SYNOPTIC CLIMATOLOGY OF DEEP SLAB AVALANCHES IN THE WESTERN UNITED STATES

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ABSTRACT: Deep slab avalanches result from season-long weather beginning with the formation of snow stratigraphy conducive to deep slab avalanches. The onset of deep slab activity is commonly preceded by heavy snowfall, wind, rain-on-snow, or rapid warming events. Local slope weather (or surface weather) is mainly driven by atmospheric circulation at higher altitudes. The field of synoptic climatology relates these atmospheric processes to surface observations. Previous work has investigated the meteorology of deep slab avalanches, as well as the synoptic climatology of snowfall and avalanche occurrence in several different locations around the world. However, there is limited research that specifically relates atmospheric circulation to deep slab avalanches. This work aims to bridge a knowledge gap by investigating the synoptic climatology of deep slab avalanches across the western United States. We obtained daily 500 mb geopotential height maps from the NCEP/NCAR Reanalysis dataset for 38 consecutive winter seasons from 1979-2017, resulting in over 6,000 days of data. We have classified these daily 500 mb height maps using Self-Organizing Maps (SOM) to obtain 20 summary map patterns characterizing the observed modes of atmospheric variability over western North America and the eastern Pacific. We used Westwide Avalanche Network (WAN) data from three ski resorts across the western U.S. that represent the three dominant snow climates (maritime, continental, and intermountain) and count the number of deep slab avalanche events for each synoptic type at each location. We investigate which synoptic types tend to occur immediately prior to deep slab avalanche events. Our work improves our understanding of the relationship between atmospheric circulation and deep slab avalanches, thereby enabling practitioners to better anticipate deep slab avalanche events.

1. INTRODUCTION

Deep slab avalanches are destructive and are particularly difficult to predict due to their low frequency of occurrence. They typically fail on persistent weak layers, which may exist in certain snowpacks for weeks or months (McClung and Shaerer, 2006) and which become difficult to collapse once they are deeply buried (Schweizer and Camponovo, 2001; Thumlert and Jamieson, 2015). Recent work has improved our understanding of the mechanics (e.g. Gaume et al., 2017; Schweizer et al., 2016) and meteorological variables (Conlan et al., 2014 Davis et al., 1999; Marienthal et al., 2015; Marienthal et al., 2012) controlling slab avalanches. However, there still remains a large amount of uncertainty in forecasting deep slab events. A better understanding of the processes driving deep slab avalanche activity will improve our ability to predict these events.

The field of synoptic climatology relates regional-scale atmospheric circulation to environmental processes (Yarnal, 1993) and has yet to be applied to deep slab avalanches. The two main methods by which synoptic climatology studies proceed are by classifying atmospheric conditions and quantifying surface observations for each circulation class or by measuring an environmental process and summarizing the circulation patterns based on a given environmental condition. Yarnal (1993) describes these two approaches as circulation-to-environment or environment-to-circulation respectively, and both have been demonstrably

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effective in identifying relationships between atmospheric circulation and surface observations. Previous work has successfully used synoptic climatology to describe snowfall patterns (Esteban et al., 2005; McGinnis, 2000; Hartley and Keables, 1998; Grundstein, 2003), summarize snowpack and avalanche activity (Birkeland et al., 2001; Fitzharris, 1987; Fitzharris and Bakkehøi, 1986; Martin and Germain, 2017; Mock and Birkeland, 2000; Yokley et al., 2014), create weather forecasts (Kidson, 2000), and to characterize weather patterns (Davis and Walker, 1992; Jiang et al., 2004;). There is extensive work investigating different techniques to classify synoptic types, but in this paper we demonstrate the utility of Self-Organizing Maps (SOM) (Kohonen, 1998) in summarizing atmospheric circulation patterns over the western United States and explore associations between these circulation patterns and onset of deep slab avalanches. By understanding the large scale atmospheric processes occurring in the days leading to deep slab avalanche cycles, we can improve our ability to forecast deep slab events.

2. METHODS

We use a record of daily 500 mb geopotential height maps from the National Center for Environmental Prediction and National Center for Atmospheric Research (NCEP/NCAR) Reanalysis (Kistler et al., 2001) to describe the upper atmosphere circulation patterns. The NCEP/NCAR reanalysis data provide "observations" on a 2.5^o grid taken daily at 2400Z. We obtain seasonal data for November 1 to April 7 from 1979 to 2017 in order to both reduce the seasonal signal in circulation patterns and to align well with ski area weather and avalanche records, which are primarily recorded during the operational season for each ski area, with some early season records included. By starting our time period in the late 1970s, we use only the NCEP/NCAR data collected after satellite observations were integrated into the reanalysis.

Daily 500 mb geopotential height maps are grouped using SOM, a neural-network based approach using unassisted computer learning to organize observations in the dataset into groups based on similarity, each of which represented by its own 'node'. Collectively, all of the nodes span the range of all of the synoptic types observed. The SOM algorithm adjusts the nodes to best describe the entire dataset first, and then assigns each daily map to the node with which it is most closely represented. Thus, each node is neither a composite nor a specific representative day from the record, rather it is a "synoptic type" created by the SOM that summarizes a group of days. The nodes are displayed in a 2-dimensional array such that similar nodes are placed near each other. A more thorough discussion of SOMs may be found in Hewitson and Crane (2002). We execute the SOM using the kohonen package in R (Wehrens and Buydens, 2007). We retain 20 nodes which characterize the main synoptic types of atmospheric variability observed over the time period of this study. The number of nodes to retain was chosen based on the number of synoptic types used in previous work (Davis and Walker, 1992; Kidson, 2000; Kalkstein et al., 1990; Kalkstein et al., 1987).

We use the Westwide Avalanche Network (WAN) database (U.S. Forest Service, 1999) to obtain weather and snowpack measurements from Alpine Meadows, CA; Alta, UT; and Berthoud Pass, CO, which represent maritime, intermountain, and continental snowpacks respectively (Mock and Birkeland, 2000). These three locations have long and consistent records relative to other locations in the WAN database. At all three locations we examine the record beginning in 1979 and extending through 1995 at Alpine Meadows and Berthoud Pass and 1990 at Alta. The three study sites enable us to compare avalanche-prone synoptic types among locations while controlling for latitude-related differences in synoptic patterns. An avalanche is identified as a deep slab event on a persistent weak layer if the crown depth exceeds .9m and is greater than three times the 72-hour storm total, or if crown depth exceeds 150% of the mean crown depth for avalanches occurring in the same day, or any event where the avalanche is recorded as failing on the ground. We study only those events occurring after February 1 for each season in order to limit the study to events failing on persistent layers. With our record of deep slab events and the SOM classification scheme, we are able to count the number of avalanche events that occurred within 72 hours of observing each circulation pattern for our entire record.

Finally, we explore the relative odds of deep slab avalanche occurrence for different groups of synoptic patterns at each location, defined by the number of avalanches associated with them. At each study site, we group nodes from the SOM into two categories (high risk or low risk) based on the number of deep slab events recorded within 72 hours of observing each synoptic type. A synoptic type is designated “high risk” if more than five “successes” (i.e. days with deep slab avalanches) were recorded for the node, or if the ratio of successes to failures was .333 or higher. The remaining synoptic types are placed in the “low risk” group. These groupings are created such that the high-risk group is guaranteed to have more avalanches than the low risk group. At each location, we calculate the odds of observing a deep slab avalanche within 72 hours of observing a high-risk or low-risk synoptic type by dividing the total number of successes by the total number of failures for all types in both the high risk and low risk groups. We then estimate the relative odds of observing a deep slab avalanche during a high-risk synoptic type versus a low-risk type in order to briefly summarize the apparent difference in deep slab avalanche frequency for different synoptic types. In this stage of the research we are investigating only the triggering period and not the formation of a snowpack conducive to deep slab avalanches. We chose to focus on triggering rather than formation in this paper because it is relatively easy to determine if snow structure is conducive to deep slab avalanches in the field, whereas there remains substantial uncertainty in predicting if conditions are ideal for actually triggering a deep slab event. Future analysis will consider the coupled analysis of both the formation and triggering periods.

3. RESULTS

Moving from top to bottom across the SOM array of 500mb geopotential heights, the plots transition from strong meridional to primarily zonal patterns (Figure 1). On the leftmost column of the display we observe a high-pressure ridge located over the Pacific, which migrates east until it is located over the Rockies in the rightmost column. We display the number of deep slab avalanche days recorded within 72 hours after observing each synoptic type in Figure 2. The synoptic types with the largest number of days with deep slab avalanche activity at each site are displayed in red, while days with no recorded events associated with them are shown in blue. We find that each location has a relatively large number of synoptic types with little to no deep slab activity and one to three types that account for a majority of deep slab avalanches. There are also a handful of types with one or two recorded events at each site, which fall into our low risk group.

At Alpine Meadows, we estimate that days in the high-risk group (nodes 4,6,8) are about 6 times more likely to be associated with a deep slab avalanche than the low-risk group. At Alta, we estimate days in the high risk group (nodes 1,8,10,17,18,19) are about 5 times more likely to be associated with a deep slab avalanche activity than the low risk. At Berthoud pass, the high-risk nodes (7,8,11,15,18,20) are about twice as likely to observe deep slab avalanches than the rest of the nodes.

4. DISCUSSION

The SOM is effective at grouping days with similar 500 mb height charts and displaying them in an easily interpreted array. This is a substantial improvement over a principal components analysis and clustering scheme we attempted on the same dataset, which detected many of the same large-scale patterns but was unable to display the patterns in a relative manner and was more sensitive to changes in the number of clusters retained.

At Alpine Meadows, we find the days with southwest zonal flow over the ski area more often occur before avalanche activity (node 4) or a slight blocking pattern with a ridge over the Rockies, which is also characterized by southwest flow (nodes 6 and 8). All three of these patterns would likely be associated with above normal temperatures with potential for precipitation as warm, moist air moves in from the Pacific (Aguado and Burt, 2015). At Alta, we observe increased activity with strong west to northwest flow at the ski area (nodes 1,8, and 10). Additionally, we identify a group of synoptic types featuring a blocking pattern and very strong northwest flow (nodes 17, 18, 19), which closely resemble conditions previously shown to be associated with increased precipitation at Alta (Steenburgh and Alcott, 2008). Interestingly,

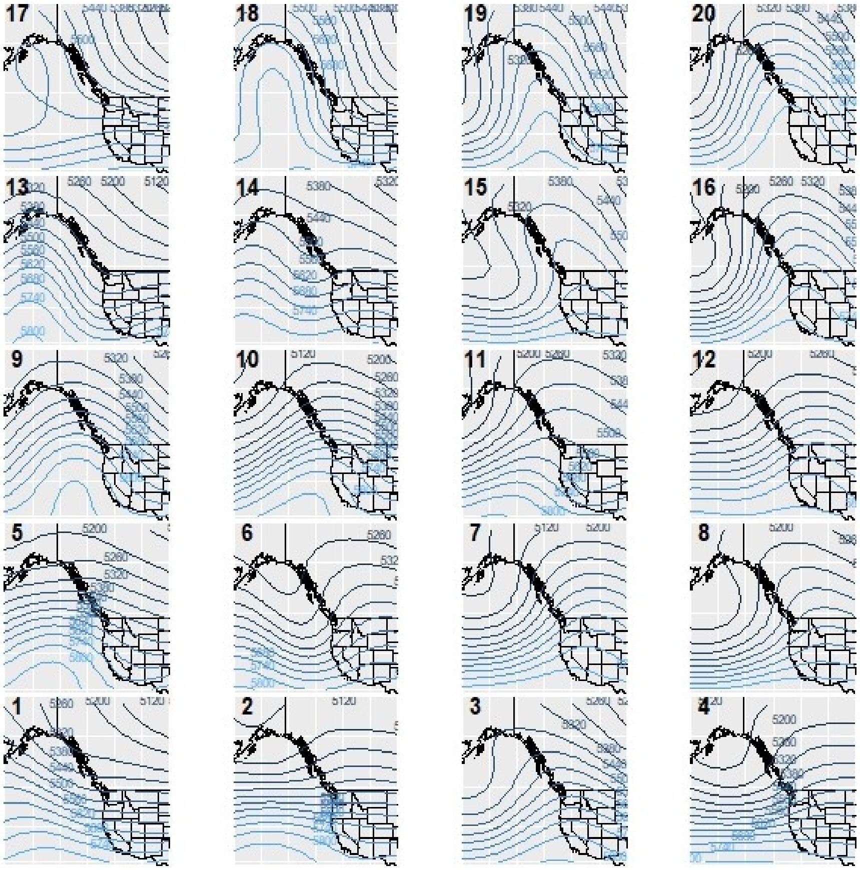

Figure 1: 500 mb height summary types obtained with the SOM algorithm. Each map represents a group of days with similar 500mb height charts.

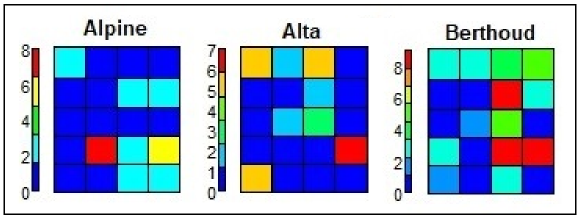

Figure 2: Heat maps displaying the number of days with deep slab avalanches recorded within 72 hours after each synoptic type was observed. Squares on these grids correspond with synoptic charts in Fig. 1.

Merrill (2002) also identified two distinct synoptic conditions favoring separate storm tracks that led to increased avalanche activity in nearby Little Cottonwood Canyon. Berthoud Pass does not show as strong of an association as the other two areas (Figure 2), with deep slab avalanche days almost spanning the entire spectrum of synoptic types. This may be a product of the generally weaker continental snowpack at Berthoud Pass as compared to Alta and Alpine. The weaker structure makes avalanches on persistent weak layers more common at Berthoud, and the thinner snowpack likely makes them easier to trigger. With the more sensitive snowpack, we observe a wider variety of synoptic conditions in which it is possible to trigger a deep slab avalanche. As a result, no single synoptic type stands out as being particularly dangerous.

5. CONCLUSION

While all three locations have specific synoptic types associated with increased tendency of observing a deep slab avalanche within 72 hours, the synoptic classification alone does not provide enough information to forecast deep slab events. It does, however, serve as an important first step in identifying an additional potential risk factor that may be incorporated to improve accuracy in statistical models similar to Davis et al. (1999) or Marienthal et al. (2015). Avalanche forecasting is a holistic process, requiring multiple types of data that may or may not be readily available. The patterns observed here may serve as one additional indicator of increased avalanche risk that may be used in conjunction with snowpack and weather observations and statistical models to aid in forecasting deep slab avalanches.

6. REFERENCES

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