SURFACE HOAR DISTRIBUTION AT THE SCALE OF A HELICOPTER SKIING OPERATION

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ABSTRACT: Understanding what controls coarse scale snowpack properties, such as surface hoar distribution, is imperative for predicting snow avalanches. Due in part to the inherent difficulties of winter travel in mountainous terrain, most spatial variability investigations of snow properties have been limited to relatively fine scales. To quantify snow surface spatial variability at the basin, region, and mountain range scales, a team of heli-skiing guides collected data throughout four major surface hoar formation periods over two heli-skiing seasons in rugged alpine terrain near Haines, Alaska across an extent of nearly 60km. Geographically weighted regression revealed a positive relationship between elevation and surface hoar crystal size with adjusted R^2 values averaging near 0.40. Geostatistical analysis yielded spherical semivariogram autocorrelation ranges from approximately 3-25km, which is similar in size to many of the basins and regions within the study area. Kriging models built from the semivariograms were produced to aid geographic visualization of coarse scale snowpack processes. The results of this research suggest it may be possible to identify areas with greater surface hoar growth and persistence potentials as a consequence of synoptic onshore or offshore flow, and glacially influenced katabatic winds. These results can help in future efforts to forecast snow stability patterns over large areas.

1. INTRODUCTION

Surface hoar is a deadly snowpack weak layer and is responsible for more accidents involving professionals than any other weak layer type (Jamieson, 1995). Many studies have examined surface hoar formation at relatively fine snowpack process scales (i.e. Lang et al., 1984; Colbeck, 1988; Hachikubo and Akitaya, 1997; Cooperstein et al., 2004; Shea and Jamieson, 2010; Lutz and Birekland, 2011) and a few have focused on coarser scales (Feick et al., 2007; Schweizer and Kronholm, 2007). This research was conducted across a very large area, compared to previous studies, within an Alaskan heli-skiing company's permitted tenure and builds upon preliminary results first presented in Borish et al., (2010).

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2. METHODS

2.1 Study Area

Southeast Alaska Backcountry Adventures (SEABA) operates in the rugged Chilkat and Takhinsha Mountains across an expanse of nearly 1000km^2 west of Haines, Alaska. During winter, onshore coastal flow, offshore northerly flow, and split flow are the predominant synoptic weather patterns of Haines' high-latitude maritime climate (Scheler et al., 2004). Onshore flow generally involves southwest to southeast maritime flow that typically brings the warmest winter temperatures. Northwest to northeast offshore flow is characterized by continental polar air masses originating from the arctic and is associated with bitterly cold temperatures. Split flow is a transitional period between the two aforementioned regimes. During split flow, relatively warm and moist air masses can override entrenched cold air blocked against massive coastal relief and produce large snowfalls at low elevations (Coleman, 1986). Low level effects of these synoptic patterns are often localized and greatly influenced by terrain.

2.2 Data Collection

SEABA guides recorded observations during four major surface hoar formation periods throughout the 2010 and 2011 heli-skiing seasons. Although this research benefitted substantially from its coupling with a heli-skiing operation, there were trade-offs. On one hand, collaboration allowed data collection across a large area in a short period of time which would have otherwise been impossible. Conversely, it meant that some sacrifices had to be made. First and foremost, guides' greatest responsibilities revolved around client and personal safety. Additionally, heli-ski guiding alone is demanding and often doesn't permit extensive snowpack analysis or avalanche risk assessment (Carter et al., 2006). As a consequence of these factors the decision was made to focus on collecting a realistic amount of data that could still be usefully analyzed.

An alpine meteorological station was constructed at approximately 1300m elevation near the center of the study area during February 2010 to monitor potential surface hoar formation periods and improve on our understanding of its formation and persistence. Instrumentation for 2010 included a Campbell Scientific, Inc. CR10x data-logger, a Vaisala HMP45C temperature and relative humidity probe, and a Met-One Instruments, Inc. 034B wind speed and direction anemometer. For 2011, a Licor LI200x pyranometer was added to measure incoming shortwave radiation. A 70W solar panel and a 32Ah absorbed glass mat battery supplied power to the alpine site. Real time weather station data was made available online using Campbell Scientific RTMC Web Server software.

When conditions looked favorable for surface hoar formation (based upon weather station wind speed, relative humidity, and satellite imagery) or it had been observed in prior days, guides were informed in morning meetings and prepared to make observations. If surface hoar was found by a guide in the field, they communicated it to other guides who then began taking observations when possible. Based upon group dynamics, terrain difficulty, and avalanche conditions, guides calculated their ability to collect project data before descending each run. If they deemed collection to be feasible, they attempted to acquire 3-6 observations per run that were approximately equally stratified by elevation. When no obvious surface hoar was observed at a sample location, the snow surface was classified as diurnally recrystallized near surface facets. Sample aspects were biased and slopes between approximately 135 to 225 degrees were rarely sampled since Alaskan heli-skiing outfits often avoid south facing slopes while seeking dry powder snow and managing avalanche risk (Carter et al., 2006).

Data collection feasibility for 2010 and 2011 was based upon practice observations and subsequent sampling strategy refinements established during the 2009 season. This study emphasized the collection of consistent data deemed to be the most valuable across an expansive amount of terrain as efficiently as possible so as not to impede guiding duties. Therefore, guides focused on collecting observation data describing the presence or absence of surface hoar, surface hoar crystal size, UTM coordinates, and elevation.

Snow crystal cards with 1 and 2 mm grids were used to measure average surface hoar size along the longest crystal axis. Garmin eTrex GPS recreational grade GPS units were used to log sampling location UTM coordinates and elevation. GPS units employed Wide Area Augmentation System (WAAS) real time differential correction capability which kept unit accuracy to approximately 5m horizontally and 15m vertically.

2.3 Data Analysis

Geographically Weighted Regression was used to examine the relationship between surface hoar crystal size and elevation. This technique has been employed in prior work by Brunsdon et al., (2001) to describe spatial variations in precipitation at meteorological stations in Great Britain. The GWR model was calculated in ESRI ArcMap™ 9.3 using an adaptive distance decay kernel which accounts for sample point density and is based upon the minimum root mean square prediction error from a range of bandwidths.

The second stage of analysis investigated surface hoar spatial structure, specifically presence or absence autocorrelation length, with indicator semivariograms built using the Gamma Design Geostatistics Plus 9.0 software package (GS+™). When looking at the presence or absence of something across a geographical area, an indicator semivariogram is the preferred method to identify spatial structure (Webster and Oliver, 2001), and this technique has been used previously for similar work (Schweizer and Kronholm, 2007; Feick et al., 2007). In essence, the semivariogram relates semivariance to sampling lag, and can be illustrated as a plot that demonstrates the spatial dependence of each point on its neighbor (Curran, 1988).

Kriging models were fit to indicator semivariograms using GS+™ which were exported to ArcMap™ and used to map field area locations that had a higher or lower probability of surface hoar presence. Kriging is a method of spatial interpolation used to discover general properties of a surface by extrapolating missing values from observational trends (Longley et al., 2005) and provides a measure of uncertainty for estimated values (Issaks and Srivasttava, 1989).

3. RESULTS AND DISCUSSION

Two surface hoar formation events occurred in 2010; one from March 20th to March 22rd and the other from April 8th to April 11th. In 2011, two more events spanning March 17th to March 22nd and April 1st to April 2nd were observed. Data from all four periods are summarized in Table 1.

Regression analysis assumes data spatial independence and failing to account for the spatial structure in data may produce inefficient regression parameter estimates and inflated or deflated standard errors which can cause potentially significant parameter estimates to appear otherwise (Fotheringham et al., 2002). Consequently, we performed a Moran's Index test to assess the amount of spatial autocorrelation present within the residuals of Ordinary Least Squares and Geographically Weighted Regression models. The Moran's Index test has been utilized in antecedent avalanche spatial variability research by both Hendrikx et al., (2009) and Eckert et al., (2011). While some spatial autocorrelation was still present within the GWR residuals, it was less evident than the OLS model and mostly found in areas where it could be expected as a result of lower data density. GWR revealed a positive relationship between elevation (explanatory variable) and surface hoar crystal size (independent variable) with adjusted R^2 values from the four events averaging near 0.40 (Table 2). Event 3 produced an artificially low R^2 value since almost all of the surface hoar observations came from only the highest elevations of the study area within a very narrow elevation band.

Geostatistical analysis yielded spherical semivariogram autocorrelation ranges from approximately 3-25km for 3 of the events, which is similar in size to many of the basins and regions within the study area (Figure 1). The fourth event had a very short range of only 1.2km. However, due to the small sample size and extent, extrapolation of these results to a larger area should be done cautiously. A stable air mass and weak air pressure gradient during event 2 may provide an explanation for its high calculated range value.

Upon examination of the kriging maps calculated from our semivariogram analysis (Figure 2), several trends were elucidated. Interpolated surface hoar probability presence was greatest towards the center of the study area. This may be a result of greater synoptic inflow and outflow wind influences which are often strongest near Lynn Canal on the eastern boundary of the study area, along the north/south oriented Tsirku River, and adjacent to the Haines Summit (pass) northwest of the study area. It is thought that katabatic winds may reach greater velocities in these areas from positive feedback interaction with synoptic winds, thus impeding surface hoar growth and persistence. Additionally, there are several large massifs close to the center of the study area which sometimes block prevailing flow near 800mb which may lead to more favorable conditions for surface hoar formation and persistence.

Day	Observations (n)	Observed S.H.	Observed N.S.F	S.H. Presence (%)	Mean S.H. Size(mm)
Event 1					
3/21/2010	78	49	29	63	4.5
3/22/2010	107	69	38	64	3.4
3/23/2010	26	12	14	46	2.1
Total	**211**	**130**	**81**	**62**	**3.7**
Event2					
4/8/2010	24	11	13	46	4.5
4/9/2010	78	72	6	92	5.2
4/10/2010	27	19	8	70	4
4/11/2010	14	5	9	36	6
Total	**143**	**107**	**36**	**75**	**4.9**
Event3					
3/17/2011	69	15	54	22	1.2
3/18/2011	46	12	34	26	1.1
3/19/2011	66	16	50	24	1.6
3/20/2011	25	9	16	36	1.4
3/21/2011	42	8	34	19	1.1
3/22/2011	42	8	34	19	1.5
Total	**290**	**68**	**222**	**23**	**1.3**
Event 4					
4/2/2011	87	62	25	71	2.8
Total	**87**	**62**	**25**	**71**	**2.8**
Grand Total	**731**	**367**	**364**	**50**	**3.4**

Table 1: Descriptive statistics summarizing the four surface hoar formation events.

Event	R^2	Adjusted R^2
1	0.52	0.37
2	0.75	0.68
3	0.13	0.07
4	0.49	0.44

Table 2: Geographically Weighted Regression correlation coefficient values describing the localized relationship between surface hoar crystal size and elevation.

Event	Support(cm)	Spacing(m)	Extent(km)	Range(km)	Lag(km)	Interval(km)
1	5	255	59.2	6.2	59.2	5
2	5	368	41.9	25.7	41.9	5
3	5	205	20.5	3.9	20.5	5
4	5	238	10.0	1.2	10.0	2

Table 3: Summary table of study scale triplet and indicator semivarogram results.

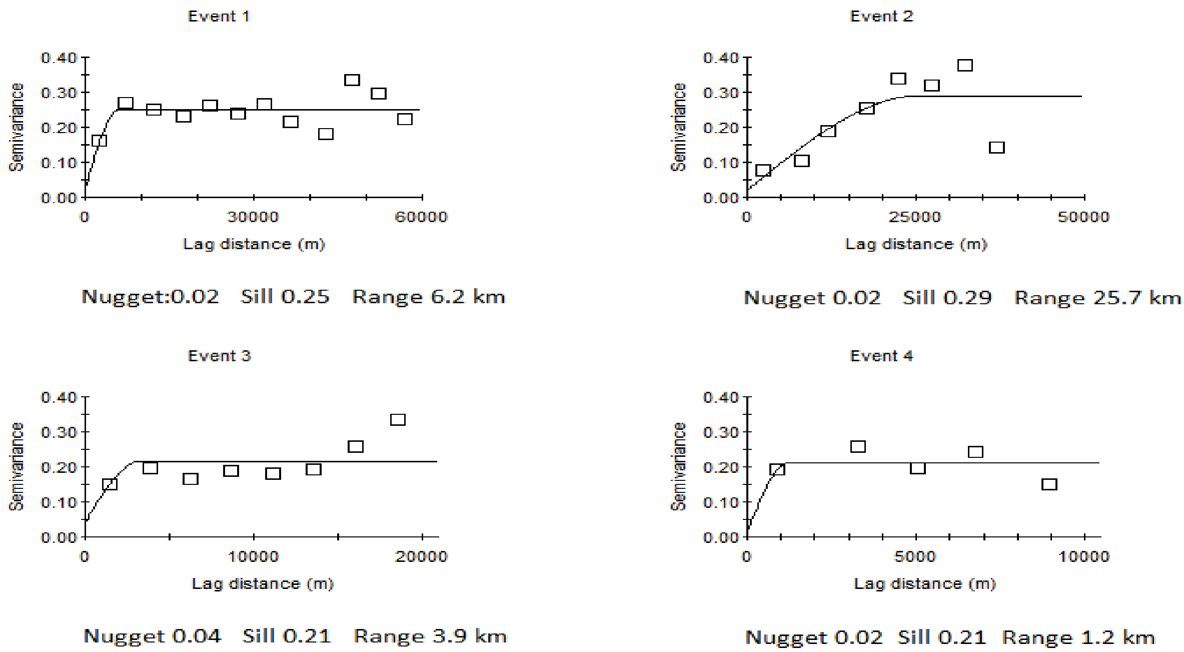

Figure 1: Indicator semivariogram analysis describing surface hoar presence spatial autocorrelation.

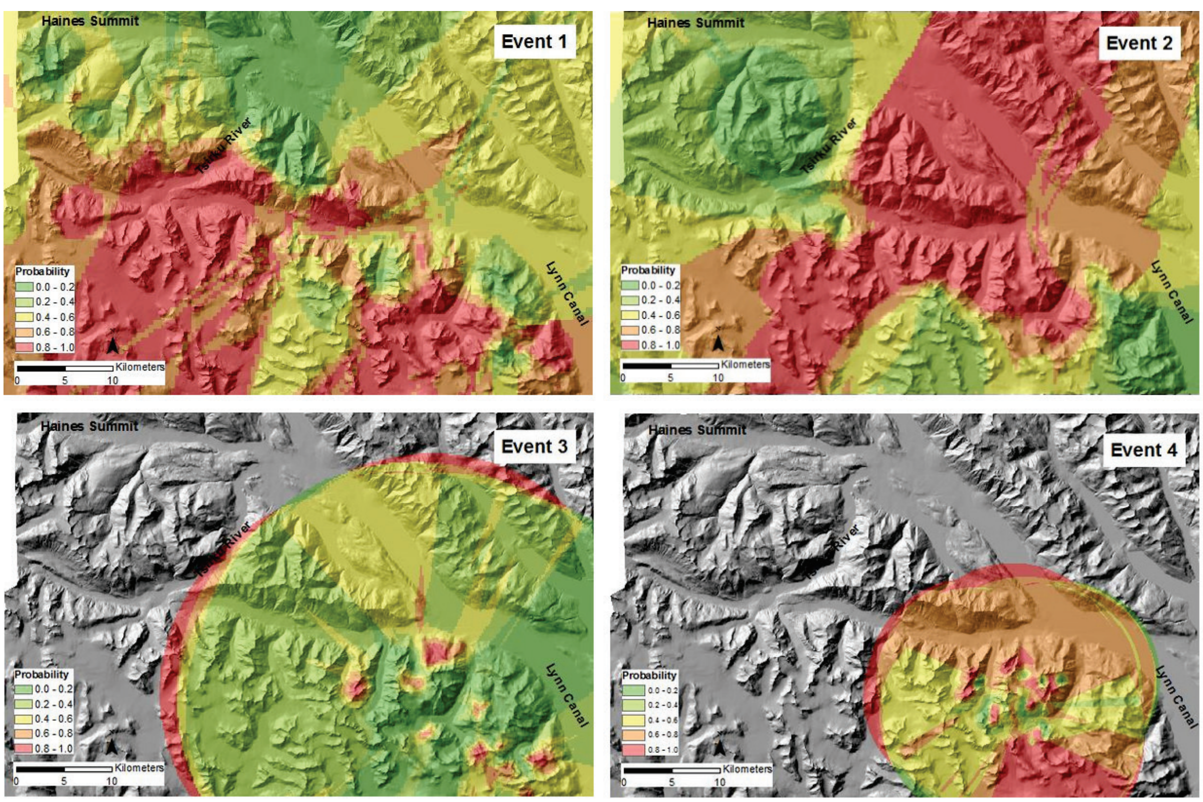

Figure 2: Kriging maps produced from indicator semivarograms based upon the presence or absence of surface hoar. Model coverage is dictated by data extent.

4. CONCLUSION

In all four of our data sets, GWR results suggest a positive relationship between surface hoar crystal size and elevation, meaning that larger crystals are often found in higher elevation avalanche starting zones. However, it is important to note that these conditions may be unique to the glaciated alpine environment around Haines which generally lacks trees commonly found on mountains of the contiguous U.S. and Canada.

Semivariogram and kriging analysis aided in the geographic visualization of coarse scale surface hoar formation and persistence patterns across a heli-skiing tenure. Our research is congruent with casual observations made in previous years and highlights several zones within the study are that are more likely to see buried surface hoar avalanches. This information is now considered during daily operational planning when buried surface hoar is thought to exist within the snowpack.

While the findings of this research present some interesting ideas, additional data are needed to gain a more complete understanding of surface hoar. Further studies focusing on slope angles, sky visibility, and radiation modeling are necessary and may aid in bringing us closer to this goal. Honing in on the proper balance between natural processes and efficient snowpack model scales leading to better transferring of information across multiple spatial scales should become more feasible in the future as our database grows from continued field observations alongside integration with ever improving weather monitoring.

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