

FIVE SEASONS OF DETAILED SURFACE HOAR OBSERVATIONS: WHAT HAVE WE LEARNED?

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ABSTRACT: Since the start of the 2011-12 season the Yellowstone Club Ski Patrol have diligently been collecting detailed observations of surface hoar (SH) presence or absence at 16 sites across Pioneer Mountain in SW Montana, USA. These manual observations have been taken on at least three days per week, and on many additional days when SH formation seemed possible. We now have over 280 days of SH / non-SH observations at 16 sites, at varying elevations, with different aspects and sky view exposures. To our knowledge there is no other data set on manual observations of SH at the mountain range scale, with this combined spatial and temporal coverage. In addition to the manual observations, we have 15 minute observations of temperature and humidity at 1.5m, sky view exposure at all sites, and 15 minute wind speed and direction at half of the sites.

Using these data we have examined the dominant controls that explain the spatial patterns of surface hoar at the plot to mountain range scale. Our results show that small-scale site characteristics which influence micrometeorological conditions and the local site level sky view exposure can greatly influence the spatial variability of surface hoar, over and above that which aspect alone can explain. Furthermore, synoptic scale analysis using NCEP/NCAR synoptic composite maps provides insight for SH absence on days when conditions would seem to be conducive for SH formation. These results highlight our incomplete, but growing understanding of some of the complexities of surface hoar formation processes at this scale, and have implications for both regional and local scale avalanche forecasting.

KEYWORDS: Spatial variability, Surface hoar, Synoptic approach, Forecasting

1. INTRODUCTION & BACKGROUND

While previous work examining the spatial variability of the snowpack has considered a range of different crystal types and weaknesses (e.g. depth hoar, surface hoar, new snow, near surface facets, partially decomposed etc.) – just surface hoar alone is responsible for a significant number of avalanche accidents and fatalities in the western USA (e.g. Chabot et al., 2012). This crystal form alone has involved more avalanche professionals than any other weak layer (Jamieson, 1995). Surface hoar was also the layer responsible for the 3 deaths at Stevens Pass, Washington in February of 2012, as popularized in the New York Times (Branch, 2012).

Previous studies have examined micrometeorological conditions that facilitate surface hoar growth (Lang et al., 1984; Colbeck, 1991; Hachikubo,

1997). These show that surface hoar develops when the snow surface is cooled to below the near-surface dew point temperature by a net longwave radiation loss. This results in excess water vapor from the near-surface air layer being deposited onto the snow surface as a weakly bonded, feathery crystal (frost). Surface hoar is a common crystal type that, once buried, can become a persistent weakness in the snowpack that can last for days, to weeks, or even months. Due to the atmospheric controls on surface hoar formation, large regions can develop surface hoar at the same time, so its spatial extent can be widespread and its temporal presence persistent.

Surface hoar formation and growth have been shown to be highly dependent on snow-surface temperature (Oke, 1987; Gubler, 1998), and the degree of supersaturation at the boundary layer relative to the snow surface (e.g. Colbeck, 1991; Hachikubo, 1997; Jamieson and Schweizer, 2000). Local-scale topographic winds, ground cover and sky view can alter both the supply of moisture and the conditions for surface hoar formation and persistence (Birkeland, 2001; Höller, 2001; Cooperstein et al., 2004). For example, surface hoar is hindered by thick forest cover due to

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radiation exchange from trees, which are generally warmer than the clear night sky. While surface hoar will most readily grow in open areas with a clear sky view, and thereby net nocturnal longwave radiation loss, it will quickly degrade on slopes that face the sun following sunrise, due to incoming solar radiation (Gubler and Rychetnik, 1991). However, these primary factors alone do not completely explain the spatial and temporal pattern of surface hoar across the landscape (Hendrikx et al., 2014).

Given this context, our focus has been to better understand the spatial variability of surface hoar formation at the slope to mountain range scale. This paper will present some of the key findings from the last 5 seasons of field work on Pioneer Mountain, SW Montana.

2. FIELD AREA

Our field work has been conducted at the Yellowstone Club on Pioneer Mountain, Madison Range, in SW Montana (Figure 1). This area is ideally suited to our research goals as it provides a very unique combination of multiple aspects within easily accessed terrain over the winter season. It is also approx. 1 hours' drive from Montana State University, providing the opportunity for cost effective season-long monitoring. Furthermore, personnel from the Yellowstone ski area have been critical in providing daily to weekly observations, maintaining meteorological equipment, and by roping off secure areas for detailed snow observations.



Fig. 1: Location map of the study site, with Montana, Wyoming and Idaho shown, and the nearby towns of Big Sky and Bozeman.

Our work has continued on from the successful studies undertaken at this location with support from the Yellowstone Club by Adams et al., (2009; 2011), Bones et al., (2012), Miller et al., (2011), Slaughter et al., (2009) and others. Using this location and the ongoing commitment from the Yellowstone Club Ski Patrol we now have five seasons of data on surface hoar formation.

3. METHODS

3.1 *Field Observations*

Our overall methods have been described in Hendrikx et al., (2012); Hendrikx et al., (2014) and Yokley et al., (2014), so will not be presented in full here.

In summary, over the last five winter seasons, 16 mini temperature and relative humidity sensors (HOBO U23 Pro v2) which were mounted inside solar radiation shields (RS3) and installed across all four aspects and at different elevations on Pioneer Mountain, at the Yellowstone Club in SW Montana. Each sensor was installed on a PVC pipe, 1.5m above the snow surface. As needed, these sensors were moved up or down the pipe to ensure that observations were made at approximately $1.5\text{m} \pm 0.2\text{m}$ above the snow surface. Automatic observations of air temperature ($^{\circ}\text{C}$), relative humidity (%) and calculated dew point temperature ($^{\circ}\text{C}$), were made every 15 minutes. In total, across the 16 sensors, more than 1,500,000 lines of data were recorded for the five seasons.

At each of these 16 sites, we also collected field data, at sub-weekly intervals, on the presence / absence and size of surface hoar and near surface facets. In total, over the two year period, 280 days of manual field observations were collected from all 16 sites. A hemispherical fisheye lens was used to capture 180° circular fisheye photos facing upwards and level for hemispheric sky visibility at each site.

3.2 *Data Analysis*

The observations of surface hoar presence / absence for each individual site were summarized, so that the frequency of occurrence of surface hoar could be calculated for each site.

Key terrain parameters including slope, elevation, aspect and an estimated wind exposure index were extracted or calculated for each site using a 1m LiDAR derived DEM. These parameters were extracted within a GIS. The hemispheric sky visi-

bility was calculated for each site using Gap Light Analyzer (GLA) (Frazier et al., 1999).

For the synoptic analysis, 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) was used. 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 the wider region.

4. RESULTS AND DISCUSSION

Our results are presented with a spatial scale as our framework, going from point to slope, to mountain, to range scales.

4.1 *Micro to point scale*

Building on the work by Adams et al., (2009) and Adams et al., (2011), our work has shown distinct differences in the habit (i.e. form) of surface hoar under different atmospheric conditions, and across small spatial distances (i.e. less than 1m) under the same atmospheric conditions. Observations of needle-style, to plate-style, to traditional feathery surface hoar have been made (Figure 2).

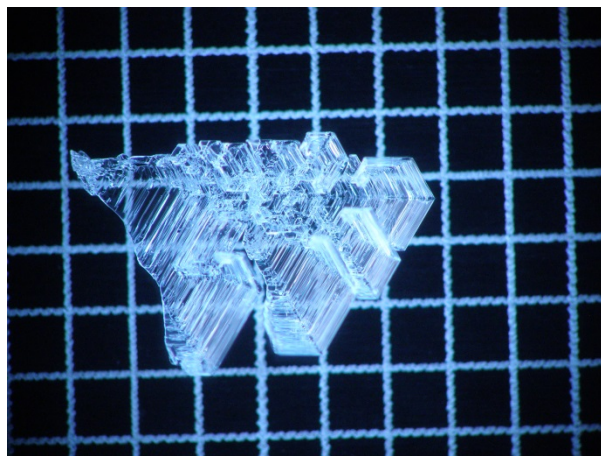


Fig 2: An example of a typical surface hoar crystal shown on a 1mm grid.

Analysis of these observed crystal habits show some correlation to the work by Bailey and Hallett, (2009) who confirmed crystal habits for atmospheric ice crystals, in that the c-axis needle style growth tended to occur during very cold condi-

tions, and the more traditional feathery surface hoar with dendritic a-axis growth during high humidity and warmer conditions.

Take home point: Surface hoar does not always have to look fine and feathery. While this seems to be a common crystal habit - it can form in multiple different crystal forms as a function of humidity (ice supersaturation) and temperature, much like ice growth in the atmosphere.

4.2 *Point to slope scale*

Observations of surface hoar formation from our 16 sites around Pioneer Mountain indicate that surface hoar forms frequently in this climate, even on aspects that we might not typically associate with its formation (i.e. Southern slopes).

Based on the analysis presented in Hendrikx et al., (2014), we note that sky view is likely more important for the preferential development of surface hoar than other, terrain based parameters such as aspect or elevation at these sites. This is consistent with some previous work, e.g. Shea (2011) but is contrary to our understanding of the dominant role of aspect on surface hoar formation at the slope scale (e.g. Cooperstein et al., 2004; Lutz and Birkeland, 2011).

Take home point: Small-scale site differences such as the size of a meadow can influence the occurrence of, and therefore spatial variability of surface hoar, over and above that which aspect alone can explain. The resulting differences in skyview likely influence the micro meteorological conditions at these sites to favor or deter the development of surface hoar, such that even southern slopes with the right tree configuration can see more regular surface hoar formation than some northern slopes.

4.3 *Mountain to range Scale*

When we combine our observations of surface hoar at the 16 sites with the NCEP/NCAR Reanalysis dataset we can observe distinct difference in the synoptic conditions that favor widespread compared to isolated observations of surface hoar.

Based on the analysis presented in Yokely et al., (2014), we note that 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.

However, this work also shows that upper level air motion is important, as the mean composite maps of 500 hPa geopotential heights there needs to be a ridge, resulting in more northerly and perhaps calmer 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 (Yokley et al., 2014). 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 (Yokley et al., 2014).

Take home point: The composite maps show what we anticipated, that higher sea level pressure, more northerly winds at 500 hPa, and higher than average 500 hPa geopotential heights facilitate surface hoar formation. We suggest that the northerly winds at the 500 hPa level bring the colder, clearer and calmer air masses needed to produce surface hoar in our region – so while high pressure is part of the conditions needed, we also need the right upper air flow to help facilitate widespread surface hoar formation.

5. CONCLUSIONS

In this short paper we have presented a summary of the key findings from our five seasons of surface hoar observations. Our analysis is still ongoing and we anticipate presenting a more detailed and quantitative manuscript in the future. The purpose of this paper is to provide a broader overview of the areas where we have made progress.

Using these unique data, collected over a five year period, we have examined the dominant controls that explain the spatial patterns of surface hoar at the slope to mountain range scale. This work highlights that: surface hoar changes as a function of the micro-meteorological conditions; that small-scale site characteristics which influence the sky view exposure can greatly influence the spatial variability of surface hoar; and that synoptic scale analysis provides insight for surface hoar presence. These results highlight our incomplete, but growing understanding of some of the complexities of surface hoar formation processes at this scale, and have implications for both regional and local scale avalanche forecasting. Given that this layer only presents a hazard once buried, future work will focus on both the preferential deposition of, but also the preservation of surface hoar at the slope to range scale.

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