ROLE OF SYNOPTIC ATMOSPHERIC CONDITIONS IN THE FORMATION AND DISTRIBUTION OF SURFACE HOAR

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ABSTRACT: Surface hoar (SH) crystals, once buried, often result in a persistent weak layer within the snowpack that contributes to instability on slopes in the mountains of southwestern Montana as well as many other mountainous regions of the world. The influence of local meteorological conditions and gross-scale topographical features (e.g. slope and aspect) that influence the formation of surface hoar are relatively well understood. However, the relationships between synoptic atmospheric conditions and the formation of surface hoar are not very well known, nor have they been extensively studied. To investigate these relationships, atmospheric patterns from NCEP/NCAR synoptic composite maps were obtained for periods with varying amounts of surface hoar presence (four intervals from <20% to >80%) for our study area in SW Montana. This study used a comprehensive suite of 127 days of manual observations of surface hoar presence and absence from Pioneer Mountain within the Yellowstone Club in southwestern Montana from December 2012 – April 2014. Each of these days provides detailed observations from 16 sites distributed across several different elevations and all aspects on Pioneer Mountain. The composite maps show that higher sea level pressure, northerly winds and higher than average 500 hPa geopotential heights tend to favor more extensive surface hoar formation. This knowledge along with further research and analysis could potentially provide better insight into long-term forecasts of the spatial distribution of surface hoar presence.

KEYWORDS: surface hoar, synoptic approach, avalanche forecasting

1. INTRODUCTION & BACKGROUND

Avalanches are a major life-threatening hazard in the mountains of the Western United States (Voight et al., 1990). Although forecasters have increasingly advanced skills and technology to forecast avalanches, there is still uncertainty associated with predicting their exact timing and location. When weak layers in the snowpack form, and subsequently fail, avalanches can be triggered. Surface hoar (SH) crystals are well known to be one of the crystal types that can form these weak layers within the snow. As such they are extremely important to avalanche forecasters (Schweizer and Lutschg, 2001). Surface hoar layers can also persist for long periods of time after burial (e.g. Jamieson and Johnston, 1994; Lutz and Birkeland, 2011), which makes determining the timing of future avalanches difficult.

Forecasting the formation of surface hoar at scales relevant to regional avalanche forecasting continues to be a challenge because there are a number of recognized factors that are required for the formation of surface hoar, and some data (for example, vapor pressure and temperature gradients) are not readily available at appropriate scales.

The atmospheric conditions most suitable for surface hoar growth include: clear, cold nights

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with high relative humidity and light winds (e.g. Lang et al., 1984; Hachikubo and Akitaya, 1997). These conditions allow for a net longwave radiation loss, resulting in the snow surface being cooled well below the surrounding air temperature, creating a large temperature gradient near the surface. Water vapor from the warmer air above is deposited on the snow surface, forming facets (surface hoar). However, while the weather conditions may be conducive to its formation, they do not always result in surface hoar. Therefore, understanding the relationship between synoptic scale atmospheric patterns and the formation of surface hoar could greatly increase the confidence of avalanche forecasting and provide better long term forecasts.

Several studies have used a synoptic approach to understand avalanche processes (e.g. Fitzharris, 1987; Mock and Birkeland, 2000; Birkeland et al., 2001; Hansen and Underwood, 2012), but none have concentrated specifically on the relationship to surface hoar. For example, Fitzharris (1987) classified avalanche winters in western Canada by using daily sea level pressure anomaly maps to determine sets of conditions that lead to significant avalanching. He found that major avalanche winters exhibit anomalous circulation patterns as well as much colder than average temperatures, in at least one month. These conditions induce strong temperature gradients within the snowpack, which leads to the development of weak layers. Also, a switch in the atmospheric circulation from a blocking pattern to predominately zonal winds also appeared to play an important role during major avalanche winters. Birkeland et al. (2001) performed a similar study in which 500 hPa composite anomaly maps as well as statistical analyses were utilized to define atmospheric conditions that led to extreme avalanche days in the western United States. Although the synoptic patterns differed by location due to topography, increased snowfall and upper level divergence where some of the conditions recognized to produce significant avalanche days.

Other avalanche research studies have also applied a synoptic scale approach to determine relationships between atmospheric circulations and heavy snowfall events (e.g. Birkeland and Mock, 1996 and Esteban et al., 2005). Birkeland and Mock (1996) analyzed 500 hPa composite anomaly maps and discovered unique synoptic conditions that lead to heavy snowfall events at Bridger Bowl, Montana. Unlike previous studies of similar mountain ranges, the location and topography of Bridger Bowl allows for a strong northwesterly flow on the backside of a trough to result in heavy snowfall.

This study aims to examine the synoptic weather conditions that are present with varying amounts of surface hoar in order to establish atmospheric patterns that are favorable to its formation.

2. METHODS

2.1 Field Data

Sixteen sites across Pioneer Mountain (Figure 1) were chosen for data collection during the 2012 – 2013 and 2013 – 2014 winter seasons (mid-December to early April). The site locations were chosen to ensure that all four aspects and several different elevations were represented.

At each of these sites, sub-weekly observations (at approximately the same time of day) of surface hoar presence/absence and size were collected by the Yellowstone Club Ski Patrol. Over the course of these two winter seasons, 127 days of manual observations were collected (64 in 2012 – 2013 and 63 in 2013 – 2014).

2.2 Data Analysis

The primary resource used for data analysis is the NCEP/NCAR 50-Year Reanalysis Project data (Kistler et al., 2001), which is a joint project between the National Center for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR). This project used data from several sources (including land surface, ship, aircraft and satellite) to create a large record of historical atmospheric conditions across the globe beginning in 1948. It also provides data that are available up to present day, which is a major limiting factor of other reanalysis datasets (e.g. 20th Century Reanalysis (V2) Dataset). This resource offers a large variety of options for selection of atmospheric layers in combination with different meteorological parameters, which are available at 6 hourly, daily and monthly intervals. The NCEP/NCAR Reanalysis dataset was used to create atmospheric composite maps of meteorological variables at the synoptic scale for our wider region. These composite maps will be the primary variable that we will consider to

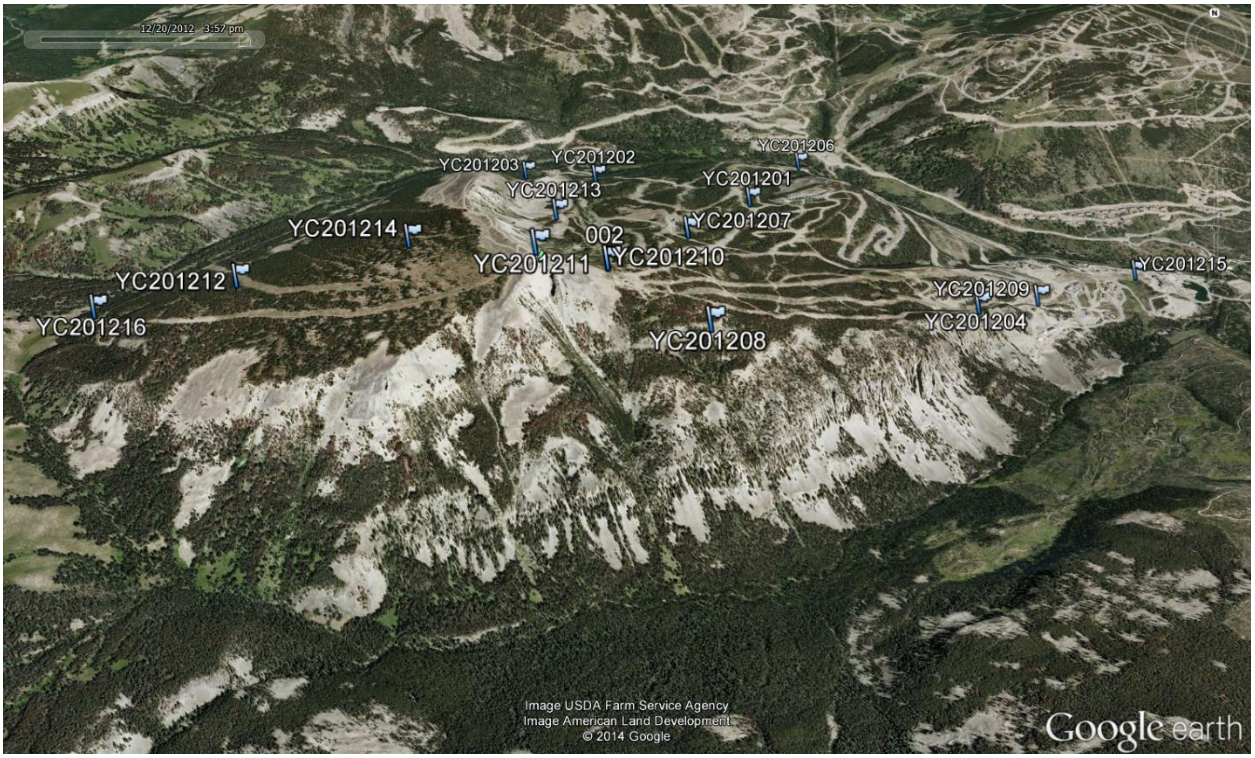

Figure 1: Image of the Yellowstone Club, looking north as seen from Google Earth, illustrating the 16 locations used for observations during the 2012-2013 and 2013-2014 winters (Google, 2014).

explain the observed variability in surface hoar formation.

To create atmospheric composite maps for the surface hoar events, surface hoar presence were broken down into four categories: (1) <20%; (2) ≥20% but <50%; (3) ≥50% but <80%; and (4) ≥80%. The percentage of sites with surface hoar present were calculated for each day (when manual observations were recorded) and placed in the corresponding percentage category. A list of days was compiled for each surface hoar percentage category and imported into the website's program, which allowed those specific days to generate a composite average map of the desired parameter.

3. RESULTS

Overall, the two study years were fairly similar with regards to surface hoar presence within the categories established for analysis (Table 1). Although the breakdown of categories was similar, we did see differences in the timing of surface hoar events between the two winter seasons. The 2012 – 2013 season has a more concentrated number of events between late December and late March, with the majority of events occurring in February (Figure 2). During the 2013 – 2014 season the surface hoar events are more equally spread out from December to April (Figure 3). However, due to the similarity of surface hoar occurrence within the percentage categories, composite maps were generated for the combined data set. The composite maps of the combined data set will be presented in this paper.

When visually analyzing the sea level pressure composite maps, we see patterns that are to be expected. As the percentage of sites with surface hoar increases, the sea level pressure mean also increases, indicating that high pressure systems are more conducive to surface hoar formation. This supports prior work that surface hoar tends to form under clear skies that typically results from high pressure. The >80% presence plot shows higher average sea level pressure (Figure 4), whereas the <20% presence plot shows lower average sea level pressure (Figure 5).

Table 1: Summary of surface hoar presence, by category, and observations for each study year.

Surface Hoar Presence	2012 - 2013	2013 - 2014
Days where < 20% of sites had SH*	45	42
Days where ≥ 20% but < 50% of sites had SH	4	6
Days where ≥ 50% but < 80% of sites had SH	6	5
Days where ≥ 80% of sites had SH	8	8

* Note that <20% category contains (and is mostly comprised of) days where no surface hoar was observed at any location.

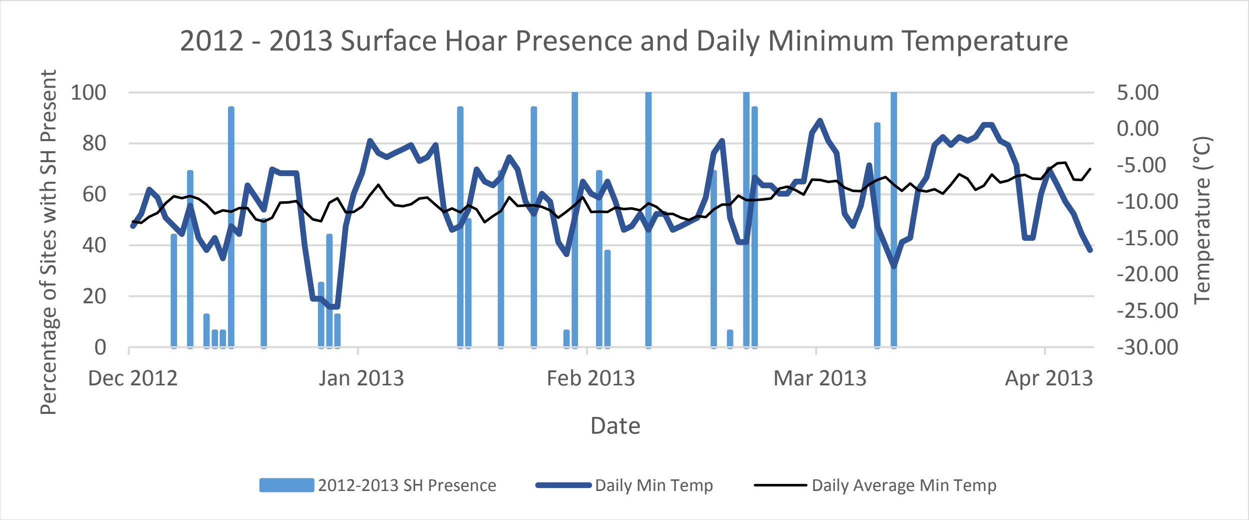

Figure 2: Graph displaying the percentage of sites (out of the 16 on Pioneer Mountain) with surface hoar present for the 2012 – 2013 winter season; the daily minimum temperature (from Lone Peak SnoTel site) as well as the daily average minimum temperature (11-year historical data from Lone Peak SnoTel site) are overlaid.

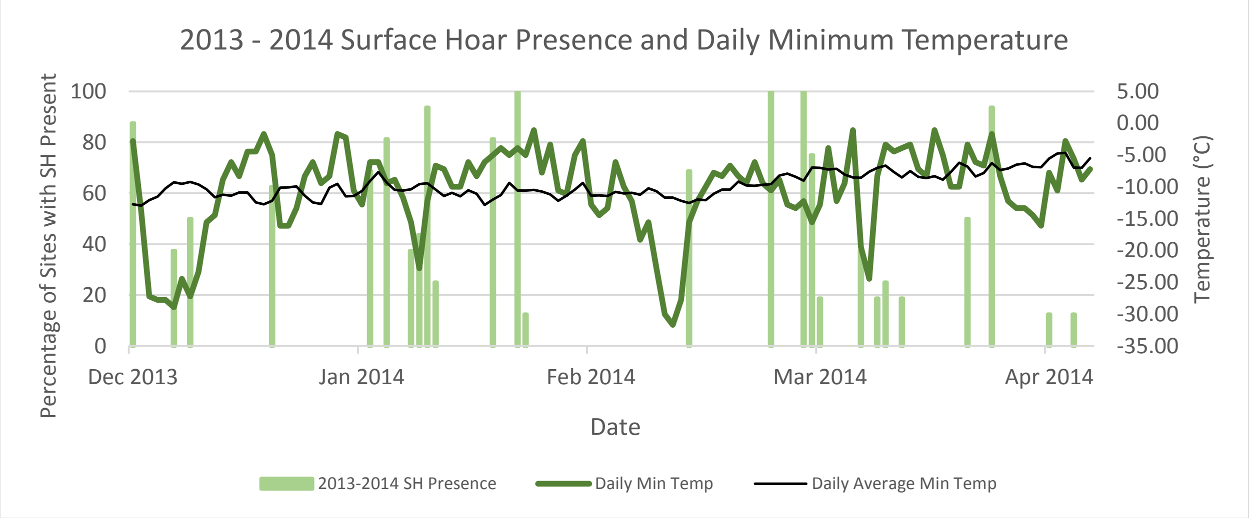

Figure 3: Graph displaying the percentage of sites (out of the 16 on Pioneer Mountain) with surface hoar present for the 2013 – 2014 winter season; the daily minimum temperature (from Lone Peak SnoTel site) as well as the daily average minimum temperature (11-year historical data from Lone Peak SnoTel site) are overlaid.

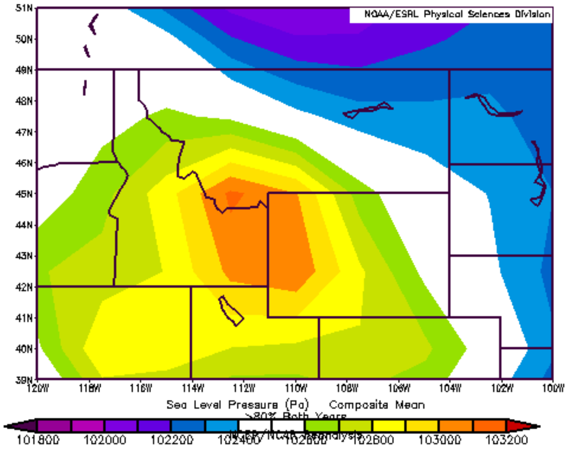

Figure 4. Composite map displaying mean sea level pressure (Pa) for days where greater than 80% of the sites had surface hoar present from 2012 – 2014.

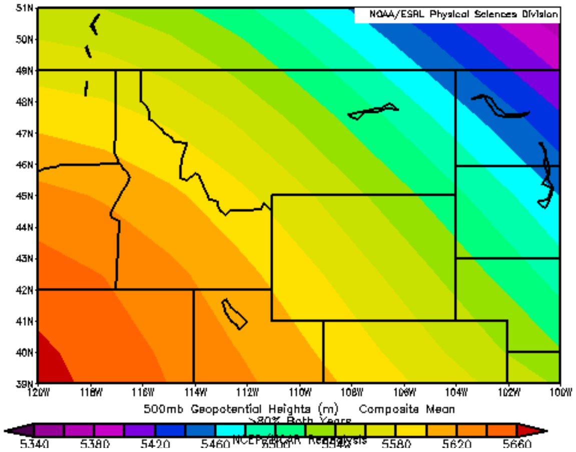

Figure 6: 500 hPa composite map displaying geopotential height (m) for days where greater than 80% of the sites had surface hoar present from 2012 – 2014.

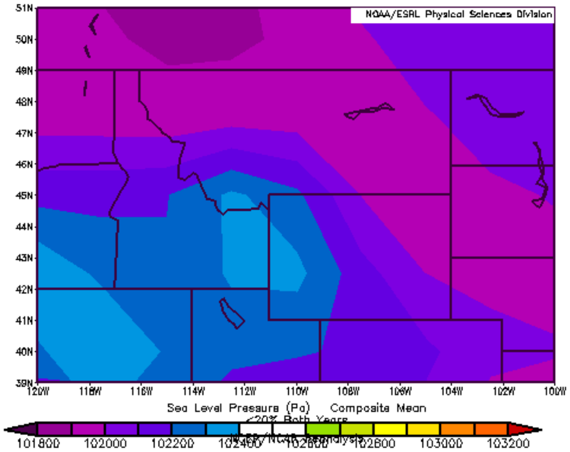

Figure 5. Composite map displaying mean sea level pressure (Pa) for days where less than 20% of the sites had surface hoar present from 2012 – 2014.

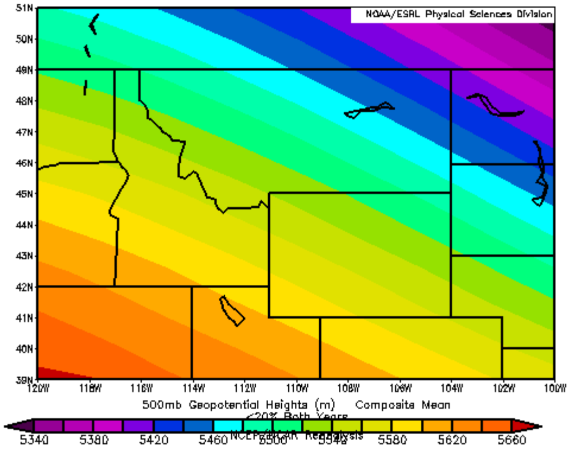

Figure 7: 500 hPa composite map displaying geopotential height (m) for days where less than 20% of the sites had surface hoar present from 2012 – 2014.

From the composite mean maps of 500 hPa geopotential heights (Figure 6 and 7), we can see an increase in the amplitude of a ridge, resulting in more northerly and perhaps calm winds, as opposed to zonal winds, as the percentage of sites with surface hoar increases. This suggests that while high pressures at mean sea level are important, an upper level northerly flow is also required.

When we consider the winds aloft, at 300 hPa, these also show a slight turn in the wind direction (from NW to NNW) with an increase in surface hoar presence. The 300 hPa winds for the lowest presence percentage illustrate a more zonal flow when compared to the other composite maps. When the percentage increases to >80%, a slight trough is present.

4. DISCUSSION & CONCLUSIONS

The composite maps show that higher sea level pressure, more northerly winds at 500 hPa, and higher than average 500 hPa geopotential heights facilitate surface hoar formation. Although not unexpected, this work is the first to quantitatively document the atmospheric conditions associated with surface hoar growth. We hypothesize that the northerly winds at the 500 hPa level bring the colder air masses to our study region, which when combined with higher surface pressures, result in the cold, clear nights needed for surface hoar formation.

While this study provides an encouraging start, additional quantitative analysis will help us better understand the different atmospheric conditions associated with varying amounts of surface hoar presence. Our future work will statistically analyze composite and anomaly maps. We will also assess the impact of removing snow days to assess of the differences between days that could have produced surface hoar but did not.

5. ACKNOWLEDGEMENTS

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