WHY SWE MATTERS: WHEN HIGH SNOW DENSITY HIDES HIGH HAZARD
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ABSTRACT: Mammoth Mountain in the Sierra Nevada Range, California, USA, is characterized by extreme wind speeds and intense snowfall events that produce high-density dry snow. In an attempt to find the largest 24-hour snow event possible, I looked at 24-hour snowfall records and 24-hour snow water equivalent (SWE). This analysis showed that intense snow loading periods from Mammoth met or exceeded the SWE from several U.S. state snowfall records but had half of the snow height of those records. For these storms, forecasting approaches focused on height of new snow (HN) can underestimate hazard. Defining a SWE-based forecasting threshold for extreme loading is essential to characterize unusual hazard in this climate.

Several recent severe incidents at Mammoth Mountain occurred within 36 hours of registering 4.25 inches or greater 24-hour SWE, a value close to the 4.7 to 5.71 inch SWE range from the snowfall records. Based on these findings, I propose using 4.0 inches of 24-hour SWE as a forecasting threshold at Mammoth and in similar climates to identify extreme loading that poses potential great risk to avalanche practitioners.

KEYWORDS: 24-hour SWE, heavy snowfall, extreme snow loading, snowfall records

1. INTRODUCTION

Major avalanche accidents at Mammoth Mountain (hereafter Mammoth) in the Sierra Nevada Range, California, USA, have occurred in connection with big loading events that measured 4.25 inches or greater of snow water equivalent (SWE) in 24 hours at morning measurement. To achieve such a high SWE value in a 24-hour period, storms must sustain heavy snowfall (a red flag for natural avalanches) for the previous operational period AND overnight when mitigation could not be performed. The benefits of 24-hour SWE as a determinant for these conditions are several-fold:

- This is a quantifiable unit that can be measured before heading out on route. Because the storm environment is dynamic and fast-changing, there is much less time to obtain information, process it, make a plan for conditions, and act. Using pre-determined thresholds based on past experience can be an effective tool to help with this high cognitive load. Such thresholds alert users to extreme or changing conditions, forcing stop and re-assess moments to bring back situational awareness.
- This method helps determine when avalanche conditions have passed into “extreme.” The SWE threshold of 4.25 inches or greater in 24 hours has identified conditions with substantial consequence to patrollers. Accidents, hard slabs, and size D2 or larger ski cuts are examples of parameters used to determine “extraordinary risk.” In addition to large explosive-triggered avalanches, large D2.5 ski cut avalanches occurred following same-day explosive use that produced no-results on that avalanche path in 3 instances from 3 different storm days.
- This metric alerts mitigators to exceptionally challenging forecast conditions that may not be suitable for human decision-making in the field. During this intense weather, information can be difficult to obtain and conditions are very dynamic. Even adjacent avalanche paths can release and reload on different time intervals, complicating the forecasting picture.
- The days returned by this metric are not only difficult for avalanche mitigation. These days pose substantial operational difficulty as well due to the difficulty of moving anything in so much new, unsettled snow.

My original estimation of 4.5 inches (Bogert, 2026) was a good place to start this investigation, but a subsequent accident occurring when winds peaked following a 4.25-inch SWE day has forced me to consider a more conservative forecasting threshold. Other elements (timing of peak winds,

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persistent weak layers) are important in individual accidents, but 24-hour SWE is the piece that unites them all; I therefore consider it the critical element. The length of time heightened sensitivity persists is uncertain, and the risk period must include consideration for the peak of wind speeds with so much new snow available for wind transport.

Dangerous conditions and avalanche accidents can happen on any day regardless of new SWE recorded. I suggest a forecasting metric of 4.0 inches of 24-hour SWE identifies extreme risk periods where it becomes necessary to withhold personnel from committing to avalanche terrain because conditions exceed the ability for human systems to provide a reasonable margin of safety. This paper examines such events and looks at both the significance of SWE and the frequency of persistent heavy snowfall rates with some ideas for the future.

2. METHODS

2.1 Study Area

Mammoth Mountain is a Class A ski resort in central California on the eastside of the Sierra Nevada Mountains (hereafter Sierra). The eastern side of the Sierra features high terrain with elevations up to 14,494 feet in close enough proximity to the coast to receive the full force of maritime storms. The area can be classified as a “maritime” or “intermountain” climate, because it gets powerful, wet storms but also frequently sees drought patterns with shallow snowpacks (Burak and Walker, 2006). Mammoth Mountain sits at 11,053 feet along the Sierra Crest and marks a highpoint at the head of the San Joaquin River drainage. Because the river drainage is oriented in a southwesterly direction, it efficiently converges the strongest storm patterns, resulting in prolonged intense snowfall periods. Data obtained by Mammoth Mountain Ski Patrol shows season snowfall totals in the last 20 years range from 151.5 to 715.5 inches. Season SWE ranges from 21.59 to 87.03 inches with a maximum of 100.33 inches winter season precipitation when rain is included.

The other defining characteristic of eastern Sierra storms is the extreme winds that accompany them. Most storms are preceded by 50 to 70 mph and higher winds that often gust over 100 mph, and often (but not always) remain windy throughout the storm cycle. It is also not uncommon for average wind speeds to reach 100mph at the summit at the storm’s peak wind speeds.

Weather data for Mammoth Mountain Ski Area is collected from 2 snow study plots and multiple wind sensors located across the mountain. The primary snow study plot is Sesame Plot at 9014 feet elevation near Main Lodge. Snow study plots measure automated temperature, snowpack height (HS), height of storm snow (HST), 24-hour snow height (HN), season SWE, and 24-hour SWE. Patrol also records manual HN, HST, and SWE values for each day of snowfall. Primary wind sensor locations are at the Summit (11,053 feet), top of Lincoln Mountain (10,067 feet), and top of Chair 1 (9875 feet). Secondary wind sensors can be found at Main Lodge and many of the chairlift towers.

2.2 Defining “extreme”

The first goal of this study was to ascertain what the highest all-snow (i.e. no rain) SWE could be and how Mammoth’s heavy snowfall events compare to it. I started by looking at 24-hour snowfall records from the western U.S obtained from the State Climate Extremes Committee (2026). This study produced the highest definitively all-snow SWE value I could find with 5.71 inches recorded at Echo Summit, Sierra-at-Tahoe in 1982 (National Centers for Environmental Information, 2025).

The snowfall records are listed below in Table 1 with recorded or estimated SWE, density, and some notes from observing parties. These record-setting events produced 65 to 78 inches of snowfall and 4.7 to 5.71 inches of SWE in 24 hours. Fourteen Mammoth events in the last 44 years fell in this SWE range but recorded new snow depths of only 14 to 42 inches (Mammoth Mountain Ski Patrol, 2026). This preliminary examination showed that Mammoth is quite capable of producing events of similar magnitude.

Table 1: U.S. 24-hour snowfall record events (State Climate Extremes Committee)

Location	***Date***	***24-hr SWE (inches)***	***HN24 (inches)***	***Density (%)***	***Observer Notes***
Alaska	2/9/1963	4.7	78	6	"Flakes were as big as silver dollars"
Colorado	4/14-15/1921	4.9	75.8	6.5	
California	1/5/1982	5.71	67	8.5	
Washington	2/24/1994	4.78	65	7	"Widespread sluffing" (no slabs)

Note: The Alaska event recorded HN but not SWE, so I estimated SWE values for a few densities (5 to 7%) based on the recorder's description of low-density snow. The range of estimates was 3.9 to 5.5 inches, and I selected the median 4.7 inches (6% density) as the most likely value. This value fits with the other data points, so I accept it as a reasonable estimate.

2.3 Regional comparison – Westwide Avalanche Network (1967 to 1995)

The suggested 4.0-inch 24-hour SWE forecasting threshold falls close to this record-setting range and is an appropriate definition of "extreme loading event." The next step was to determine how common (or not!) these events are. Since I did not have recent SWE data from locations other than Mammoth, I relied on the older Westwide Avalanche Network (WAN) dataset that was compiled from operations across the western U.S. starting around 1967 and ending in 1995. I used this data to do a regional study, comparing the frequency of SWE events 4.0 inches or greater across several U.S. maritime ski areas and other operations (highway and National Park Service).

For the regional comparison, I selected ski areas from the WAN database that were near enough to the coast to receive the full force of powerful maritime storms and had greater than 2000 weather data entries to provide a good data sample. These include: Alyeska (AK), Alpental (WA), Mt. Baker (WA), Crystal Mountain (WA), Mt. Rainier (WA), Snoqualmie Pass I-90 (WA), Stevens Pass (WA), Mt. Hood (OR), Alpine Meadows (CA), Heavenly (CA), Palisades-at-Tahoe (CA), Mammoth Mountain (CA), and Sugar Bowl (CA). The years of data collection were roughly 1967 to 1995 with some variation that did not hinder comparison for generalized trends. Table 2 summarizes the relevant 4.0 inch and greater 24-hour SWE events at these areas.

Since the Mammoth accident events did not include rain, I had to address the occurrence of rain in the larger datasets. Not all data entries effectively isolated rain measurement from SWE measurement, and determining amount of rain from data without field notes is difficult. To address this, I excluded *obvious* rain events. For my purposes, I defined these as:

- SWE 6.0 inches and greater <u>and</u> high temperature greater than or equal to 32F
- HN <10 inches <u>and</u> high temperature greater than or equal to 32F

I discuss this decision in further detail under the "Discussion" section of this paper.

3. RESULTS

The regional comparison from the Westwide Avalanche Network (1967 to 1995) showed Mammoth had the highest number of qualifying events by a comparatively large margin. The 4.0-inch or greater metric produced 40 qualifying events across all operations examined. Of these 40 events, Mammoth had 11 events. The next closest results came from Tahoe: Palisades-at-Tahoe and Alpine Meadows each had 6 events. Snoqualmie I-90 (Washington) had 4 results with an unusual data pattern that stood out against other results: low HN with all values less than 20 inches and high density values, all greater than 25%. Alyeska (Alaska) had 3 events and they all flirted with the rain line (high temperatures 32 to 34F). Other Washington and Oregon operations and the remainder of the Tahoe resorts had 0 to 2 events each.

Table 2: 4.0 inch and greater 24-hour SWE events from Westwide Avalanche Network

Location	Date	T-max (F)	T-min (F)	SWE (in)	HN24 (in)	Density (%)	Events
Alpine Meadows	12/9/1992	31	29	**4.7**	33	14%	6
	2/8/1985	28	22	**4.52**	24	19%	
	2/16/1986	32	29	**4.41**	22	20%	
	11/26/1989	28	20	**4.26**	31	14%	
	1/5/1982	30	26	**4.09**	40	10%	
	3/23/1995	27	14	**4.07**	34.5	12%	
Heavenly	3/23/1995	24	8	**4.8**	24	20%	2
	3/11/1995	31	24	**4.32**	24	18%	
Palisades-at-Tahoe	2/8/1985	28	28	**5.3**	27	20%	6
	1/15/1995	31	19	**5.21**	22	24%	
	1/9/1995	32	25	**4.51**	22	21%	
	1/28/1981	34	30	**4.4**	25	18%	
	12/4/1994	31	25	**4.25**	21	20%	
	1/5/1982	32	28	**4.02**	34	12%	
Mammoth Mountain	3/10/1995	32	26	**5.75**	37	16%	11
	2/16/1986	24	23	**5.25**	26	20%	
	2/13/1986	28	23	**4.95**	24	21%	
	1/27/1983	48	22	**4.7**	25	19%	
	3/21/1995	30	16	**4.65**	22	21%	
	2/17/1986	26	24	**4.6**	24.5	19%	
	12/1/1982	26	14	**4.52**	28	16%	
	1/11/1995	26	17	**4.19**	17	25%	
	12/25/1983	32	30	**4.05**	28	14%	
	2/15/1986	31	22	**4**	16	25%	
	2/13/1987	28	26	**4**	23.5	17%	
Sugar Bowl	2/2/1975	26	22	**4.05**	27	15%	1
Alyeska	3/17/1995	33	0	**5.1**	36	14%	3
	12/6/1993	32	26	**4.75**	31	15%	
	4/12/1988	34	30	**4.25**	39	11%	
Alpental	--	--	--	**--**	--	--	0
Mt. Baker	12/26/1972	32	26	**5**	28	18%	1
Crystal Mountain	2/24/1994	25	16	**4.78**	65	7%	1
Mt. Hood	2/24/1994	30	27	**4.27**	32	13%	2
	1/9/1980	26	11	**4.25**	38	11%	
Mt. Rainier	1/11/1972	28	15	**4.55**	37	12%	2
	1/15/1976	34	27	**4.27**	20	21%	
Snoqualmie I-90	3/5/1974	33	29	**5.38**	16	34%	4
	2/1/1974	32	26	**5.07**	14	36%	
	2/19/1974	31	28	**5.0**	18.5	27%	
	2/14/1974	32	26	**4.6**	18	26%	
Stevens Pass	2/16/1967	30	21	**5.21**	41	13%	1

3.1 Recent data - Mammoth Mountain (Mammoth Mountain Ski Patrol, 1995 to 2026)

The WAN dataset is old, and its data collection concluded in the spring of 1995. To bring this historical study to present circumstance, I concluded with a look at recent Mammoth Mountain Ski Patrol weather data. Using the 4.0-inch and greater 24-hour SWE forecasting metric produced 21 events at Mammoth in the last 31 years. There were 1 to 3 events meeting this threshold in *each* of the last 6 winters (8 events).

Figure 1 demonstrates the relative infrequency of 4.0-inch and greater 24-hour SWE storm days (red) compared to all storm days over the years of 1995 to 2026. These events represent only 1.2% of all measurable-snowfall days in this time period. The most recent years show a larger cluster of qualifying events between 2020 and 2026 where 4.0-inch and great events comprise 2.6% of measurable-snowfall days.

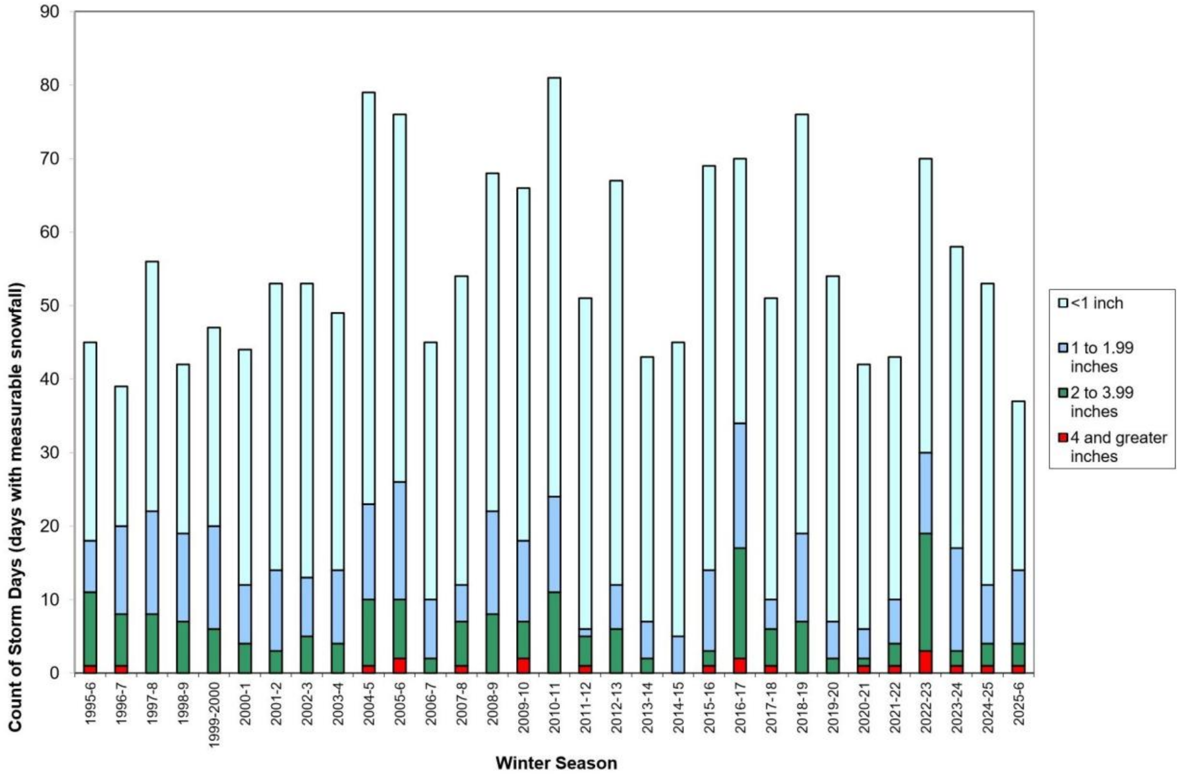

Figure 1: Mammoth Mountain storm day comparison by SWE (1995 to 2026)

4. DISCUSSION

Storm events included in this study frequently produced high-density snow, making SWE an important tool to compare them. Although SWE values from this study match record-setting events, snow totals fall behind by a substantial amount. Thus, using new snow height alone does not identify the high-density snowfall and subsequent heavy load common in this environment.

The storm events that produced snowfall height records may have different characteristics than most of the events in the WAN dataset. For the snowfall records, the Alaska event is suspected to have featured warm, wet air overrunning cold air entrenched in the valley (Rozell, 2023), the Colorado event was a windy, convective spring storm (Paulhus, 1953), and the Washington event occurred when a powerful storm air mass split around Mt. Rainier and converged over Crystal Mountain (Barker and Blanchard, 2025). Little is known about storm characteristics from the WAN dataset, but the temperature data shows that these are often warm storms with maximum temperatures frequently 27F and higher (32 out of 40 events or 80%).

4.1 Mammoth Mountain

In this study, Mammoth Mountain was a high-producer of extreme snow-loading events captured by the 4.0 inches or greater in 24-hour SWE qualifying criteria that has been connected to recent avalanche accidents. In the older regional comparison, Mammoth had nearly twice as many qualifying events as the next highest ski resorts (11 events vs. 6 events, data from Table 2).

The more recent Mammoth Mountain Ski Patrol data suggests that these extreme events may be happening more frequently. Compared to the 11 Mammoth qualifying events in the original 27-year study period from the WAN data, the recent 31-year period after spring 1995 has produced 21 events. While the time scales and datasets do not entirely match, this observation encourages deeper research into frequency trends.

Since these large events represent only 1.2% of all measurable-snowfall days since 1995 (see Figure 1), they mark infrequent but high-hazard mitigation days. The last 6 consecutive winters have produced 1 to 3 qualifying events each year with 3 avalanche accidents and a higher 2.6% event frequency. This finding is about double the 31-year rate of 1.2% of storm days. A small numerical increase in frequency can have an outsized effect on outcomes in the setting of such low-frequency, high-hazard events. The general limited occurrence of these events also complicates heuristics and is difficult to address with operating procedures. The implications of this scenario are important and days meeting this criteria require special attention and consideration.

4.2 All-snow vs. rain events

Many of the storms in the WAN dataset were warm and produced daily high temperatures approaching or around 32F. Intensity and duration of rainfall can vary greatly in this warm storm environment, so periods of rainfall can be hard to interpret from data alone. Maximum temperatures of 32F also do not guarantee the occurrence of rain. Additionally, high-density snow occurs in the WAN dataset even with maximum temperatures that remained below 32F.

The relationship between rain and the snowpack is complex and can produce different avalanche conditions than all-snow events. I suggest there is a “pre-rain” environment where warm temperatures affect the snow density and increase the amount of riming on precipitation particles (especially when very windy) but snow remains dry or moist. This can have important effects on the avalanche problem, as dry snow is a higher hazard for wind transport than wet snow. Given this complicated picture, I decided not to exclude events based solely on high temperatures of 32F or greater and used 2-part definitions to provide a threshold for rain events. I excluded days with *obvious* rain (indication of rain in HN or SWE values with maximum temperature greater than or equal to 32F) as defined above in the “Methods” section. None of the Mammoth accident events included rain in the storm period, so rain events are not examined here.

4.3 High density

Snowfall ranged from 65 to 78 inches and 4.7 to 5.71 inches SWE in the U.S. states’ snowfall records data. The WAN data table shows multiple events meet this SWE range but fall short on snow height. The lone qualifying event from Crystal Mountain was the Washington state snowfall record of 65 inches in 1994. Other than this single result, the next highest 24-hour snowfall value was 41 inches. A common finding in the 40 events meeting the snowfall and SWE thresholds in the WAN data is high-density snow. Out of 40 events, 27 (68%) recorded densities of 15% and higher. While some of these high-density events had high temperatures of 32F or higher, many did not. For reference, at Mammoth the highest snow density was 25%, recorded twice with high temperatures of 26F and 31F. Typical Mammoth snowfall averages 10 to 13% snow density. For the snowfall events considered here, the average density from Mammoth is greater at 19%. Not every event shows such high-density new snow, but enough events exist to warrant consideration and future exploration. Mammoth and Palisades-at-Tahoe appear to be particularly prone to high-density snow in these large loading events. The Snoqualmie events were even higher density, occurring in conjunction with consistently low HN values and high temperatures from 31 to 33F. This standout data pattern begs the question of rain although this is indeterminate with the given data available.

4.4 Limitations – SWE measurement

While most operations had recording columns for “rain,” rain was not always separated from SWE measurements. This may stem from measurement choices or practical difficulty of separating the two.

I excluded SWE values > 6.0 inches for rain involvement after checking that maximum temperatures were 32F or greater. Entries with maximum temperature of 32F are unclear if there was rain or how much, so I had to make some reasonable guesses. Below I discuss some problematic data and how I chose to address it.

Most of the Mammoth Mountain patrol data separated rain from SWE measurements, but not every year. There was a 7.24 inch value from October 2021 that was recorded as SWE with a maximum temperature of 39F and HN of 1 inch. This value has been excluded from analysis. Another value from 1969 of 9.8 inches SWE had been recorded as a 24-hour SWE value but appears from examination of corresponding snow height values to have been a Storm SWE comprising several storm days. This value was also excluded from the Mammoth data.

There were two SWE data entries from Palisades that also proved problematic. One recorded 6.12 inches SWE with a maximum temperature of 38F; this one was an easy decision to exclude. The other recorded 7.12 inches SWE from the middle of March 1995. Maximum temperature was 32F and HN was 30 inches. Since the WAN data does not include field notes, it is unclear whether there was rain or not, or how much rain. Given the lack of other events at this level of SWE that are clearly not rain-affected, I decided to exclude this result from this study under the current information available.

4.5 Old dataset issues

The older WAN dataset had some inconsistencies in recording. It is unsurprising that measurement techniques and protocols changed between the 1960s and 1990s, as well as starting and ending times of winter operating seasons. The dataset is not perfect, but it is adequate to build broad-scale patterns and relationships among the ski areas and other operations included in the study.

4.6 Morning measurement is not always true to heaviest 24-hour snowfall period

New snow measurements are routinely measured at similar times each day, making the 24-hour period measured conform to operational timelines. Thus, 24-hour SWE values measured may not correspond to the true highest snowfall periods. In the mitigation setting, morning measurement has important implications for operations, and 24-hour SWE values measured in the morning before mitigation has begun gives a good indication of hazard to mitigators. High 24-hour SWE values of 4.0 inches and greater at morning measurement indicate heavy loading overnight as well as the previous day. When the overnight period that cannot be actively mitigated falls at the beginning of the heavy loading period, there is less snow accumulated at the commencement of mitigation. When the overnight period falls after a whole day of heavy loading, the expected avalanches will be of greater size, and may push from an acceptable D1 size to a dangerous D2 and greater size. Morning measurement, therefore, has great utility to mitigation operations.

5. FUTURE WORK

This paper stresses the importance of rate-driven instability. Previous research performed by Bair et. al (2012) found that many avalanches at Mammoth fail within storm snow and suggests that this failure occurs in conjunction with high precipitation rates:

“Nonpersistent crystals in failure layers were not significantly harder or softer than slabs above, but had significantly harder layers below…We conclude that the best way to locate a potential failure layer of nonpersistent crystals is to search for a harder layer below a slab of new snow. Fracture will most likely occur just above the harder layer… Also important to note is that most failures occurred in the storm snow, rather than at the storm snow/old snow interface. For instance, 65% (13/20) of the crown profiles failed in storm snow. Similarly, avalanche control records from Mammoth show 68% of avalanches failed in storm snow. Storm snow may initially bond well to old snow because most Sierra storms begin with low precipitation rates that gradually increase. Low precipitation rates at the start of a storm allow initial storm layers to strengthen via compaction. Conversely, high precipitation rates overwhelm strengthening from compaction by rapidly increasing stress. The result is stronger snow from the beginning of the storm, when precipitation rates are low, than snow that is deposited later in the storm, during high precipitation rates.” (Bair, 2012)

Because the Sierra is susceptible to prolonged heavy snowfall rates, it would be an ideal place to study rate-driven instability. Such studies could increase our understanding not only of storm slab mechanics but also natural avalanche triggering. Other questions to consider include: How quickly does instability decrease once heavy loading has ended? Does rate-based instability show a linear increase or it threshold-based?

6. CONCLUSION

This research is a starting point for defining and examining extreme snow-loading events. The data shows high-density snow is common in western U.S. storms that produce these intense snowfall events, making SWE a necessary part of their identification. The 24-hour SWE measurement identifies storm intensity trends that may be under-recognized by depth-focused metrics, thereby strengthening hazard identification. Using the 4.0-inch in 24-hour SWE forecasting threshold can help identify unusual loading events that may exceed operational safety margins and is transferable across different storm patterns.

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