UNDER-FORECASTING WET AVALANCHE CYCLES: CASE STUDIES AND LESSONS LEARNED FROM TWO WET AVALANCHE CYCLES IN NORTHWEST MONTANA AND CENTRAL COLORADO

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ABSTRACT: Predicting the timing and location of natural wet avalanche events is challenging, especially the release of wet slabs. In this study, we describe the existing snowpack structure, weather, and observed avalanche activity for two separate wet avalanche cycles in different avalanche climate types: northwest Montana and central Colorado. In both cases, the regional avalanche forecast centers initially predicted an avalanche hazard rating lower than the observed avalanche hazard and did not initially predict the occurrence of wet slab avalanches. Large wet slab avalanche activity began during the early stages of the first, rapid warming event of the season in both regions, challenging the notion that a lack of overnight refreeze is important for large wet avalanche cycles. This highlights the need for improvement in forecasting wet avalanche events/cycles. Here, we discuss lessons learned and operational strategies for improving forecast accuracy during significant melting events. These include focused field assessments in shallow snowpack areas and low elevation terrain, proactive late-day monitoring beyond normal field hours, and additional meteorological considerations, such as cloud cover and energy balance assessments, prior to and during notable warm-ups.

KEYWORDS: wet slabs, forecasting, wet avalanches

1. INTRODUCTION

Wet snow avalanches are destructive and are likely to become more common as the climate changes (Pielmeier et al., 2013; Ballesteros-Canovas et al., 2018). Recent research provides a better understanding of wet snow avalanche processes through case studies (Součková et al., 2022) and statistical (Helbig et al., 2015) and physical modeling approaches (Wever et al., 2016). However, forecasting the start and end of wet snow avalanche cycles, particularly wet slab avalanches, remains challenging. Here, we describe two case studies of large, wet snow avalanche cycles in two different snow climates, intermountain and continental. The timing and avalanche magnitude of both cycles proved difficult to forecast. Our objective is to characterize two major wet slab avalanche cycles and provide potential forecasting strategies learned through these case studies.

2. CASE STUDY #1: CENTRAL COLORADO

2.1 *Study Region*

The Crested Butte study region is situated in the Elk Mountains of central Colorado (Figure 1). The study region spans approximately 1010 km^2 surrounding the town of Crested Butte, within the Gunnison and White River National Forests. Based out of Crested Butte, Colorado, the Crested Butte Avalanche Center (CBAC) produces daily avalanche forecasts for two zones that span the study region, the Northwest and Southeast Mountains. Based out of Boulder, Colorado, the Colorado Avalanche Information Center (CAIC) also produces daily avalanche forecasts for the study area as part of a larger statewide forecast program using dynamic forecast boundaries. The Elk Mountains are classified as having a continental snowpack (Mock and Birkeland, 2000). Microclimates within the Elk Mountains yield a consistently deeper snowpack in the Northwest Mountains (the Ruby Range and Anthracite Range), which becomes increasingly shallower in the Southeast Mountains (Brush Creek and Cement Creek). Elevations range from approximately 2700 m near the valley bottom to over 4000 m on the highest summits, with treeline extending up to approximately 3500 m. This study utilizes temperature data from the Crested Butte Mountain Resort (CBMR) station, centrally located on Mount Crested Butte at 3444 m. Radiation data come from Chair Mountain station, located approximately 15 km northwest of the study area at 3137 m.

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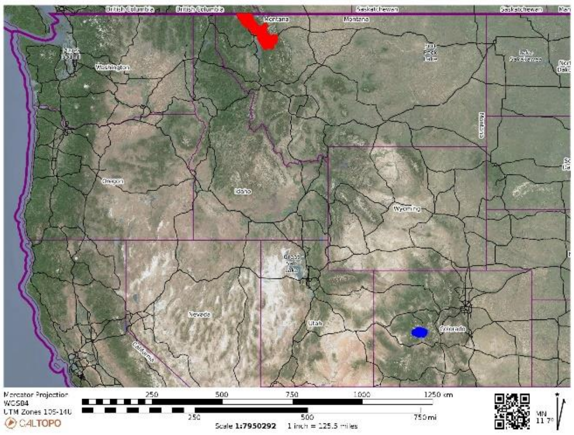

Figure 1: The Crested Butte study region (in blue) is in central Colorado. The Flathead study region (in red) is in northwest Montana.

2.2 *Snowpack History and Structure*

The winter and spring of 2023 was characterized by consistent storm cycles and an above average bulk snow water equivalent (SWE). By the start of the wet avalanche cycle on April 9, the Gunnison River Basin Snowpack was at 163% of average with 64 cm of snow water equivalent (NRCS, 2023b). Nevertheless, persistent and deep persistent slab problems existed throughout the winter, though triggering avalanches generally became difficult to all but the largest triggers by April. A 3-week dry spell in December contributed to the formation of a layer of depth hoar near the ground, and several shorter dry spells in March contributed to the formation of a series of faceted crusts in the upper 1 to 2 meters of the snowpack (Figure 2). Meltwater within the snowpack was limited due to an unusually wet and cool spring until April 9. A wind event in early April deposited a notable desert dust layer that persisted near or at the snow surface during the ensuing warmup.

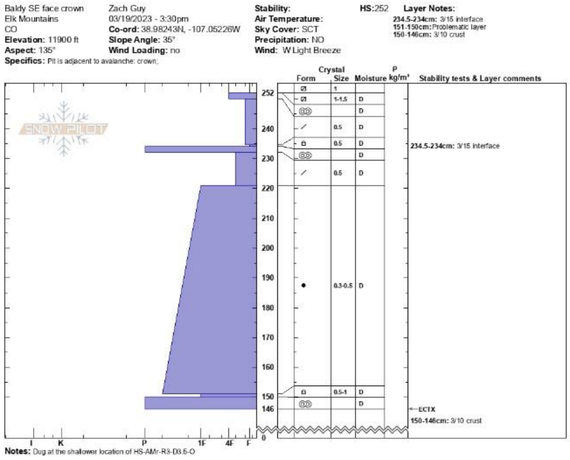

Figure 2: A crown profile on March 19, 2023, showing several faceted crusts in the upper snowpack located in terrain with a relatively deep snowpack within the Crested Butte region.

2.3 *Weather and Avalanche Activity*

A high-pressure ridge caused the first major warming period of the season and a noteworthy wet avalanche cycle to the region from April 9 to April 13, 2023 (Figure 3). The period began with average temperatures rising to just above freezing on April 7 and 8. A more dramatic warming trend followed, with high temperatures reaching 2°C on April 9, 8°C on April 10, and peaking at 10°C on April 11. Overnight lows first remained above freezing on the night of April 10. Temperatures remained above freezing but gradually decreased through April 13 before a cold front on the night of April 13 ended the warm period. Skies were clear with the greatest inbound shortwave radiation values from April 9 through April 11 when the high-pressure ridge was centered over the region. Wind at upper elevations was generally light until April 11, and increased to moderate speeds on April 12 and 13.

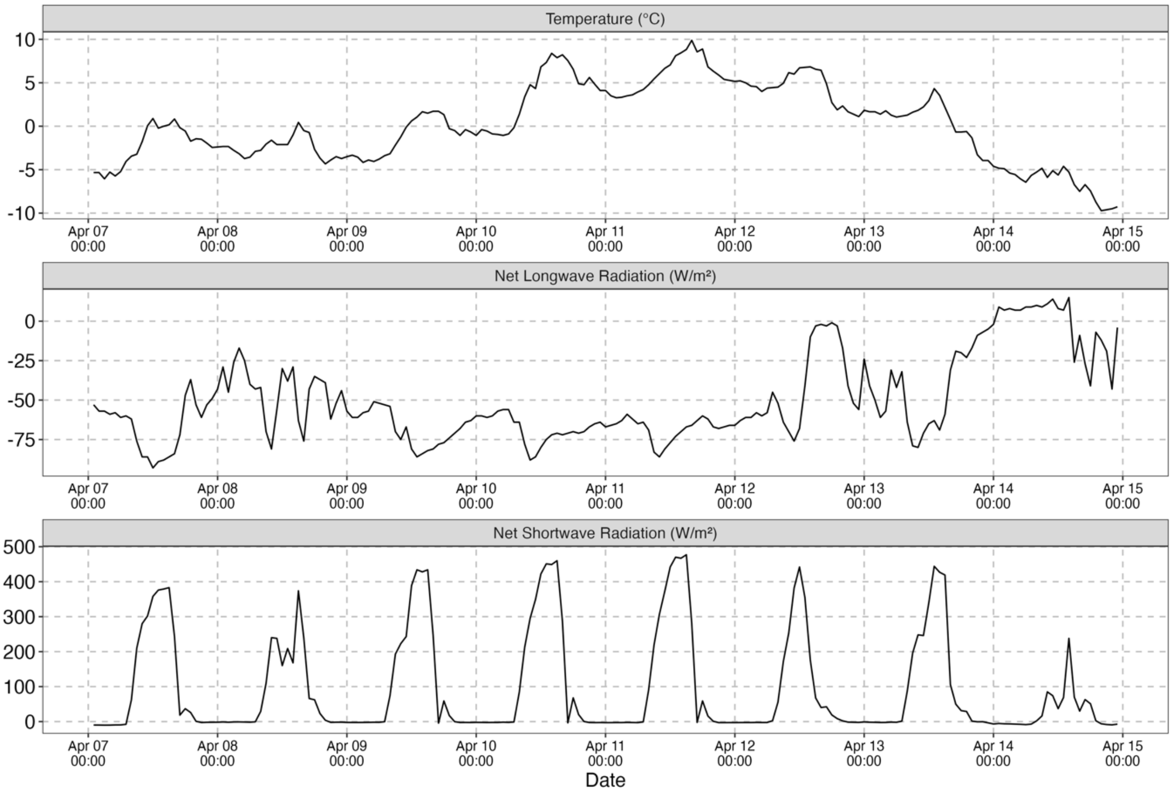

Figure 3: Meteorological variables for the Crested Butte region. Temperature data are from Crested Butte Mountain Resort station at 3444 m. Longwave and shortwave radiation data are from Chair Mountain station at 3137 m.

A 5-day cycle of large wet avalanches occurred from April 9 through April 13 (Figure 4). Wet slab avalanche activity (size D2 to D2.5) began on April 9 and intensified in both frequency and magnitude (≥D3) on April 10 and 11 before decreasing in frequency on April 12 and 13. D1.5 to D2.5 wet loose and glide avalanches occurred the first three days of the cycle as well. Of the 103 wet avalanches documented during the cycle, 50 were wet slabs. Most of the wet avalanche activity occurred on near and below treeline slopes; five wet slabs released in above treeline terrain. Wet avalanche activity was almost exclusively confined to east, south, and west aspects, with only two documented wet avalanches on northerly facing terrain. Several cornice falls and dry slab avalanches also released during the first several days of the cycle. To summarize the observed avalanche activity, we calculated an Avalanche Activity Index (AAI), following Schweizer et al. (2003), where the weights for each avalanche are 0.01, 0.1, 1, and 10 for the sizes 1 to 4, respectively. Therefore, we multiplied the total number of avalanches by the respective weight and summed the index for each day for a daily AAI. In this study, we rounded avalanche half sizes down to the nearest integer.

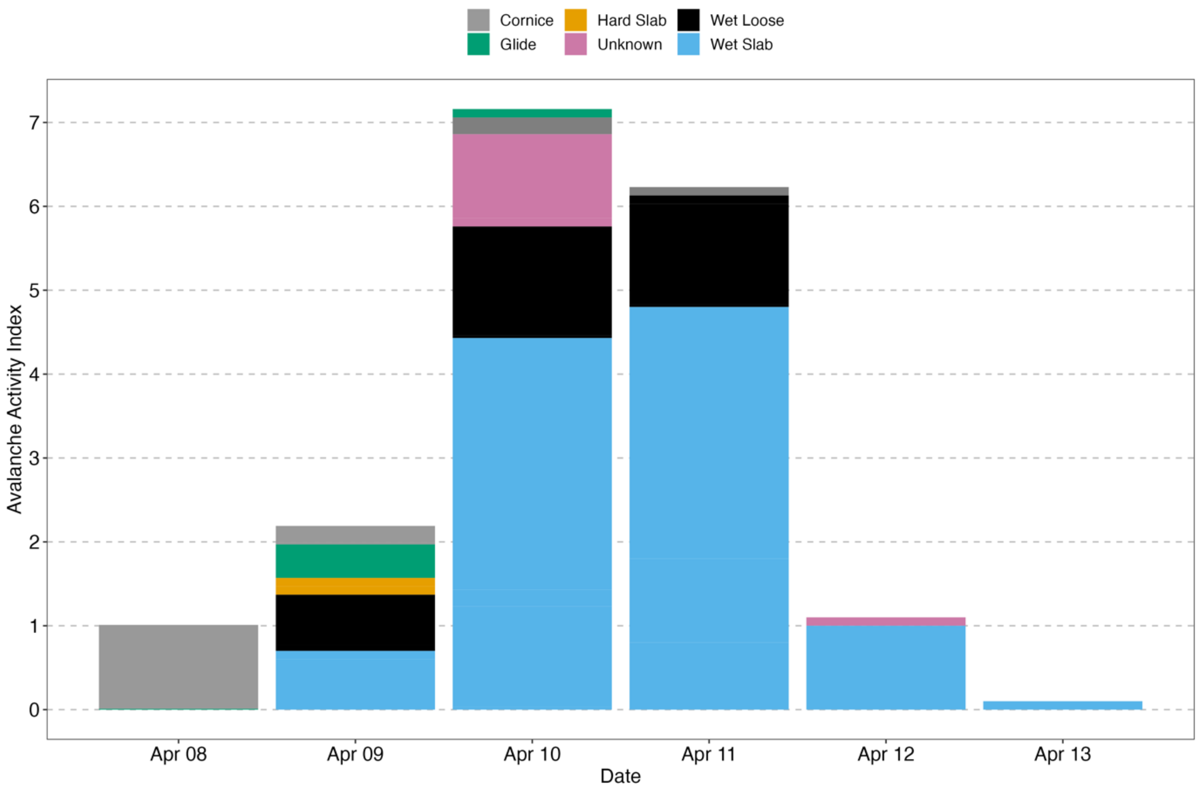

Figure 4: Avalanche activity index for the Crested Butte wet cycle categorized by avalanche type. We calculated the Avalanche Activity Index (AAI) following Schweizer et al. (2003), where the weights for each avalanche are 0.01, 0.1, 1, and 10 for the sizes 1 to 4, respectively. Therefore, we multiplied the total number of avalanches by the respective weight and summed the index for each day for a daily AAI.

2.4 *Regional Forecast Assessment*

CBAC forecast staff collected daily snowpack and avalanche observations from numerous locations throughout the study area, typically from two or three drainages per day, during this avalanche cycle. After each field day, forecasters re-assessed the avalanche danger ratings (on a scale from 1 to 5) for each of the three elevation bands within the forecast area of travel. Forecast staff reevaluated these assessments during a staff debriefing following the cycle using a more comprehensive view of the week's avalanche activity. Note that some re-assessed danger levels occupy a half-level category when there was not clear agreement on a single danger level. Presenting half-level danger ratings provides perspective on the different assessments within a forecast center's staff rather than scaling up to the highest re-assessed danger level. Forecasted danger ratings are produced the morning of or afternoon prior to the day's conditions.

Within the study area, both avalanche centers under-forecasted the avalanche danger during the early and peak phase of the cycle and over-forecasted the avalanche danger during the late phase of the cycle (Figure 5). During the first two days of the cycle, forecasted danger ratings were one danger level different than re-assessed ratings in Below and Near Treeline zones. Levels were consistent in Above Treeline zone for the first two days. Furthermore, both avalanche centers were late in listing wet slabs as an avalanche problem: the CBAC listed wet slabs on April 10 and the CAIC listed wet slabs on April 11. Wet slab activity accounted for the largest AAI values throughout the entire cycle, which started on April 9 (Figure 6).

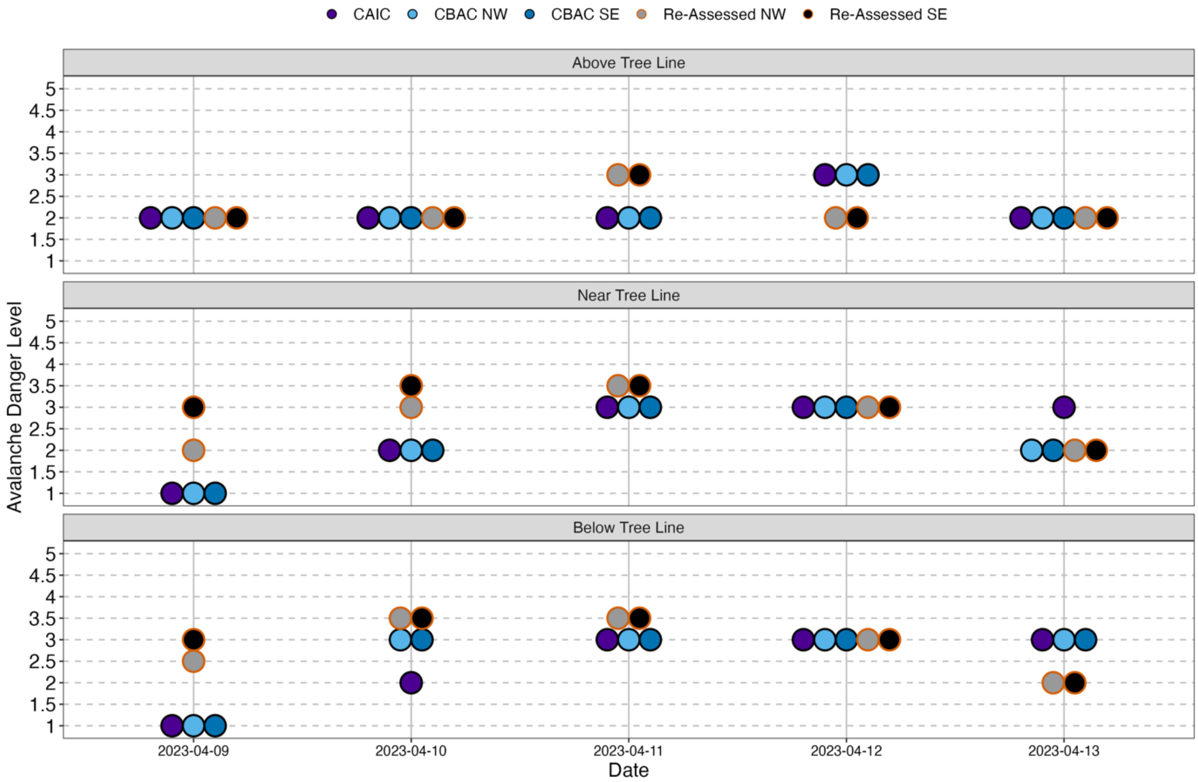

Figure 5: Comparison of forecasted (purple (CAIC), light blue (CBAC NW zone), and royal blue (CBAC SE zone)) vs. re-assessed (gray circle (NW zone) and black (SE zone)) danger levels for each day of the Crested Butte wet avalanche cycle. Note that some re-assessed danger levels occupy a half-level category in cases where there was not a clear consensus between forecast staff.

Figure 6: This wet slab released around noon on April 9 just south of the town of Crested Butte - one of numerous wet slabs that occurred earlier than forecasted when the danger rating at below treeline elevations was rated Low. Credit: Crested Butte Avalanche Center.

3. CASE STUDY #2: NORTHWEST MONTANA

3.1 *Study Region*

The Flathead study region is situated in northwest Montana (Figure 1). Based out of Hungry Horse, Montana, the Flathead Avalanche Center (FAC) produces daily avalanche forecasts for three zones that span the region. The study region encompasses approximately 4050 km^2 that includes the Flathead, Whitefish, portions of the Swan Ranges within the Flathead National Forest and the Apgar Range, and portions of the Livingston and Lewis Ranges in Glacier National Park. These mountain ranges generally run parallel to each other in a northwest-to-southeast direction. The westernmost ranges in this region are classified as hosting an Intermountain snow climate (Mock and Birkeland, 2000). In contrast, the snowpack becomes increasingly shallower and continental moving east into Glacier National Park toward the Continental Divide. Elevations range from approximately 900 m near the valley bottom to over 2700 m on the highest summits, with treeline extending up to approximately 2200 m. This study utilizes temperature data from the Big Mountain Summit station, centrally located at 2053 m in the southern Whitefish Range. Radiation data are from Snowslip station at 2140 m in southern Glacier National Park.

3.2 Snowpack History and Structure

The winter and spring of 2019 was characterized by drier and colder conditions than normal. By the start of the wet cycle on March 17, the Middle Fork of the Flathead snowpack was at 84% of average with 49 cm of snow water equivalent (NRCS, 2023a). The two most prominent weak layers in the snowpack were basal facets that formed during a dry spell in November, and a melt-layer recrystallization crust formed on February 2 (Figure 7). Both of these layers produced noteworthy persistent slab avalanche activity earlier in the season but trended toward unreactive by mid-March. Several rain crusts also existed within the snowpack from December and January rain-on-snow events. Following the formation of the February 2 crust, air temperatures remained below average for the six weeks leading up to the first major warming period in mid-March. This cold period contributed to faceting throughout much of the snowpack, especially in shallow and low elevation areas.

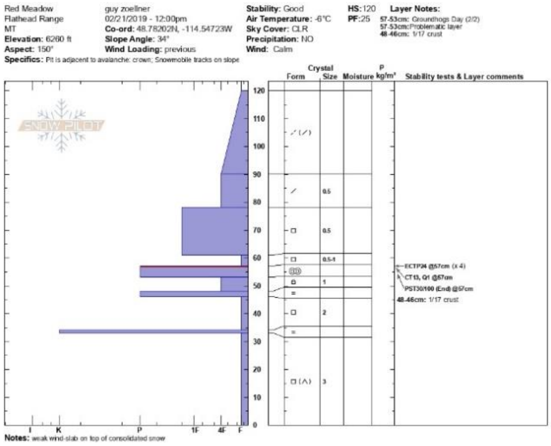

Figure 7: A crown profile conducted February 21, 2019, showing several facet layers and crusts in the lower half of the snowpack in the Flathead region.

3.3 Weather and Avalanche Activity

A strong and persistent high-pressure ridge brought a prolonged warmup to the region (Figure 8) and an extended wet avalanche cycle from March 17 through March 22, 2019. This period was the first notable warming event of the late winter and early spring season. High temperatures first rose above freezing on March 16 and continued to increase by 3 to 5°C each day until peaking at 14°C on both March 20 and 21. Big Mountain Summit station recorded four nights of above freezing temperatures beginning the night of March 18. Temperatures decreased to below freezing the night of March 22. Clear skies and consistent shortwave radiation were common from March 18 through March 22. Broken and thin, hazy cloud cover occurred on March 16 and 17, respectively, and incoming shortwave radiation began decreasing again on March 23 with increasing cloud cover over the next several days. Wind at upper elevation was generally light throughout the period.

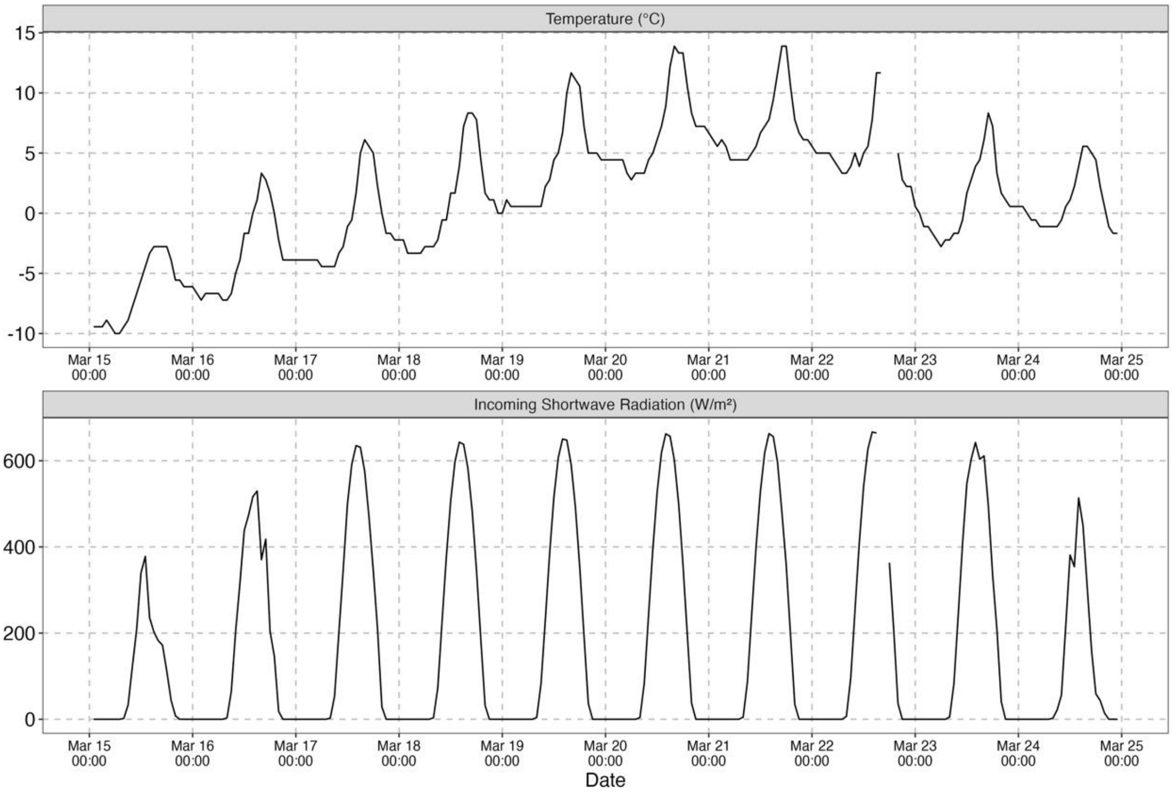

Figure 8: Meteorological variables for the Flathead region. Temperature data are from Big Mountain Summit at 2053 m. Incoming shortwave radiation data are from Snowslip station at 2140 m.

A large wet avalanche cycle occurred from March 17 through March 22 (Figure 9). Small wet loose avalanche activity occurred on March 16. Then, 52 D2 to D3.5 wet loose avalanches, many of which gouged to the ground, occurred on March 17. Over the next three days, wet loose avalanche activity continued but gradually decreased in frequency while wet slab avalanches became larger and more widespread. The first wet slab, a D1.5, occurred on March 18, followed by three D2 to D3 wet slab avalanches on March 19 (Figure 10), and 29 D2 to D3 wet slabs on March 20. Both wet loose and wet slab avalanche activity peaked on March 21, with an AAI nearly four times higher than any other day. During this peak of the cycle, 25 wet slab avalanches (size D2 to D4) and 71 wet loose avalanches (size D2 to D3) occurred. Wet avalanche frequency sharply decreased on March 22 and diminished to isolated activity on March 23 and 24. All wet slab avalanches released on southeast through west aspects and only a few small wet loose avalanches released on north facing terrain during the cycle. Several dry slab avalanches occurred early in the warming period and several glide avalanches released later in the cycle.

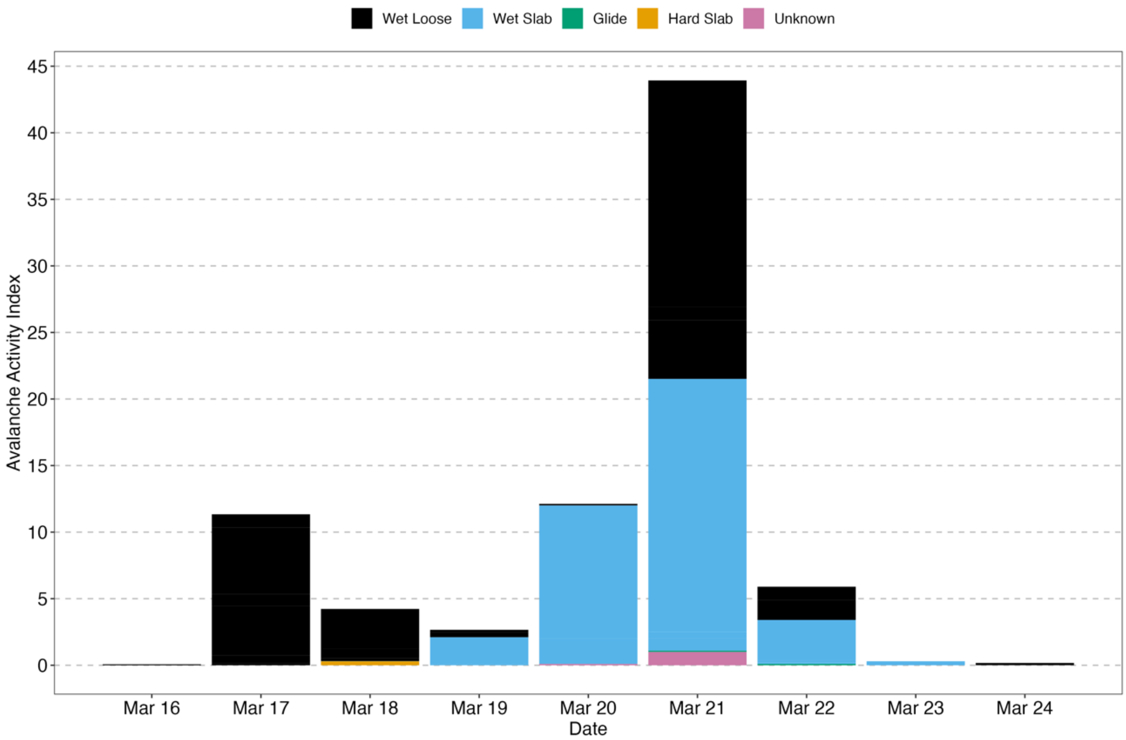

Figure 9: Avalanche activity index for the Flathead wet cycle categorized by avalanche type. We calculated the Avalanche Activity Index (AAI) following Schweizer et al. (2003), where the weights for each avalanche are 0.01, 0.1, 1, and 10 for the sizes 1 to 4, respectively. Therefore, we multiplied the total number of avalanches by the respective weight and summed the index for each day for a daily AAI.

3.4 *Regional Forecast Assessment*

In the wake of the cycle, the FAC forecast team re-assessed the Tier 1 danger ratings based on observed avalanche activity and fieldwork notes. Tier 1 danger ratings represent only the highest danger of the day for any of the three elevation bands and across the three forecast zones. Similar to the Crested Butte study, the FAC generally under-forecasted the avalanche danger during the early phases of the cycle and over-forecasted the avalanche danger during the late phase of the cycle (Figure 11). The forecasted danger rating was a level off from the re-assessed danger rating during half of forecast days.

The FAC first listed wet slab avalanches as a problem on March 20, two days after the first observed wet slab activity. It is probable that many more wet slabs occurred on March 19 but avalanche observations on that day were limited.

Figure 10: Wet slab debris broke numerous trees in Canyon Creek in the Southern Whitefish Range. Most of these ran on March 19, 2019, on a day when wet slabs were not listed as a problem. Credit: Flathead Avalanche Center.

Figure 11: Comparison of forecasted (orange) vs. re-assessed (gray) Tier 1 avalanche danger levels for each day of the wet cycle in the Flathead study.

4. DISCUSSION

Both case studies highlight some of the challenges associated with predicting the timing, frequency, and magnitude of wet avalanche cycles. All three avalanche centers (CAIC, CBAC, and FAC) across two different regions (central Colorado and northwest Montana) underestimated the avalanche danger the first several days of the cycle, and all lagged in listing wet slab avalanches as an avalanche problem. Predicting the movement and destabilizing effects of meltwater through the snowpack is difficult (Peitzsch, 2009; Techel and Pielmeier, 2011; Madore et al., 2022). Many forecasters draw upon experience and nearest neighbor examples, of which there are relatively few compared to dry avalanche cycles during an operational season. Furthermore, feedback for wet slab avalanches is infrequent and difficult to interpret until avalanche activity begins. Often avalanche activity occurs late in the day; thus, it may not be documented or incorporated into the forecast products until the following day. Stability tests that are commonplace tools for assessing dry slab concerns, such as the Extended Column Test or Propagation Saw Test, are highly dependent on timing and presence of meltwater for drawing conclusions in wet snow. It can be difficult to find representative slopes given the variability in meltwater flow patterns, especially early in a warming period.

In both case studies, the early onset of wet slab activity relative to our expectations and forecast challenges some traditional rules of thumb, such as one or multiple nights without refreeze are necessary for wet slab activity. In the Crested Butte study, wet slab activity initiated with mountain temperatures rising to 2°C under strong solar radiation, following a full night of below freezing temperatures as low as -4°C with clear skies overnight. Low elevation stations around the forecast area recorded even lower overnight temperatures due to an inversion. Wet slab activity peaked on the second and third days of the cycle under high temperatures of 8°C and 10°C, respectively, while the first night without freezing temperatures occurred only before the third day.

In the Flathead region, wet slab activity initiated with mountain temperatures rising to 8°C under strong solar radiation following a full night of below freezing temperatures as low as -3°C. Wet slab activity became increasingly larger and more widespread over the next three days of the cycle, each of which lacked solid overnight freezes. The wet cycle peaked after the third night of poor refreeze with daytime temperatures peaking at 14°C.

Both wet slab cycles intensified and peaked with higher daytime temperatures. A decrease in avalanche activity corresponded with a decrease in daily high temperature despite overnight low temperatures generally plateauing and remaining above freezing. Regional forecast centers also lagged in capturing this decrease in avalanche activity in their danger ratings.

Both case studies emphasize the importance of the first substantial warming period of the winter season. Anecdotally, the snowpack appears to be more sensitive to warming when it is mostly dry. Snowpack structure is also important in producing wet slab activity (Baggi and Schweizer, 2009). Persistent weak layers in both regions produced activity earlier in the season and these weak layers persisted through the winter and early spring.

Furthermore, snowpack characteristics in the tracks and runout will influence the size of wet avalanche activity. For example, in the Flathead region, an unusually shallow and faceted snowpack in the track and runout zones remained cohesionless and contributed to the early occurrence of large (D2 to D3.5) wet loose avalanches. As a result, avalanches gouged and entrained the entire snowpack in the track and runout zones. In the Crested Butte region, the presence of the surface dust layer likely contributed to the timing and intensity of the wet avalanche cycle. The dust lowered the albedo of the snow surface, effectively absorbing more solar energy and accelerating meltwater production (Landry, 2014).

In the Flathead region, weather forecast models underestimated the high temperatures by an average of 4.4°C during the warming period. In both studies, models overestimated cloud cover on one or several days early in the cycle. The energy balance at the snow surface is highly dependent on these weather factors (Bair et al., 2015). Cloud cover forecasting during transitional synoptic patterns such as a developing or exiting high pressure systems is challenging. It is not unusual for real temperatures to outperform modeled high temperatures during unusually strong high-pressure systems. This highlights the importance of comparing forecasted to realized temperatures during these specific patterns.

Avalanche forecast centers rely on a combination of professional and public observations to document avalanche activity. The observed avalanche activity described in this study is far from comprehensive because the forecast areas are large with challenging access. The data presented here likely reflect a larger pattern of avalanches that occurred during these cycles. Avalanche forecasters typically estimate the occurrence date at the peak of the cycle for avalanche crowns and debris piles observed after the cycle without clear timing on their release. This can bias the data to show a more intense peak, when the activity may be more evenly distributed across the entire cycle. Both studies utilized techniques to reduce this uncertainty, such as photo documentation of start zones and repeated visits to the same vantage points to track progress of avalanche activity.

5. CONCLUSION

This study describes the snowpack structure and meteorological conditions that contributed to large wet avalanche cycles in northwest Montana and central Colorado. In both cases, regional forecast centers were surprised by how quickly and how severe the cycles progressed. Wet slab cycles are difficult to predict and avalanche forecasts can be behind the curve with danger ratings.

By comparing the temperature and radiation profiles with avalanche activity for these two case studies, we see that thresholds or “rules of thumb” for predicting the onset or peak of wet slab avalanches vary depending on existing snowpack structure and snow climate. This study challenges the notion that a lack of refreeze is necessary for initiation of wet slab events.

Given the challenges of forecasting for large wet avalanche events, the authors suggest the following forecasting strategies and considerations:

- Extra caution and attention should be given to the first major warming period of the late winter or early spring.
- Leading into the first few days of a warming period, expand the focus from traditional start zones and put more resources toward observing the warmer lower elevation terrain and shallow snowpack areas where melting will occur faster and move farther through the snowpack, respectively.
- Shift fieldwork schedules to late afternoon to better capture the peak of instabilities. Numerous wet slabs during these cycles ran after 4 p.m. and were not documented or incorporated into the forecast decisions until the next day.
- Modeling tools such as SNOWPACK supported with field observations are helpful (Wever et al., 2016; Mitterer and Schweizer, 2013; Bellaire et al., 2017). Forecast centers should look for ways to incorporate modeling the snowpack energy balance into workflow routines for improving wet avalanche forecasts.
- Give extra consideration to the snowpack albedo when near surface dust layers are present.

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DISCLAIMER

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

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