

EXAMINING THE DRIVERS THAT CONTROL THE SPATIAL VARIABILITY OF SURFACE HOAR AND NEAR-SURFACE FACETS

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ABSTRACT: Surface hoar and near-surface facets, once buried, often produce a persistent weak layer that is a common instability problem in the snow pack in SW Montana and many other areas around the world. It is relatively well understood that aspect plays an important role in the location of the growth, and survival of these grain forms, due to the unequal distribution of incoming radiation. However, this alone does not completely explain the complex and often confusing pattern of these grains forms throughout the landscape at larger spatial scales.

In this paper we make a preliminary analysis of the spatial variability of near-surface facets and surface hoar, using data from a detailed case study located at the Yellowstone Club in southwestern Montana. We examine paired snowpack and meteorological observations for 15 sites distributed across all four aspects and at different elevations on Pioneer Mountain. At every site, sub-weekly manual observations of surface grain forms were made, while 15 minute data on air temperature and relative humidity data were continually recorded at 1.5m above the snow surface. Using these snowpack and meteorological data, combined with topographic variables and modeled solar radiation, we examine the dominant controls that can discriminate between periods of surface hoar and periods without. We also consider each site individually and note that not one site always exhibits surface hoar during every facet event. This analysis highlights that small-scale meteorological differences and local scale lapse rates can greatly influence the spatial variability of these grain forms, over and above that which aspect alone can explain. These results highlight our incomplete understanding of the processes at this scale, and are likely to have implications for both regional and local scale avalanche forecasting in environments where these grain forms cause ongoing instabilities.

1. INTRODUCTION & BACKGROUND

Knowledge of spatial variations in snow stability and snowpack properties is critical for understanding and predicting snow avalanches. One type of weakness that is commonly responsible for slab avalanches is surface hoar (Schweizer and Lutschg, 2001). This is a weak, feathery type of snow crystal that grows on the surface of the snow under specific atmospheric conditions, and once buried can remain in the snowpack for months, presenting a persistent avalanche hazard.

Surface hoar can be thought of as frozen dew that grows on to the snow surface. The surface snow needs to be cooled to well below the air temperature by a net longwave radiation loss,

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and excess water vapor from the near-surface air deposits onto the snow surface through deposition. Surface hoar formation and growth have been shown to be highly dependent on snow surface temperature (e.g. Oke, 1987; Gubler, 1998), and the degree of supersaturation at the boundary layer relative to the snow temperature (e.g. Jamieson and Schweizer, 2000). Many studies have examined the micro-meteorological conditions that facilitate surface hoar growth (e.g. Lang et al., 1984; Colbeck, 1991; Hachikubo, 2001). It has been recognized that local scale topographic winds and topographic variances and ground cover, can alter both the supply of moisture and the conditions for surface hoar formation and persistence (Birkeland, 2001; Höller, 2001; Cooperstein et al., 2004). Furthermore, it is relatively well understood that aspect plays an important role in the location of the growth, and survival of surface hoar, due to the unequal distribution of incoming radiation (e.g. Feick et al., 2007; Lutz and Birkeland, 2011). Despite all of this work, these variables alone do not completely explain the complex and often

confusing pattern of these grains forms throughout the landscape at larger (e.g. Mountain range) spatial scales.

Though recent research has investigated the spatial variability of various weak layers on individual slopes (e.g. Birkeland et al., 2004; Landry et al., 2004; Lutz et al., 2007), and more recently at larger mountain range scales (e.g. Feick et al., 2007; Borish et al., 2010; Borish et al., 2012), almost all of the previous work has simply looked at a single snapshot in time of an extremely dynamic system. The studies that have considered the temporal component are limited to small, uniform study slopes, and not of the wider mountain-range scale (e.g. Hendrikx et al., 2009; Lutz, 2009; Lutz and Birkeland, 2011). In sharp contrast, this wider mountain range scale is the typical scale at which avalanche forecasts are issued.

This paper aims to provide a preliminary step towards filling this temporal and spatial scale-gap in our knowledge by addressing the following question: How does the spatial variability of surface hoar growth vary at a large, mountain range scale?

2. METHODS

2.1 Field Data

On 9 January 2012, we deployed 15 mini-temperature and relative humidity sensors (HOBO U23 Pro v2) which were mounted inside solar radiation shields (RS3). These were installed across all four aspects and at different elevations on Pioneer Mountain, at the Yellowstone Club in SW Montana (Figure 1). Topographic attributes including aspect, elevation and exposure were recorded or calculated for each site. The sensors were installed on PVC pipes, 1.5m above the snow surface (Figure 2). 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 15 sensors, more than 220,000 lines of data were recorded.

At each of these sites, we also collected field data, at sub-weekly intervals, on the presence / absence and size of surface hoar and near surface facets. Data was collected from 9 January until 15 April,

2012. In total over 22 periods with 170 individual observations of snow conditions were collected, with 99 recording no surface hoar or near surface facets and 71 with surface hoar evident.

2.2 Data Analysis

For each period of observations (i.e. times when the field observations were made), we assessed if the presence of surface hoar or near surface facets was; spatially complete, partial or absent across the landscape. We noted the times when these differing spatial extents occurred and will review these results in more detail in a later paper. Due to the lack of near surface facets recorded over this period, we limited ourselves to surface hoar.

In addition, for each site we examined the number of facet events as a percentage of the number of times the site was visited. We plotted these percentages against simple topographic parameters such as elevation and aspect to determine if there were any obvious trends. We then combined the manual snowpack observations and the automatic meteorological record by sampling the period during, and prior to, a recorded event. A recorded event was classed as either a non-facet event (i.e. no surface hoar or near surface facets) or a facet event.

For each facet event and non-facet event we extracted both the current and the prior 24 hours of meteorological data from the relevant site. In addition to these observations, we recorded the elevation, aspect and exposure of each site, where exposure is a simple index based on sky view and terrain convexity. We also modeled incoming solar radiation for each of the periods, at each of the sites. To estimate incoming solar radiation we used ESRI ArcGIS 10.1, spatial analyst. However, we only used these estimates of solar radiation in three categories of; low, moderate and high and only for the site specific analysis. A more robust estimation and ground truthing of incoming solar radiation is required for a more quantitative assessment. Using these data, we then plotted simple box and whisker plots to examine if there were any obvious difference between these meteorological parameters for periods with surface hoar and periods without. We also undertook a simple non parametric statistical analysis, the Kolmogorov-Smirnov two-sample test (Conover, 1999), to compare facet events with non-facet events.



Figure 1: An oblique image of the Yellowstone Club, looking SW as seen from Google Earth showing the location of the sensors for the 2011/12 winter study. Sensors were placed on each aspect, and at multiple elevations (Note the SW aspect is mostly obscured from this view) (Google, 2012)



Figure 2: Members of the Yellowstone Club Ski Patrol assists with the installation of the 15 mini temperature and RH loggers for the 2011/12 winter study. Each of these sites was visited at least weekly to measure surface hoar and when needed to download the data (Photo: Jordy Hendrikx, 2012)

3. RESULTS

During the period of observation from 9 January to 15 April 2012, we collected data on 22 unique periods. Out of these 22 periods sampled, only 5 periods exhibited surface hoar at all sites visited, while 7 periods displayed more spatially diverse surface hoar extents, with between one and eleven sites having surface hoar present depending on the period. A further 10 periods had no surface hoar evident at any of the sites visited.

When we consider the data by site, rather than by period, we observe that none of the sites always had surface hoar when it was observed somewhere within the study area. Two locations (site 9 and 1) had 10 and 11 facet events respectively. Interestingly, these sites are both approximately south facing, but are in sheltered locations. When the number of facet events at each site is expressed as a percentage of the number of times that each site was visited we see that there are three main groups of sites (Table 1). Group 1 are sites with facets at each site at least 50% of the time, and is comprised mainly of northern aspect sites, or southern aspect sites that are very well sheltered. Group 2 are sites with

facets at each site more than 33% of the time, but less than 50% of the time, and the locations are more diverse with aspects ranging from south to north east and north west. Group 3 sites are sites that seldom see facets at each site, with less than 33% of the time, and somewhat surprisingly, are mainly north and north east aspects. When we plotted these percentages against simple topographic parameters such as elevation and aspect there were no distinct or significant trends in the data, other than a very slight positive trend (with a low linear R^2 of 0.2), with increasing elevation.

Table 1: The percentage of facet events for each of the sites and the associated topographic parameters of aspect, exposure, elevation and calculated incoming solar radiation. Sites are grouped by %SH from; Group 1 $\geq 50\%$; Group 2 $\geq 33\%$, $< 50\%$; Group 3 $< 33\%$.

Site	% SH	Aspect	Solar radiation	Exposure	Elevation (m)	Group
1	60%	S	High	Sheltered	2758	1
5	55%	N	Low	Sheltered	2532	1
11	55%	N	Low	Exposed	3006	1
9	53%	S	Mod	Sheltered	2340	1
6	50%	N	Low	Exposed	2804	1
13	50%	NW	Mod	Sheltered	2862	1
14	46%	S	High	Exposed	2877	2
7	38%	E	Mod	Sheltered	2292	2
10	38%	NW	Mod	Sheltered	2621	2
12	35%	E	Mod	Sheltered	2201	2
4	33%	NE	Mod	Exposed	2847	2
15	27%	N	Low	Sheltered	2370	3
3	23%	NE	Low	Sheltered	2554	3
2	0%	NE	Low	Sheltered	2582	3
8	0%	NE	Low	Sheltered	2295	3

When we consider the pooled meteorological data for the periods with facet events and non-facet events, the non-parametric Kolmogorov-Smirnov two-sample test indicated that some of the meteorological parameters are statistically different for facet events when compared to non-facet events (Table 2). Of the parameters that were statistically significant, two were significant at the $p < 0.025$ level (Relative Humidity 24 hours prior and DewPoint 24 hours prior), while the air temperature 24 hours prior was significant at the $P < 0.005$ level. Note that dew point is a calculated variable using temperature and relative humidity and is not independent.

Table 2: Kolmogorov-Smirnov two-sample test comparing facet events with non-facet events. Shaded rows indicate tests were significant at the $p < 0.05$ level.

	p-value	Mean Facet	Mean Non-Facet	Std.Dev Facet	Std.Dev Non-Facet
Exposure*	$p > .10$	1.78	1.83	0.41	0.37
Elevation (m)	$p > .10$	2564	2512	259	251
Aspect ($^{\circ}$ from N)	$p > .10$	175.7	144.3	84.80	92.28
Temp ($^{\circ}$ C)	$p > .10$	-4.11	-1.41	4.29	8.17
RH (%)	$p > .10$	67.94	60.95	17.62	21.76
DewPoint ($^{\circ}$ C)	$p < .10$	-9.68	-9.07	2.85	6.56
Temp T-24 ($^{\circ}$ C)	$p < .005$	-4.44	-3.70	3.56	7.58
RH T-24 (%)	$p < .025$	72.16	60.48	20.73	19.49
DewPoint T-24 ($^{\circ}$ C)	$p < .025$	-9.53	-10.97	3.62	5.03

* Where exposure is an index based on sky view and terrain convexity.

4. DISCUSSION AND CONCLUSIONS

The analysis of the pooled meteorological and topographic variables result in findings consistent with previous work, that highlights the importance of higher levels of relative humidity and cool temperatures to facilitate surface hoar growth (e.g. Lang et al., 1984; Colbeck, 1991; Hachikubo, 2001). This is evident from the statistically significant difference in the air temperature, relative humidity and dew point temperatures for the period 24 hours prior to surface hoar observations for the facet events, when compared to the non-facet events. This is likely to have been the period during, or just prior to, surface hoar growth.

However, when we consider the data regarding the individual sites, we note that not one site exhibits surface hoar during every facet event, where a facet event is considered to occur when at least two sites have surface hoar present. We also note that contrary to our understanding of the dominant role of aspect (e.g. Cooperstein et al., 2004; Lutz and Birkeland, 2011), and hence the

incoming solar radiation, that the sites with the greatest % of surface hoar presence were not solely the sheltered northerly aspects, as expected. While northerly aspects did feature in our group 1 (with presence $\geq 50\%$ of the time), so too did two southern aspect locations. Furthermore, and somewhat surprisingly, our group 3 sites, with the lowest presence of surface hoar recorded ($< 33\%$ of the time), were mainly north and north east aspects, contrary to expectations. In part, these results may be an artifact of the sampling regime, in that not all sites were sampled every time, nor every day when there was surface hoar somewhere in the study area, and therefore we are dealing with a heterogeneous sample for each site. For example, site numbers 8 and 2, both with a recorded surface hoar occurrence of 0% and NE facing, where only visited 3 and 4 times respectively. With a smaller sample size of observations, it is probable that these may have been during occasions when, by chance, no surface hoar was present. Despite these limitations, and our small data set, our data indicates that the spatial variability of the presence of surface hoar is more typically not homogenous and continuous across the landscape, but rather, much more heterogeneous at this larger spatial scale.

This preliminary analysis highlights that small-scale meteorological differences and local scale lapse rates can greatly influence the spatial variability of these grain forms, over and above that which aspect alone can explain. A more in-depth study, including more quantitative modeling of solar radiation across these spatial scales is needed, to better understand the controls of the spatial distribution of surface hoar at these larger spatial scales. Our current lack of understanding at these spatial scales, compound our efforts to spatially extrapolate point information at these scales. A better understanding of these limitations in our abilities to extrapolate these data is likely to have implications for both regional and local scale avalanche forecasting in environments where surface hoar can cause persistent instabilities.

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REFERENCES

- Birkeland, K.W. 2001. Spatial patterns of snow stability throughout a small mountain range. *Journal of Glaciology* 47(157), 176-186.
- Birkeland, K., Kronholm, K., and Logan, S., 2004. A comparison of the spatial structure of the penetration resistance of snow layers in two different snow climates. *Proceedings of the International Symposium on Snow Monitoring and Avalanches*, Manali, India.
- Borish, M., Birkeland, K.W., Challender, S., Custer, S., 2010. The spatial distribution of two surface hoar events in the Chilkat and Takhinsha Mountains of southeast Alaska. *Proceedings of the 2010 International Snow Science Workshop*, Squaw Valley, California.
- Borish, M., Birkeland, K.W., Custer, S., Challender, S., Hendriks, J., 2012. Surface hoar distribution at the scale of a helicopter skiing operation. *Proceedings of the International Snow Science Workshop*, September 17-21, 2012, Anchorage, Alaska.
- Colbeck, S.C. 1991. The layered character of snow covers. *Review of Geophysics* 29(1), 81-96.
- Conover, W.J., 1999. *Practical Nonparametric Statistics* (3rd Edition). Wiley, USA. 592pp.
- Cooperstein, M., Birkeland, K., and Hansen, K., 2004. The effects of slope aspect on the formation of surface hoar and diurnally recrystallized near-surface faceted crystal: implications for avalanche forecasting. *Proceedings of the 2004 International Snow Science Workshop*, Jackson Hole, Wyoming.
- Feick, S., Kronholm, K., and Schweizer, J., 2007. Field observations on spatial variability of surface hoar at the basin scale. *Journal of Geophysical Research – Earth Surface*, 112, F02002, doi:10.1029/2006JF000587
- Google, 2012. Google Earth Image of Pioneer Mountain, 45°14'27.15" N 111°26'24.62" W. 11 August, 2011. Accessed, 21 January, 2012.

- Gubler, H. 1998. A model to determine snow surface properties from remote measurements. *Proceedings of the 1998 International Snow Science Workshop*, Sunriver, OR., U.S.A., pp. 35-48.
- Hachikubo, A. and Akitaya, E. 1997. Effect of wind on surface hoar growth on snow. *Journal of Geophysical Research* 102, 4, 4367-4373.
- Hendrikx, J., Birkeland, K., and Clark, M.P., 2009. Assessing changes in the spatial variability of the snowpack fracture propagation propensity over time. *Cold Regions Science and Technology*, 56, 152-160. DOI: 10.1016/j.coldregions.2008.12.001
- Höller, P., 2001. The influence of the forest on night-time snow surface temperature. *Annals of Glaciology*, 32: 217-222.
- Jamieson, J. B., and Schweizer, J., 2000. Texture and strength changes of buried surface hoar layers with implications for dry snow-slab avalanche release. *Journal of Glaciology*, 46 (152): 151-160.
- Landry, C., Birkeland, K., Hansen, K., Borkowski, J., Brown, R., and Aspinall, R., 2004. Variations in snow strength and stability on uniform slopes. *Cold Regions Science and Technology*. 39, 205-218.
- Lang, R.M., Leo, B.R., Brown, R.L. 1984. Observations on the growth process and strength characteristics of surface hoar. *Proceedings of International Snow Science Workshop*, 1984, Aspen, CO, 188–195.
- Lutz, E.L. 2009. Spatial and temporal analysis of snowpack strength and stability and environmental determinants on an inclined, forest opening. Ph.D. Dissertation, Department of Earth Sciences, Montana State University. 364 pp.
- Lutz, E.R. and Birkeland, K.W., 2011. Spatial patterns of surface hoar properties and incoming radiation on an inclined forest opening. *Journal of Glaciology* 57(202), 355-366.
- Lutz, E.R., Birkeland, K.W., Kronholm, K., Hansen, K., and Aspinall, R., 2007. Surface hoar characteristics derived from a snow micropenetrometer using moving window statistical operations. *Cold Regions Science and Technology* 47(1-2), 118-133, doi:10.1016/j.coldregions.2006.08.021.
- Oke, T. R., 1987. *Boundary layer climates*. Routledge, London, U.K. pp. 435
- Schweizer, J. and M. Lutschg, 2001. Characteristics of human-triggered avalanches. *Cold Regions Science and Technology*, 33, 147–162.