THE EFFECTS OF CANOPY COVER AND SHADING ON SURFACE HOAR SIZES IN SMALL FORESTED MEADOW OPENINGS

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ABSTRACT: Understanding variations in slope scale snowpack properties influences stability assessments at the slope and regional scale. Previous studies have shown that surface hoar, a prominent weak layer type, can vary in initial crystal size and height across small, seemingly homogenous meadows and sparsely forested areas on northerly aspects. The differences in size have generally been attributed to the radiation balance, which is difficult to estimate in the field. This study aims to further investigate the effect of canopy cover and shading on the growth of surface hoar in small forested meadow openings just after initial growth and prior to burial. Two small (approx. 30m x 50m) study plots located in southwest Montana were selected. The study plots, one northern and one southern aspect, are mostly planar 10° meadows surrounded by heavy tree cover. We collected 200 samples with 2119 individual crystal observations, and estimated shading and hemispheric sky visibility to explain the difference in sizes of surface hoar in each meadow. Findings indicate that the strength of these determinants varies depending on aspect and how the surface hoar size is determined.

KEYWORDS: surface hoar, canopy cover

1. INTRODUCTION

Layers of buried surface hoar present a challenge for backcountry recreationalists and avalanche forecasters when creating a stability assessment or hazard forecast. While surface hoar has been observed to grow over large areas during specific meteorological conditions, its distribution can be difficult to describe at both large (mountain range) and small (slope) spatial scales. To further increase its spatial variability after growth but before burial, surface hoar may be destroyed by elements such as wind or solar radiation (McClung and Schaerer, 2006).

Simply stated, surface hoar forms through a process known as deposition. During the night-time and potentially during the day, snow surface temperatures are largely a function of net longwave radiation loss to the atmosphere. As the snow surface cools, the boundary layer air mass is also cooled and depending on moisture content, becomes supersaturated (Lang et al., 1984). A large vapor pressure gradient forms at the surface and deposits this moisture onto the snowpack with light winds needed to replenish lost moisture.

Surface hoar does not pose a hazard until it is buried by subsequent snowfalls. Buried layers form persistent weak layers that are difficult to destroy via metamorphism once buried and can remain unstable for some time. While the growth mechanisms, mechanical properties and strength of surface hoar have been studied (e.g., Lang et al. 1984; Colbeck, 1988; Hachikubo and Akitaya, 1998; McClung and Schaerer, 2006), the spatial distributions of surface hoar at mountain and slope scales are not well understood (Hendrikx et al., 2012; Feick et al., 2007). Since the rate of strengthening for surface hoar can depend on grain size (Jamieson and Schweizer, 2000), understanding the distribution of surface hoar sizes across small slopes is important for stability evaluations.

Cooperstein (2008) found that surface hoar layers can be unevenly distributed across small slope scales in both presence and size and these factors were strongly related to aspect and radiation. Feick et al. (2007) suggest that in complex mountain terrain, predicting surface hoar formation would be nearly impossible unless high spatial resolution local winds were

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known. Lutz and Birkeland (2011) found that even with aspect held relatively constant, surface hoar weak layer height distributions varied from 3 to 21 mm in a north facing meadow with tree canopy cover and radiation differences a likely cause. Shea (2011) examined surface hoar sizes from north facing, sparsely treed slopes and skyview using 175° circular fisheye photography and found positive correlations between surface hoar size and open skyview percentage. Hendrikx et al. (2012) and Schweizer and Kronholm (2004) found that surface hoar can be aspect dependent but small scale meteorological and other factors such as tree cover can greatly influence its distribution at larger mountain range scales.

Clearly the variables driving small scale surface hoar distributions are not well understood. This makes stability evaluations for backcountry users difficult when there is a buried layer of surface hoar, especially when skiing multiple aspects, elevations and locations during the day with no prior knowledge of the surface hoar distribution or small scale meteorological patterns. While estimating small spatial scale winds for a formation event are nearly impossible, field estimates of canopy cover and shading may be easier to estimate and could provide a proxy for relative sizes for a surface hoar formation event.

This paper investigates the differences in relative surface hoar size across small forested and inclined meadow openings typical of backcountry skiing and snowmobiling terrain in southwest Montana, USA. We seek to determine if canopy cover or shading plays a role in the patterns of relative size on overnight formations of surface hoar, prior to burial or subsequent formation events. The study aims to improve the understanding of tree shading along with aspect. We hope results will allow for a better understanding of the distribution of surface hoar sizes for areas lacking any high resolution land cover data or meteorological instrumentation, including a full radiation balance.

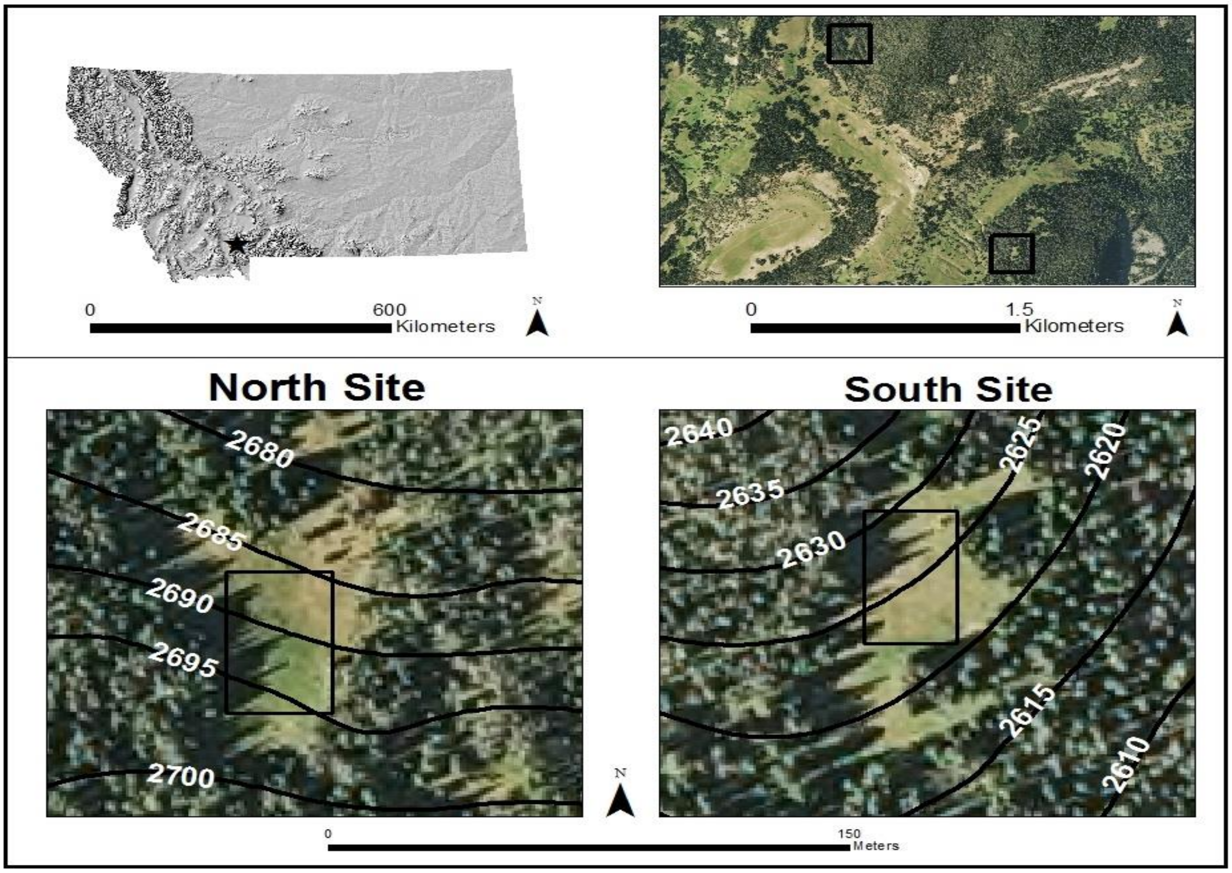

Fig. 1: The Taylor Fork study sites (44° 58' N; 111° 16') are located in southwestern Montana. The sites are separated by a distance of 1.7 kilometers.

2. METHODS

2.1 *Field area*

This study is located in the Madison range of southwest Montana in the area between Big Sky and West Yellowstone (Fig. 1). The south site faces approximately 140° and lies in the Sage creek drainage. This site is approximately 30 m x 50 m and surrounded by primarily subalpine fir and lodgepole pine trees on most sides. There are two small openings on the eastern and western edge of the site. The average slope angle for the site is 10 degrees. The north site faces approximately 15° and lies in the Little Wapiti drainage. The site is approximately 50 m x 60 m with an average slope angle of 11 degrees. A radiation shielded Hobo Pro v2 temperature and relative humidity data logger was placed in the middle of each meadow at the beginning of the winter season.

Data collection occurred immediately following an overnight surface hoar formation event. On the field day, the southerly site was visited first to reduce the possible destruction or morphological changes to the individual crystals due to the larger amounts of incoming radiation during the collection period.

2.2 *Field measurements*

Two hundred samples were collected at each study site on January 25, 2014. At each location from a semi-structured random grid, surface hoar was marked present or absent (Fig. 2). If present, the surface hoar was examined under a hand lens and general size recorded as per Fierz et al. (2009). A sample from a 2 cm^2 was again gathered on the crystal card and the entire card photographed for later verification of size estimates and for recording multiple crystal sizes to quantify the crystal size distribution (Fig. 3). A hemispherical fisheye lens was used to capture 180° circular fisheye photos facing upwards (and level) for later calculations of hemispheric sky visibility (v%) and direct sunlight duration estimates. The height of the lens was approximately 40 cm above the snow surface to allow for the user to not be included in the picture. One hundred crystal card samples and photographs were taken at each site but only 68 were useable on the north site due to a shift in focal length due to creep of the lens zoom while in the field. While numerous attempts were made at collection days during the 2013/2014 season, only one was found to have surface hoar at both sites while also providing optimal conditions for hemispherical photography.

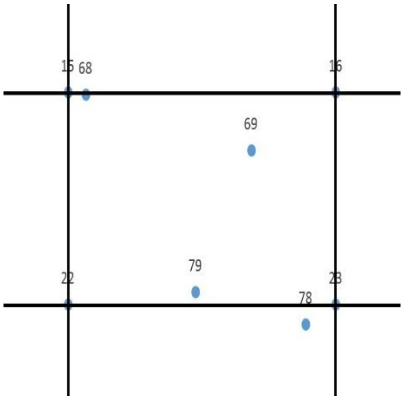

Fig. 2: Partial overview of the sampling method. Gridded points (points 15, 16, 22 and 23) were spaced in a 5 meter grid spacing. Random points were a random distance and direction from each of the gridded points. Numbered points correspond with sequential sample number.

3. DATA ANALYSIS

Sizing of surface hoar crystals on the crystal card for each point were conducted on a computer with the ability to zoom in to each crystal to size. Each sample photo was randomly selected to limit spatial bias. Using these photos, 1203 individual surface hoar crystals were sized on the north facing site and 916 were sized on the south facing site. In order to be sized, only crystals that were easily identifiable were used

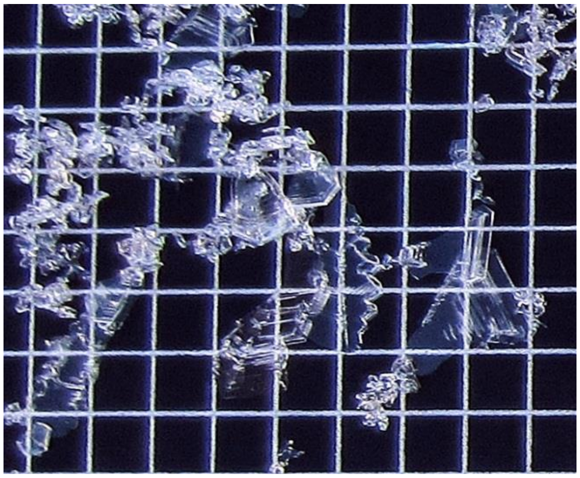

Fig. 3: Photograph of surface hoar crystals from a point on the north facing site on a 2 mm grid.

in the analysis. Sizes were rounded to 0.5 mm, and every observable crystal was recorded, so that an average, maximum and minimum size could be determined.

Determination of hemispheric sky visibility (v%) and shading (via minutes of direct sunlight) was conducted using the program Gap Light Analyzer (GLA) (Frazier et al., 1999). Thresholding of each image was done automatically in the program Sidelook for consistency and to reduce user bias in the conversion to black and white pixels. As the photos were taken under blue sky conditions, the thresholding used a blue channel filter to accurately distinguish between sky and trees. These black and white photos were then imported into GLA and calculations run to produce estimates v% and minutes of direct radiation for 24 January, 2014. One hundred photos were used at the south site and 68 were used at the north site.

The Pearson product-moment correlation coefficient test is used to find correlations between the surface hoar sizes and the environmental factors of hemispheric sky visibility and minutes of direct solar radiation. A $p \leq 0.05$ was used to determine statistical significance. A Welch's t-test is used to test for differences in crystal sizes in the north and south meadow.

4. RESULTS AND DISCUSSION

On the north study site, sky visibility is positively correlated to all crystals sized (Tbl. 1). There are no significant relationships found between mean and maximum crystal size and sky visibility. There are also no significant relationships found between minutes of direct solar radiation and all crystals sizes, mean crystal size or maximum crystal size.

On the south study site, no significant correlations existed between sky visibility and all crystal sizes, mean crystal size or maximum crystal size (Tbl. 1). However, there is convincing evidence ($p < 0.01$) of negative correlations between minutes of direct solar radiation and all crystal sizes, mean crystal size and maximum crystal size at each sample point (Tbl. 1).

While the south site has nearly the same range of canopy openness, the average openness is 11% lower than the north facing site. This southern site saw less variability with crystal sizes as compared with the north site but also had a different distribution of v% (Figs. 4 & 5). With the north facing site exhibiting greater canopy openness, longwave losses may be greater and coupled with less solar radiation, sky visibility may have been the dominating factor. The southern site received, on average, 100 minutes more direct sunlight than the north site. This longer amount of direct sunlight may be a reason why relationships were only found on this site for minutes of direct solar. This is in some agreement with our understanding of surface hoar growth when relating it to aspect (Lutz and Birkeland, 2010 and Cooperstein, 2008). Like Cooperstein (2008), we did find a significant different between crystal size between the north

Tbl. 1: Pearson's product-moment correlation results using all crystal sizes, mean crystal size and maximum crystal size at the study plots. Bold signifies significance ($p \leq 0.05$).

Variables	*Coefficient of Correlation (r)*	*p-value*
North Crystal - All and v%	**0.0755**	**0.04**
North Crystal - Mean and v%	0.134	0.29
North Crystal - Maximum and v%	0.1015	0.43
South Crystal - All and v%	0.0065	0.85
South Crystal - Mean and v%	-0.042	0.67
South Crystal - Maximum and v%	-0.0258	0.79
North Crystal - All and Minutes of Direct Solar	-0.0096	0.79
North Crystal - Mean and Minutes of Direct Solar	-0.2906	0.82
North Crystal - Maximum and Minutes of Direct Solar	-0.1229	0.34
South Crystal - All and Minutes of Direct Solar	**-0.29**	**0.01**
South Crystal - Mean and Minutes of Direct Solar	**-0.4526**	**0.01**
South Crystal - Maximum and Minutes of Direct Solar	**-0.3952**	**0.01**

and south study plots (Welch's t-test, p-value < .01) (Fig. 5).

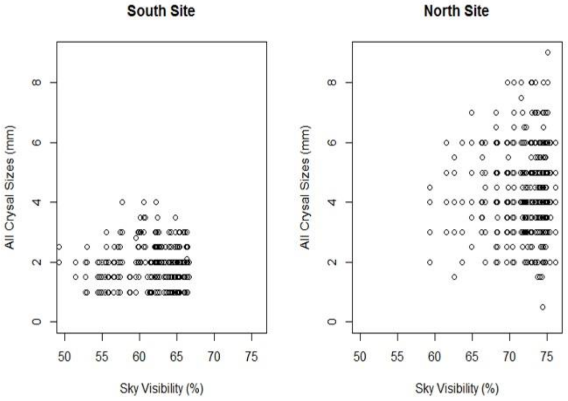

Fig. 4: Scatterplot for all crystals sized versus the sky visibility on the south and north study plots. The X axis is the hemispheric sky visibility (%) and the Y axis is the crystal size (mm).

Findings on the north site are somewhat different than previous work (Lutz and Birkeland, 2011 and Shea and Jamieson, 2010). Lutz and Birkeland (2011) found trends with both v% and minutes of direct sun exposure on their northerly facing study plot that was very similar in nature to the one in this study but with a steeper slope (24-29° vs. 9-11°). However, they measured the thickness of the surface hoar weak layer using a SnowMicroPen and did not measure the surface hoar size, so this might be a reason for our differing results. While Shea (2011) did find correlations between mean surface hoar size and v% while looking at sparsely forested northerly facing areas as opposed to meadow openings, mean size for each point in this paper did not show any significant correlations and similar findings were only evident when looking at all identified crystals at the north plot.

While the south site does not appear to be as affected by sky visibility, there is convincing evidence that areas that receive lower amounts of direct solar, e.g., shadier areas, did grow larger surface hoar in this meadow. This result may be a function of the early morning sampling and possible destruction before burial would change this. Lacking any prior meteorological data, an observer may have a good chance of finding the larger surface hoar in a meadow by looking at the daytime shading. Our findings indicate that distributions of overnight surface hoar growth in north and south meadow openings are still difficult to forecast and possibly depend on how crystals are sized or additional untested factors.

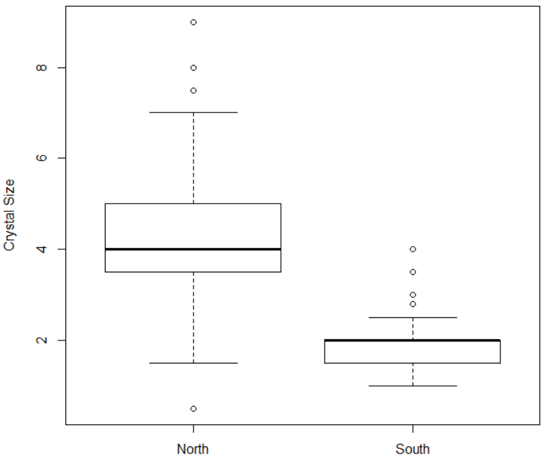

Fig. 5: Box plot showing all crystals sized on the north and south study plots. The bold line represents the median, the box represents the interquartile range, and the whiskers 1.5 the interquartile range. Dots represent outlier values.

One important factor that was not included in our study is the effect of wind. Since wind helps to replenish the moisture that is lost during deposition, and excess wind may prevent surface hoar formation, not accounting for this in the study may be a limiting factor. Measuring wind velocities on a scale that Fieck et al. (2007) suggest is inherently difficult in these small meadow openings and the surface wind field networks that would be required are not readily available to backcountry users or in this forecasted area. Using hemispheric sky visibility as a proxy for net longwave loss may also not be adequate to capture the complex radiation balance that occurs in these small areas. Re-radiation from trees and also small irregularities in the snow surface create a more complex system that only energy balance models such as RadThermRT may estimate (Adams et al., 2009).

Finally, another difficult concept is the sizing of the surface hoar. While studies have used surface hoar sized both in the field, in a lab with a microscope, or both, most have not accounted for the large variability in sizes that can occur in a small (2 cm^2) area. Like Stössel et al. (2010), we found that crystal sizes varied by a large amount in a small sample. This presents a challenge when deciding on analysis parameters. Our results on the north site indicate that if only maximum crystal size is used, there may be no relationships to our studied variables. However, our results change if we look at all crystals on the card.

This study is one of the few to quantify the distribution of surface hoar sizes found at a single location. We quantified a great deal of variability in sizes at almost every observation. Smaller crystals were almost always nested within larger ones. This variability may lead to different outcomes depending on the analysis of a sample or the sampled area. Further, if just maximum crystal size is used, this may also present challenges as sometimes these larger crystals are not seen at a high density and may also be tilted in an orientation that would not correspond with a weak layer height equaling the crystal size when buried. Future work should consider this micro-scale variability when looking at the spatial patterns of surface hoar.

5. CONCLUSIONS

While some results matched previous work, others were not in agreement showing that predictions remain difficult. In south facing forested meadows it may be possible to find the largest surface hoar in areas that see the most shading. Changes in canopy cover in both meadows only showed useful trends in north facing areas when all crystals were considered. While the findings of this research provide additional insight, a larger set of study days are needed for a further understanding of these events. Surface hoar continues to be a difficult persistent weak layer to forecast for relative sizes in the field.

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