.2 Weather

A multi-day melt event began on April 9, 2023 at our study site (Figure 2). Air temperature was above freezing each day from April 9 through

April 12, with a peak on April 11. Air temperatures remained above freezing on the nights of April 9 and 10, while falling below freezing for only one hour on the night of April 11. Snow surface temperature, as measured by our in-situ radiometer, climbed steadily starting on April 7 and peaked on April 10, before remaining elevated on April 11 and 12. The AWS-measured snow depth decreased from approximately 1.35 m on April 9 to 1.1 m on April 12. Forecasted LWC_{index} reached above 0.3 for the first time on April 10 and increased to over 1 on April 11 and 12.

3.3 *Initial Observed Snowpack*

We conducted a full snow profile on the morning of April 10 (Figure 3). The height of snow (HS) was 145 cm and the snowpack consisted of melt

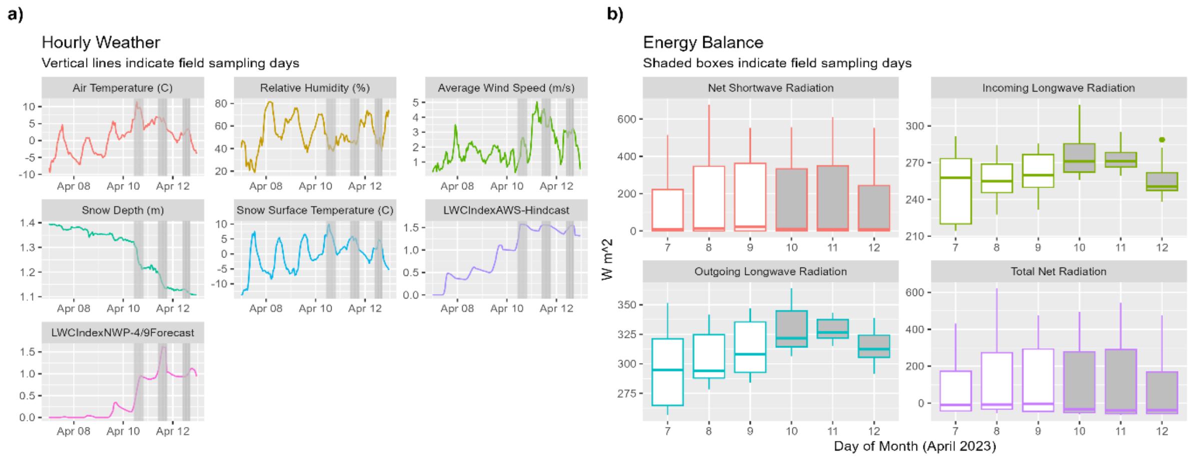

Figure 2: (a) Hourly weather from April 7-12, 2023. Vertical gray lines indicate field sampling periods. Air Temperature (°C), Relative Humidity (%), Average Wind Speed (m/s), and Snow Depth (m) were recorded by our in-situ Automated Weather Station (AWS). LWC_{index} was derived from SNOWPACK. (b) Energy balance from April 7-12, 2023, recorded by AWS. Gray-shaded boxes indicate sampling days.

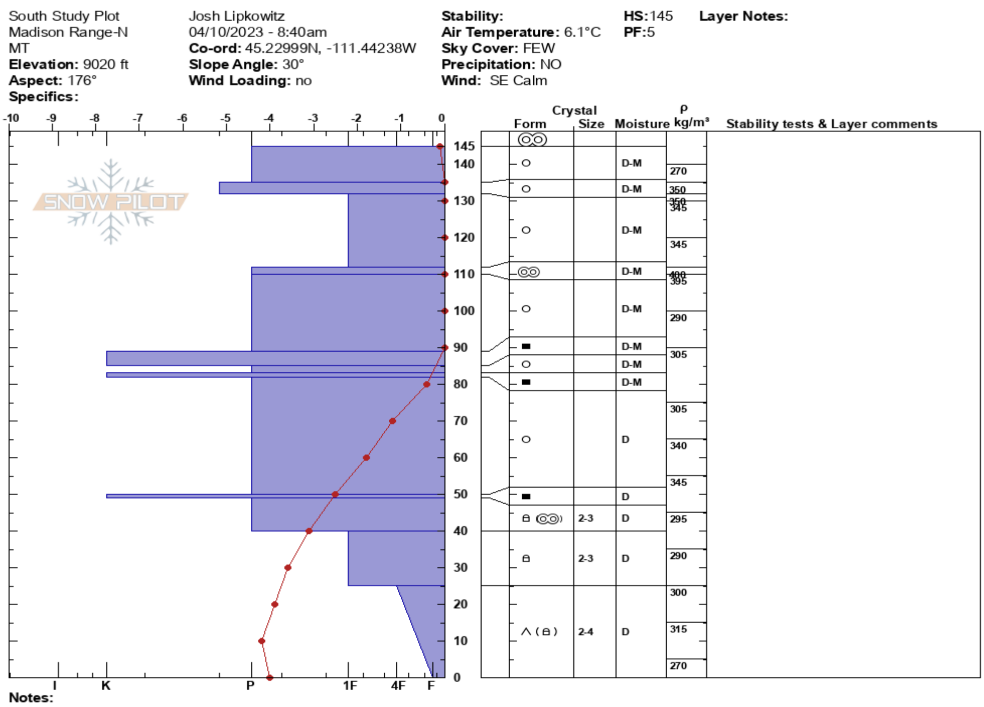

Figure 3: Snow profile prior to beginning sampling on April 10, 2023. Height of snow is noted in cm along the y-axis. A temperature profile in degrees C is shown as a red line with values along the upper x-axis, while a hand hardness profile by layer is shown in purple with values along the lower x-axis. Grain form symbols can be found in American Avalanche Association (2022). Grain size is in mm. D-M indicates dry to moist snow, while D indicates dry snow. A density profile is noted under the **ρ** column.

forms and various melt-freeze crusts from the surface down to 50 cm. Below that were layers of rounding facets on top of a 20 cm thick layer of 2 to 4 mm fist to four-finger hard depth hoar. There were no signs of water percolation below the bottom 50 cm of the snowpack and snowpack temperature was below freezing from 80 cm to the ground.

3.4 PST Results

There are four different possible results of a PST (American Avalanche Association, 2022): The crack propagates along the weak layer ahead of the saw until the end of the column (End), the crack propagates ahead of the saw but stops within the column and fractures vertically through the slab (slab fracture, SF), the crack propagates ahead of the saw but self-arrests somewhere within the weak layer before reaching the end of the column (arrest, Arr), or the entire column is cut without the fracture propagating ahead of the saw (X). A result of End with a cut length of less than 50% of the column length can be interpreted as having high propagation propensity. An End result with a cut length of more than 50% of the column length, or results of X, Arr, and SF, regardless of cut length, can be interpreted as having low propagation propensity (eg. Gauthier, 2007; Gauthier and Jamieson, 2008a and 2008b).

On Day 1 (April 10, 2023), 33% (6 of 18) of PSTs showed a high propagation propensity (13 End, 5 X) (Figure 4a). Test results at the end of the day produced shorter cut lengths compared to earlier in the day and showed high propagation propensity. On Day 2 (April 11, 2023), 66% (16 of 24) of PSTs indicated a high propagation propensity (20 End, 3 Arr, 1 SF). The first Arr result occurred at 1547. Of the last 9 tests on Day 2, three were Arr, one was SF, and five were End results. 12% (3 of 25) of PSTs on Day 3 (April 12, 2023) showed a high propagation propensity (16 SF, 7 End, 2 X). The SF results occurred throughout the day. At 1230, we observed the last high propagation propensity result of the day, after which time we observed 16 consecutive low propagation propensity results (10 SF, 4 End, 2 X).

3.5 LWC and Cut Length

On Day 1, weak layer and slab LWC values were variable, but exhibited a general increase through the late afternoon before a slight decline at the end of the day (Figures 4b and 4c). Slab LWC was equal to or greater than weak layer LWC for all columns except one. Cut length decreased throughout the day as LWC increased.

Weak layer and slab LWC were similar at the beginning of Day 2 as they were at the end of Day 1. Slab LWC increased sharply after 1000, while weak layer LWC increased sharply in the early afternoon. After 1300, both remained above 10% except for three columns where weak layer LWC was measured between 5 and 10%. Cut length continued to decrease through Day 2 as LWC increased.

At the beginning of Day 3, both slab and weak layer LWC were lower than values measured during the afternoon of Day 2. Slab LWC decreased throughout the early morning while weak layer LWC was variable with values between 5 and 7%. Slab LWC began to increase around 1100 and both slab and weak layer LWC increased sharply after 1400, reaching similar values as those observed on the afternoon of Day 2. Despite these elevated LWC levels on the afternoon of Day 3, crack propagation propensity was low. Cut length was slightly higher at the beginning of Day 3 than it was at the end of Day 2. There was no clear relationship between cut length and LWC on Day 3.

4. DISCUSSION

4.1 Trends, Patterns, and Implications

Notable patterns emerged in terms of propagation propensity and mode during our sampling period. We observed a progression from mostly long cut-lengths associated with End and X modes at the beginning of Day 1 to low cut-lengths associated with End mode on Day 2. After a long string of results indicating a high propagation propensity on Day 2, we observed Arr and SF modes of propagation, indicating lower propagation propensity in the afternoon on Day 2. This shift occurred despite comparable weak layer and slab LWC levels to those measured during the previous period of high propagation propensity. This suggests there is a point where the relationship we observed through the first two days between increasing LWC, increasing propagation propensity, and decreasing cut length no longer holds. Slab fractures continued throughout the bulk of Day 3. In the early afternoon of Day 3, long cut-lengths associated with X and End propagation modes occurred in addition to the slab fractures. The change from high to low propagation propensity and the shifting of propagation modes suggest decreasing fracture propagation propensity along the weak layer as a result of changing slab or weak layer properties, or a combination of the two. On the afternoon of Day 3, slab and weak layer LWC values reached values similar to the

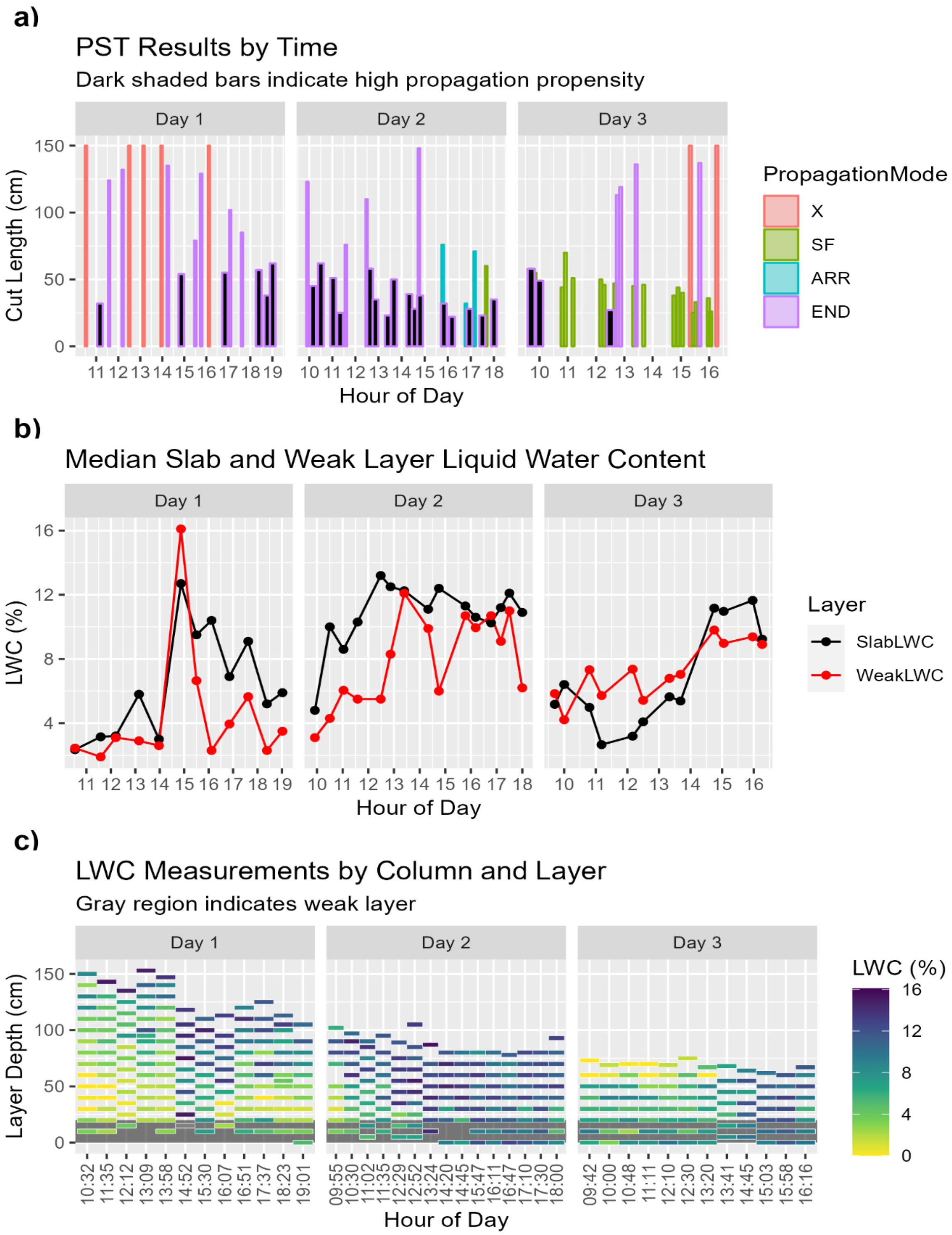

Figure 4: (a) Cut length and propagation mode by time. Dark shaded bars are End modes with cut lengths of less than 50% of the column length, indicating high propagation propensity. (b) Median liquid water content (LWC) by column and layer. Slab LWC was calculated from the median of LWC measurements from a given column taken between the surface and 25 cm above the ground. Weak layer LWC was calculated from the median of LWC measurements from a given column taken between 0 and 20 cm above the ground. (c) LWC measurements by column and layer. Gray region shows the weak layer. Multiple LWC measurements were taken at 10 cm increments from the surface to the ground. A median value was calculated from all measurements at a given depth in a column. There are some gaps within a column due to ice lenses, melt-freeze crusts, or talus at the ground making measurements difficult to obtain.

period of consistently high propagation propensity on Day 2, but the trend toward low propagation propensity continued all day on Day 3.

The results of this study suggest that the PST could be a valuable tool for assessing propagation propensity in wet snow (Reiweger et al., 2016; Reiweger and Mitterer, 2017). The observed patterns suggest that propagation mode could help pinpoint the onset, peak, and decline of wet-snow fracture propagation propensity. This could be especially helpful for better understanding the timing of the end of a wet-snow slab avalanche cycle. The corresponding patterns between LWC and cut length late on or after Day 2 in our study indicate that while modeling LWC and LWC_{index} may help predict the onset of a cycle, these measurements alone may not prove effective at predicting the end of a cycle and a return to stability.

4.2 Challenges, Limitations, and Future Work

There was a consistent decrease in HS across the three days of sampling. Our AWS depth sensor recorded an approximate 18.5% decrease in HS over the three days due to settlement. HS, as measured at each of our columns, decreased by 30-50% throughout the sampling period. This indicates that there were differences in HS between our columns that were not caused by settlement alone. As slab thickness plays a critical role in fracture mechanics and crack propagation (e.g., Gaume et al., 2017), we will account for slab thickness in future analyses. Furthermore, the inherent spatial variability of snow stratigraphy and the heterogenous nature of liquid water flow through the snowpack also require us to account for these spatial effects. We will account for these effects in future work by using mixed linear models that assess for the random effects of both space and time through an autoregressive function. We also plan on analyzing the spatial auto-correlation of LWC in our dataset.

Our measurements yielded a series of low cut-length slab fractures beginning the afternoon of Day 2 and continuing on Day 3. These low cut-length results complicate interpretation of results if we were to only use cut length as a proxy for propagation propensity, or when trying to understand the effect of LWC on propagation propensity. For example, a result of PST 30/150 (End) suggests high propagation propensity, while a PST 30/150 (SF) indicates low propagation propensity (Gauthier and Jamieson, 2008b). Comparing these results in wet snow conditions is difficult, and future work could include creating a propagation propensity index for using the PST in wet snow. This index could allow for mode and cut length to be combined in a way that would allow for robust statistical analyses of PST results to account for potential bias by low cut length SF or Arr results. This may also serve as another tool for avalanche forecasters when predicting wet avalanche problems.

5. CONCLUSION

We tracked the temporal evolution of cut length, PST results, and weak layer and slab layer LWC at the slope scale over the duration of the first critical melt event of the season. During the first two days of sampling, as liquid water infiltrated into the snowpack for the first time, we observed a transition from low to high propagation propensity with decreasing cut lengths and increasing LWC. This was followed by a period of low propagation propensity on Day 3, even as LWC levels remained elevated. The patterns of propagation mode and low or high propagation propensity results show interesting potential to improve our understanding of wet-snow processes and ultimately wet-snow avalanche forecasting.

6. ACKNOWLEDGMENT

We would like to acknowledge the Yellowstone Club Ski Patrol for their many contributions to this project. Matt Kelly, Ross Palomaki, Alex Haddad, and Shannon Regan provided critical field support. Sally Slipher and Greta Linse of Montana State University Statistical Consulting and Research Services provided support with statistical analyses. We are grateful to Karl Birkeland for his insights during initial project development. We thank Alex Marienthal and Max Stevens for independent reviews of earlier drafts of this manuscript.

7. DISCLAIMER

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

8. REFERENCES

American Avalanche Association: Snow, Weather, and Avalanches: Observation Guidelines for Avalanche Programs in the United States, 4th Edition., American Avalanche Association, Denver, CO, 2022.

Baggi, S. and Schweizer, J.: Characteristics of wet-snow avalanche activity: 20 years of observations from a high alpine valley (Dischma, Switzerland), Nat Hazards, 50, 97–108, https://doi.org/10.1007/s11069-008-9322-7, 2009.

Ballesteros-Cánovas, J. A., Trappmann, D., Madrigal-González, J., Eckert, N., and Stoffel, M.: Climate warming enhances snow avalanche risk in the Western Himalayas, Proceedings of the National Academy of Sciences, 115, 3410–3415, https://doi.org/10.1073/pnas.1716913115, 2018.

Bellaire, S., van Herwijnen, A., Mitterer, C., and Schweizer, J.: On forecasting wet-snow avalanche activity using simulated snow cover data, Cold Reg Sci Technol, 144, 28–38, 2017.

Conway, H. and Raymond, C. F.: Snow stability during rain, J Glaciol, 39, 635–642, 1993.

Gauthier, D. and Jamieson, B.: Evaluation of a prototype field test for fracture and failure propagation propensity in weak snowpack layers, Cold Reg Sci Technol, 51, 87–97, https://doi.org/10.1016/j.coldregions.2007.04.005, 2008a.

Gaume, J., van Herwijnen, A., Chambon, G., Wever, N., and Schweizer, J.: Snow fracture in relation to slab avalanche release: critical state for the onset of crack propagation, The Cryosphere, 11, 217–228, https://doi.org/10.5194/tc-11-217-2017, 2017.

Gauthier, D. and Jamieson, B.: Fracture propagation propensity in relation to snow slab avalanche release: Validating the Propagation Saw Test, Geophys Res Lett, 35, https://doi.org/10.1029/2008GL034245, 2008b.

Gauthier, D. M.: A practical field test for fracture propagation and arrest in weak snowpack layers in relation to slab avalanche release, Ph.D. thesis, University of Calgary, Calgary, Canada, 2007.

Hendrick, M., Techel, F., Volpi, M., Olevski, T., Pérez-Guillén, C., Herwijnen, A. van, and Schweizer, J.: Automated prediction of wet-snow avalanche activity in the Swiss Alps, J Glaciol, 1–14, 2023.

Hirashima, H., Yamaguchi, S., Sato, A., and Lehning, M.: Numerical modeling of liquid water movement through layered snow based on new measurements of the water retention curve, Cold Reg Sci Technol, 64, 94–103, https://doi.org/10.1016/j.coldregions.2010.09.003, 2010.

Madore, J.-B., Fierz, C., and Langlois, A.: Investigation into percolation and liquid water content in a multi-layered snow model for wet snow instabilities in Glacier National Park, Canada, Front Earth Sci, 10, 2022.

Mitterer, C. and Schweizer, J.: Comparing Models of Different Levels of Complexity for the Prediction of Wet-Snow Avalanches, International Snow Science Workshop 2014 Proceedings, Banff, Canada, 9–14, 2014.

Mitterer, C., Hirashima, H., and Schweizer, J.: Wet-snow instabilities: comparison of measured and modeled liquid water content and snow stratigraphy, Ann Glaciol, 52, 201–208, 2011.

Mitterer, C., Techel, F., Fierz, C., and Schweizer, J.: An Operational Supporting Tool for Assessing Wet-Snow Avalanche Danger, International Snow Science Workshop 2013 Proceedings, Grenoble – Chamonix Mont-Blanc, France, 334–338, 2013.

Mitterer, C., Heilig, A., Schmid, L., Herwijnen, A. van, Eisen, O., and Schweizer, J.: Comparison of Measured and Modelled Snow Cover Liquid Water Content to Improve Local Wet-Snow Avalanche Prediction, International Snow Science Workshop 2016 Proceedings, Breckenridge, CO, USA, 125–131, 2016.

Mock, C. J. and Birkeland, K. W.: Snow Avalanche Climatology of the Western United States Mountain Ranges, Bulletin of the American Meteorological Society, 81, 2367–2392, https://doi.org/10.1175/1520-0477(2000)081<2367:SACOTW>2.3.CO;2, 2000.

Peitzsch, E., Birkeland, K. W., and Hansen, K. J.: Water Movement and Capillary Barriers in a Stratified and Inclined Snowpack, International Snow Science Workshop 2008 Proceedings, Whistler, Canada, 179, 2008.

Peitzsch, E. H., Hendrikx, J., Fagre, D. B., and Reardon, B.: Examining spring wet slab and glide avalanche occurrence along the Going-to-the-Sun Road corridor, Glacier National Park, Montana, USA, Cold Reg Sci Technol, 78, 73–81, 2012.

Peitzsch, E. H., Pederson, G. T., Birkeland, K. W., Hendrikx, J., and Fagre, D. B.: Climate drivers of large magnitude snow avalanche years in the U.S. northern Rocky Mountains, Sci Rep, 11, 10032, https://doi.org/10.1038/s41598-021-89547-z, 2021.

Reiweger, I. and Mitterer, C.: How to determine wet-snow instability, EGU General Assembly 2017, Vienna, Austria, 23-28 April 2017, 1916772R, 2017.

Reiweger, I., Zöchling, M., Forster, M., Wiesinger, T., and Mitterer, C.: Wet-Snow Fracture Propagation, International Snow Science Workshop 2016 Proceedings, Breckenridge, CO, USA, 655–657, 2016.

Schneebeli, M.: Mechanisms in wet snow avalanche release, Proceedings of Snowsymp, International Symposium on Snow, Manali, India, 245–248, 2004.

Techel, F. and Pielmeier, C.: Wet Snow Diurnal Evolution and Stability Assessment, International Snow Science Workshop 2009 Proceedings, Davos, Switzerland, 256–261, 2009.

Techel, F. and Pielmeier, C.: Point observations of liquid water content in wet snow - investigating methodical, spatial and temporal aspects, The Cryosphere, 5, 405–418, https://doi.org/10.5194/tc-5-405-2011, 2011.

Techel, F., Pielmeier, C., and Schneebeli, M.: Microstructural resistance of snow following first wetting, Cold Reg Sci Technol, 65, 382–391, 2011.

Waldner, P. A., Schneebeli, M., Schultze-Zimmermann, U., and Flühler, H.: Effect of snow structure on water flow and solute transport, Hydrol Process, 18, 1271–1290, https://doi.org/10.1002/hyp.1401, 2004.

Wever, N., Valero, C., and Fierz, C.: Assessing wet snow avalanche activity using detailed physics based snowpack simulations - Wever - 2016 - Geophys Res Lett - Wiley Online Library, Geophysical Research Letters, 43, https://doi.org/10.1002/2016GL068428, 2016.

Wever, N., Vera Valero, C., and Techel, F.: Coupled Snow Cover and Avalanche Dynamics Simulations to Evaluate Wet Snow Avalanche Activity, J Geophys Res-Earth, 123,1772–1796, https://doi.org/10.1029/2017JF004515, 2018.