

A CASE STUDY AND COMPARISON OF MID-WINTER WARMING AND SOLAR DRIVEN WET SLAB AVALANCHE CYCLES

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ABSTRACT: Wet slab avalanches are poorly understood and often difficult to forecast. Yet, wet slab avalanches can be destructive and may become more common in a changing climate. As the onset of wet avalanches moves earlier in the winter season due to climate change, understanding snowpack and meteorological characteristics of wet slab avalanches will become increasingly important. In this study, we examined two recent late-January wet slab cycles triggered by warming and solar input in the Rocky Mountains of Idaho and Montana, United States. We posed two questions to help us understand these potentially increasingly frequent, mid-winter wet slab cycles: i) what are the weather and snowpack patterns of two mid-winter wet slab cycles and ii) how did these non-rain-on-snow, mid-winter warming events compare to the historical climate normal? In both locations, a short-lived ridge of high pressure strengthened over the region from late January to early February 2024. Temperatures rapidly increased to 6° C at middle and upper-elevation locations and remained above freezing for 48 to 72 hours. Wet slab avalanches (Montana: n=68, Idaho: n=11) released on a layer of facets resting on a crust formed in late December and slab depths averaged 40 to 150 cm. Avalanches primarily occurred on southeast, south, and southwest aspects at middle and upper elevations. Additionally, positive January monthly temperature trends exist in both locations from 1990 to 2020, and these two cycles from 2024 highlight impacts of mid-winter warming events with unstable snowpack conditions. These cycles also highlight how a relatively uncommon mid-winter warming event with low radiative input can produce very large destructive wet slab avalanches. Understanding mid-winter warming events and associated wet slab avalanche cycles will help us prepare and forecast for potentially more common scenarios like this in the future.

KEYWORDS: Wet slab avalanche, climate, case study

1. INTRODUCTION

Wet snow avalanches impact settlements, transportation corridors, and recreationists worldwide. Wet slab avalanches, specifically, are destructive and less well understood compared to dry snow avalanches (Peitzsch et al., 2012). Recent research suggests warming drives an increase in wet snow avalanche hazard (Ballesteros-Canovas et al., 2018; Pielmeier et al., 2013), a decrease in dry avalanche types (Eckert et al., 2013), or a shift in avalanche climate types resulting in relatively novel weather-related avalanche events for a region (Eckert et al., 2024). For example, in the northern Rocky Mountains, United States, an increase in large warm spring storm related avalanche events

potentially counters the overall decreasing trend in large magnitude avalanche activity (Peitzsch et al., 2021). Future projections also indicate a potential earlier onset and greater prevalence of wet snow avalanches coincident with projected warming and increased upper elevation precipitation (Kruyt et al., 2023; Castebrunet et al., 2014; Eckert et al., 2024). However, trends in avalanche activity are largely regionally dependent with complex interactions among climate drivers and elevation influences (Eckert et al., 2024). Increased mid-winter, rain-on-snow events (Ombadi et al., 2023) will also likely contribute to a higher frequency of wet snow avalanches during winter months. Additionally, winter warming and an increase in melt on dry winter days (Hu and Nolin, 2020) indicates potential for increased mid-winter wet avalanche activity driven by warming, rather than rain-on-snow. This scenario of dry, mid-winter warming events leading to widespread wet slab avalanche activity is likely to become more common in a changing climate. Here, we examine two case

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studies of warming and solar driven wet slab avalanche cycles in Montana and Idaho. We posed two questions to help us understand these potentially increasingly frequent, mid-winter wet slab cycles: i) what are the weather and snowpack patterns of these two mid-winter wet slab cycles and ii) how did these two non-rain-on-snow, mid-winter warming events compare to historical climate and other similar warming events within the past 30 years?

2. STUDY SITES

Northwest Montana is classified as both coastal transition and intermountain avalanche climates (Mock and Birkeland, 2000) and exhibits characteristics of both continental and coastal climates. Avalanche release zones within the study site for this case study range from ~ 1500 to 2135 m in elevation and cover south, southwest,

and west aspects (Figure 1a). The mean annual precipitation across the starting zone elevation of the avalanche paths is 1693 mm, and peak snow water equivalent (SWE) typically occurs mid- to late-April with a median value of ~ 1100 mm at the highest elevation station (1920 m, 1970–2023) (NRCS, 2024).

South-central Idaho exhibits characteristics of both continental and intermountain avalanche climates. The avalanche release zones within this study site display more continental avalanche climate characteristics. Avalanche release zones at this site for this case study range from ~ 2600 to 3000 m in elevation and cover south, southwest, and west aspects (Figure 1b). The mean annual precipitation across the starting zones is 900 mm, and peak snow water equivalent (SWE) occurs in mid-April, averaging 510 mm (NRCS, 2024).

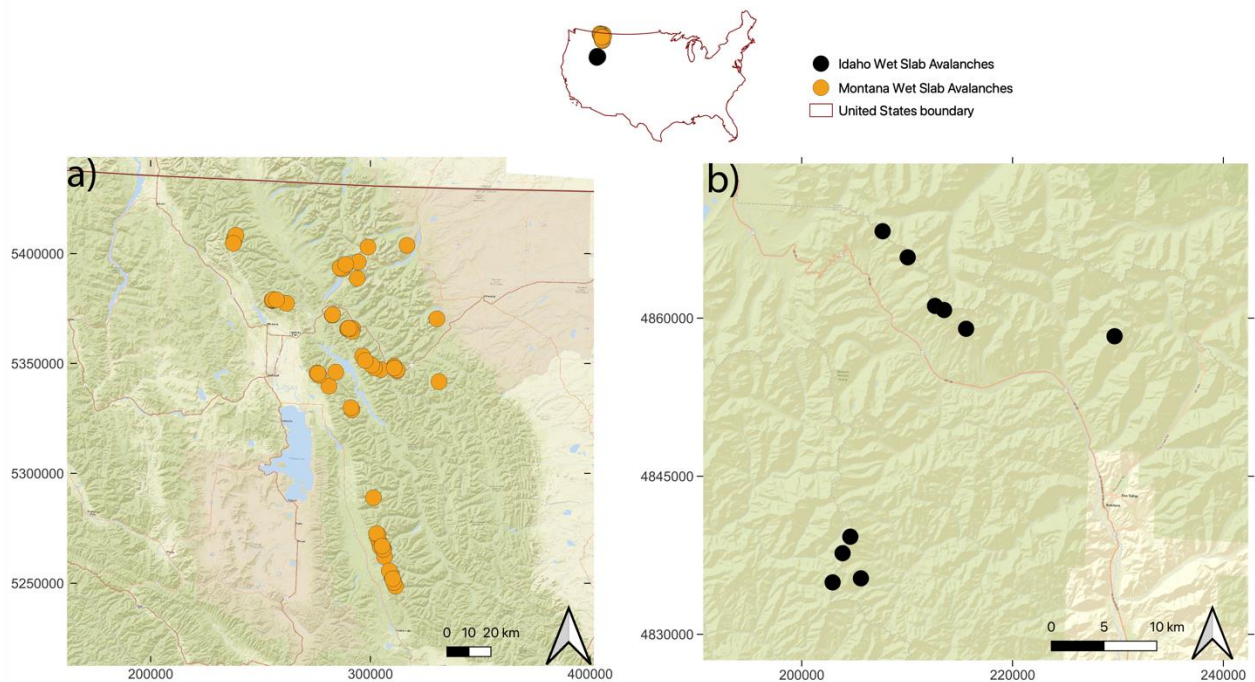


Figure 1: Study site locations. An overview map of the United States shows the general location of the wet slab avalanches at both study sites. Note that the avalanches do not extend into Canada. a) Orange dots represent the locations of observed avalanches throughout the Flathead Avalanche Center forecast region. b) Black dots represent the locations of observed wet slab avalanches within the Sawtooth Avalanche Center forecast region. Note the difference in scales in a) and b). Map: (ESRI, 2024)

3. WEATHER & SNOWPACK HISTORY

3.1 *Northwest Montana*

In northwest Montana, the weak layer responsible for the widespread wet slab cycle in late January and early February was a layer of near-surface facets resting on a hard melt-freeze crust. This melt-freeze crust formed between the dates of December 18th to December 22, 2023 during an extended period of warm and wet weather. Field observers noted that this crust was more developed on all aspects at low and middle elevations (up to 1980 m), and on aspects receiving more solar radiation at all elevations.

Temperatures dropped below freezing the night of December 22. In the following days, field observers noted loose dry snow above a hard and supportable crust. Cold, clear weather followed between December 24 and December 26, which created a strong temperature gradient in the top 8 to 25 cm of snow resting on a hard and supportable crust.

Snowfall returned to the region in early January. The Flathead Avalanche Center received reports of audible collapses, natural avalanches, and human-triggered avalanches failing on a facet and crust combination on January 7. Between the time the weak layer was buried in early January until the start of the wet slab cycle in late January, snowpack height at an automated weather station (Noisy Basin SNOTEL; (NRCS, 2024)) increased 80 cm. During this time, the region also experienced three dry slab avalanche cycles between January 8 and 18.

A ridge of high pressure strengthened over northwest Montana from January 28 to February 2. A brief rain event (15 mm of precipitation) occurred on January 27 and 28 as air temperatures rose to 1° C at nearby remote weather stations. Air temperatures remained above freezing from January 28 to the end of the avalanche cycle on February 1 reaching maximum values of 6° C at 2200 m on January 31. A cooling trend followed, and temperatures decreased below 0° C on February 2.

The Flathead Avalanche Center documented 22 avalanches (size D1 to D4) on January 28, and 99 avalanches between (size D1 to D3) on January 29. Observers reported avalanche crown heights of approximately 70 cm and avalanche widths up to approximately 1000 m. Documented avalanche activity dropped substantially from January 30 to February 2 despite increasing

temperatures and sustained solar radiation. Avalanche slab depths averaged 46 to 76 cm. Crown profiles before and during the warming event indicated slabs failing on a weak layer of near-surface facets above the December 22 melt-freeze crust.

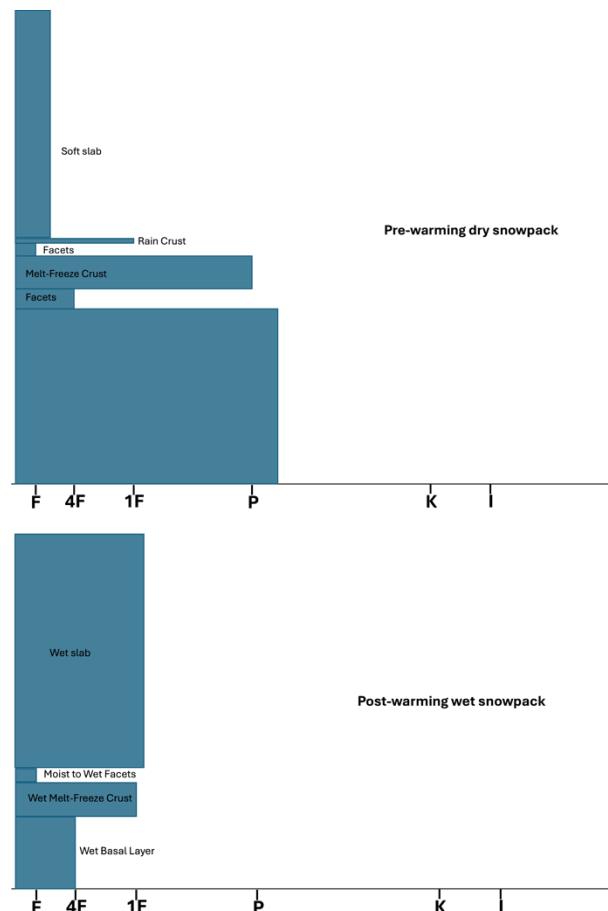


Figure 2: Generalized snow profiles for both locations. The snowpack prior to the warming event consisted of facets surrounding a melt-freeze crust with a soft slab above this facet-crust combination. Crown profiles of wet slabs revealed a harder slab (1F hardness) sitting atop moist to wet facets above a melt-freeze crust. The failure layer of these wet slab avalanches was the layer of facets atop the crust.

3.2 *South Central Idaho*

In south central Idaho, early season weather created a thin (45 to 50 cm) snowpack at the Lower Titus weather station by December 10, 2023. A high-pressure weather system dominated the region from December 11 to December 22. A small disturbance deposited 3 to 5 cm of snowfall on December 18. Solar radiation

and temperatures ranging from -4°C to above 6°C formed widespread crusts and faceted snow in the upper 20 cm of the snowpack in mid-December. On December 22, a small storm deposited 5 to 10 cm of low-density snow. Colder weather (-15 to -9°C) on December 22 to 23 quickly caused faceting within the storm snow. Additional light snowfall and cool temperatures (-14 to -6°C) through early January contributed to more facet layer formation near crusts within the snowpack.

During the first part of January, a series of cold storms increased snowpack depth to approximately 100 cm. This created a snowpack structure that consisted of a 50 cm slab resting on a weak layer of faceted snow that was buried January 6. Consequently, widespread natural and remotely triggered avalanche activity occurred. From January 20 to 26, little additional precipitation and mild temperatures just below and near -6°C led to diminished human-triggered avalanche activity.

On January 27 and 28, temperatures warmed abruptly to -1 to 2°C , skies were cloudy to obscured, and winds were calm to light. While Lower Titus weather station registered no precipitation, field observers reported sporadic light rain that produced wet rollerballs and isolated, small (size D1) wet loose avalanches. No slab avalanches were observed. On January 29, skies cleared, temperatures increased to over 6°C , and winds were calm to light.

From approximately 1400 to 1800 on January 29, Sawtooth Avalanche Center (SAC) staff observed several large natural wet slab avalanches in the Boulder Mountains. The observed avalanches (sized D2 to D3) occurred exclusively on south and southwest facing aspects between 2850 to 3200 m, primarily in above tree line terrain. The avalanche crowns were approximately 30 to 120 cm in height and 60 to 200 m wide. The observed natural wet slab activity on January 29 was confined to a 32 km^2 area in the Boulder Mountains.

Temperatures remained above freezing overnight, and warm, clear weather continued until February 1. No additional natural wet slab activity was observed or reported on January 30. On January 31, avalanche center staff remotely triggered a 60 m wide, 30 cm thick wet slab avalanche at 2600 m on a southeast aspect in the Smoky Mountains, approximately 25 km south of the observed natural avalanche activity.

Avalanche center staff observed other similar wet slab avalanches (size D2, 30 to 45 cm crown height, southeast and east aspects, 2600 to 2800 m) in the immediate vicinity in the Smoky Mountains. Other than the observed pockets of activity in the Smoky and Boulder Mountains, SAC staff neither observed nor received reports of any other wet slab activity in their $\sim 10,000\text{ km}^2$ forecast region.

4. SNOWPACK, METEOROLOGICAL, AND CLIMATE PATTERNS

4.1 *Comparisons across two study sites*

Meteorological patterns at both sites were distinct and resulted in different avalanche spatial extent and temporal duration. Air temperature at both locations increased rapidly, but the onset of avalanching occurred a full day earlier in Montana when compared to Idaho (Figure 2). Several factors likely contributed to both an earlier onset of avalanche activity and a greater spatial extent in Montana. First, while solar radiative input was relatively low on January 28 compared to later in the warming cycle in Montana, a small amount of measurable rain-initiated surface melt. In Idaho, observers reported light drizzle on January 28, but nearby representative automated weather stations reported no precipitation. A second factor contributing to a larger avalanche cycle in Montana was sustained air temperatures above 0°C and four days combined with consistent solar radiative input. In Idaho, air temperature dropped below freezing before remaining above the freezing threshold for two days.

The bulk of the avalanche activity in Idaho occurred during the first full day after the most recent refreeze. The more southerly location and hence greater solar radiative input combined with a shallower and potentially weaker snowpack and more abrupt warming in Idaho may have allowed for a wet slab cycle (albeit small and localized) with diurnal refreezing patterns. The energy balance is an important driver of wet slab avalanches (Mitterer and Schweizer, 2013). Despite relatively low solar radiative input during these two cycles, the small amount of rain prior to sunny, warm days were likely catalysts in releasing latent heat within the snowpack and causing initial surface melt.

The snowpack structure across both sites was similar, consisting of weak snow resting on a melt-freeze crust. The snowpack structure at both locations contributed to widespread dry snow

avalanche cycles two to three weeks prior to this wet slab cycle. During these cycles, observers in Idaho and Montana noted a wet weak layer at the avalanche crown locations, and either wet, dry, or a combination of wet and dry snow within the slab. This represents the complex nature of water

movement through the snowpack (Donahue et al., 2022). Snow settlement at both study sites was another indication of changing snowpack properties during wet avalanche cycles (Peitzsch et al., 2012).

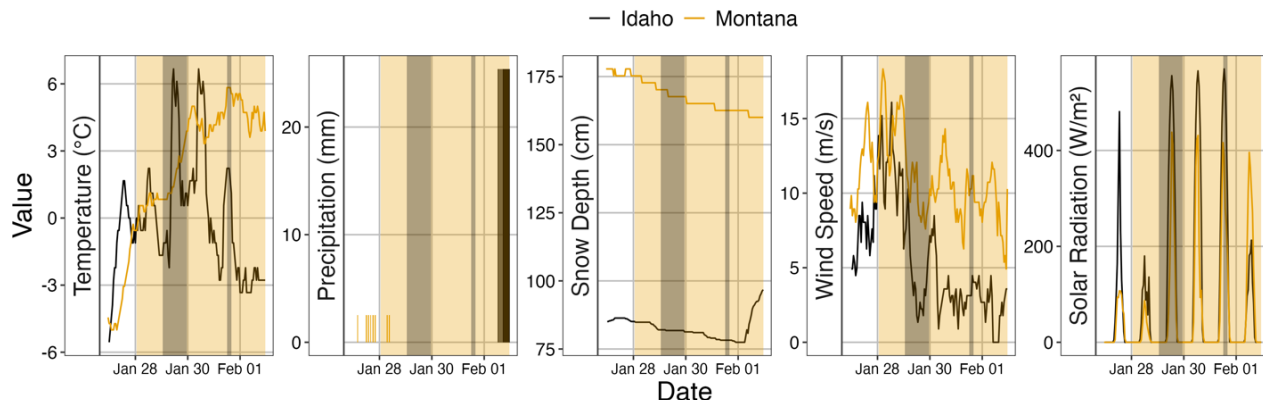


Figure 3: Meteorological factors at both locations from January 27 through February 1. Variable names and values on y-axis and dates on x-axis. Orange lines represent values in Montana and black lines represent values at Idaho study sites. Light orange and gray background shading depicts the duration of the wet slab avalanche cycle in Montana and Idaho, respectively. These data were recorded from the most representative sites in proximity and similar elevation to observed avalanches.

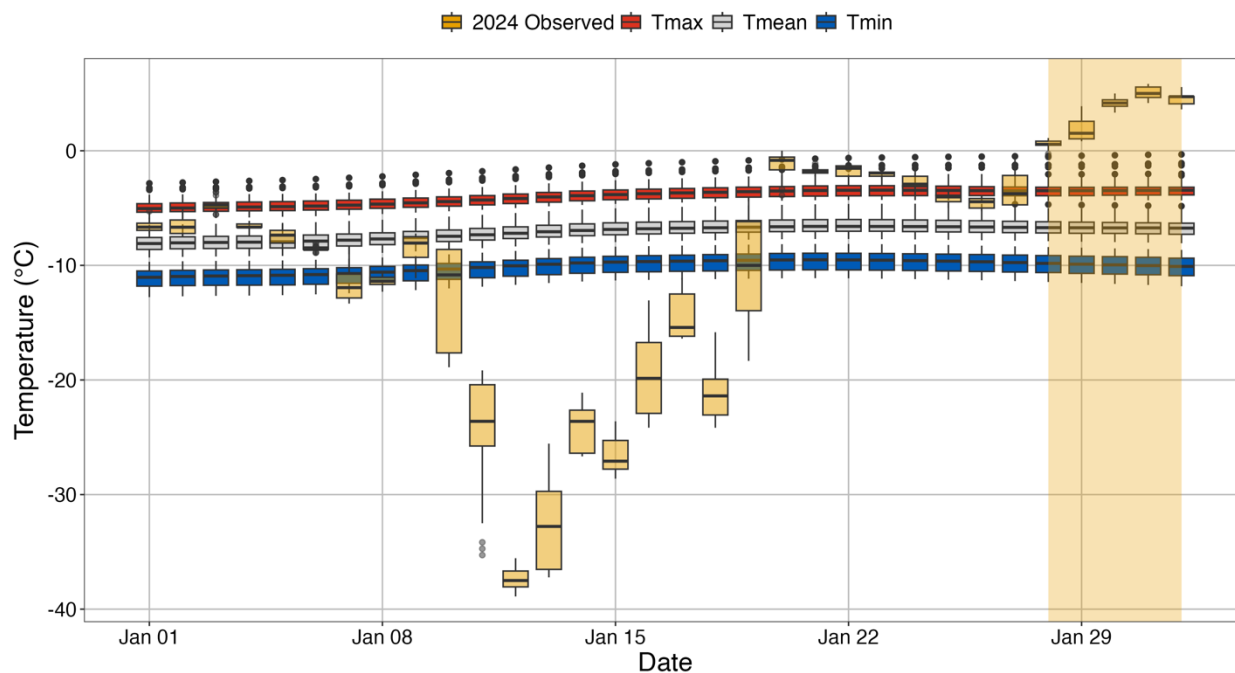
4.2 Historical mid-winter climate patterns

We used a gridded (800 m) climate dataset (PRISM, 2024) to derive historical temperature and precipitation metrics for all of the avalanche starting zones in the two study sites. We first compared temperatures from January 2024 to the 30-year (1991-2020) climate normal. In Montana, mid-January consisted of well below normal temperatures followed by a few days of temperatures just below 0° C (Figure 3a). Then, temperatures increased well above normal and remained above 0° C until the end of the avalanche cycle. This dramatic temperature fluctuation is also a likely contributor to this mid-

winter wet slab avalanche cycle with relatively low radiative input (Reuter and Schweizer, 2012; Mitterer and Schweizer, 2013).

In Idaho, temperature fluctuation ranges were not as distinct compared to Montana during January 2024, but substantial temperature anomalies where minimum daily temperatures were well above 30-year normal temperatures occurred for 5 consecutive days. The comparison to 30-year climate normal values helps place this cycle in context. It also provides insight to potential future scenarios in a warming climate as wet snow avalanches become more frequent throughout the winter and spring (Mayer et al., 2024).

(a) Montana



(b) Idaho

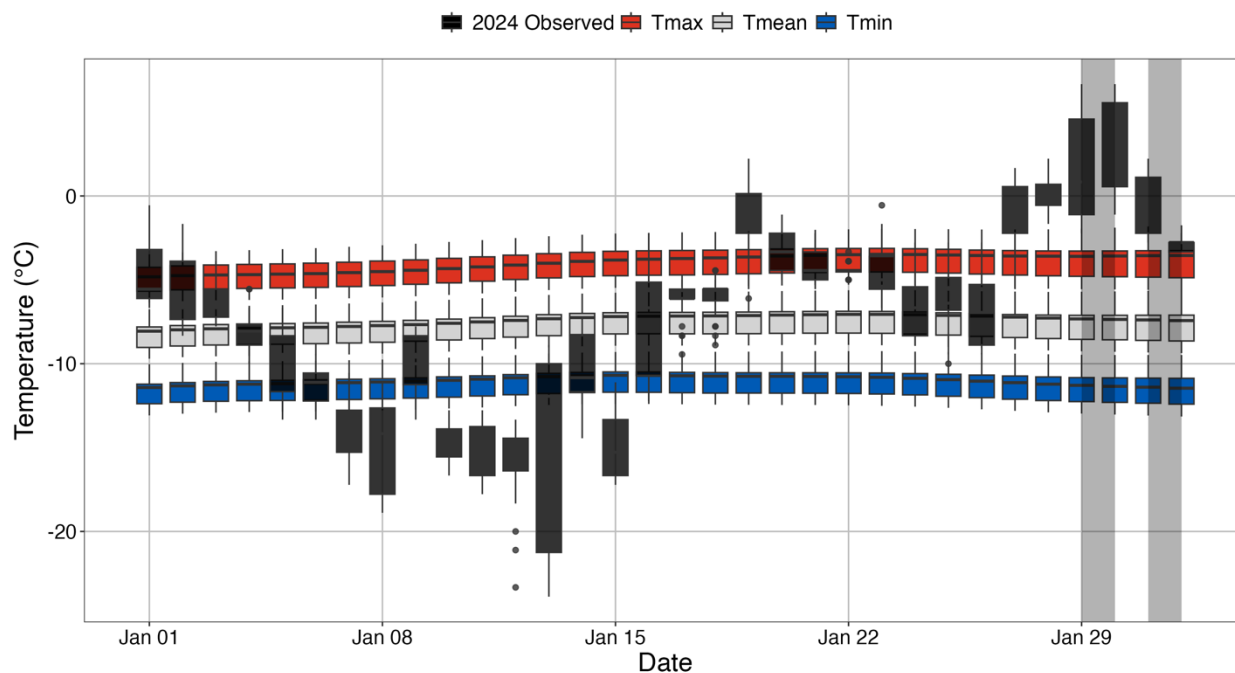


Figure 4: Daily temperature values for January for a) Montana and b) Idaho. Light orange and black boxplots represent the range of daily temperatures for 2024 from the automated weather stations in Montana and Idaho, respectively. Red, gray, and blue boxplots represent temperature values from the gridded climate dataset (PRISM) of 30-year (1991 to 2020) daily normal temperature values for January averaged across the starting zone locations at each study site. Light orange and gray background shading depicts the duration of the wet slab avalanche cycle in Montana and Idaho, respectively.

As such, we analyzed monthly mean January temperature trends for both study sites from 1895 to 2024. We found a significant increase in January monthly temperatures for the starting zone elevations in these case studies (Montana: $\tau=0.12$, $p=0.04$; Idaho: $\tau=0.16$, $p=0.01$) from 1895 to 2024. The increase is even greater in recent years (1990 to 2024) (Montana: $\tau=0.25$, $p=0.01$; Idaho: $\tau=0.3$, $p<0.01$). With projected continued warming (Whitlock et al., 2017), these types of mid-winter, warming driven wet avalanche cycles could become more common.

To place the frequency of these cycles in context with historical records, we examined daily temperature and precipitation conditions similar to these 2024 avalanche cycles. We calculated the frequency of days from January 1 to February 15 with minimum daily temperatures above 0° C with no precipitation for at least two consecutive

days. We recognize that in Idaho, avalanches occurred the day after a sub-freezing night. However, for simplicity we limited the analysis to the above conditions. We found four instances (2005, 2015, 2016, and 2024) at Noisy Basin SNOTEL in Montana from 1990 to 2024 that satisfy these conditions (Figure 4). The event in 2024 was the only event with three or more consecutive days above 0° C and the warmest of all four instances. Note that Noisy Basin is 295 m below the mean elevations of the starting zones in the 2024 avalanche cycle. Therefore, this indicates the historical rarity of this type of mid-winter wet slab avalanche cycle. In Idaho, we used the Galena Summit SNOTEL (NRCS, 2024) dataset and found no instances of at least two consecutive days with minimum temperatures above 0° C and no precipitation.

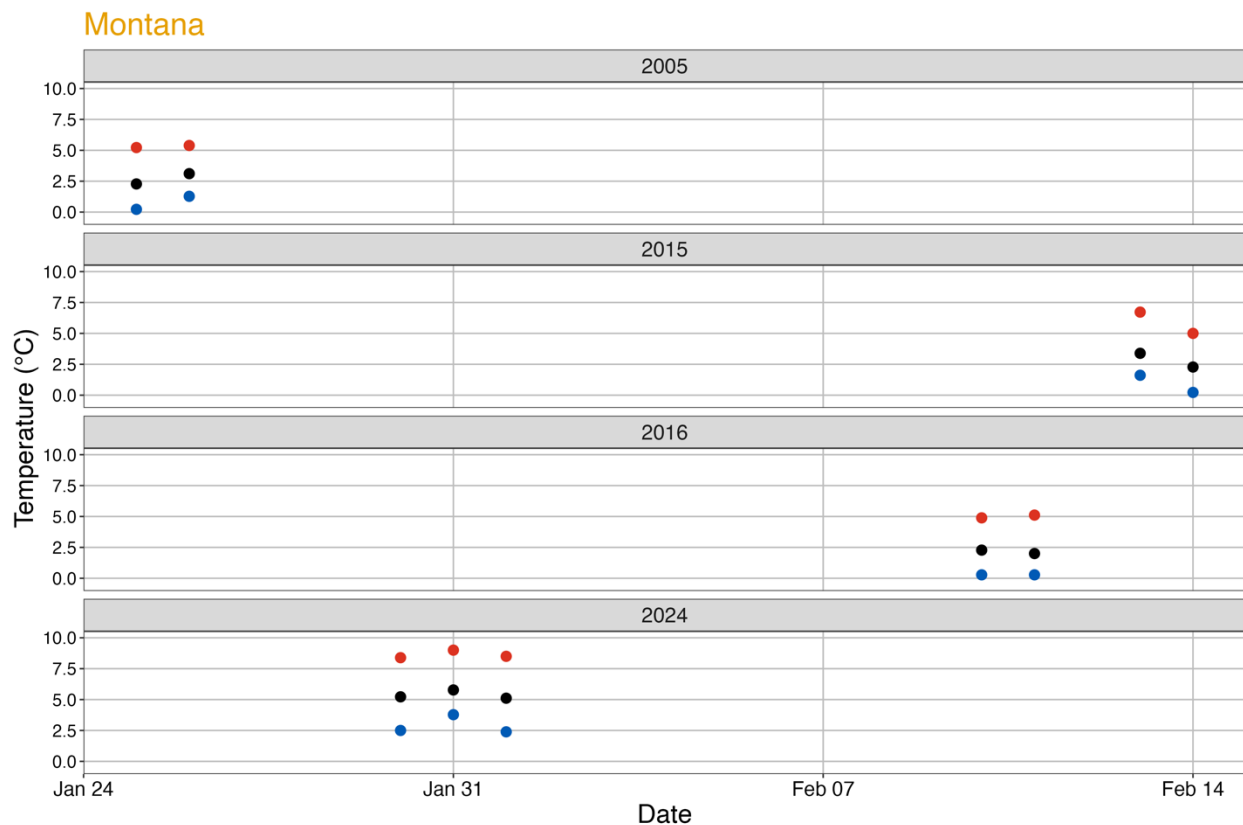


Figure 5: Days from January 1 to February 15 with minimum daily temperatures above 0° C with no precipitation for at least two consecutive days at Noisy Basin SNOTEL, northwest Montana. Red circles = maximum daily temperature, Black circles = mean daily temperature, Blue circles = minimum daily temperature. Note that minimum temperatures are all above 0° C.

5. CONCLUSION

In late January to early February 2024, a strong high-pressure system accompanied by above normal temperatures and clear skies resulted in a widespread wet slab avalanche cycle in two locations in the northern Rocky Mountains, USA. We examined meteorological and snowpack characteristics at these two study sites – south-central Idaho and northwest Montana – and compared these patterns to the historical climate normal. Temperatures rapidly increased to 6° C at middle and upper-elevation locations and remained above freezing for 48 to 72 hours. Wet slab avalanches (Montana: n=68, Idaho: n=11) released on a layer of facets resting on a crust formed in late December and slab depths averaged 40 to 150 cm. Avalanches primarily occurred on southeast, south, and southwest aspects at middle and upper elevations. The warming period in 2024 was well above normal maximum temperatures at both locations. Additionally, positive January monthly temperature trends exist in both locations from 1895 to 2024, and these two cycles from 2024 highlight impacts of mid-winter warming events with unstable snowpack conditions. These cycles also highlight how a relatively uncommon mid-winter warming event with low radiative input can produce very large destructive wet slab avalanches. Understanding mid-winter warming events and associated wet slab avalanche cycles will help us prepare and forecast for scenarios like this potentially occurring more frequently in the future.

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