DEEP PERSISTENT SLAB AVALANCHES DURING THE 2019-2020 SEASON IN THE BRIDGER RANGE, MONTANA, USA: METEOROLOGICAL METRICS, ATMOSPHERIC PATTERNS, AND FORECASTING LESSONS

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ABSTRACT: During the 2019-2020 winter there was widespread deep persistent slab avalanche activity in Southwest Montana, with major avalanche cycles in multiple mountain ranges in the region. This case study examines documented avalanches on persistent weak layers and deep slab avalanche activity in the Bridger Range near Bozeman, Montana between January and February of 2020. We focused on the Bridger Range because there is a continuous daily weather record kept by Bridger Bowl ski patrol which allows us to summarize and compare seasonal and historic local patterns, and the Bridger Range has a large proportion of regularly observable avalanche terrain to provide a relatively more thorough record of avalanche activity. We applied methods similar to previous research on deep slab avalanches in this region, and identified local-scale meteorology and synoptic-scale atmospheric drivers related to the processes that formed the problematic snowpack of the 2019-2020 season as well as those processes that ultimately pushed the snowpack to its breaking point. We demonstrate the utility of using local meteorologic summaries and synoptic climatology patterns to characterize this challenging snowpack scenario, and as potential tools to aid forecasting deep slab avalanches. For the 2019-2020 seasons we found synoptic atmospheric drivers and seasonal meteorological metrics were similar to patterns associated with historic deep slab avalanches. The poor performance of the daily classification trees underscores the difficulty of forecasting deep slab avalanches and the need for an extra conservative mindset when the snowpack has potential to avalanche on persistent weak layers. This research supports the importance of tracking the snowpack and meteorology from the start of the season. Avalanche forecasters can utilize summaries of meteorological variables and atmospheric circulation patterns to look for signs of weak layer development.

KEYWORDS: deep slab, meteorology, synoptic climatology

1. INTRODUCTION

During the 2019-2020 season, deep slab avalanche activity was abundant in the mountains of southwest Montana. Throughout the Gallatin National Forest Avalanche Center (GNFAC) forecast area there was a persistent weak layer of facets near the ground which produced many large and very large (D2-D3.5) avalanches. In this study we focus specifically on avalanche activity in the Bridger Range near Bozeman, Montana. Avalanches of similar quantity and magnitude also broke on a persistent weak layer at the base of the snowpack near Big Sky, Cooke City, and in the northern Gallatin Range south of Bozeman.

We focus on the Bridger Range because there is a continuous daily weather record kept by Bridger Bowl ski patrol which allows us to summarize and analyze local patterns. Also, the Bridger Range has a large proportion of regularly observable avalanche terrain to allow a more thorough record of avalanche activity. For this case study we compared the 2019-2020 season's meteorological conditions to the historical meteorological conditions found to be associated with deep slab avalanches in the Bridger Range in previous research by Marienthal et al. (2015) and Schauer et al. (2021). We compare early-season precipitation totals to previously identified thresholds separating seasons with and without avalanches on deep persistent weak layers, and investigate the atmospheric drivers associated with those trends. We also consider daily meteorologic thresholds that historically differentiate avalanche days from non-avalanche days (Marienthal et al., 2015), as well as the associated atmospheric patterns prior to days with avalanches on persistent weak layers (Schauer et al., 2021). Through our brief analysis and perspective of this remarkable avalanche season, we hope to better enable forecasters to manage similar challenging scenarios in the future.

2. BACKGROUND

Deep slab avalanches, or avalanches that fail on deeply buried persistent weak layers, are notoriously difficult to forecast (LaChapelle and Atwater, 1961) and are typically larger and more destructive than other avalanche types (Tracz, 2012; Comey and McCollister, 2008). Other types of avalanches such as those that involve new snow or recently buried weak layers are common during and after storms (Atwater, 1954). While deep slab avalanches often occur during and after loading events, many loading

events will not produce deep slab avalanches, even during a season with a snowpack that seems conducive to deep slab avalanches. This makes it difficult to differentiate between loading events that will trigger a deep slab and events that will not (e.g., Conlan et al., 2014). Due to these challenges, deep slab avalanches have received well-deserved attention by researchers over the last two decades (e.g., Conlan et al., 2014; Schweizer et al., 2009; Savage, 2006; Jamieson et al., 2001; Davis et al., 1999). Much of the previous research focused on meteorological conditions over the days leading up to and including days with deep slab avalanches versus days that didn't have deep slabs (e.g., Conlan et al., 2014; Jamieson et al., 2001). We will consider conditions on the days leading up to deep slabs, and also incorporate meteorological metrics and atmospheric patterns from early in the season to incorporate conditions during the time persistent weak layers often form.

We previously investigated meteorological conditions (Marienthal et al., 2015) and atmospheric patterns (Schauer et al., 2021) over the days leading up to deep slab avalanches as well as at the start of seasons with deep slabs versus seasons without deep slabs using historical weather and avalanche data from Bridger Bowl Ski Area in southwest Montana. Marienthal et al. (2015) used classification trees to identify meteorological metrics associated with deep slab avalanches. and found metrics that best split seasons with deep slabs from seasons without deep slabs, as well as metrics that split days with deep slabs from day without deep slabs.

Much of the meteorology observed at the surface is driven by synoptic-scale atmospheric circulation patterns. These synoptic-scale associations have been studied for decades, including work identifying patterns related to precipitation and snowfall in the Western U.S. (e.g., Wise, 2012; Birkeland and Mock, 1996) and avalanche activity around the world (Hancock et al., 2021; Martin and Germain, 2017; Birkeland et al., 2001; Fitzharris, 1987). Previous work has highlighted specific circulation patterns that favor heavy precipitation events at Bridger Bowl, and as a result are more commonly associated with increased avalanche activity (Birkeland et al., 2001; Schauer et al., 2021). Specifically, a favorable setup for snowfall involves a northwesterly flow pattern facilitated by an upper-level trough over the Intermountain West with a gentle ridge over the U.S. west coast. This pattern transports moisture inland from the coast over minimal orographic barriers then interacts with the local topography of the Bridger Range to produce large storms. Conversely, a southwesterly flow or an upper-level blocking ridge tend to leave the Bridger Range dry. Persistent periods of either type of setup can shape the snowpack for a season, and have the potential to drive weak layer formation in the beginning of the winter. They may also drive the big storms that load the snowpack and tip the scales of instability throughout the season.

3. SNOWPACK AND AVALANCHE ACTIVITY

The snowpack during the 2019-2020 season was characterized by a widespread layer of depth hoar that formed during cold, dry weather in November and December (Figure 1). At the start of January steady snowfall created a slab over this layer, made the snowpack unstable (Figure 2), and caused natural avalanches (Table 1). Through January steady snowfall caused natural and skier-triggered large avalanches on persistent weak layers near the bottom of the snowpack (Table 1). February began with larger, more intense storms with a widespread avalanche cycle on Feb 6-9, and by late February we had witnessed widespread large, destructive avalanches throughout the Bridger Range. Many paths had full width avalanches, 4-5 feet deep (1.5 meters) with debris engulfing trees and reaching the end of runout zones (Table 1, Figure 3).

In the GNFAC annual report the snowpack summary stated,

"The poor snowpack structure prompted months of strongly worded forecasts with phrases such as, 'Avoid avalanche terrain. Avoid heavily wind loaded slopes… As weak layers get deeper there are fewer warning signs. Multiple tracks can cross a slope before one finds the weak spot and collapses the whole hillside... A conservative mindset is essential. Big objectives should wait until late spring or next season… Think carefully about the terrain you plan to ride… Come home alive.'… Avalanche activity peaked with a widespread deep slab avalanche cycle in February. More snow followed and there was steady avalanche activity through April…."

Of note, there was minimal wet slab avalanche activity on these persistent weak layers when temperatures warmed in the spring.

4. METHODS

We analyzed synoptic-scale atmospheric and local meteorological data for the beginning of the season when persistent weak layers were forming at the bottom of the snowpack, and for the periods immediately prior to onset of avalanche activity.

Avalanches on persistent weak layers were recorded on 11 days (Figure 1, Table 1). To simplify parts of the analysis these events can be grouped into five main avalanche cycles: January 3-4, January 15-19, February 6-9, February 15-18, and February 26.

Work by Marienthal et al. (2015) and Schauer et al. (2021) considered events after February 1st as "deep slabs" to isolate events that are more difficult to forecast, and because there is limited intimate knowledge of events through historical seasons.

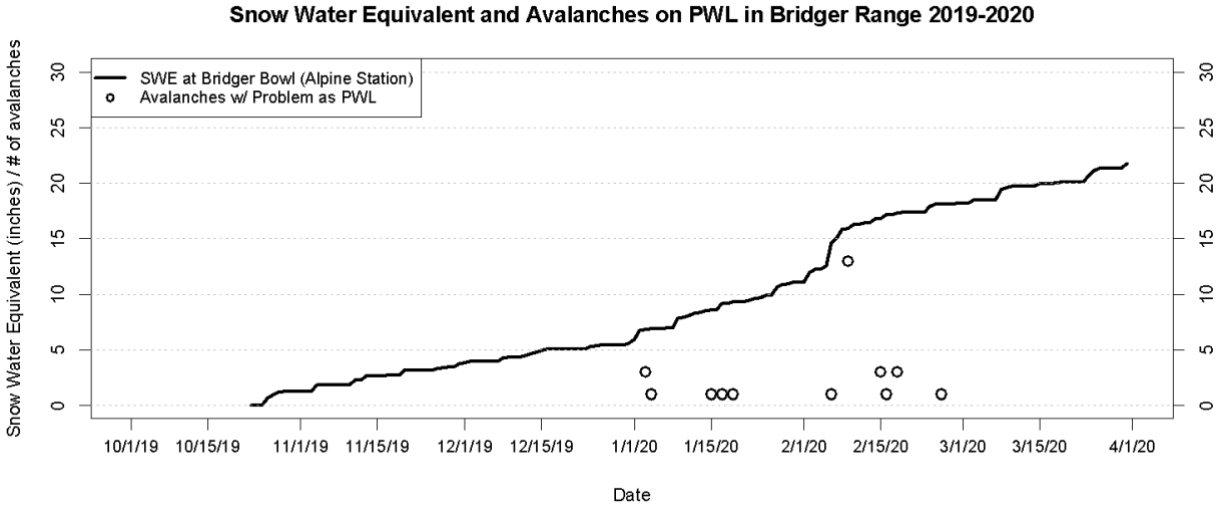

Figure 1: Seasonal snow water equivalent (solid line) and number of avalanches per day (points) for the 2019/20 season.

Table 1. Days with noteworthy avalanches on persistent weak layers in the Bridger Range for the 2019-20 season.

Date	*Description*	*Code*	*# of slides*	*Elev. (m)*	*Aspect*	*Depth (in)*	*Depth (cm)*
1/3/20	Natural slides and collapsing in Bridger Range/Saddle Peak	SS-N-R3-D2.5-O	3	2720	E	36	91
1/4/20	Bridger patrol triggered deep slab	HS-ABc-R4-D3-O	1	2591	NE	48	122
1/15/20	Skier triggered avalanche near Saddle Peak	SS-ASu-R3-D2.5-O	1	2621	E	36	91
1/17/20	Large natural avalanche near Hardscrabble Peak	HS-N-R3-D3-O	1	2743	E	24	61
1/19/20	Skier triggered north of Bridger	HS-ASu-R2-D2-O	1	2438	SE	24	61
2/6/20	Natural Deep Slab Saddle Peak	HS-N-R3-D3.5-O	1	2713	NE	60	152
2/9/20	Truman Gulch Natural Deep Slabs	HS-N-R4/3-D3.5-O	13	2591, 2438	W, NE	48	122
2/15/20	Many naturals near Flathead Pass	HS-N-R4-D3-O	3	2438	NE	55	140
2/16/20	Big natural avalanches on Flathead Pass	SS-N-R2-D2-O	1	2560	E	48	122
2/18/20	Wolverine Bowl natural avalanche, Bridgers	HS-N-R3-D2.5-O	3	2438	NE	48	122
2/26/20	Naturals near Flathead Pass	HS-NC-R3-D2.5-O	1	2530	E	48	122

Because the noteworthy events of the 2019-2020 season were all observed by or reported directly to the authors of this paper, we will consider events noted in Table 1 for this study. We note that the earlier of these events may be considered persistent slab avalanches rather than deep slabs by some definitions, including those used in Marienthal et al. (2015) and Schauer et al. (2021), which may slightly affect our results.

4.1 Atmospheric circulation patterns

We classified daily 500 mb geopotential height maps (Figure 4) using the synoptic types developed in Schauer et al. (2021). These were generated using Self-Organizing Maps (SOM), a machine learning algorithm that uses artificial neural networks to categorize a set of observations into a specified number of similar groups. We use gridded daily 500-mb geopotential height maps obtained from the NCEP/NCAR reanalysis (Kalnay et al., 1996) to summarize the daily atmospheric circulation for the 2019-2020 season (Nov. 1-Mar. 31). Daily geopotential heights are given on a 2.5^o x 2.5^o grid extending from 20°N to 70°N and 160°E to 60°W, or roughly from central Mexico to Northern Alaska, and Western Siberia to Eastern North America (Figure 4); the same grid used in Schauer et al. (2021). We assigned each day from the 2019-2020 season to its most representative pattern in the classification scheme by minimizing Root Mean Square Error (RMSE) between corresponding gridpoints on daily gridded maps and each gridded SOM map. We examined the most frequent circulation patterns in

the beginning of the season (Nov. 1-Dec. 31), during which period we observed persistent weak layers develop that would produce avalanches throughout the season. We also identified circulation patterns dominating each of the three major avalanche cycles summarized in Table 1. Similar to the methods described in Schauer et al. (2021), we are interested not only in the days with avalanche activity, but also in the 72-hour window prior to avalanche activity when cumulative loading is adding stress to the snowpack. We defined five periods of interest by grouping clusters of days that had significant avalanche activity, and also including the 72 hours prior to the first day of recorded avalanche activity for each cluster: Dec 31- Jan 4, Jan 12-19, Feb. 3-9, Feb. 12-18, and Feb. 23-26. We generated

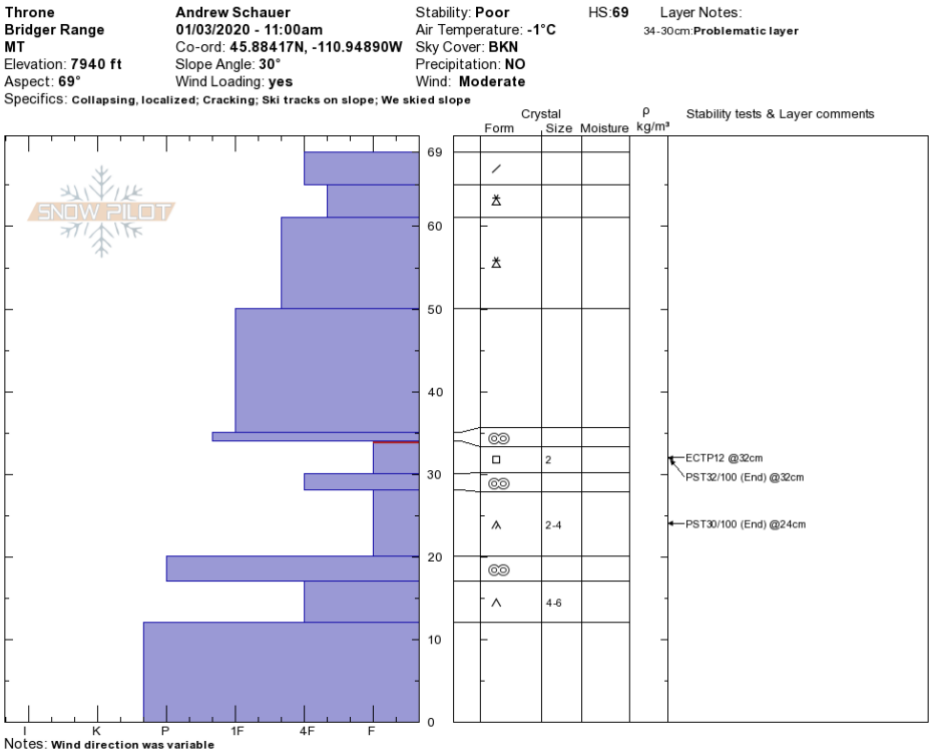

Figure 2. Snow profile from north of Bridger Bowl on January 3 showing poor structure due to buried depth hoar, as well as poor stability test results. Natural avalanches on the depth hoar were noted the same day.



Figure 3. Avalanche debris melting out in June 2020 at the bottom of Truman Gulch on the west side of the Bridger Range. This was from an avalanche that happened in February (Table 1). Photo: J. Hagar

composite 500 mb geopotential height charts for these five time periods, and compared those composites to historical patterns observed at Bridger Bowl.

4.2 Meteorological thresholds

We looked at summaries of the meteorological variables in Marienthal et al. (2015) which classified splits in overfit classification trees between seasons with deep slab avalanches and seasons without deep slab avalanches.

We investigated if the 2019-2020 season is classified as a deep slab year using the threshold values of the three metrics that split seasons with deep slabs and seasons without deep slab avalanches in Marienthal et al. (2015). These metrics are: 1) total SWE from November 1st to December 31st (mm), 2) total SWE in December (mm), and 3) maximum height of snow in November (cm).

Of the 44 historical seasons studied (1969-2013), 32 seasons had less than 308mm of SWE from November 1st to Jan 31st and 23 (72%) of these seasons had deep slab avalanches. 12 seasons had more than 308mm SWE from November 1st to January 31st and 11 (92%) of these seasons did not have deep slab avalanches. Additionally, of the 32 historical seasons that had less than 308mm of SWE from November through January, 12 seasons had less than 56 mm of SWE in December and all 12 (100%) had deep slab avalanches.

The 20 historical seasons that had more than 56 mm of SWE in December were further split by maximum height of snow in November. Eight seasons had more than 88.1 cm maximum height of snow in November and 7 of the 8 (88%) had deep slabs. Twelve seasons had less than 88.1cm maximum height of snow in November and 4 of those 12 (33%) had deep slab avalanches.

In addition to the early-season meteorological thresholds, we also summarized variables that were found to be significant in classification trees that split days with deep slab avalanches from days without deep slabs in Marienthal et al. (2015). The six

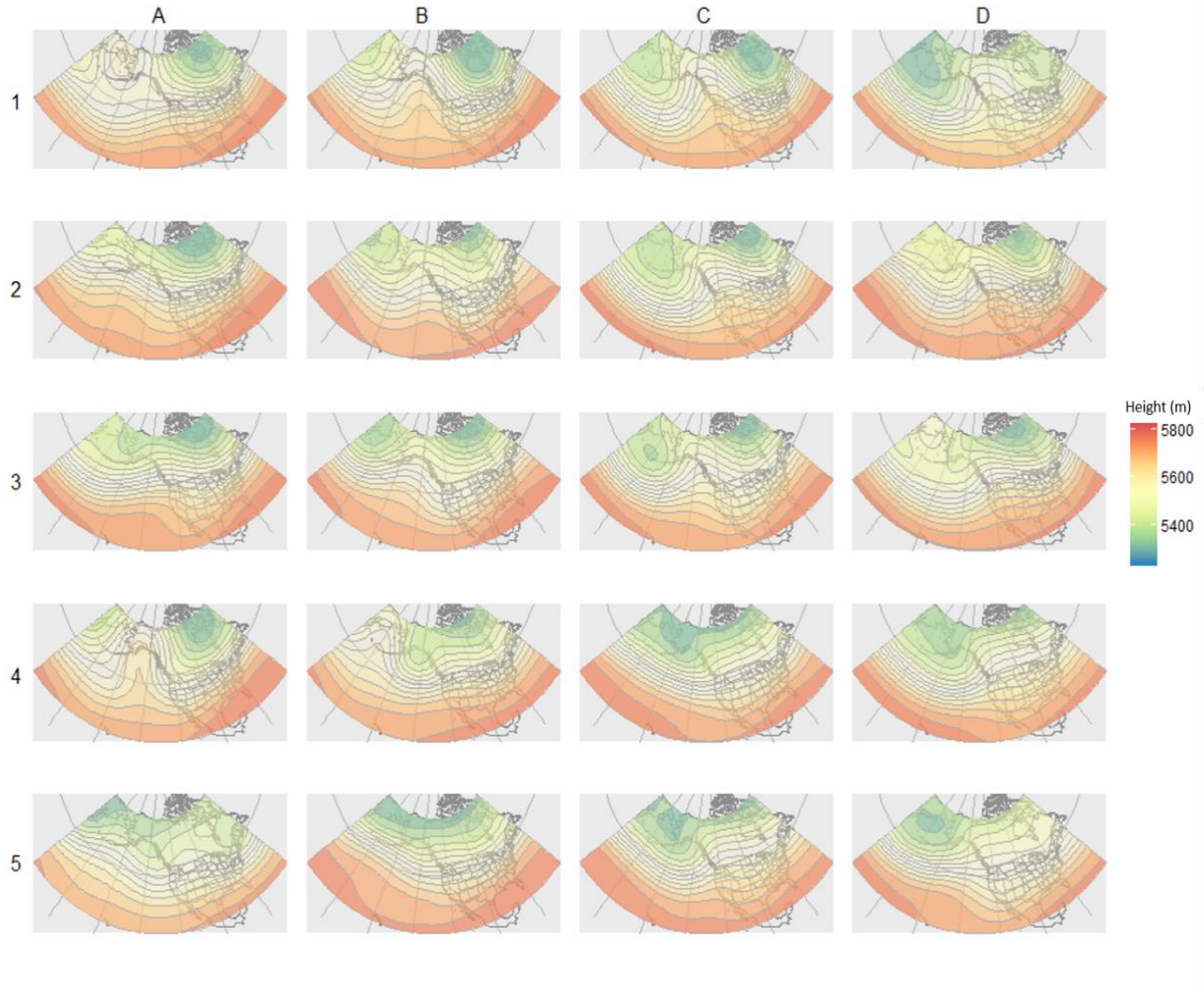

Figure 4: Synoptic classification scheme characterizing atmospheric circulation for North American Winters. Taken from Schauer et al. (2021).

variables that best split days with deep slabs from days without deep slabs were: 1) Minimum air temperature over the last 24 hours (C°), 2) snow water equivalent total over previous 5 days (mm), 3) average maximum air temperature over previous 3 days (C°), 4) change in snow depth over previous 7 days (cm), 5) height of snow (cm), and 6) change in snow depth over previous 3 days (cm). For the eleven days that had a persistent or deep persistent slab avalanche in 2019-2020 we used these variables to see whether the overfit classification tree in Marienthal et al. (2015) would predict a deep slab day or not.

5. RESULTS

5.1 Early winter

During November 2019, 12 days (40.0% of total November days) were characterized by a pattern in which Southwest Montana is situated on the downstream side of a blocking ridge off the west coast of North America (type B2 in Figure 4). Historically, this is one of the coldest circulation patterns at Bridger Bowl, and it is also the most likely to result in precipitation (Schauer et al., 2021). For the month of December, 7 days (22.6%) were represented by type C3, which is characterized by a strong ridge over the intermountain West, typically associated with mild temperatures and rarely associated with precipitation. Types C4 and D5 each represented 6 days (19.4% each), both of which are characterized by zonal flow almost directly out of the west (Figure 4). Historically, these patterns are associated with near average temperatures and precipitation (Schauer et al., 2021).

From November 1st, 2019 to January 31st, 2020 Bridger Bowl received 249mm SWE. This is considerably less than the 308mm threshold used in the classification tree. December 2019 had 46mm of SWE, less than the 56mm threshold in the classification tree which would group 2019-2020 with seasons that had deep slab avalanches. Both these SWE measurements classify the 2019-2020 season with a group of 12 historical seasons that had deep persistent slab avalanches, and zero historical seasons without deep slabs met these same criteria.

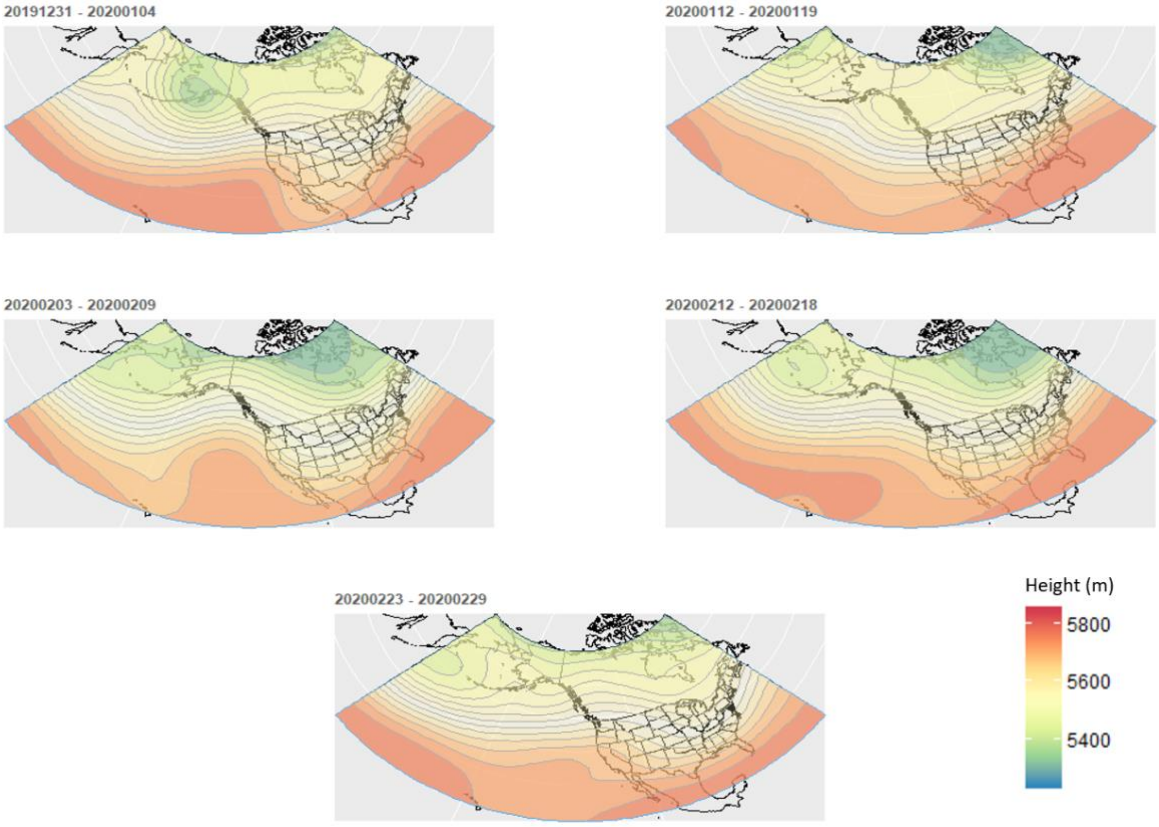

Figure 5: Composite 500 mb geopotential height charts for the five major avalanche cycles. The charts show key similarities, with low pressure centers Hudson Bay, and a westerly to northwesterly flow. The Feb 12-19 period stands out as a primarily zonal flow pattern, while the other four periods have moderate ridging near the North American west coast.

Table 2.Observations on the major avalanche days of the 2019/20 season for the meteorological thresholds identified in Marienthal et al., (2015) as predictors of days with deep slab avalanche activity.

Date	*Min Temp (C)*	*Avg. Max temp 3 days*	*HS 7 days (cm)*	*HS (cm)*	*HS 3 days (cm)*	*SWE 5 days (mm)*	*Avalanche predicted by classification tree?*
1/3/20	-7.15	-2	22.86	101.6	15.24	34.9	no
1/4/20	-4.4	-1	25.4	101.6	-2.54	37.4	yes
1/15/20	-17.6	-7	7.62	139.7	7.62	16.4	no
1/17/20	-8.8	-1.7	7.62	139.7	0	23.4	yes
1/19/20	-6.6	-0.7	-2.54	129.54	-10.16	19.6	yes
2/6/20	-6.6	-8	73.66	208.28	48.26	90.2	yes
2/9/20	-14.85	-4.3	40.64	205.74	-5.08	91.5	yes
2/15/20	-10.45	-2	-2.54	203.2	-2.54	12.7	no
2/16/20	-6.6	-2.7	-2.54	210.82	2.54	21.6	yes
2/18/20	-12.65	-5	2.54	218.44	7.62	21.6	no
2/26/20	-9.9	-2.3	-2.54	203.2	-5.08	19.1	no

The maximum height of snow in November was not used to classify the 2019-2020 season because it is used to split season that have >56mm SWE. However, in 2019 the maximum height of snow in November was 81.3 cm. This is slightly below the 88.9 cm threshold that tends to separate non-deep slab seasons from deep slab seasons (when Dec SWE is > 56mm).

5.2 Mid-season avalanche cycles

Composite 500-mb geopotential height maps for the five avalanche cycles show striking similarities (Figure 5). For all five cycles, a strong upper-level trough extends from the Hudson Bay area down through the eastern United states, coupled with a moderate ridge over the east Pacific and low pressure over the Bering Sea and western Alaska. This situates Bridger Bowl directly under a northwesterly zonal flow pattern– one of the most favorable atmospheric setups for precipitation at Bridger Bowl.

Of the eleven days that had a persistent or deep persistent slab avalanche in 2019-2020 the overfit classification trees in Marienthal et al. (2015) classified 6 of eleven days as a day with a deep slab avalanche. The variables and results are summarized in Table 2.

6. DISCUSSION

The upper-level circulation patterns associated with the problematic 2019-20 snowpack are in generally good agreement with the findings from Schauer et al. (2021). The combination of periodic northwesterly flow followed by sustained blocking patterns in the beginning of the season facilitates a weather pattern in which snow would accumulate and then undergo faceting. Four out of the five periods of significant avalanche activity during the season coincided with enhanced northwesterly flow and upper-level troughing over western Montana. This pattern has previously been demonstrated to be a major storm producer for the Bridger Range. The exception to this rule was the February 15-19 avalanche cycle. That period featured a westerly zonal flow pattern. While purely zonal flow does not always favor the Bridger Range for precipitation, it does tend to produce modest storm totals consistently. This period was also the longest time frame of the five periods of interest, so it is possible the zonal pattern may be a result of noise in the daily 500 mb charts.

The 2019-2020 season was classified by the seasonal classification tree from Marienthal et al. (2015) as a season with deep slab avalanches. The metrics used in this tree are based on precipitation during the beginning of the season when weak layers form. The values for total SWE from November through January, and December SWE, were low for the 2019-2020 season compared to historical seasons that did not have deep slabs. Additionally, the maximum height of snow in November was slightly lower than the threshold that splits seasons with and seasons without deep slabs. These variables reflect a presence of early season snow in November followed by a generally dry December. This is consistent with typical meteorological conditions associated with the upper-level circulation patterns that we observed at the beginning of the season, as well as conditions conducive to weak layer development.

Barely more than half the days in the 2019-2020 season that had deep slab avalanches were correctly classified by the daily classification tree in Marienthal et al. (2015) (Table 2). This is an unsatisfactory result for a practical in-situ forecasting application, but this does not discount classification trees as a data research tool. For the largest avalanche cycle of the season, on Feb 6-9, the variables that summarize the height of snow over the previous 7 days and the total SWE over the previous 5 days show large storm totals (Table 2). Heavy loading on a weak snowpack is an obvious indicator of decreasing stability, and

this is in line with previous research that showed higher cumulative snowfall or precipitation totals prior to deep slab avalanches (e.g., Conlan et al., 2014; Tracz, 2012; Schweizer et al., 2009).

The daily classification trees heavily weight variables based on temperature to split days with deep slabs and days without deep slabs (Table 2). In the 44 seasons of data studied by Marienthal et al., (2015) there were many seasons and days that had deep wet slab avalanches. This may be why the classification tree uses temperature more heavily. Because there were no wet slabs recorded in 2019-2020, this season's metrics on days with deep slabs may be farther from the historical average, which may partially explain the poor prediction rate for this season.

The poor performance of the daily classification trees underscores the difficulty of forecasting deep slab avalanches and the need for an extra conservative mindset when the snowpack has potential to avalanche on persistent weak layers. Forecasting the exact timing of deep slabs and avalanches on persistent weak layers remains difficult. We suggest maintaining a wide margin for uncertainty with persistent weak layers, as they have surprised many experienced forecasters. Rather than attempt to pinpoint days when persistent weak layers may be "dormant" or stable as avalanche danger rises and falls, maintain a conservative mindset for weeks, months or entire seasons, even when obvious signs of instability are absent.

7. CONCLUSION

This research supports the importance of tracking the snowpack and meteorology from the start of the season. Avalanche forecasters can utilize summaries of meteorological variables and atmospheric circulation patterns to look for signs of weak layer development. These tools can be useful during the early season as weak layers form, and a review of these data later in the season serves as a reminder to remain conservative when instability is not obvious.

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