# THE SPATIAL DISTRIBUTION OF TWO SURFACE HOAR EVENTS IN THE CHILKAT AND TAKHINSHA MOUNTAINS OF SOUTHEAST ALASKA

Matthew Borish[1,2*], Karl W. Birkeland[1,3], Stuart Challender[1], Stephan Custer[1]

[1]Department of Earth Sciences, Montana State University, Bozeman, Montana, USA
[2]Southeast Alaska Backcountry Adventures, Haines, Alaska, USA
[3]USDA Forest Service National Avalanche Center, Bozeman, Montana, USA

ABSTRACT: Understanding the spatial distribution of weak layers is a significant challenge for avalanche forecasters. Thus, improving our understanding of the processes that dictate the formation and persistence of surface weak layers across large areas is critically important for improving backcountry avalanche forecasting accuracy. For this work, heli-skiing guides mapped unburied surface hoar and near-surface facets across the Chilkat and Takhinsha Mountains of southeast Alaska during two major formation events of the 2010 season. After burial, we monitored weak layer persistence and avalanche activity. Our study area encompasses 900 km$^2$ of rugged, glaciated, alpine terrain, at elevations ranging from 300 m to 2000 m. Guides collected information on crystal attributes and terrain characteristics at each location, and used handheld GPS units to reference locations. Incorporating the data into a Geographic Information System (GIS) proved to be invaluable for managing and visualizing observations. For example, the GIS allowed the creation of surface condition maps that we used operationally in guide meetings and in the helicopter for making run decisions. Data analyses quantified observed patterns. In particular, we often found that surface hoar crystal size lessened with decreasing elevation, possibly due to stronger katabatic winds in valley bottoms. Additionally, we observed areas of inhibited surface hoar formation and persistence which may have resulted from the influence of synoptic inflow and outflow drainage winds. By better understanding the distribution of surface hoar and near-surface facets, this work provides insights into improved backcountry forecasting of avalanche conditions over large areas.

## 1. INTRODUCTION

Buried surface hoar crystals are a dangerous snowpack weak layer. Surface hoar comprised the weak layer in 34% of fatal Canadian avalanches between 1972 and 1991 (Jamieson and Johnston, 1992). In Switzerland, Föhn (1992) found that surface hoar accounted for approximately 40% of snowpack weak layers. Furthering our knowledge of surface hoar crystal formation and persistence across relatively large areas will aid avalanche forecasters' understanding of this important weak layer.

Surface hoar crystals form as water vapor sublimates onto a snow surface cooled below the dew point of the overlying air. This process most often occurs at night during meteorological conditions of clear skies, high relative humidity, and light winds (Lang et al., 1984). Hachikubo and Akitaya (1997) observed optimal formation conditions when snow surface temperature was 5° C (or more) less than the ambient air temperature, relative humidity was higher than 90%, and wind speed was 1-2ms$^{-1}$ at 0.1m above the snow surface.

*Corresponding author address: Matthew J. Borish, Department of Earth Scienes, Montana State University, Bozeman, MT, (406) 994-3331; email: matt@skiseaba.com

Haegeli and McClung (2003) used observations to trace layers of buried surface hoar across large areas, sometimes over several mountain ranges. Conversely, Feick et al. (2007) described surface hoar layer discontinuities likely resulting from snow surface topography at the centimeter scale. Wind turbulence over convoluted terrain and varying solar radiation are believed to be primary influencing factors of snowpack spatial variability (Colbeck, 1991; Sturm et al., 2004; Schweizer et al., 2008). However, spatial variability has been observed on seemingly 'uniform' slopes (Landry et al., 2004). Lutz et al. (2007) documented how small changes in incoming and outgoing short and longwave radiation can lead to variations in surface hoar layer thickness by a factor of two. Cooperstein et al. (2004) found a statistically significant difference in surface hoar crystal sizes on differing aspects and observed larger crystals on north versus south facing slopes on the same mountain. At the basin scale, Feick et al. (2007) documented larger surface hoar crystals near ridge tops than those found on adjacent terrain and suggested the discrepancy to be a consequence of katabatic wind impedance on favorable growth conditions. At the mountain range scale, Schweizer and Kronholm (2007) proposed variability to be the result of several processes with different scales.

After its formation, surface hoar can be destroyed by above freezing temperatures, insolation, ablation sublimation, rain, or wind, often increasing spatial variability (Gubler, 1998; McClung and Schaerer, 2006). Surface hoar spatial variability can be observed relatively easily while crystals remain unburied; however, determining the persistence of buried surface hoar is much more difficult (Tremper, 2001).

This research set out to investigate surface hoar spatial variability at the mountain range (900 km$^2$) scale. Specifically:

1) What is its formation pattern in terms of presence or absence?

2) What is its persistence pattern in terms of presence or absence?

3) Does surface hoar crystal size vary by elevation and location within the study area?

## 2. METHODS

### *2.1 Study area*

The study area is located in Southeast Alaska Backcountry Adventures' (SEABA) permitted heli-skiing terrain, which is composed of approximately 900km$^2$ in the Chilkat and Takhinsha Mountains, west of Haines, Alaska. Haines is located near the northern terminus of Alaska's panhandle (59° N, 135° W), at an elevation of 30m a.s.l. Mountain peaks in the vicinity reach near 2000m. The vast majority of the study area is above tree line which averages approximately 800m. Haines' mountains are characterized by large relief, complex terrain, and steep slopes. Most valleys are heavily glaciated.

The mean October-April temperature in Haines is 0.6°C and the average annual snowfall is 2.94m (NWS 2006). No long-term upper elevation weather data exists for the study area at this time. Onshore coastal flow, offshore northerly flow, and split flow are the predominant synoptic weather patterns (Scheler et al., 2004).

A thorough description of the avalanche climate of the Haines vicinity does not exist. However, comparing Haines' seasonal cumulative snowfall and snow depth data with records from the relatively similar location of Girdwood, Alaska reveals shared coastal avalanche climate characteristics, though snow density and temperature gradient data sometimes exhibit intermountain characteristics (Mock, 1996). Moving further inland, the snow climate can shift from the coastal category rapidly and may even be described as continental some years.

### *2.2 Field methods*

This research was integrated into the context of a heli-skiing operation which provided a tremendous advantage for accessing terrain with speed and efficiency that would otherwise be impossible. As a result, sampling areas were biased to where heli-skiing operations occurred each day, which often meant away from sun affected south facing slopes. Three heliports located 7, 29, and 53 kilometers west of Haines offer access to unique microclimates throughout the permit area.

During the 2010 heli-skiing season, SEABA expanded operations to include two helicopters for the first time. This allowed data collection over a much greater extent than was previously possible and provided the opportunity to take measurements at opposite sides of the permit area, over 50km apart, simultaneously.

On a typical heli-skiing day, between four and eight guides were in the field, a few of which were able to collect data. Average heli-skiing runs consist of 1000m of relief. A stratified random sampling technique with the goal of acquiring 4 or 5 approximately evenly spaced data points per run was employed to facilitate data efficacy. However, objective hazards such as cliff bands and areas of high avalanche danger or required guiding duties resulted in some deviations from the sampling scheme.

Snow surface measurements included the presence or absence of surface hoar and near-surface facets, surface hoar crystal size, and crystal type. Terrain variables included UTM (NAD 27) coordinate location within the permit area, slope steepness, and aspect.

To better understand the conditions under which surface hoar forms and persists near Haines, an alpine meteorological station was constructed. The station is located at 59˚ 21' 13" N, 139˚ 9' 21" W, at an elevation of 1300m on a ridge near the summit of SEABA's permitted snowcat skiing mountain, Old Faithful. Instrumentation 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. Installation of additional instrumentation to monitor solar radiation, SWE, and snow depth is planned for 2011.

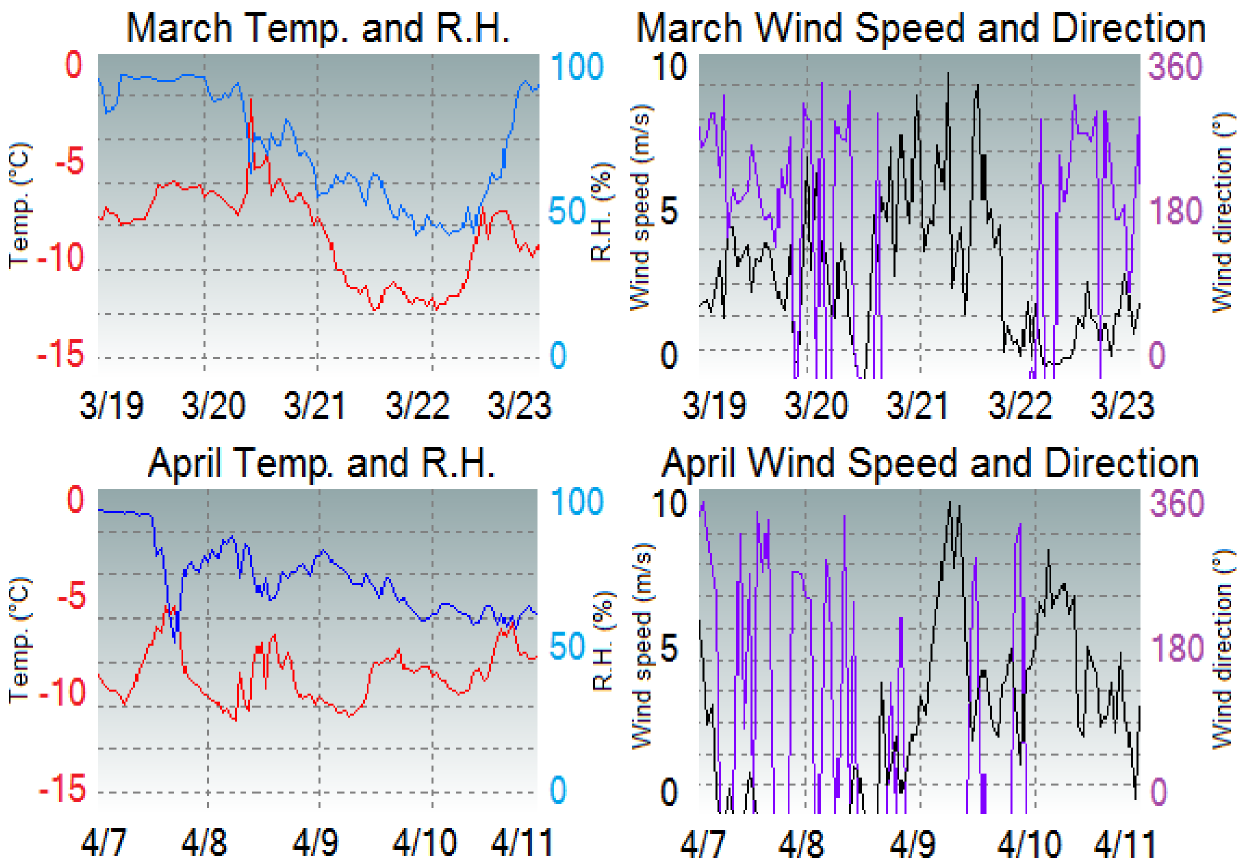


Figure 1: Old Faithful meteorological station data during the surface hoar forming events.

## *2.3 Data analysis*

A GIS managed the project data. Thirty meter resolution digital elevation models (DEMs) and 1:24000 topographic maps were used as reference base layers. Run perimeter polygons and snow observation point layers on top aided geographic visualization and allowed efficient data querying.

Terrain hillshade maps illustrating buried surface hoar locations were placed in each helicopter to assist guides' terrain selection. As new data became available, it was easily updated in the GIS and reflected in future forecasts.

We used two different analyses on our data. First, we utilized geographically weighted regression (GWR) to test if a significant relationship existed between elevation and surface hoar size for our data. We chose GWR over standard regression techniques to better account for spatial autocorrelation in our data. Second, we used an indicator semivariogram to test for spatial structure in the presence or absence of surface hoar, as has been done in previous work (e.g., Schweizer and Kronholm, 2007; Feick et al., 2007). We fit a model to the variogram and used our results to map the field area for locations that had a higher or lower probability of surface hoar presence.

## 3. RESULTS AND DISCUSSION

## *3.1 Surface hoar formation*

Two major surface hoar formation events occurred during Haines, Alaska's 2010 heli-skiing season. The first event was observed between March 20th and March 22rd. The second surface hoar formation period transpired from April 8th to April 11th.

Examination of Old Faithful Mountain weather station data from the March event coincides well with the necessary conditions required for surface hoar formation (Figure 1). As the weather began to clear on the evening of March 19th, alpine temperatures were moderate, relative humidity was high, and the wind speed was light. Not surprisingly, guides began to encounter surface hoar on March 20th.

During the March event, temperatures stayed seasonably cold, though the relative humidity decreased down to nearly 45% on Old Faithful by the night of March 21st. Average wind speed at the meteorological station nearly doubled from the 20th to the 21st.

Comparison of data from the 20th and the 21st on runs which were visited both days reveals only a small amount of crystal growth occurred between the first day and the second. By mid-day on the 22nd a winter storm entered the study area and ended the March surface hoar formation event.

Throughout the April event, air temperatures were generally warmer than March's event and had larger diurnal fluctuations. While the air temperature and relative humidity were within the necessary parameters for surface hoar formation between the 8th and 11th, increased wind speed and on the 9th and 10th may have impeded surface hoar formation.

Relatively more stable air masses were predominant in April compared to March and provided a longer period for surface hoar observations to take place. In contrast to the March event, surface hoar formation ceased to negligible levels after a few days in spite of April's continual clear skies.

## *3.2 Surface hoar distribution*

During the period from March 20th to March 23rd, over 200 measurements documented the snow surface across the heli-skiing permit zone. The maximum spacing between measurements approached 60km while the minimum spacing was near 50m, with the latter value due to data collection by multiple guides on the same run. Buried surface hoar avalanche observations were recorded during a widespread avalanche cycle on March 25th which followed a large snowstorm on March 22nd through the 24th.

During the March event, on runs where surface hoar was present, it was often observed as continuously present across the slope. Crystal sizes varied between 1 and 10mm across the study area, with generally smaller crystal sizes towards the bottom of runs.

A widespread avalanche cycle commenced in the alpine with a load of approximately 80cm of new snow received during three days immediately following the March surface hoar event. Many natural avalanches were observed across the complete spectrum of aspects and elevations, including some in close proximity to logged surface hoar locations during a brief break in the clouds on March 25th. Aggressive ski cutting by guides produced numerous avalanches on the 25th on east, west, and north aspects (Figure 2). The following day, snow resumed for 3 more days bringing the week's total precipitation to nearly 11.5cm of snow water equivalent at sea level.

Upon returning to the field on the afternoon of March 29th, guides estimated over 2m of medium to high-density snow had fallen in the study area on top of the March surface hoar. Additional natural avalanches were observed, mainly on warm west aspects, some of which appeared to step down to the deeply buried surface hoar. The March layer was continually loaded by a barrage of heavy snowstorms until it became unrecognizable in the snowpack around the beginning of April.

For the second event during April 8th to 11th, about 150 snow surface measurements were collected. The extent of measurements was near 40km and the minimum spacing was similar to the March event at approximately 40m.

In April, surface hoar presence on individual ski runs exhibited greater discontinuity than March's layer. Additionally, more diurnally recrystallized near-surface facets were interspersed between surface hoar observations. Guides reported crystal sizes from 1mm to 1.1cm during April's event. Surface hoar crystal size was again observed to be inversely proportional to elevation on individual runs.

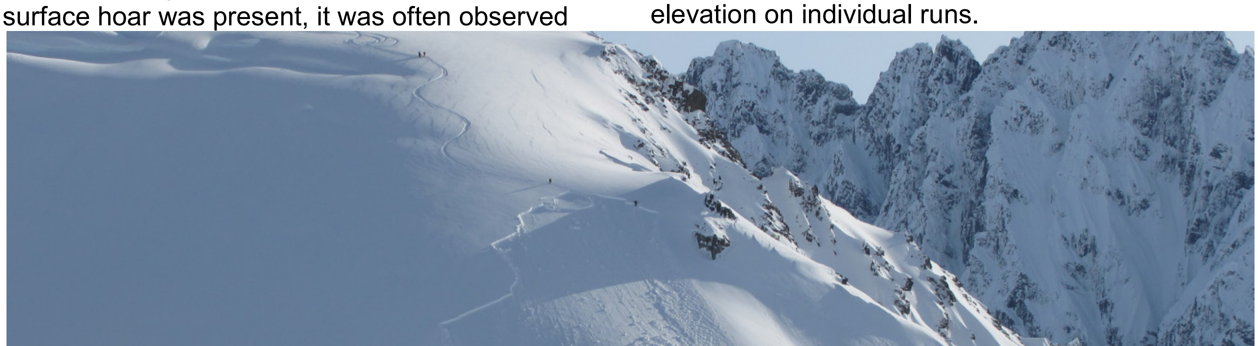

Figure 2: SS-ASc-R2-D2-O on March, 25th from the Garrison Glacier.

### 3.3 Statistical analysis

To check for spatial autocorrelation of our surface hoar observations we performed a Moran's Index test. Statistically significant (*p*< .05) Moran's I scores of 0.21 and 0.58 for March and April's surface hoar layers confirmed a high degree of spatial autocorrelation within the data sets when we evaluated the relationship between surface hoar crystal size and elevation across the study area. As a consequence, we decided to use GWR to explore data locally rather than globally.

Following GWR methods described by Fotheringham and Brunsdon (2002) we analyzed our data using an adaptive Gaussian kernel based upon the Akaike Information Criterion to predict the effect of elevation on surface hoar crystal size. An adjusted $R^2$ value of 0.38 and an AICc of 506.00 indicated a positive correlation between local elevation and crystal size for the March surface hoar layer and a relatively good model fit. The adjusted $R^2$ value rose to 0.68 and the AICc lowered to 377.10 suggesting a stronger correlation between elevation and surface hoar crystal size for the April event. Thus, GWR quantitatively confirmed our casual observations that larger surface hoar crystals formed at higher elevations locally (e.g., on a given run) in our study area. Greater diurnal temperature variance in April produced stronger katabatic winds that may have been why the relationship was stronger in April, similar to the processes described by Feick et al. (2007).

The second stage of our analysis investigated the spatial structure of the presence or absence of surface hoar. 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) Kriging is based upon semivariograms which measure spatial correlation between two points and provide a measure of uncertainty for estimated values (Issaks and Srivasttava, 1989). When looking at the presence and absence of something like surface hoar, an indicator semivariogram is the preferred method (Webster and Oliver, 2001), and this technique has been used previously for similar work (Schweizer and Kronholm, 2007; Feick et al., 2007).

Semivariogram modeling of surface hoar presence versus absence for March's surface hoar layer produced a range of approximately 6km (Figure 3). Nugget variance and sill values measured 0.02 and 0.25 respectively. Interestingly, the range for this layer indicated by the semivariogram is analogous to the average basin size within the study area and is in good agreement with the results of Schweizer and Kronholm (2007), who found a range of approximately 10 km throughout a region. The semivariogram calculations for the April layer gave a much larger range of just over 25km. In spite of the increase in range, the nugget variance and sill remained close to March's layer at 0.02 and 0.29. We believe the mottled character of the April surface hoar layer may be the reason for the increased semivariogram range for April.

Our map of the kriged surface hoar presence probability provides insights into the distribution of surface hoar throughout the study area (Figure 4). Areas regularly observed to be under the influence of katabatic or regional inflow and outflow winds possessed the lowest krigged surface hoar presence probability values. Conversely, zones with large amounts of adjacent relief were estimated to have the best chance of surface hoar presence. Our map matches our observations well.

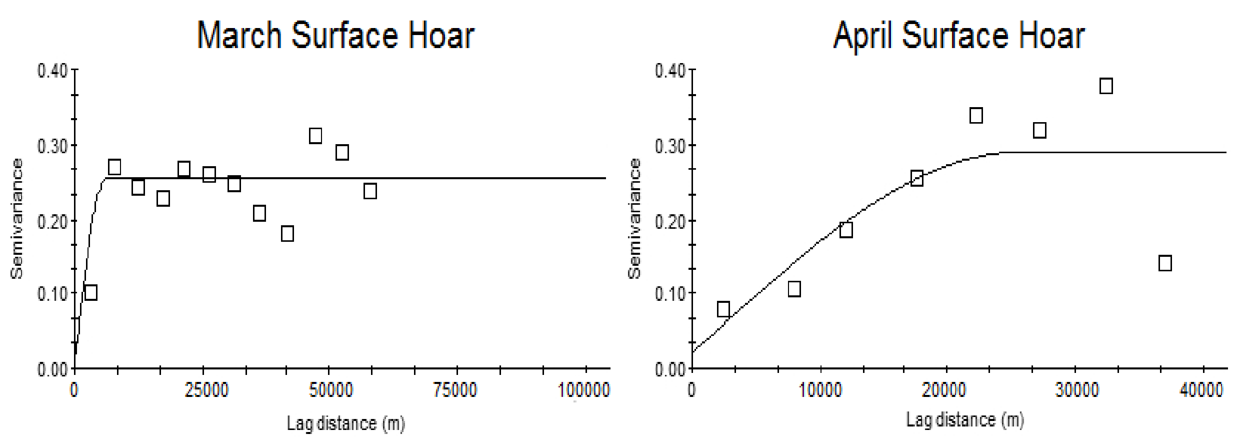


Figure 3: March and April surface hoar presence indicator semivariograms.

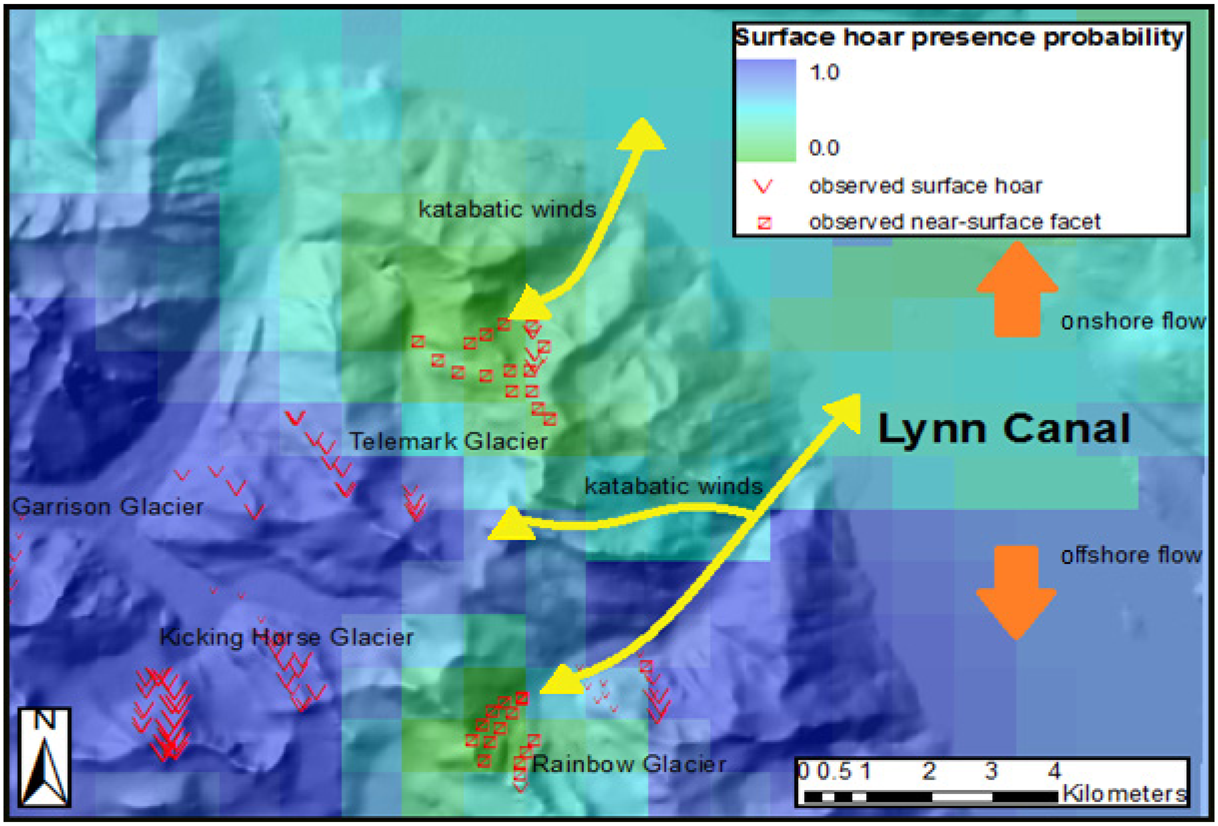


Figure 4: Ordinary kriging surface hoar presence probability calculated from March's surface hoar formation event. Areas heavily influenced by katabatic and synoptic winds are also illustrated.

## 4. CONCLUSIONS

Using a GIS to manage project data enabled a more comprehensive observational overview than compared to previous methods such as writing run names down in guide and log books where surface hoar was observed. Additionally, the GIS greatly improved our ability to query and analyze data. Geographic visualization furthered the conceptualization of several trends in our data set that may not have otherwise been obvious and would thus be overlooked. GIS outputs were easily integrated into SEABA's daily operations which increased efficiency and safety.

GWR analysis illustrated an inverse relationship between crystal size and local elevation for both surface hoar events. This is important to note since larger surface hoar crystals are thought to persist longer in the snowpack and possess lower shear strength (Chalmers and Jamison, 2001). Thus, these results suggested more dangerous conditions at higher elevations after the surface hoar was buried. Birkeland (2001) also found more unstable conditions at higher elevations with different weak layers in a small mountain range. However, each situation is unique so we cannot definitively state that higher elevations are always more dangerous.

A sizeable amount of research has been conducted on surface hoar formation and persistence at the slope scale and this work provides avalanche forecasters with a great deal of useful information (Lang et al., 1984; Landry et al., 2004; Lutz et al., 2007). By considering coarser surface hoar process scales, this research located a number of surface hoar formation and persistence hot spots at the mountain range measurement scale through the use of semivariogram modeling and ordinary kriging. A 6km semivariogram range for a layer of relatively continuous surface hoar was found to be similar to the width of many basins in the study area and suggests the ability to extrapolate surface hoar presence at this distance. Thus, if surface hoar exists anywhere in a basin, it is likely to exist throughout that basin.

This finding is in good agreement with the work Schweizer and Kronholm (2007) conducted in the Swiss Alps and may have resulted from synoptic drainage and katabatic winds. If regional avalanche forecasters could implement similar methods it might be possible to better understand their forecast areas and therefore improve their forecasts.

Another field season is scheduled for the 2011 heli-skiing season with the goal of collecting more surface hoar and near-surface facet data. Further information is needed to quantify empirical observations regarding the formation and persistence of surface hoar on steep slopes near Haines, Alaska.

## Acknowledgments

This research would not have been possible without the support of SEABA, and the hard work of the guide team. Additional funding was provided by the American Avalanche Association, The Montana Association of Geographic Information Professionals, The Mazamas, The USFS National Avalanche Center and Montana State University. Don Sharaf provided some helpful insights which improved the project.

## 5. REFERENCES

Birkeland, K.W. 2001. Spatial patterns of snow stability throughout a small mountain range. Journal of Glaciology 47(157), 176-186.

Chalmers, T.S., Jamieson,B. 2001.Extrapolating the skier stability of buried surface hoar layers from study plot measurements. Cold Regions Science and Technology 33, 163– 177.

Colbeck, S.C. 1991. The layered character of snow covers. Review of Geophysics 29 (1), 81-96.

Cooperstein, M.S., Birkeland, K.W., Hansen, K. The effects of slope aspect on the formation of surface hoar and diurnally recrystallized near-surface faceted crystals: Implications for avalanche forecasting. Proceedings of International Snow Science Workshop, 2004, Jackson, WY, 83-93.

Feick, S., Kronholm, K., Schweizer, J. 2007. Field observations on spatial variability of buried surface hoar at the basin scale. Journal of Geophysical Research 112, 10.1029/2006JF000587.

Föhn, P.M.B. 1992. Characteristics of weak snow layers or interfaces. Proceedings of International Snow Science Workshop 1992, Breckenridge, CO, 160-170.

Fotheringham, A.S., Brunsdon, C., Charlton, M.E. 2002. Geographically Weighted Regression The Analysis of Spatially Varying Relationships, John Wiley and Sons, Inc. Hooken, NJ.

Hachikubo, A. and Akitaya, E. 1997. Effect of wind on surface hoar growth on snow. Journal of Geophysical Research 102, 4, 4367-4373.

Haegeli, P. and McClung, D.M. 2003. Avalanche characteristics of a transitional snow climate- Columbia Mountains, British Columbia, Canada. Cold Regions Science and Technology 37, 255-276.

Issaks, E.H., Srivastava. R.M. 1989, An Intoduction to Applied Geostatistics Oxford University Press. New York, NY.

Gubler, , H. 1998. A model to determine snow surface properties from remote measurements. Proceedings of International Snow Science Workshop, 1998, Sun River, OR, 35-48.

Jamieson, B., Johnston, C.D. 1992. Snowpack characteristics associated with avalanche accidents. Canadian Geotechnical Journal 29 (5), 862-866.

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.

Landry, C., Birkeland, K., Hansen, K., Borkowski, J., Brown, R., Aspinall, R. 2004. Variations in snow strength and stability on uniform slopes. Cold Regions Science and Technology 39, 205-218.

Longley, P.A., Goodchild, M.F., Maguire, D.J., Rhind. D.W. 2005. Geographic Information Systems and Science John Wiley and Sons Ltd. Hoboken, NJ.

Lutz, E.R., Birkeland, K., Kronholm, K., Hansen, K., 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.

McClung, D.M., Schaerer, P. 2006. The Avalanche Handbook, The Mountaineers. Seattle, WA.

Mock, C.J. 1996. Avalanche Climatology of Alyeska, Alaska, U.S.A. Arctic and Alpine Research 28 (4) 502-508.

Scheler, K., Carter, P., Hood, E. 2004. The relationship between synoptic weather patterns and snowpack stability in a high latitude maritime snow climate. Proceedings of Western Snow Conference, 2004.

Schweizer, J., Kronholm, K. 2007. Snow cover spatial variability at multiple scales: Characteristics of a layer of buried surface hoar. Cold Regions Science and Technology 47, 207-223.

Schweizer, J., Kronholm, K. Jamieson, B., Birkeland, K.W., 2008. Review of spatial Regions Science and Technology 51, 253-272.

Sturm, M., Benson, C.S. 2004. Scales of spatial heterogeneity for perennial and seasonal snow layers. Annals of Glaciology. 38, 253-260.

Tremper, B. 2001. Staying Alive in Avalanche Terrain, The Mountaineers. Seattle, WA.

Webster, R., Oliver, M.A. 2001. Geostatistics for environmental scientists. Wiley, Chichester, England.