

SURFACE HOAR OBSERVATIONS AT THE SCALE OF A HELICOPTER
SKIING OPERATION

by

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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 recorded observations describing surface hoar presence or absence coordinates, crystal size, and elevation throughout four major surface hoar formation periods over two heli-skiing seasons in rugged alpine terrain near Haines, Alaska across an extent of nearly 60 km. Geostatistical analysis yielded spherical semivariogram autocorrelation ranges from approximately 3-25 km, 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. Geographically Weighted Regression revealed a positive relationship between elevation and surface hoar crystal size with adjusted R^2 values averaging near 0.40. 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. Additionally, larger surface hoar crystals may be found in the higher elevation avalanche starting zones in the alpine glaciated terrain near Haines, Alaska. These results can help in future efforts to forecast snow stability patterns over large areas.

1. INTRODUCTION

Avalanches cause property damage, economic loss, and injure or kill many people each winter. During the last decade, approximately 30 people have perished each winter season as a result of avalanches in the United States (Colorado Avalanche Information Center, 2013). Current trends indicate increasing numbers of recreationists are venturing into the backcountry searching for fresh powder snow in dangerous avalanche terrain.

Understanding the phenomena which dictate mountain range scale snowpack properties is imperative for predicting snow avalanches. However, due in part to the inherent difficulties of winter travel in mountainous terrain, many attempts to assess snow stability through snow pits or other types of field data collection have been limited to relatively fine scales (i.e. slope scale, <100 m), and challenged by less than optimal signal-to-noise ratios (Birkeland and Chabot, 2006; Campbell, 2004) which makes extrapolation of observations across different snow process scales challenging. Therefore, the crux of avalanche forecasting lies in applying realistically available data which elucidates fundamental snowpack processes at relevant scales of interest.

Paying particular attention to the snow surface is paramount because after it becomes buried by new snowfall or wind-deposited snow, it may become a weak layer which can act as the failure plane in subsequent slab avalanches. This research assesses snow surface spatial variability within a heli-skiing company's permitted tenure with a focus on: 1) unburied surface hoar presence or absence and 2) variation in surface hoar

crystal size with elevation. Integration with a heli-skiing operation provided a tremendous advantage for accessing a very large area with speed and efficiency that would otherwise be difficult and prohibitively expensive.

Though a number of snow crystal varieties or interfaces may play significant roles in snow avalanches, buried surface hoar crystals are especially dangerous. 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. Additionally, surface hoar is responsible for more accidents involving avalanche professionals than any other weak layer type (Jamieson, 1995).

When considering surface hoar, it is also important to note the existence of near-surface faceted crystals. Like surface hoar, near-surface faceted crystals are another type of weak layer which forms at the top of the snowpack, and can lead to slab avalanche activity after becoming buried (Birkeland, 1998). In fact, research by Birkeland et al. (1996) found near-surface facets to be the failure plane in 59% of 51 large avalanches they investigated.

Diurnally recrystallized near-surface facets are one of three types of near-surface faceted crystals and they grow under atmospheric conditions similar to those required to form surface hoar. Depending on specific and often very fine scale metrological scenarios, it is possible to observe the growth of near-surface facets and surface hoar

occurring simultaneously, the formation of either of the two, or neither of them (Birkeland et al., 1996).

Many studies have described surface hoar formation conditions (Lang et al., 1984; Colbeck, 1988; Hachikubo et al., 1994; Hachikubo and Akitaya, 1997) and as a result avalanche forecasters are generally aware of surface hoar growth periods. However, surface hoar layers exhibit high spatial variability. Their distribution is influenced by numerous environmental processes, both during formation, and also while the crystals linger on the snow surface where they are susceptible to destruction. To complicate matters further, factors affecting variability are heterogeneous at different scales. In other words, weak layers form and persist differently on large planar alpine slopes compared to small heavily vegetated ones. In practice, this means that forecasts for large areas may not hold true for smaller slopes within the forecast area (Bakermans et al., 2010).

Therefore, after identifying snowpack weak layers, the next logical steps are identifying their characteristics and describing their geographic distribution. Recent advances in geographic information science (GIS), along with great strides in sub-fields such as terrain modeling, geographic visualization, spatial data analysis, and digital data sharing are bringing us closer towards understanding the complexities of snow surface weak layer spatial variability.

1.1 Objectives

More information on how surface hoar behaves across large areas is needed for better avalanche prediction. This research investigates surface hoar spatial variability within a helicopter skiing operation's permit area across several mountain ranges near Haines, Alaska. The specific research questions are:

- 1) Where does surface hoar form and persist? Otherwise stated, where is surface hoar present and where is it absent?
- 2) How does surface hoar crystal size vary by elevation within the study area?

This research is the first study to examine surface hoar spatial variability in detail at the mountain range scale (Table 1.1). The goal is to provide useful guidance for avalanche forecasters, guides, researchers, and advanced recreationists who often forecast at this scale.

1.2 Thesis Organization

Chapter 2 provides a selective literature review featuring critical information on the layered character of snowpacks and how this trait influences slab avalanche activity. The formation and persistence of snow surface weak layers, specifically surface hoar and diurnally recrystallized near-surface facets, are discussed. Lastly, a brief overview of snow scale processes and how they influence snowpack spatial variability is given along with a summary of pertinent research, modeling attempts, and areas needing further investigation.

Chapter 3 discusses this study's research methods. The geography of the mountains near Haines, Alaska is detailed, and includes a climatic description. Field data collection and management techniques are highlighted along with a synopsis of the weather stations constructed for this study. Semivariogram analysis, Ordinary Kriging, and Geographically Weighted Regression statistical techniques are introduced to familiarize the reader with their fundamental concepts before data is chronicled in the results chapter, and explored more thoroughly in the discussion.

Chapter 4 details this study's results. The data are described in four parts; one section for each surface hoar event which took place during the period of study. Descriptive statistics and weather data are related for each event in addition to the results of the statistical analyses introduced in Chapter 3, which quantify surface hoar presence or absence spatial variability and the effect of elevation on surface hoar crystal size.

Chapter 5 is a discussion of this study's results, reasoning on why they occurred, and how they relate to previous research. The local topography and its interactions with the weather during the study area data collection periods are examined in order to explain how they affected the size and distribution of surface hoar during data collection periods.

Chapter 6 summarizes this research and makes recommendations for future studies.

2. LITERATURE REVIEW

2.1 Snowpack Properties and Slab Avalanche Formation

Snowpacks form in layers due to snowstorm variations such as temperature, humidity, and wind speed (Colbeck, 1991). Over time, these layers continue to evolve and are affected by many variables including topography, weather, solar radiation, and vegetation. Consequently, spatial patterns may often be observed across individual slopes, basins, or even entire mountain ranges in some cases (Hageli and McClung, 2003; Schweizer et al., 2008). Blöschl and Sivapalan (1995) introduced a classification scheme to describe the scales of snowpack processes (Table 2.1).

Table 2.1 Snowpack process scales (from Blöschl and Sivapalan, 1995).

Scale	Observation Distance	Traits
Layer	1 cm -0.5 m	Common snow layer thickness
Snowpack	0.5 m -5 m	Typical snowpack thickness
Slope	5 m -100 m	Size of avalanche slope
Basin	100 m-1 km	Aspect, steepness, radiation vary
Region	1 km – 10 km	Precipitation varies
Mountain Range	0 – 100 km	Storm track path affects deposition

One of the easiest snowpack structural characteristics to observe is layer hardness. Its variation is quantifiable in the field and ranges from layers so soft and weak that they provide almost no resistance to a gloved fist, to others so hard that they can only be penetrated by a blade (Greene et al., 2009). When present, surface hoar is commonly one of the weakest layers in the snowpack. Once buried, surface hoar may

persist as a weak layer in the snowpack for weeks or even months (Jamieson and Schweizer, 2000).

If a scenario arises in which a relatively weak layer becomes sandwiched between two relatively harder layers, a slab avalanche may occur if the weak area fractures over a sizeable area. For a fracture to initiate, snowpack surrounding the fracture plane must rapidly debond from each other (van Herwijnen and Heierli, 2009). Additionally, the slope must be steep enough for gravity to overcome the frictional contact forces of the fracture plane (Heierli et al., 2009). The threshold for avalanche initiation is generally around 25 degrees from horizontal, although avalanches are occasionally observed on flatter slopes (McClung and Schaerer, 2006; Tremper, 2008).

2.2 Surface Hoar Formation

Early avalanche researchers recognized the importance of surface hoar studies. Seligman (1936) refined surface hoar nomenclature which evolved from several European influences, described surface hoar characteristics, and noted conditions under which it forms. Subsequent research by LaChapelle (1969) chronicled surface hoar as an important weak layer with respect to slab avalanches. International surface hoar standardization was further improved with the publication of *The International Classification of Seasonal Snow Cover on the Ground* (Colbeck et al., 1990). Surface hoar crystals form as water vapor sublimates onto the snow surface, often at night, when the snow is cooled below the dew point of the overlying air during

meteorological conditions consisting of clear skies, high relative humidity, and very light winds (Lang et al., 1984; Hachikubo et al., 1994). Hachikubo and Akitaya (1997) observed optimal formation conditions when the snow surface temperature was at least 5° C lower than the air temperature, relative humidity was higher than 90%, and wind speed was 1-2 ms⁻¹ at 0.1 m high.

Several differing surface hoar crystal types have been observed, resulting as a function of specific formation conditions. *The International Classification of Seasonal Snow Cover on the Ground* lists surface hoar as striated; usually feathery crystals, aligned, usually flat, and sometimes needle-like (Colbeck et al., 1990). Lang et al. (1984) associated needle-like forms characterized by well-developed c-axis growth with formation temperatures below -21°C. Kobayashi (1961) described sector plates or dendritic forms, often feather-like in appearance, to form between -10° C and -21° C. Jamieson and Schweizer (2000) described three dimensional cup or scroll shaped crystals nearly indistinguishable from depth hoar. Combinations of growth regimes can combine to form conglomerate or composite forms (Geldsetzer et al., 1998). The American Avalanche Association's publication: *Snow, Weather and Avalanches: Observational Guidelines for Avalanche Programs in the United States* (Greene et al., 2009) presents a summary of surface hoar form sub-classes.

As surface hoar crystals grow, they may form a generally homogenous layer, or one of mixed forms. Measuring densities of surface hoar layers is difficult since they are too thin to use volumetric density samplers; however Davis et al. (1996) estimated

values to be near 160 kg m^{-3} for two recently buried layers. Surface hoar layer thicknesses usually correlate well to the size of the larger crystals composing the layer (Jamieson and Schweizer, 2000). Surface hoar crystal sizes can range from less than 1 mm to several centimeters (McClung and Schaerer, 2006).

2.3 Near-Surface Facets

Although surface hoar was this study's focal point, it is important to discuss near-surface facets since they also form in the upper snowpack and may lead to avalanche activity. If large temperature gradients necessary for surface hoar formation exist close to the snow surface, relatively minor differences in wind speed, available moisture, or topography can preclude it from forming and lead to the development of other near-surface faceted weak layers. Colbeck (1988) hinted at the processes leading to the formation of what Birkeland (1998) later described as near-surface facets. Three subclasses of near-surface facets exist: radiation recrystallized, melt-layer recrystallized, and diurnally recrystallized. Though they share a common categorization, the conditions which facilitate their growth are quite different.

During radiation recrystallization, shortwave radiation is absorbed within the top several centimeters of the snowpack while the snow surface simultaneously cools as it emits longwave radiation. This process often leads to very large temperature gradients; however it is only common at latitudes much lower than those found in Alaska.

Melt-layer recrystallization occurs when new snow falls on a snow surface which has previously melted. Although this process isn't uncommon in Southeast Alaska, especially at lower elevations, it is dissimilar to the environment required for surface hoar formation.

Diurnally recrystallized near-surface facets form as the temperature fluctuates relatively widely throughout a 24 hour period in the upper portion of the snowpack, while the middle and basal snowpack section temperatures remain relatively constant. Of the three types of near-surface facets, the formation process for the diurnally recrystallized variety is most similar to the conditions in which surface hoar grows. Therefore, surface hoar and diurnally recrystallized near surface facets often grow in tandem. Previous research by Hood et al. (2005) documented the formation of diurnally recrystallized near-surface facets, and resulting avalanche activity, in Southeast Alaska near Eagle Crest Ski Area outside of Juneau. Their study area is located approximately 100 km southeast of Haines.

2.4 Surface Hoar and Snow Surface Spatial Variability

Snowpack layers vary across both space and time which has been documented by a sizeable number of researchers (Schweizer et al., 2008). In addition to the complexities of temporal evolution, deciphering snowpack spatial variability is a primary challenge in avalanche forecasting (McClung, 2002; Feick et al., 2007). To overcome this conundrum, localized stability tests are performed in sites chosen to be relatively

representative of adjacent areas of concern. However, extrapolation of test results across multiple spatial scales is difficult especially if surface hoar is the primary weak layer (Campbell et al., 2004; Lutz and Birkeland, 2011; Helbig and van Herwijnen, 2012).

After its formation, surface hoar can be easily destroyed or degraded by radiation, heat, rain, or wind (Figure 1.1), often leading to patterns of high spatial variability (Gubler, 1998; McClung and Schaerer, 2006). Surface hoar spatial variability can be observed relatively simply while the crystals remain unburied; however, determining the location of buried surface hoar is exponentially more difficult (Tremper, 2008). Feick et al. (2007) summarized the effect of various environmental factors on surface hoar formation and destruction (Table 2.2).

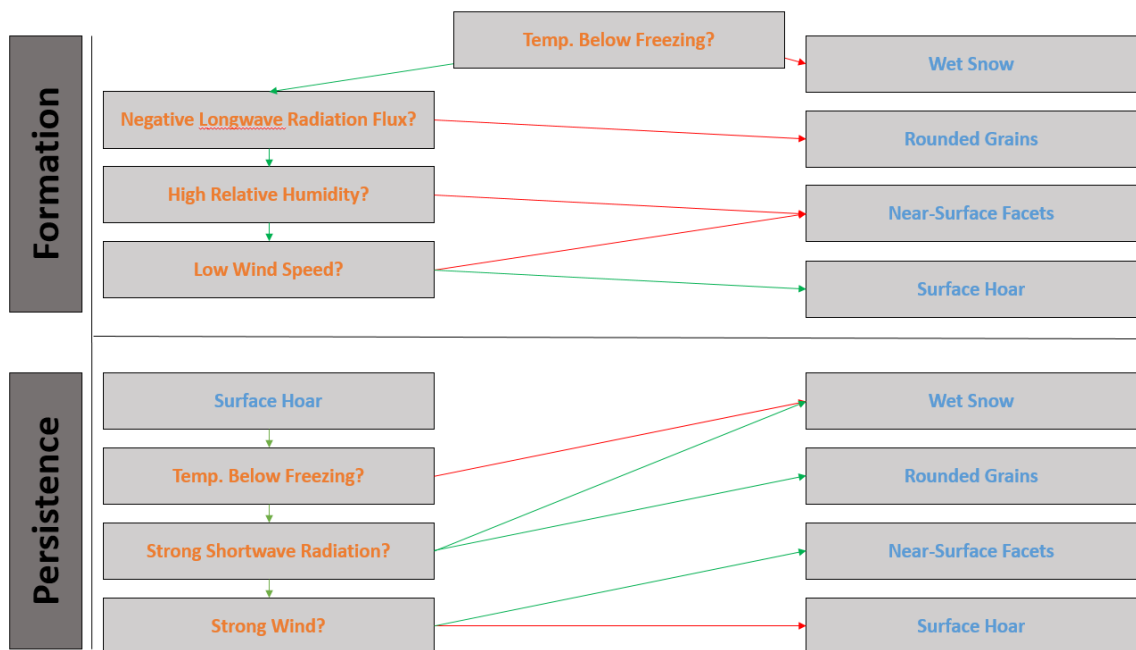


Figure 2.1: Generalized flowchart of surface hoar formation and persistence. Blue text depicts grain types. Orange text represents environmental processes. Green arrows signify yes situations and red arrows symbolize no conditions.

Previous studies focused on surface hoar spatial variability have produced some interesting findings. Hageli and McClung (2003) observed that layers of surface hoar could be traced across large areas, sometimes over several mountain ranges. Conversely, Feick et al. (2007) described surface hoar formation discontinuities resulting from snow surface topography at the centimeter scale.

It is a common belief that wind turbulence over convoluted terrain is a primary influencing factor of spatial variability (Colbeck, 1991; Sturm et al., 1995; Feick et al., 2007; Schweizer and Kronholm, 2007). However, it has also been demonstrated that spatial variability may also exist on seemingly uniform slopes (Landry et al., 2004, Lutz et al., 2007, Hoyer et al., 2014).

Table 1.2: Factors affecting surface hoar spatial variability (from Feick et al., 2007).

Variability Cause	Influence	Scale	Formation Effect	Destruction Effect
Thermal winds	wind	1- 1000 m	high	low to moderate
Pressure gradient winds	wind	1 – 100 km	low	high
Topography	wind	10 -100 m	high	high
Topography	S.W. radiation	10 – 100 m	high	high
Snow surface traits	wind	1 cm – 1 m	moderate	low to moderate
Snow surface traits	S.W. radiation	1 cm – 1 m	moderate	low to moderate

Lutz et al. (2007) selected such a site in the Henry's Fork Mountains of Southwest Montana which consisted of an open slope surrounded by trees. With minimal effects of terrain and wind, they documented small changes in incoming shortwave and outgoing longwave radiation which led to a difference in surface hoar weak layer thickness by a factor of two.

Since aspect plays a large role in radiation budgets, it should be no surprise that it also affects surface hoar growth and persistence. Gubler and Rychetnik (1991) suggested surface hoar growth was most efficient on aspects shaded from shortwave insolation and possessing unimpeded paths for longwave radiation. Cooperstein (2008) further investigated the effect of slope aspect on surface hoar in Southwest Montana and found crystals grew larger and persisted longer on northern aspects that received less insolation, which led to differences in temperature and vapor pressure gradients.

Several prominent studies have been conducted at coarser scales in the Swiss Alps. Feick et al. (2007) observed larger surface hoar crystals near ridge tops versus those found on adjacent level terrain and concluded the discrepancy to be a consequence of disrupted favorable growth conditions via humidity decreasing katabatic winds. Research by Schweizer and Kronholm (2007) described ranges

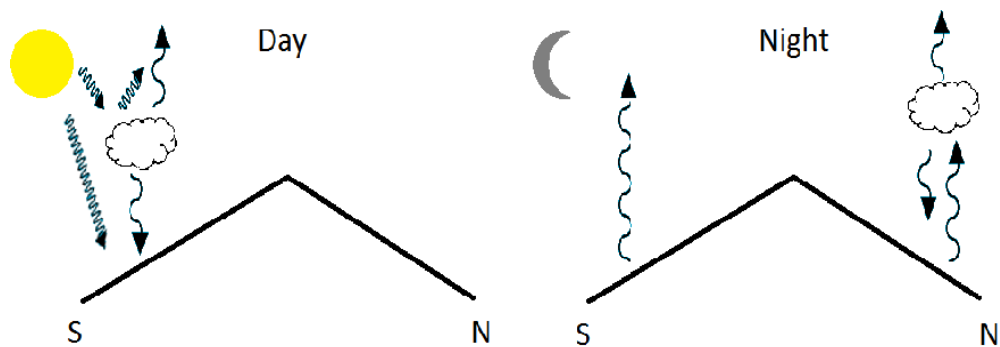


Figure 2.2: Simplified radiation budget affecting surface hoar formation and persistence. Solar shortwave radiation unimpeded by clouds often destroys surface hoar on southerly aspects. During the evening, clouds can inhibit cooling of the snow surface by blocking longwave radiation from the snow surface.

of surface hoar presence autocorrelation from 500-1500 m at the slope scale up to approximately 10 km at the mountain range scale. However, it should be noted that recent mountain range scale research by Hendrikx et al. (2014) suggests that fine scale site characteristics which affect micro-meteorological conditions can confound surface hoar spatial variability beyond what might be expected from the effect of aspect alone. Research conducted by Shea and Jamieson (2009) in Canada's Columbia Mountains near Rogers Pass described another type of coarse scale surface hoar spatial variability where distinct surface hoar elevation bands formed which as a result of valley stratus clouds.

Though surface hoar crystals may persist in the snowpack with little change for periods of up to several months (Geldsetzer et al., 1998 and Feick et al., 2007), several factors have been found to affect the shear strength of buried surface hoar crystals. Increased load facilitates intergranular bonding, weak layer thinning, and penetration of surface hoar crystals into surrounding layers (Jamieson and Johnston, 1999; Jamieson and Schweizer, 2000). Chalmers and Jamieson (2001) investigated the extrapolation of skier stability of buried surface hoar layers from study plot measurements and noted layers of buried surface hoar are less reactive to skier triggering when the overlying slab thickness reaches 0.65-1.00 m. They also observed surface hoar layer strengthening and stabilization thresholds when weak layer thicknesses decreased by 20-45%. Research by Lutz et al. (2007) using the SnowMicroPen (SMP) also supports the theory of increasing shear strength with layer thinning. Jamieson and Johnston (1999) observed an inverse relationship between the size and shear strength of surface hoar crystals. However,

Geldsetzer et al. (1998) noted that nearly identical surface hoar crystals can have vastly different shear strengths.

2.5 Surface Hoar Modeling

With some degree of success, several models have been employed to estimate surface hoar deposition. Föhn (2001) developed a model for daily simulation of surface hoar measurements derived from automated weather stations in the transitional to continental avalanche climate of the Swiss Alps (Schweizer and Jamieson, 2007; Schweizer and Wiesinger, 2001). Using an aerodynamic bulk method over half-hour simulation times, Föhn was able to deduce surface hoar formation or ablation periods. Föhn simulated snow surface deposition rates with near 90% mean accuracy from measured amounts, and approximated layer thickness values up to 70-80% accurately.

Hachikubo (2001) compared the numerical Simple heat balance model (Hachikubo and Akitaya, 1997) and Crocus model developed by Brun et al., (1989) in the maritime avalanche climate of northern Hokkaido, Japan (Ikeda et al., 2009). Hachikubo (2001) found the Simple model results suggested that when relative humidity is low (60-70%) with wind speeds from 0-6 ms^{-1} , deposition rates change from positive to negative (sublimation) with increases in wind speed, and deposition rates are largest under high relative humidity (>90%), with wind speeds from 0.5-3.5 ms^{-1} . Crocus overestimated deposition rates by about $1.3 \times 10^{-6} \text{ kg/m}^2 \text{ s}^{-1}$, and underestimated snow

surface temperatures by about 2-3° C when compared to Hachikubo's empirical observations.

The Swiss model, SNOWPACK estimates surface hoar by calculating turbulent flux of moisture towards the snow surface (Lehning et al., 2002). Stossel et al. (2010) evaluated SNOWPACK in the Swiss Alps and determined it was able to predict whether or not surface hoar was forming on most nights. However, they stated estimating crystal size and quantifying the modeled surface hoar deposition amounts versus measured values remains difficult.

In spite of various model successes, Feick et al. (2007) suggested predicting surface hoar distribution from automated weather stations to be nearly impossible unless local wind regimes are known at a scale of less than ten meters, which is unfortunately not practical for large area avalanche forecasting. In an attempt to mitigate this challenge, Horton et al. (2012) coupled SNOWPACK with the Canadian regional weather prediction model, Global Environmental Multiscale (GEM) to model surface hoar in the transitional avalanche climate of British Columbia Canada's Columbia Mountains (Haegeli and McClung, 2003) and predicted size reasonably well ($R^2 = 0.44$) with growth rates of 2.1 and 2.6 mm/day, however specific rates varied by season. Additionally, their surface energy balance model estimated crystal size against real station data well ($R^2 = 0.74$) but did not see an improvement when integrated with the output of GEM15 ($R^2 = 0.49$).

Helbig and van Herwijnen (2012) described the influence of terrain characteristics on the spatial distribution of surface hoar from an ensemble of 1800 simulated complex topographic scenarios. They focused on elucidating areas that could satisfy the longwave radiative needs necessary for surface hoar formation and the zones receiving enough incident shortwave radiation for its destruction. From their research they related two important findings; more shading via lower sun angles produced larger surface hoar correlation lengths and spatial correlation distances are strongly related to the typical spacing between mountains.

3. METHODS

This chapter gives a look into the methodology used in this research. The study area's local and regional geography are overviewed, and followed by a description of the weather stations constructed for this project to improve our understanding of the meteorological conditions around Haines. Next, I outline the field methods and data management protocols. Finally, the GIS based data analysis techniques used to quantify surface hoar presence or absence and the effect of elevation on surface hoar crystal size are introduced.

3.1 Study Area

Alaska is the largest state in the union with an area of 1,717,854 km². It is separated from the conterminous United States by Canada. Canada's Yukon Territory borders Alaska along its northern portion. Southeast Alaska is bordered by the Canadian province of British Columbia.

The study area is located in Southeast Alaska Backcountry Adventures' (SEABA) 2013 permitted heli-skiing terrain and in zones of historical heli-skiing, which contain approximately 900 km², predominately in the Chilkat and Takhishna Mountains, west of Haines, Alaska. Several relatively smaller unnamed sub-ranges make up the remainder of the study area (Figure 3.1).

Haines is 30 m a.s.l. and its geographic coordinates are 59°14'09" N 135°26'72" W, WGS84 (World Geodetic System 1984). Mountain peaks surrounding Haines reach near 2000 m. The vast majority of the study area is above tree line which averages approximately 800 m. Haines' adjacent mountains are characterized by large relief, complex terrain, steep slopes, heavy glaciation, and an abundance of avalanche paths. The Takhinsha Mountains stretch nearly 50 km along a southeast/northwest axis running from just southwest of Haines to the British Columbia border. The Chilkat Mountains are oriented approximately north/south and run for nearly 150 km from Haines to Icy Strait.

The mountain ranges near Haines are part of the greater Coast Range which extends along the majority of the North American West Coast. The major peaks of the Coast Range vary in elevation from approximately 1500 m to 3000 m but are relatively small in comparison to the nearby Wrangell-St. Elias Mountains which are the world's largest coastal mountains and rise to almost 6000 m.

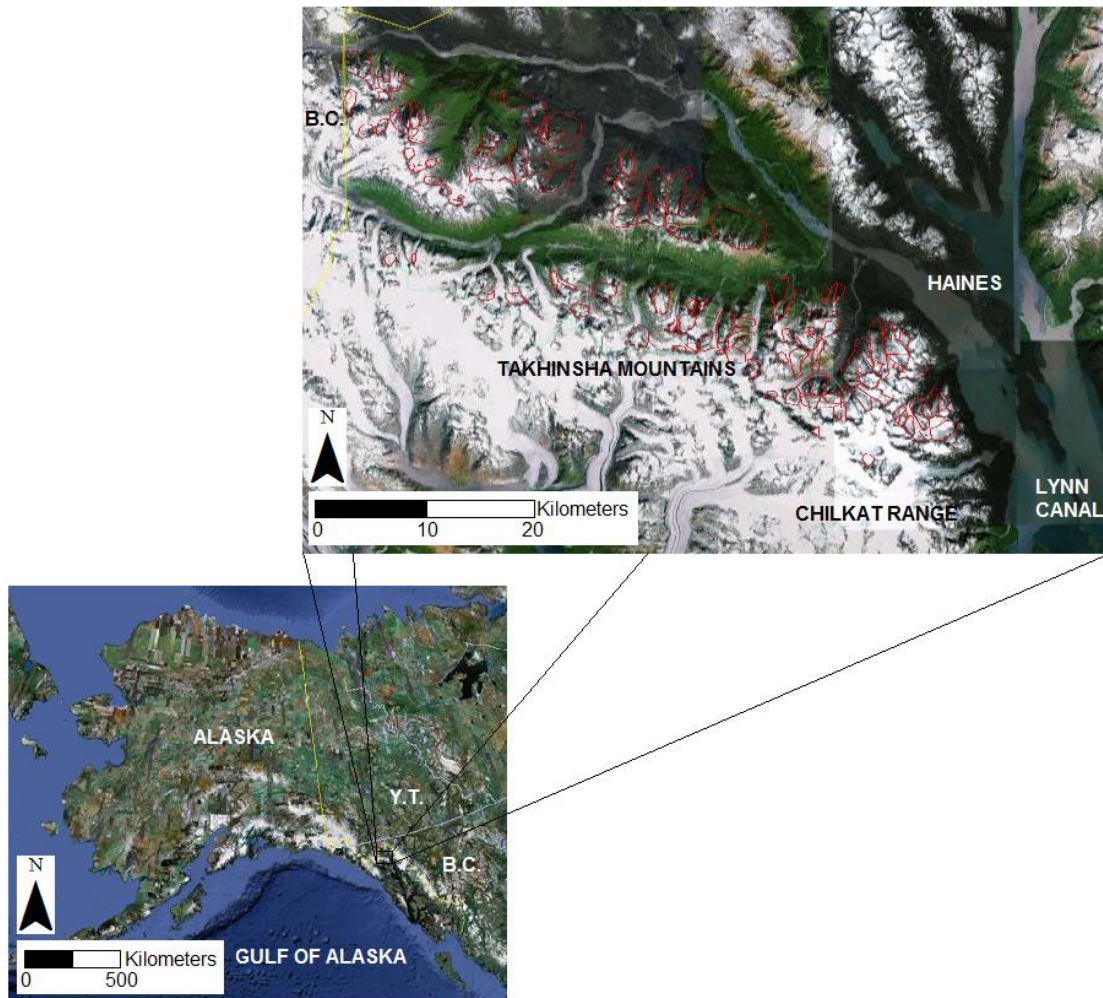


Figure 3.1: Inset of study area in Southeast Alaska, near the town of Haines. Generalized ski runs are outlined in red.

The global patterns which dictate Haines' winter climate are dominated by a number of fronts and semi-permanent cyclonic and anticyclonic phenomena (Figure 3.2). The Polar Front oscillates in an intermittent band along the earth's middle to high latitudes and divides cold polar air masses from warm tropical air masses. The strength of the Polar Front increases with greater horizontal temperature gradients, and consequently stronger pressure gradients, along the front. The Aleutian Low is a semi-

permanent maritime low pressure center that typically resides in the Gulf of Alaska near Alaska's Aleutian Islands and it reaches its peak strength during winter. In this area, sub-tropical cyclones often stall and reach maximum intensity. In contrast, the continental North American High generally resides over Canada's Yukon Territory. This area is capable of hosting strong anti-cyclonic systems during winter, but typically not as strong as those of the Siberian High over Russia (Hordon, 2005).

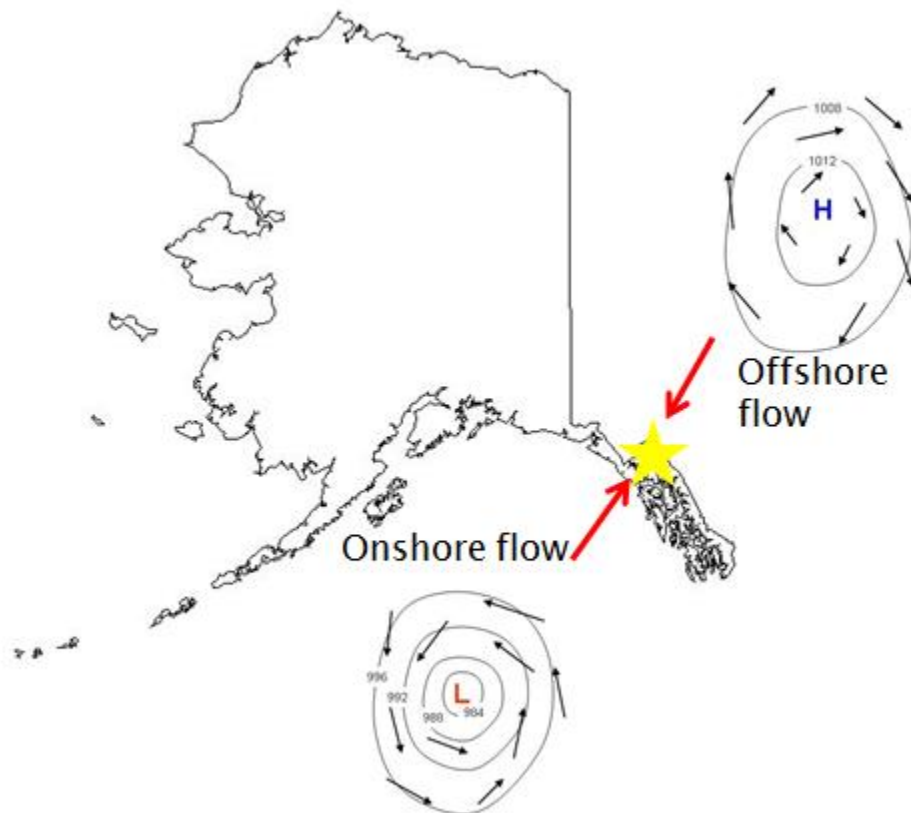


Figure 3.2: Overview of the Aleutian Low, North American High, and direction of synoptic scale pressure gradient winds.

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. Offshore flow is often composed of north or northeast continental polar air masses originating from the arctic and is associated with bitterly cold temperatures (Figure 3.3). 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 large coastal relief and produce heavy snow at low elevations (Coleman, 1986).

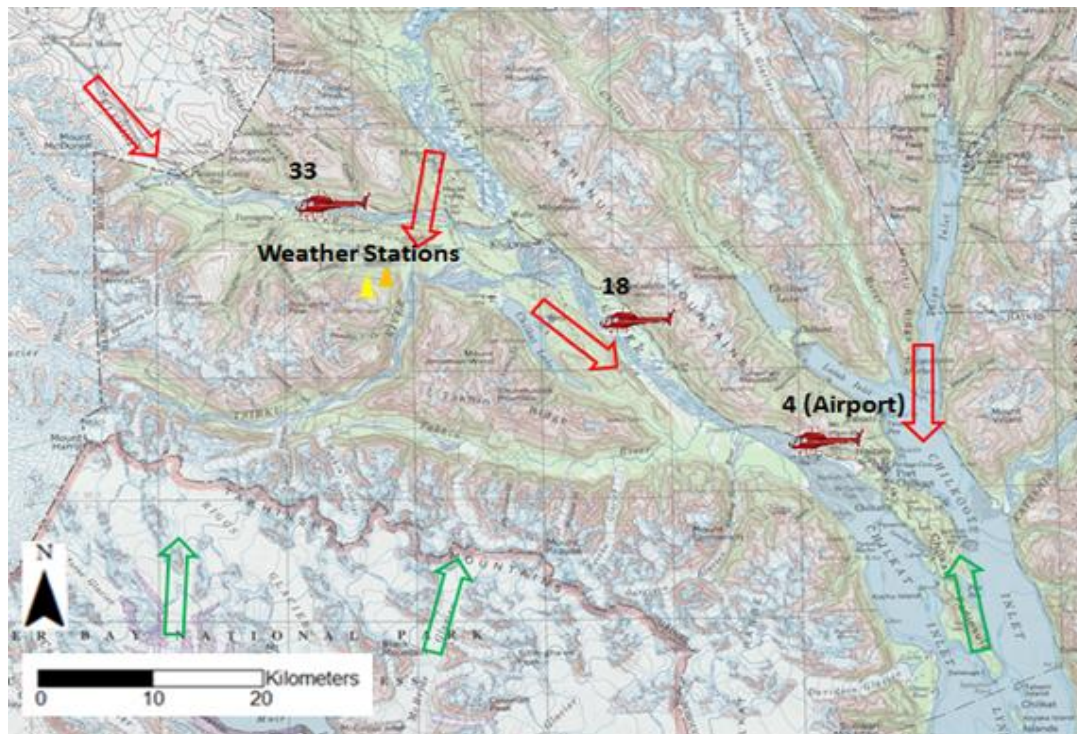


Figure 3.3: Regional map indicating predominant areas of offshore (red arrows) and onshore (green arrows) flow. The alpine weather station is symbolized by a yellow triangle and the subalpine weather station is denoted as an orange triangle. Helicopters signify heli-ski staging areas.

From 1973-2005, the mean February - April temperature in Haines was 1° C during which time an average monthly snow water equivalent (SWE) of 7.32 cm was received (WRCC, 2013) (Table 3.1). No long-term high elevation climate records exist for the study area.

Table 3.1: Climate summary from Haines, Alaska during the heli-ski season months for years 1981-2010 (WRCC, 2013).

Month	Mean Temperature (°C)	Mean S.W.E. (cm)
February	-2.9	7.40
March	0.4	9.48
April	5.5	5.10
February - April	1	7.33

A thorough description of the avalanche climate near Haines does not exist. However, comparing Haines' seasonal cumulative snowfall and snow depth data with records from the relatively similar location of Girdwood, Alaska which is located approximately 700 km northwest of Haines, reveals shared coastal avalanche climate characteristics, though snow density and temperature gradient data sometimes exhibit intermountain characteristics (Mock, 1996). Similar to Girdwood, most avalanches near Haines are direct-action events, resulting from recent precipitation and wind. When moving further west away from Haines and the salt water of the Inside Passage, the snow climate can rapidly shift away from maritime conditions, and may even be described as continental some years.

3.2 Weather Stations

To better understand the conditions under which surface hoar forms and persists in the study area, two remote weather stations were installed. These stations continued to evolve during the project as more instrumentation was acquired and site infrastructure improved. Instrumentation was installed according to specifications outlined by the United States Forest Service (Zachariassen et al., 2003) and World Metrological Association (WMO, 2006).

An alpine meteorological station (Figures 3.3 and 3.4) was built during February, 2010. The station is located at 59°21'46' N, 136°07'32" W, WGS 84 at an elevation of approximately 1300 m on a ridge near the summit of SEABA's permitted snowcat skiing mountain, Old Faithful.



Figure 3.4: Installation of the weather station near the summit of Old Faithful. The camera is pointed South down the Tsirku River valley.

Instrumentation at the alpine site for 2010 included a Campbell Scientific CR10x data-logger, a Vaisala HMP45C temperature and relative humidity probe, and a Met-One Instruments 034B wind speed and direction anemometer. For 2011, a Licor LI200x pyranometer was added to measure shortwave radiation (Figure 3.5). A 70 W solar panel and a 32 Ah absorbed glass mat battery supplied power to the alpine site.

A sub-alpine station was completed in March 2011 at 59°22'17" N, 136°05'51" E, WGS 84 at approximately 700 m elevation. Measurements at the lower site included snow depth and air temperature recorded on a Campbell Scientific CR200x data-logger from a Campbell Scientific SR50A sonic ranging sensor and a Campbell Scientific 109A temperature probe. Power was supplied at the sub-alpine station using a 35 W solar panel and a 32 Ah absorbed glass mat battery.

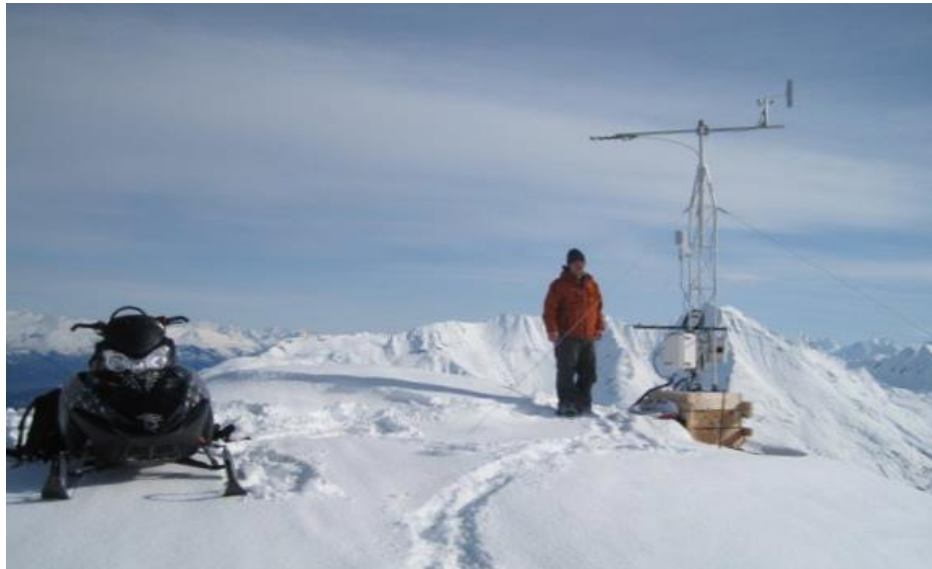


Figure 3.5: The Old Faithful alpine weather station in 2011 after installation of the Licor LI200x pyranometer. The camera is pointed east towards the Tsirku River and Haines.

A base station was setup with Campbell Scientific Logger Net 4.0 software at SEABA's snowcat headquarters about 6 km from Old Faithful Mountain. Communication between the two remote weather stations and the base station was transmitted via Campbell Scientific RF450 900 MHz spread spectrum radios. The alpine site data logger was configured to work as a repeater since the subalpine station lacked a necessary direct line of sight required for data transmission. The two remote sites employed Yagi directional antennas, while the base station used an omni-directional antenna.

Real time weather station data was made available online using Campbell Scientific RTMC Web Server software. This aided the project greatly by allowing us to identify potential surface hoar formation periods.

3.3 Data Collection

For this study, SEABA guides recorded observations during four major surface hoar formation periods. Data was collected during the 2010 and 2011 heli-skiing seasons (Feb.- April). All members of the SEABA guide team possess extensive avalanche and backcountry route-finding experience. Most hold U.S. level three avalanche certifications, and the rest are level two certified. Guides were verbally briefed individually on the study particulars and given access to the most relevant surface hoar literature at the beginning of each season. Major topics covered included data collection safety, sampling scheme strategies, measurement techniques, and GPS (Global Positioning System) unit use.

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. 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.

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 not to impede guiding duties. Therefore, guides focused on collecting data describing the presence or absence of surface hoar (surface hoar absence was classified as non-surface hoar presence for simplicity), surface hoar crystal size, observation UTM coordinates, and observation 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 UTM coordinates and elevation at each sampling location. The GPS units employed Wide Area Augmentation System (WAAS) real time differential

correction capability that kept unit accuracy to approximately 5 m horizontally and 15 m vertically. Guides recorded observations in field books which were shared during daily debriefing sessions.

When conditions were 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 single guide during a day in the field, they communicated it to other guides using radios and clipboards in the helicopters who then began taking observations for the day when they were able to do so. 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. If data collection was not possible, the location of the run was noted and no data was logged for this terrain.

When possible, photographic records of each event were collected. Pictures of surface hoar crystals during each formation event were taken and cataloged. Photographs of avalanches believed to have failed on surface hoar based upon crown heights and snow fall history were also added to the database. These aided in monitoring layer evolution and will be useful in comparison with future events.

For the bulk of the season SEABA operates with only one helicopter, although a second helicopter was present during the peak season at the end of March and beginning of April. On a typical SEABA operating day, 2 to 4 guides per helicopter were in the field together and able to collect data. Each guide completed 6-8 runs on average per day while skiing with the general public. However, guides skiing with film crews generally only skied 2-4 runs each day.

The goal of our sampling design revolved around characterizing surface hoar layers within the study area while simultaneously trying to avoid impeding normal heli-skiing operations. A truly random sampling scheme is the preferred method for sampling data in an observational study (Longley et al., 2005). However it is unrealistic and dangerous in rugged avalanche terrain. Thus, quasi-randomization in this study resulted from run selection based upon safety and clients' needs, as opposed to unburied surface hoar considerations.

Skøin and Blöschl (2006) recommend a sampling scheme which utilizes a longer extent and shorter spacing than the process correlation length of interest. In an attempt to capture the mountain range surface hoar process scales, guides were instructed to take surface observations on each run near the upper landing zone (LZ), by the lower pickup zone (PZ), and in the neighborhood of 300 m vertical intervals in between landing zones (Figure 3.6). Individual heli-skiing runs in Haines average near 1000 m of relief. Terrain complexity, avalanche conditions, and client concerns, and other issues caused some deviations from the preferred sampling scheme.

Sample aspects were biased since Alaskan heli-skiing operations often avoid south facing slopes while seeking dry powder snow and managing avalanche risk (Carter et al., 2006). Consequently, this meant that most study observations were biased towards aspects which receive less insolation, especially later in the season. Aspects between approximately 135 to 225 degrees were rarely sampled which is explained further in the Results chapter.

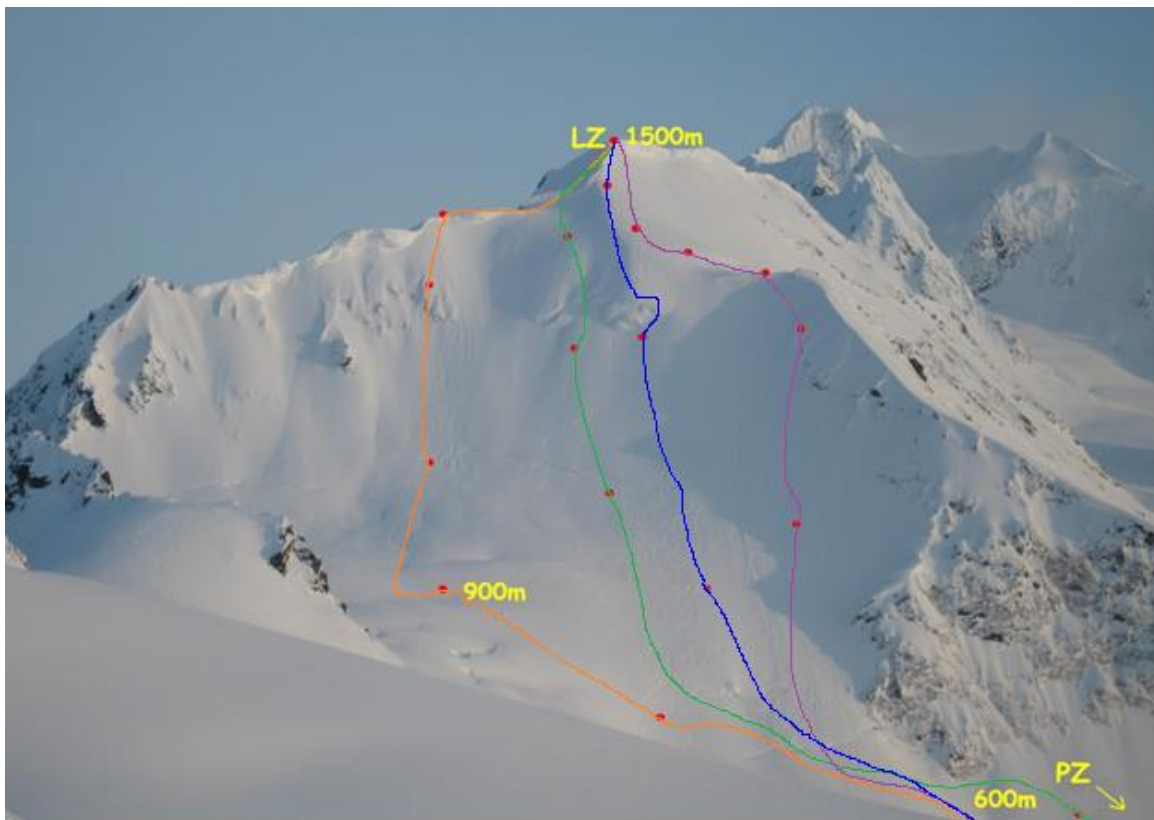


Figure 3.6: A hypothetical four run sampling scenario. The LZ indicates the landing zone while PZ symbolizes the pick-up zone. Red dots are potential sampling locations and colored lines represent approximate guide routes.

It is common for guides to “stack” on the same runs. This practice has several benefits, including increased safety from keeping the groups in the field tight,

maximizing the run to cost ratio, and allowing the leading guides to suggest runs with the best snow. Stacking is also advantageous from a research perspective since it spreads guided groups seeking fresh powder across the slope, providing a more representative sample than a single guide is capable of collecting.

3.4 Data Management

GPS location data was downloaded from the Garmin eTrex units using DNR Garmin (MDNR, 2009). Project data was managed with ESRI ArcGIS 9.3.1 (ESRI, 2009). Fifteen minute USGS raster digital elevation models with 30 m resolution served as the primary study area reference layer. Hillshade maps of the study area were created from USGS 30 m DEMs using the ArcMap Spatial Analyst extension to aid in geographic visualization. Digital .tiff topographic maps at 1:250,000 and 1:63,360 scales were used as ancillary reference layers.

Several vector feature layers were created to facilitate data management. Surface hoar layers were created for each individual surface hoar event. Surface hoar feature attributes include crystal type, crystal size (mean), elevation, UTM coordinates, observation date, guide, run, and presence or absence. A polygonal run catalog was built to aid a number of tasks including data querying and increasing measurement accuracy. Run boundaries were delineated based upon proximity to LZ/PZ locations, probable descent routes, and natural topography. Run feature attributes consist of the run name, vertical relief, and hyperlinked photos.

3.5 Data Analysis

3.5.1 The Spatial Distribution of Surface Hoar Presence or Absence

The first stage of analysis investigated surface hoar spatial structure in terms of presence or absence. This was accomplished using semivariogram analysis and Ordinary Kriging. When looking at the presence or absence of something across a geographical area the semivariogram is the preferred tool for describing spatial structure (Webster and Oliver, 2007). In essence, the semivariogram relates semivariance to separation distance, and can be illustrated as a plot that demonstrates the spatial dependence of each point on its neighbor (Curran, 1988).

The indicator semivariogram (Cressie, 1993) is a commonly used geostatistical technique in avalanche research (e.g. Schweizer and Kronholm, 2007; Belleaire and Schweizer, 2008; Helbig and van Herwijnen, 2012). Indicator semivariograms are practical for evaluating discrete data. Individual samples can be assigned values of 0 or 1 based upon whether or not they meet a certain criteria. In this study, point locations where surface hoar was present were assigned a value of 1 while and samples where it was absent were assigned 0. After stratification, traditional semivariogram techniques are employed.

The three fundamental parts of the semivariogram are the nugget, sill and range (Figure 3.7). The nugget describes fine scale variation, data uncertainty, and possible measurement error. The sill is the total sum of variation from the nugget variance and structural variance sum. The range quantifies the distance of spatial autocorrelation,

and the point where the model semivariance levels off. These three values form the foundation for kriging which was used to interpolate surface hoar presence probabilities across the study area.

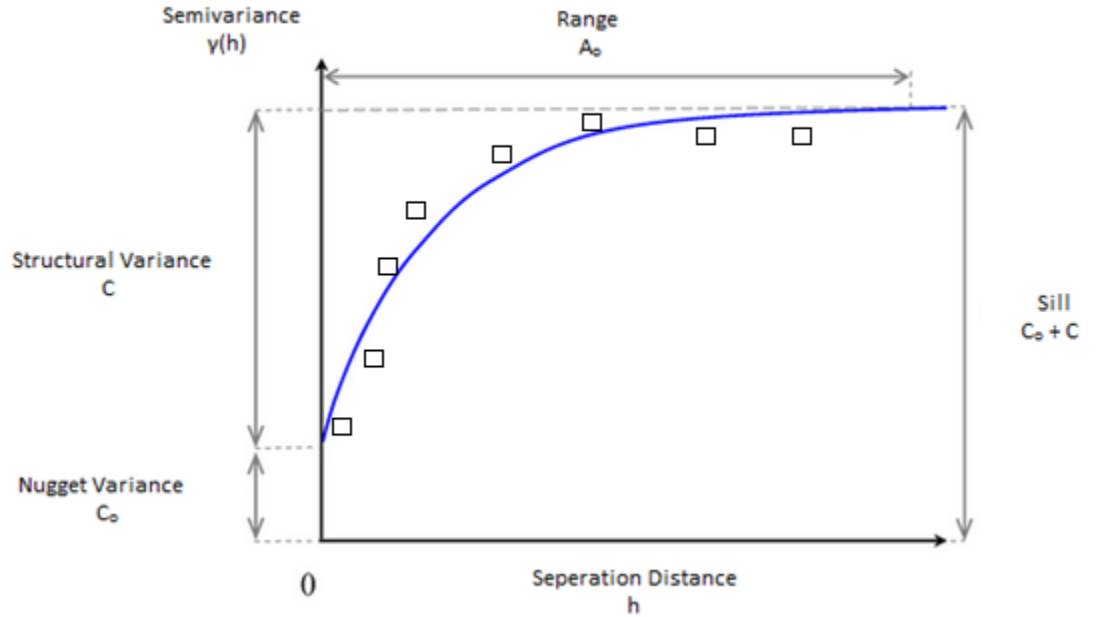


Figure 3.7: An example spherical semivariogram and associated parameters. The small squares are the empirical semivariogram and the blue line is the theoretical semivariogram model.

Isotropic empirical semivariograms were built from surface hoar and near surface facet location coordinates using the Gamma Design GS+ 9.0 software package (Robertson, 2011):

$$\gamma(h) = \frac{1}{2N(h)} \sum \{z_i - z_{i+h}\}^2 \quad (1)$$

where $\gamma(h)$ is the semivariance for interval distance class h , z_i is a measured sample value at point i , z_{i+h} is a measured sample value at point $i+h$, and $N(h)$ is the total number of sample couples for the lag interval h .

The GS+ autofit option was used in conjunction with a trial and error approach to build empirical semivariogram models. Chosen lag distances were sized to resemble the extent of each surface hoar event. Bins sizes were selected so observations were split approximately equally between them.

After selecting the best empirical models, theoretical spherical semivariograms were fitted using the empirical semivariance estimates by minimizing the Residual Sum of Squares (RSS) errors:

$$\gamma(h) = c_o + c_1 \left\{ 1.5 \left(\frac{h}{A_o} \right) - 0.5 \left(\frac{h}{A_o} \right)^3 \right\} \quad (2)$$

where h is the lag distance interval, C_o is the nugget variance ≥ 0 (and also the y -intercept), C is the structural variance $\geq C_o$, and A_o is the range. Spherical semivariogram models were selected as the preferred theoretical model type based upon their visual fit to the empirical data as well as their prevalence in previous avalanche research (Kronholm, 2004; Schweizer and Kronholm, 2007; Shea, 2011).

In order to ascertain a realistic semivariogram model, data needs to be collected according to an appropriate sampling strategy. Kronholm and Birkeland (2007) suggested that the optimal sampling scheme is achieved through changing the sample

spacing, extent, and support, known cumulatively as the scale triplet. Although, they related that even with scale triplet optimization, semivariogram accuracy is still a concern and recommended some degree of randomization should be built into the sampling design for the best results. Complicating things further, comparing studies with different scale triplets is difficult since they may have different integral scales and biases (Skøien and Blöschl, 2006).

As might be expected, higher observation density often improves semivariogram calibration (Webster and Oliver, 1992 in Kronholm and Birkeland, 2007). Additionally, Shea (2011) suggests a sampling method which collects data well beyond the expected range in order to obtain more robust spatial correlation measurements. Considering the size of this study's extent, the sampling scheme we used, generally satisfied these recommendations (Table 4.2).

Kriging is a method of spatial interpolation used in previous surface hoar research (Kronholm and Birkeland, 2004; Lutz and Birkeland, 2011). The technique helps in discovering general properties of a surface by extrapolating missing values from observational trends (Longley et al., 2005) and providing a measure of uncertainty for estimated values (Issaks and Srivastava, 1989). Ordinary Kriging models were fit to spherical semivariograms using GS+ which were exported to ArcGIS and used to visualize field area locations that had a higher or lower probability of surface hoar presence. The kriging models cover the radial distance (based upon the size of the

event's extent) from each observation and model accuracy decreases with increasing distance from observation locations.

3.5.2 The Effect of Elevation on Surface Hoar Crystal Size

The second part of data analysis focused on the relationship between elevation and surface hoar crystal size. Ordinary Least Squares regression modeling (O.L.S) is a classic statistical technique which estimates a line to describe the relationship between observed and predicted data by minimizing the sums of squares of their differences. However, an assumption of ordinary least squares regression is that observations may not be spatially autocorrelated, and must instead be independent of one another (Ramsey and Schafer, 2002). Spatial autocorrelation is a data characteristic in which the value of a variable is related to neighboring values of the same variable. Failing to account for the spatial structure in model residuals 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).

To test for spatial autocorrelation in the O.L.S. model residuals, I used the Moran's Index (Moran, 1948). The Moran's Index test has been utilized in previous avalanche spatial variability research by both Hendrikx et al. (2009) and Eckert et al. (2011) to quantify spatial autocorrelation. Perfectly dispersed data receives a value of -1.0 and completely clustered data is delineated as 1.0 (Tiefelsdorf, 2000) (Figure 3.8).

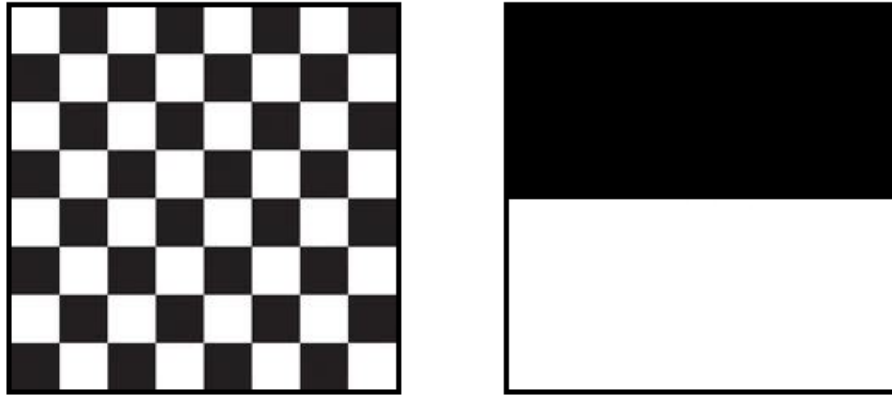


Figure 3.8: A graphical representation of Moran's I scores. The left side represents perfectly dispersed data and would receive a score of -1.0. The right side describes perfectly clustered data and a value of 1.0.

To calculate Moran's I scores, I used the ArcMap 9.3.1 Spatial Statistics, Moran's I test tool which operates under the form:

$$I = \frac{N \sum_i \sum_j W_{ij} (x_i - \bar{x})(x_j - \bar{x})}{(\sum_i \sum_j W_{ij}) \sum_i (x_i - \bar{x})^2} \quad (3)$$

where I is the Moran's index score, N is the number of cases, x_i is the variable at a particular location, x_j is the variable at another location, $\bar{x}$ is the global mean of variable x, and w_{ij} is a matrix set of weights applied to the comparison between a location i and location j.

In addition to the Moran's I value, this tool calculates a Z score value to test the null hypothesis of no spatial clustering present within the data. For this analysis, when Z scores were larger than 1.96 (95% significance level) the null hypothesis was rejected.

Since the O.L.S. residuals exhibited a statistically significant spatial autocorrelation, I decided it was not appropriate to use ordinary least squares regression to test the relationship between crystal size and elevation.

Instead, I used the ArcMap Geographically Weighted Regression (G.W.R.) Spatial Statistics tool described by Brunsdon et al. (1996) and Fotheringham et al. (2002). Given a dependent variable and a set of one or more independent variables from known locations, this tool fits a regression model at each data point, and allows parameters to be estimated anywhere, with observations closer to that location receiving greater weights than observations further away via a distance decay function. Geographically Weighted Regression was used to calculate the relationship between surface hoar elevation as an explanatory variable and surface hoar crystal size as a response variable:

$$y_i = \beta_{i0} + \beta_{i1}(u_i, v_i)x_{i1} + \varepsilon_i \quad (4)$$

where y_i is the predicted surface hoar crystal size, β_{i0} is the y intercept, (u_i, v_i) is the observation location, x_{i1} is the observation elevation and ε_i is a random error term. β_{i1} is locally estimated at each location (u_i, v_i) using a weighted distance-decay function which accounts for sample point density and is based upon the minimum root mean square prediction error from a range of bandwidths following the form:

$$w(x) = \exp\left(\frac{-d_i}{b}\right) \quad (5)$$

where $w(x)$ is the weight at location x , b is the bandwidth parameter distance and d_i is the distance between x and sample location i .

After fitting the Geographically Weighted Regression models, the Breusch-Pagan Test (Breusch and Pagan, 1979) was performed in R- Project for statistical computing (R Development Core Team, 2012) with the car package (Fox and Weisberg, 2011) to check for residual_heteroscedasticity. The null hypothesis for the Breusch-Pagan test states that variance is constant when testing a linear regression model (LM) against another regression model using the same explanatory variables and is assessed via a Chi-squared distribution:

$$LM = nR^2 \quad (6)$$

where n is the number of observations and R^2 is the coefficient of determination of squared residuals from the model being tested.

To assess normality of the Geographically Weighted Regression residuals, the Shapiro-Wilk test statistic (Shapiro and Wilk, 1965) was calculated in R using the nortest package (Gross and Ligges, 2012):

$$W = \frac{(\sum_{i=1}^n a_i y_i)^2}{\sum_{i=1}^n (y_i - \bar{y})^2} \quad (7)$$

where y_i is the i^{th} order statistic, $\bar{y}$ is the sample mean, and a represents the expected random variables from a standard normal distribution. The null hypothesis of the Shapiro-Wilk test states that the population comes from a normal distribution.

4. RESULTS

During the 2010 and 2011 heli-skiing seasons, data were collected over four surface hoar formation events. The weather during both study seasons was characterized by extreme and in some instances record breaking events. An El Niño pattern persisted in the Pacific throughout the 2009-2010 winter season which often brought strong onshore flow to the study area. Conversely, La Niña conditions and offshore flow prevailed during the winter of 2010-2011 (NWS, 2011).

Two surface hoar formation events occurred in 2010, one from March 20th to March 22nd and the other from April 8th to April 11th (Table 4.1, Figure 4.1, Figure 4.2). In 2011, two more events spanning March 17th to March 22nd and April 1st to April 2nd were observed. These events will be referred to in chronological order as Events 1-4 for the remainder of this thesis.

Figure 4.2 used values derived from a 30 m DEM to compare the distribution of elevation, slope, and aspect from observation locations with terrain from a rectangular zone which enclosed the entirety of the study area. The sampling scheme captured good representations of elevation and slope within the local vicinity. However, it is clear that the observations were strongly biased against southerly aspects and heavily favored northerly facing slopes. This occurred because guides generally avoid runs between aspects of approximately 120° to 240° which receive large amounts of solar shortwave radiation and consequently often have the poorest snow conditions for powder skiing.

In this chapter, the general characteristics of each formation event are conveyed through descriptive statistics and a summary of weather records. The spatial distribution of surface hoar presence is quantified through indicator semivariogram analysis and Ordinary Kriging. Finally, the effect of elevation on surface hoar crystal size is explored using Geographically Weighted Regression.

Table 4.1: Descriptive statistics summarizing the four surface hoar formation events.

Day	Observations (n)	Observed S.H. (n)	Observed No S.H. (n)	S.H. Presence (%)	Mean S.H. Size (mm)	S.H. Size SD (mm)
Event 1						
3/20/2010	78	49	29	63	4.5	2.2
3/21/2010	107	69	38	64	3.4	1.5
3/22/2010	26	12	14	46	2.1	0.7
Total	211	130	81	62	3.7	1.8
Event2						
4/8/2010	24	11	13	46	4.5	2.0
4/9/2010	78	72	6	92	5.2	2.3
4/10/2010	27	19	8	70	4	1.6
4/11/2010	14	5	9	36	6	1.2
Total	143	107	36	75	4.9	2.2
Event3						
3/17/2011	69	15	54	22	1.2	0.4
3/18/2011	46	12	34	26	1.1	0.5
3/19/2011	66	16	50	24	1.6	0.5
3/20/2011	25	9	16	36	1.4	0.5
3/21/2011	42	8	34	19	1.1	0.5
3/22/2011	42	8	34	19	1.5	0.5
Total	290	68	222	23	1.3	0.5
Event 4						
4/2/2011	87	62	25	71	2.8	0.8
Total	87	62	25	71	2.8	0.8
Grand Total	731	367	364	50	3.4	2.1

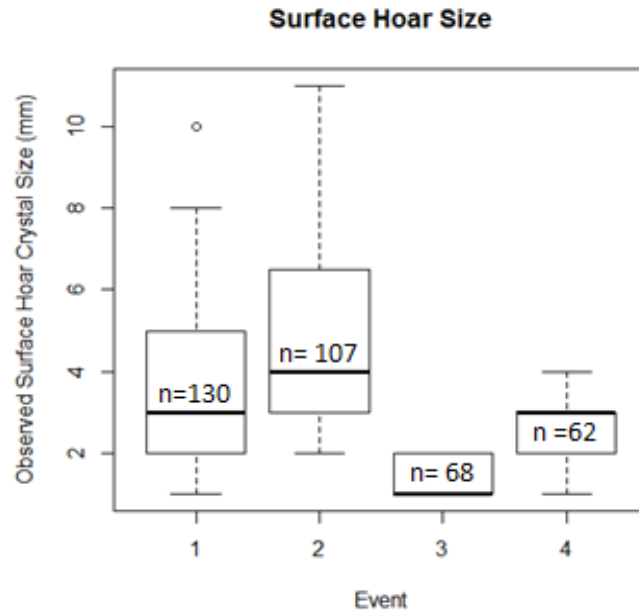


Figure 4.1: Boxplots depicting surface hoar crystal size from all four observation events. Boxes contain 25th to 75th percentiles. Medians are illustrated by bold lines. Whiskers represent minimum and maximum values excluding outliers. Outliers are greater than 1.5 times the upper or lower quartile values.

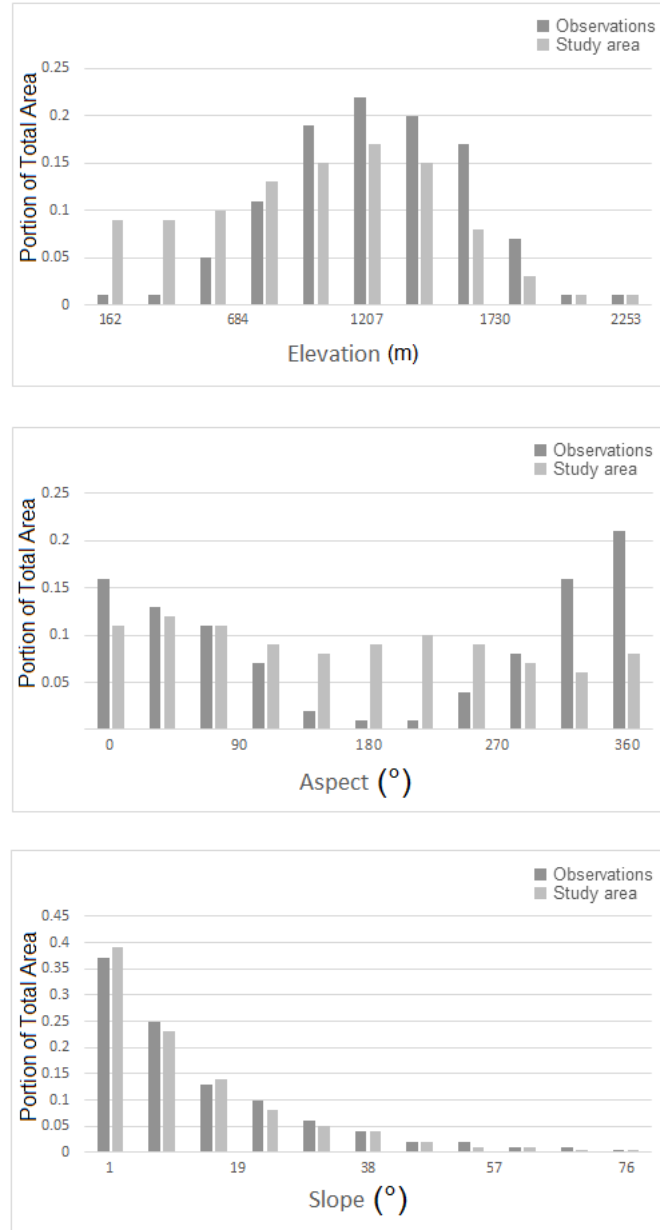


Figure 4.2: Distribution of elevation, aspect, and slope study observations compared with a rectangular shape that enclosed the study area. Study area values were calculated using a 30 m DEM.

4.1 Event 1

4.1.1 Event 1 Background and Weather

March 2010 was dominated by strong onshore and spilt flow in Haines as evidenced by the precipitation gauge located at the Haines airport which measured over 35 cm of SWE during the month (NWS, 2011) which is greater than 300% of normal (Table 3.1). Guides also observed very heavy snowfall in the higher elevation alpine terrain throughout the month of March. The airport average monthly temperature was 1.8°C (NWS, 2011) which is slightly warmer than normal (Table 3.1).

Following an extended longwave low pressure pattern which brought nearly continuous onshore flow and measurable precipitation at the Haines airport for 20 days straight, the weather began to clear on the afternoon of March 19th. The Old Faithful alpine weather station (1300 m) low temperature on the night of the 19th dropped to around -7°C while the relative humidity hovered near 90% (Figure 4.3). Average ridge top wind speeds ranged from about 2 ms^{-1} to 7 ms^{-1} mostly from the SW (Figure 4.4). Not surprisingly, guides began to encounter surface hoar on March 20th.

During Event 1, temperatures were seasonably cold and ranged from about -2°C on the 20th to about -11°C on the 21st. Relative humidity decreased to Event 1's lowest value of 45% on Old Faithful by the night of March 21st. Average wind speed at the alpine meteorological station doubled to about 10 ms^{-1} from the 20th to the 21st. Wind direction data is missing for about 24 hours during Event 1, likely as a result of anemometer icing, though the remaining values reflect generally SE-SW winds. By mid-

day on the 22nd, a winter storm entered the study area and ended the Event 1 surface hoar formation period.

Snowfall beginning on March 22nd totaled approximately 1 m in upper elevation alpine areas when guides returned to the field on March 29th. Guides observed numerous storm cycle avalanches that fractured on the Event 1 surface hoar layer (Figures 4.5, 4.6, 4.9). Over the duration of this study, Event 1 was the only surface hoar formation event that produced widespread observed avalanche activity.

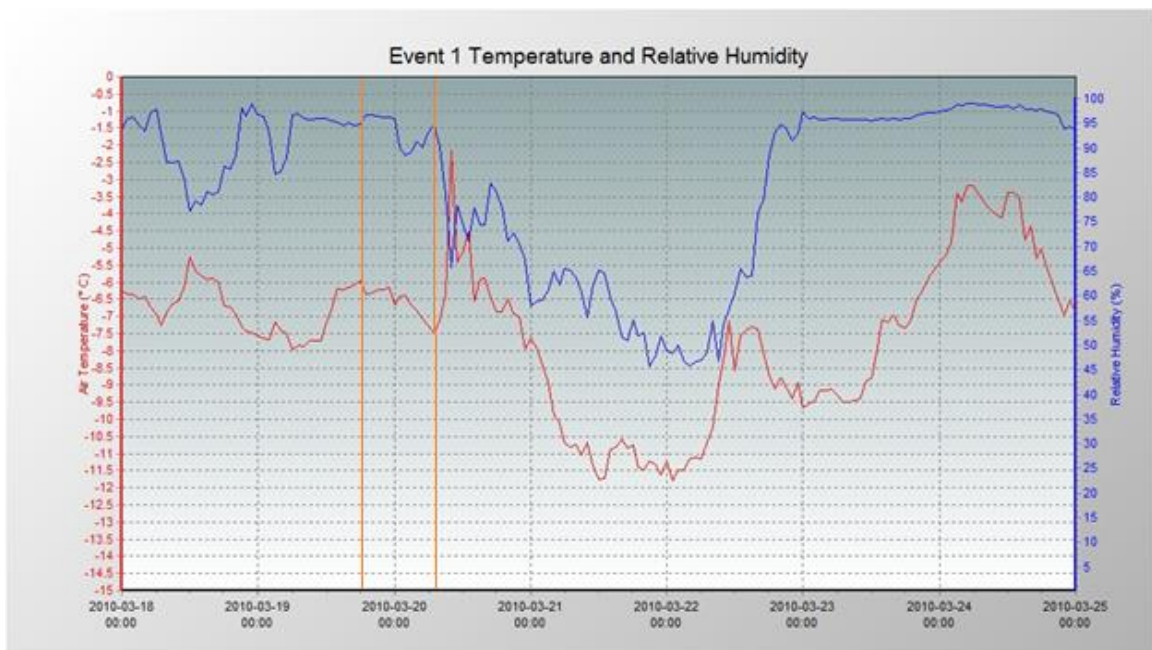


Figure 4.3: Event 1 air temperature and relative humidity recorded at the Old Faithful alpine weather station. Orange lines represent estimated window of surface hoar formation. Relative humidity near 95% overnight between the 19th and 20st allowed the bulk of Event 1's surface hoar growth to occur. The temperature rose relatively rapidly with the initial clear skies on the 20th before cooling. The large increase in relative humidity on the 22nd resulted from an incoming storm which dropped about 1 m of snow in the alpine.

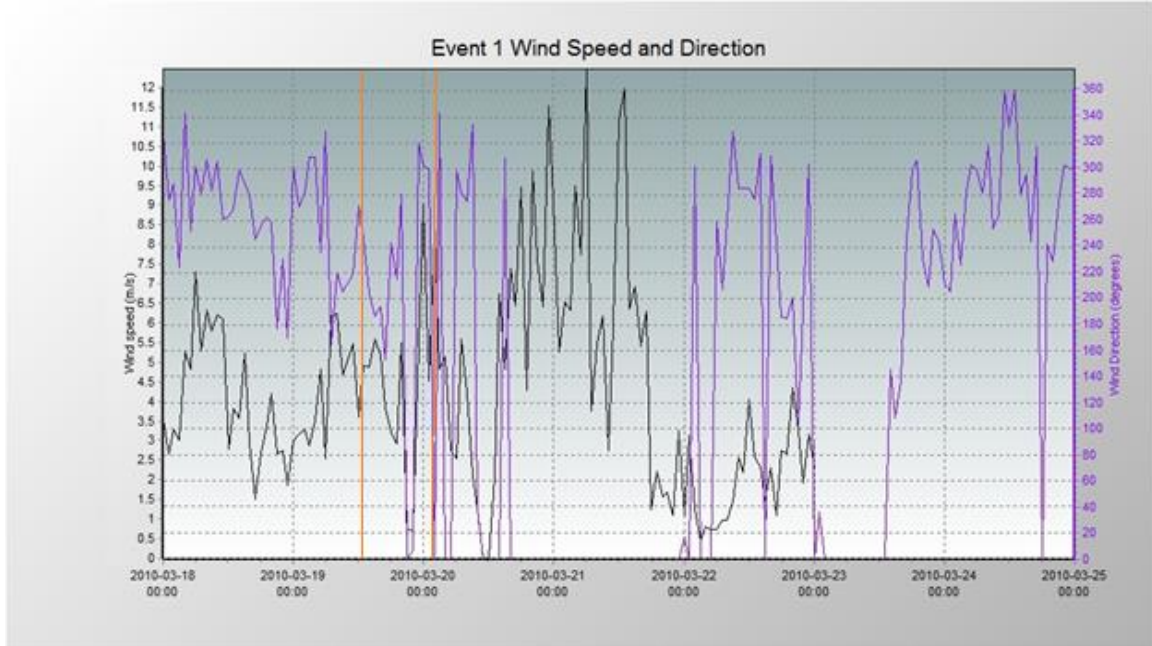


Figure 4.4: Wind speed and direction recorded at the Old Faithful alpine station during Event 1. Light ridgetop winds on the night of the 19th made for favorable surface hoar growth conditions. Orange lines represent estimated window of surface hoar formation.



Figure 4.5: After being buried by about 1 m of new snowfall, surface hoar from Event 1 produced many large natural avalanches including the northwest facing SS-N-R3-D2-I pictured here at about 1300 m on March 29th. Crown height is close to a meter and the slope angle is approximately 40°.



Figure 4.6: A SS-NI-R2-D2-I avalanche photographed on April 2nd at about 1400 m that failed on buried surface hoar from Event 1. The crown height is approximately 1 m. Slope aspect is northerly with an angle of about 25° near the crown.

4.1.2 Event 1 Spatial Distribution of Surface Hoar Presence

Over 200 measurements documented the snow surface during Event 1 across nearly the entire width of the study area. Surface hoar was present at approximately 62% of the observation sites. Maximum extent between point measurements approached 60 km while the minimum spacing was near 50 m, with the latter value resulting from data collection by multiple guides on the same run (Table 4.2).

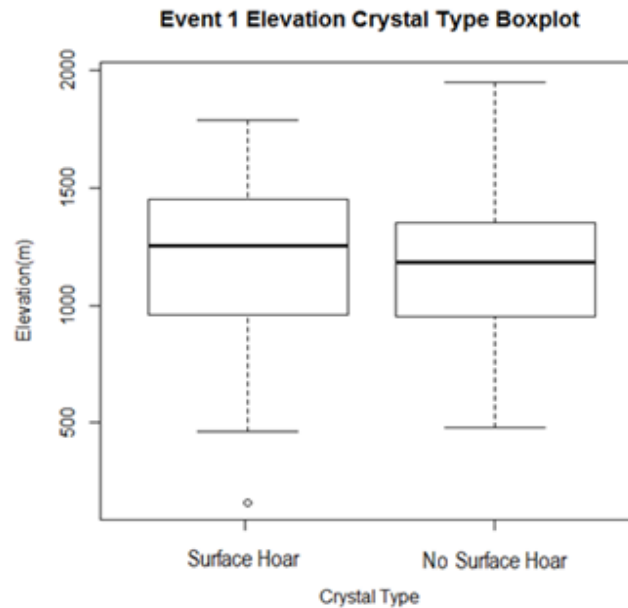


Figure 4.7: Box plots describing the presence or absence of surface hoar by elevation. Boxes represent 25th and 75th percentiles. Whiskers signify minimum and maximum values. Surface Hoar n=130. No Surface Hoar n=81.

On runs where surface hoar was found during Event 1, it was often continuously present across the slope. Event 1 took place about midway through the season, just before the guides typically start avoiding west facing aspects as spring temperatures arrive. Therefore, some runs were skied – and sampled – during Event 1 which would not often get skied during April due to warming snow and/or crusts.

Semivariogram modeling of Event 1's surface hoar presence versus absence over a lag of nearly 60 km produced a range of approximately 6 km (Figure 4.8 and Table 4.3). This means that the presence of surface hoar in one location could be extrapolated to another location up to about 6 km away. However, fine scale variation resulting from aspect or slope angle should still be expected. In other words, it wouldn't make much

sense to expect surface hoar on a steep south facing slope because it was observed on a relatively flat north facing slope 3 km away. Still, we would expect that slopes of similar aspect and elevation would have similar presence/absence of surface hoar within about 6 km. Beyond 6 km there is no surface hoar spatial autocorrelation and practical decision making should be based upon a new frame of reference.

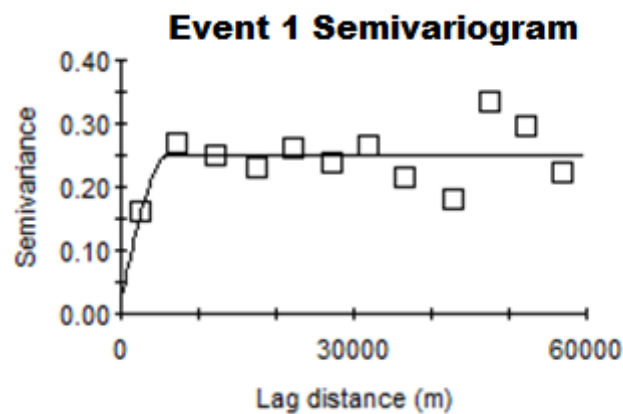


Figure 4.8: Event 1 surface hoar presence or absence indicator semivariogram.

Nugget and sill values measured 0.02 and 0.25 respectively giving a nugget to sill ratio of 8% (Figure 4.8 and Table 4.3) which suggests strong spatial structure within the data. According to Cambardella et al., (as cited in Balasundram et al., 2008) nugget/sill ratios below 0.25 indicate strong spatial dependence, values between 0.25 and 0.50 suggest moderate spatial dependence, and values greater than 0.75 are associated with weak spatial dependence. Interpolated surface hoar presence probability was highest in the areas protected from northerly outflow winds including the Garrison and Takhin Glaciers (Figures 3. 3 and 4.9). Conversely, areas exposed to pressure gradient winds

such as slopes near Lynn Canal and the Chilkat River Valley were less likely to have persistent surface hoar.

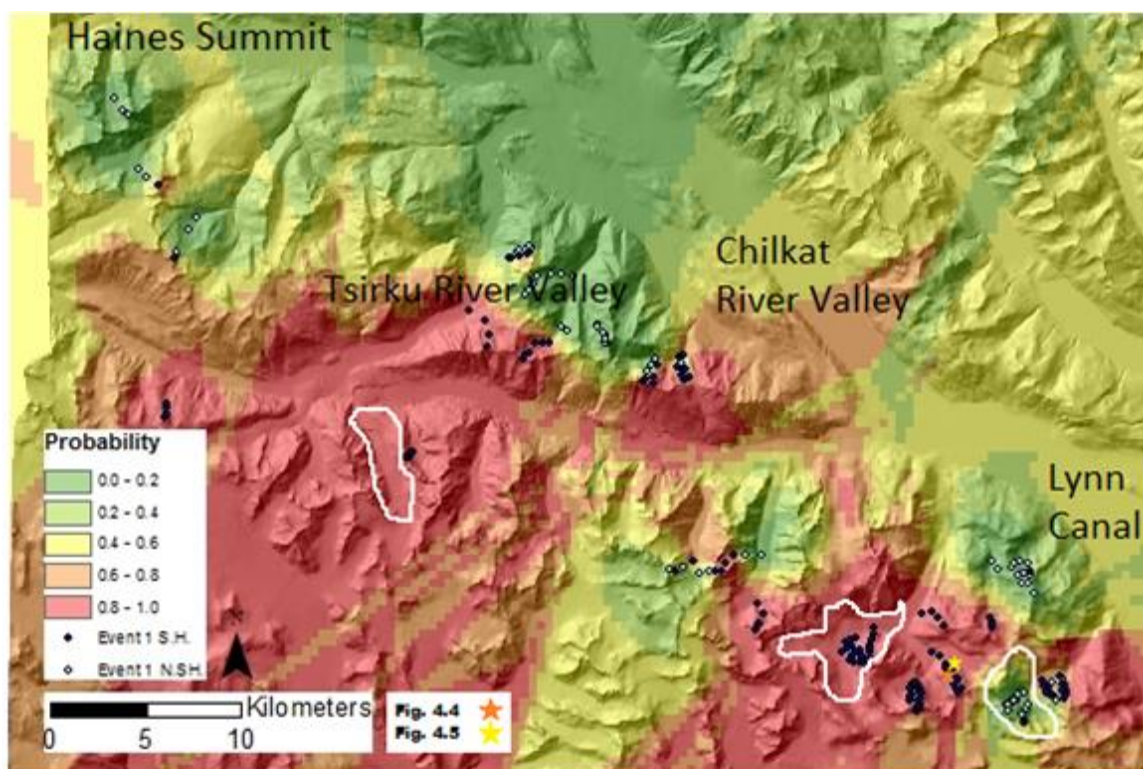


Figure 4.9: Event 1 kriging interpolation of surface hoar presence probability. Presence likelihood was lowest in areas exposed to synoptic onshore and offshore winds such as the Rainbow Glacier (far-right white outline). Surface hoar was more likely to be present in wind protected areas comparable to the Garrison (middle outline) and Taklin Glaciers (far-left white outline). Interpolations are less reliable with increasing distance from sampled data and on slopes dissimilar to observation locations, which were biased toward northerly aspects (Figure 4.2).

4.1.3 Event 1 Effect of Elevation on Surface Hoar Crystal Size

Throughout Event 1, sector plate crystals (Figure 4.10) between 1 mm and 10 mm were observed, with generally smaller sizes towards the bottom of runs. Event 1 mean crystal size was 3.7 mm with a standard deviation of 1.8 mm (Figure 4.1 and Table

4.1). Comparison of data from March 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.

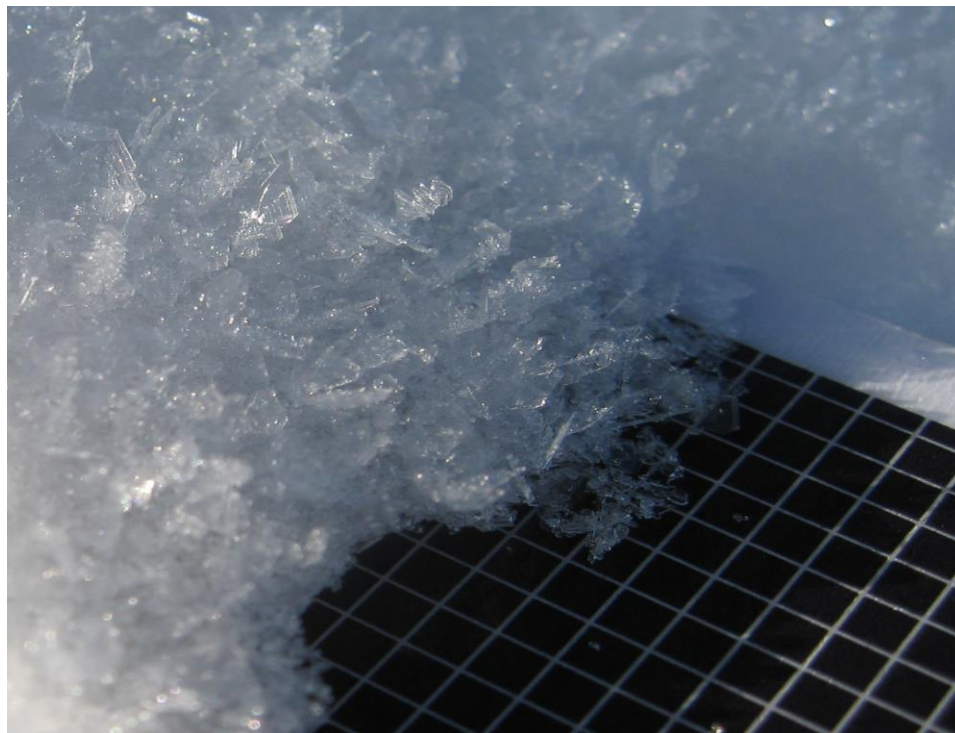


Figure 4.10: Sector plate crystals formed during Event 1. Grid size is 2 mm.

Plotting Event 1 surface hoar crystal size against elevation displays a moderate linear trend satisfying the assumption of linearity necessary for linear regression analysis (Figure 4.11). A second assumption of linear regression states that regression residuals should be spatially independent. To check for spatial autocorrelation, a Moran's Index test was performed on ordinary least squares residuals used to evaluate the relationship between surface hoar crystal size and elevation across the study area (Table 4.4). Due

to the overall autocorrelation of the four surface hoar events described by the Moran's I results, O.L.S. was abandoned.

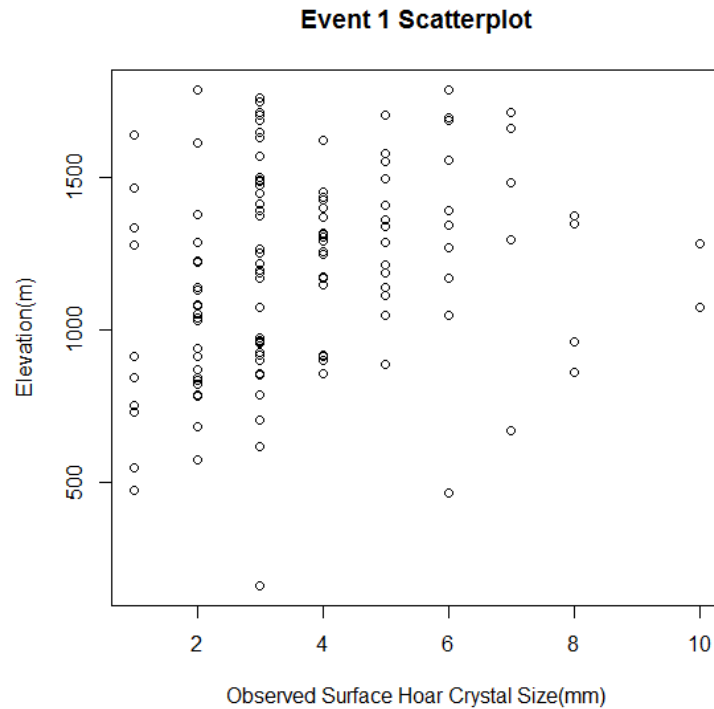


Figure 4.11: Event 1 scatterplot of elevation and surface hoar crystal size observed during March 20th to March 22nd, 2010. $n=130$. Mean elevation of observed surface hoar crystals is 1214 m and standard deviation is 308 m.

Geographically Weighted Regression produced an adjusted R^2 value of 0.37 for the Event 1 surface hoar layer (Table 4.5 and Figure 4.12). This suggests a moderate linear relationship between elevation and surface hoar crystal size. In other words, elevation can explain 37% of the Event 1 surface hoar crystal size and 63% is due to other variables.

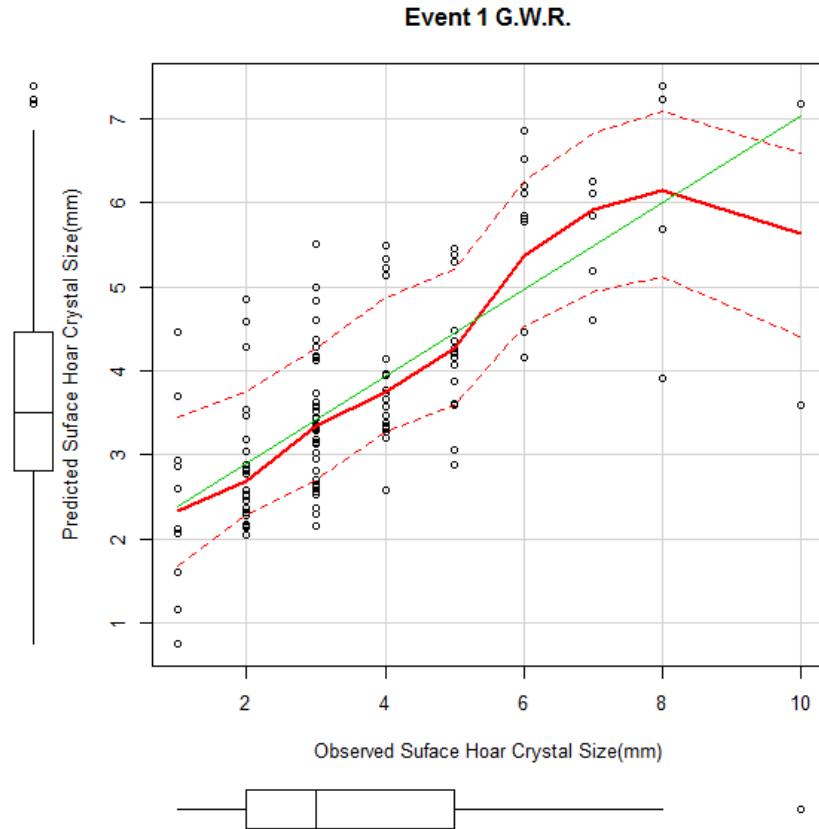


Figure 4.12: Geographically Weighted Regression with best fit lines and box plots describing 130 surface hoar observations from Event 1. Two 10 cm observed outliers are included. Adjusted $R^2 = 0.37$.

Evaluating the Event 1 Geographically Weighted Regression residuals for homoscedasticity using the Breusch-Pagan test initially suggested non-constant variance $\chi^2(2, n=130) = 13.55, p < 0.05$, due to two outlier observed crystals that measured 10 mm during Event 1 (Table 4.6). However, removing the outliers and running the test again led to a score of $\chi^2(2, n=128) = 1.22, p > 0.05$ which suggests that the model was generally a good fit and met the linear regression assumption of constant variance (Figure 4.13).

The Shapiro-Wilk test was calculated to assess whether the G.W.R. model satisfied the linear regression assumption of normality. Similarly to the results of the non-constant variance test, the outliers from Event 1 affected the results of the Shapiro-Wilk test enough to produce a non-normal result. Computing the test again, minus the outliers, brought the residuals back to an approximately normal distribution with a S-W test statistic of 0.98 (p-value > 0.05) (Table 4.7 and Figure 4.13).

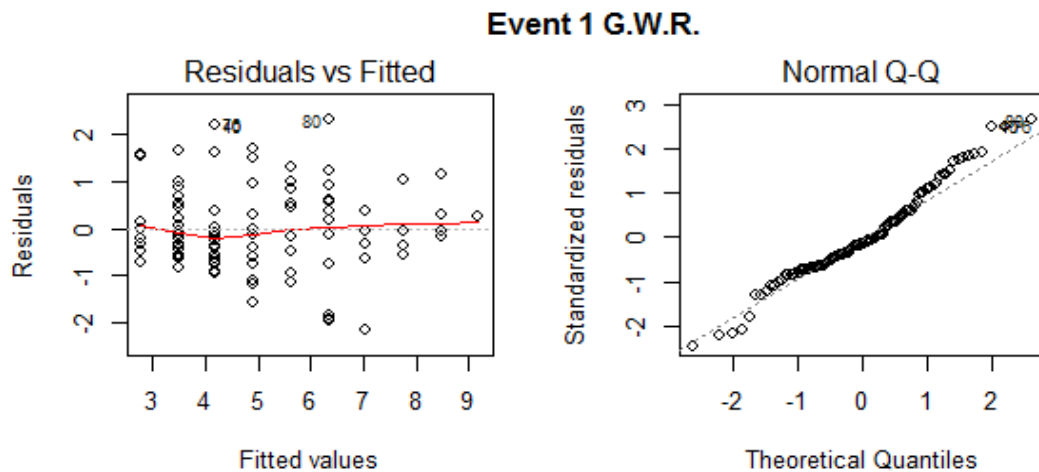


Figure 4.13: Residual versus fitted and normal quantile-quantile plots for Event 1 including two 10 mm outlying values. Slight deviations from heteroscedasticity and normality exist with the outliers, although Breusch-Pagan and Wilk-Shapiro tests suggest a return to constant variance and normal distribution with the outliers removed.

4.2 Event 2

4.2.1 Event 2 Background and Weather

In stark contrast to the previous month's weather, Event 2 was characterized by moderate offshore flow and much clearer conditions. Throughout the month, the Haines airport precipitation gauge only recorded about 3 cm of SWE with a slightly

above average temperature of 5.8°C (NWS, 2011) (Table 3.1). The week before Event 2 saw light to moderate snowfall in the alpine which was observed by guides in the field during which time the airport recorded about 1 cm of SWE.

On the afternoon of April 6th at the alpine weather station relative humidity hovered near 90% under a slight cooling trend with a low of about -8°C (Figure 4.14). Alpine winds just before Event 2 averaged close to 10 ms^{-1} out of the WNW, but during the evening, the winds died down to values near 2 ms^{-1} and shifted to the SSE (Figure 4.15). Relative humidity dropped to about 55% on the afternoon of April 7th, but increased to near 90% by that evening. Guides began to notice surface hoar in the field by April 8th.

Conditions remained favorable for surface hoar development until the winds picked up again early on April 9th to about 9 ms^{-1} , mostly from the SE. Wind velocity decreased slightly to about 4 ms^{-1} by the 11th. Wind direction data on the 10th and early on the 11th is missing, though the prevailing winds were observed to be light and southerly by guides in the field during that time. Alpine temperatures stayed between -5°C and -10°C during Event 2.

A sizeable warming trend took place during the latter part of Event 2, while relative humidity trended lower to about 50% through the 10th. Although no precipitation occurred in the study area, guides no longer observed surface hoar after April 11th. Since the surface hoar was destroyed, it did not play any role in future avalanches, unlike the numerous avalanches associated with Event 1.

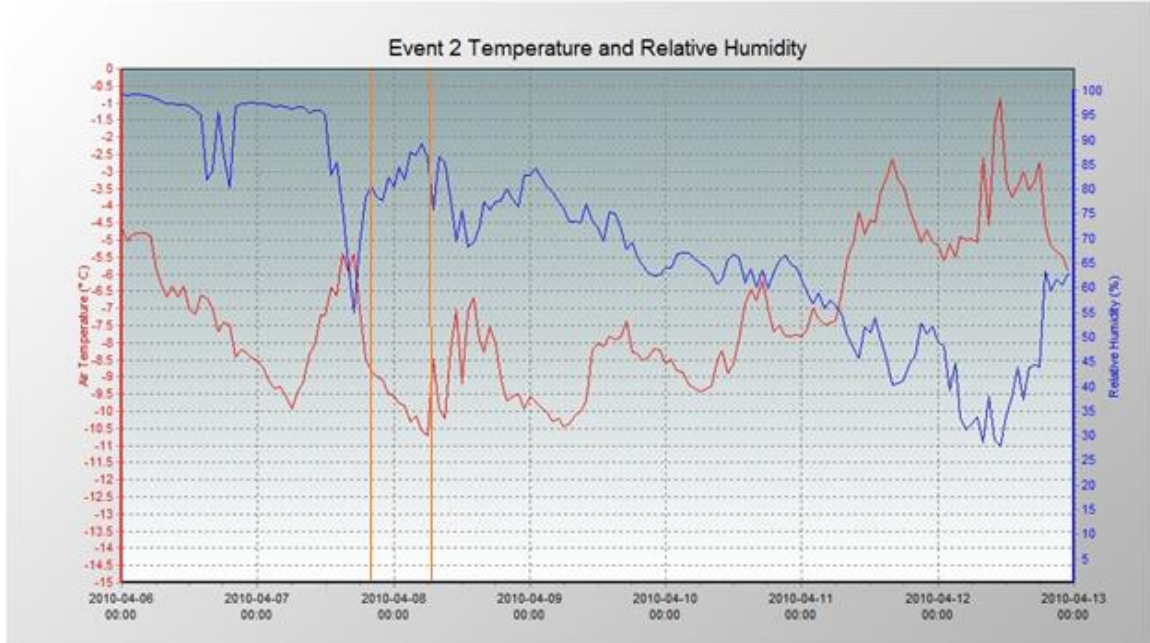


Figure 4.14: Event 2 temperature and relative humidity recorded at the Old Faithful alpine weather station. Orange lines represent estimated window of surface hoar formation. The bulk of Event 2's surface hoar formed on the night of April 7th. The warming trend that started on April 10th destroyed much of the Event 2 surface hoar.

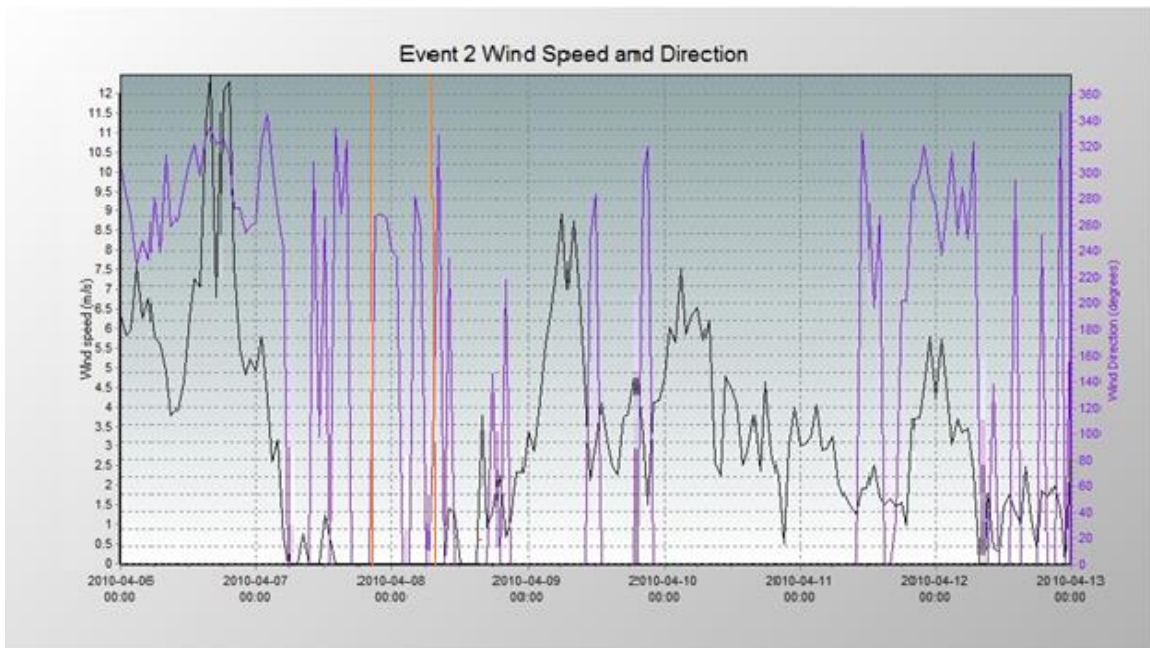


Figure 4.15: Wind speed and direction recorded at the Old Faithful alpine station during Event 2. The wind was likely too light to register values from the night of April 7th. Orange lines represent estimated window of surface hoar formation.

4.2.2 Event 2 Spatial Distribution of Surface Hoar Presence

Over the duration of Event 2 on April 8th through the 11th about 150 snow surface measurements were collected. Guides noted the presence of surface hoar at 75% of their observations sites. The extent of point measurements was nearly 40 km and the minimum spacing was similar to Event 1 at approximately 40 m (Table 4.2).

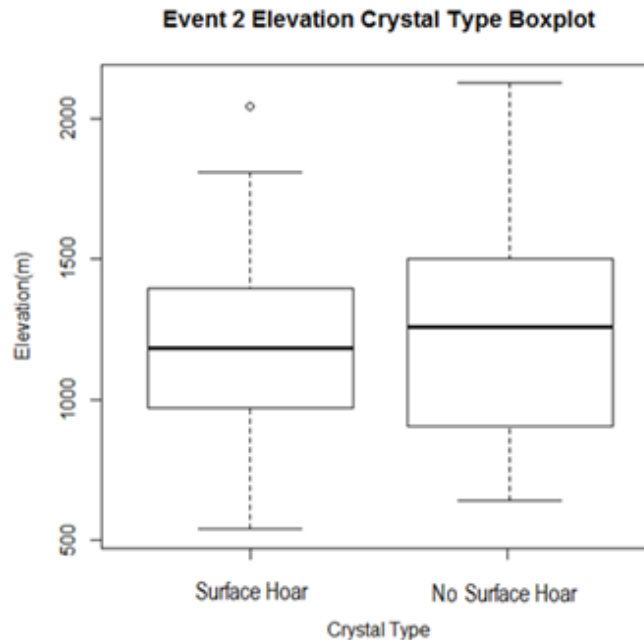


Figure 4.16: Boxplots illustrating the presence or absence of surface hoar by elevation. Surface Hoar n=107. No Surface Hoar n=36.

Event 2's surface hoar presence on some individual ski runs towards the edges of the study area exhibited greater discontinuity than those closer to the center of the study area. Additionally, more observations devoid of surface hoar were interspersed between surface hoar observations on runs away from the central parts of the study area. However, near the center of the study area, the surface hoar was observed to be

nearly continuous and present at almost all observation locations. Due to Event 2's occurrence relatively late in the season, guides skied a higher percentage of northerly slopes than they might during mid-winter conditions. Higher elevation pickups are also more common later in the season.

Semivariogram calculations for the Event 2 layer gave the largest range in the study at just over 25 km from a lag of just under 42 km (Figure 4.17 and Table 4.3). In spite of the large range, the nugget variance and sill remained close to the other Events with respective values of 0.02 and 0.29. The nugget sill ratio of 0.07 is indicative of strong spatial structure within the Event 2 surface hoar layer.

The area with the highest kriging modeled Event 2 surface hoar presence probability was clustered near the center of the study area (Figure 4.18). Lower presence probability values were calculated closer to the perimeter of the study area in zones which see greater inflow and outflow pressure gradient winds.

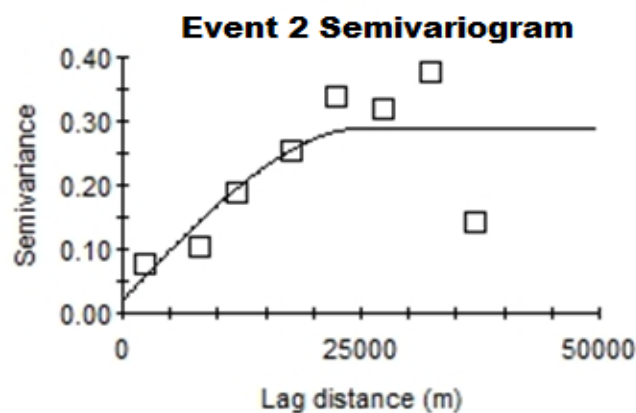


Figure 4.17: Spherical indicator semivariogram describing the presence or absence of Event 2 surface hoar.

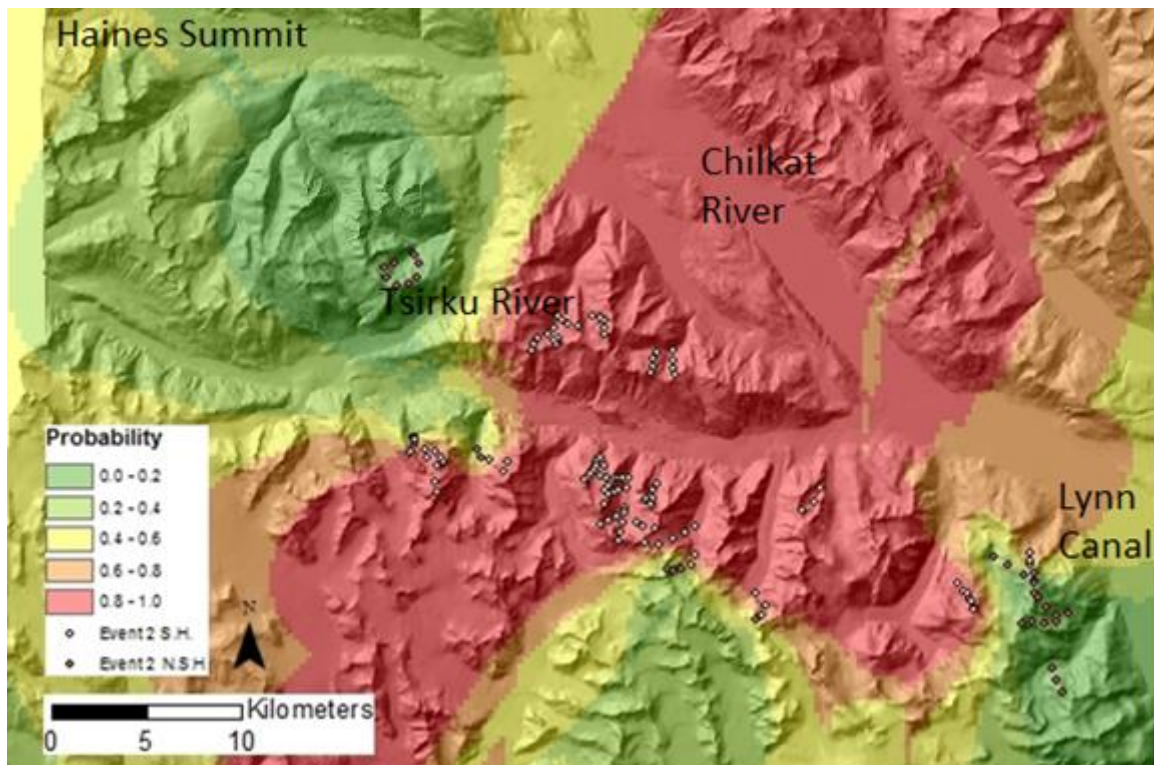


Figure 4.18: Event 2 kriging interpolation of surface hoar presence probability. Areas near Lynn Canal and the Tsirku River which are exposed to the coupled effects of synoptic winds and glacial katabatic winds had lower surface hoar presence probabilities. In contrast, wind protected slopes near the center of the study area had a higher likelihood of surface hoar presence. Interpolations are less reliable with increasing distance from sampled data and on slopes dissimilar to observation locations, which were biased toward northerly aspects (Figure 4.2).

4.2.3 Event 2 Effect of Elevation on Surface Hoar Crystal Size

Guides reported both sector plate and feathery crystal types with sizes from 1 mm to 11 mm during Event 2 (Table 4.1 and Figure 4.19). Mean crystal size during Event 2 was 4.9 mm with a standard deviation of 2.2 mm (Figure 4.1). Surface hoar crystal size was observed to be linearly related to elevation on individual runs during Event 2 with larger crystals at higher elevations (Figure 4.20). Geographically Weighted Regression analysis of the effect of elevation on surface hoar crystal size produced an adjusted R^2

value of 0.67 (Figure 4.21), meaning that elevation alone could explain about 67% of the variance in Event 2 surface hoar crystal size.

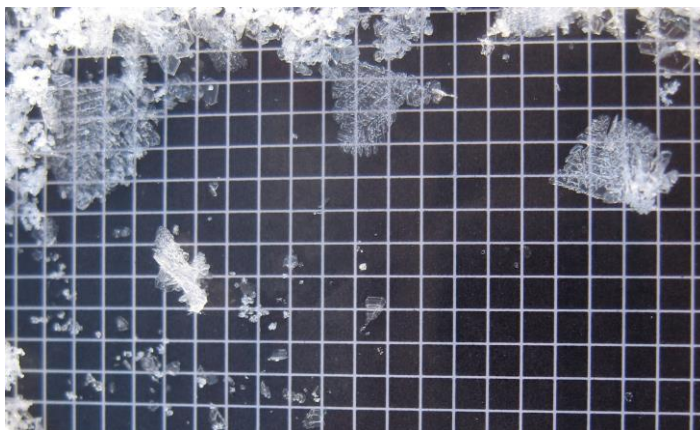


Figure 4.19: Large feathery surface hoar crystals photographed on a 2 mm grid during Event 2.

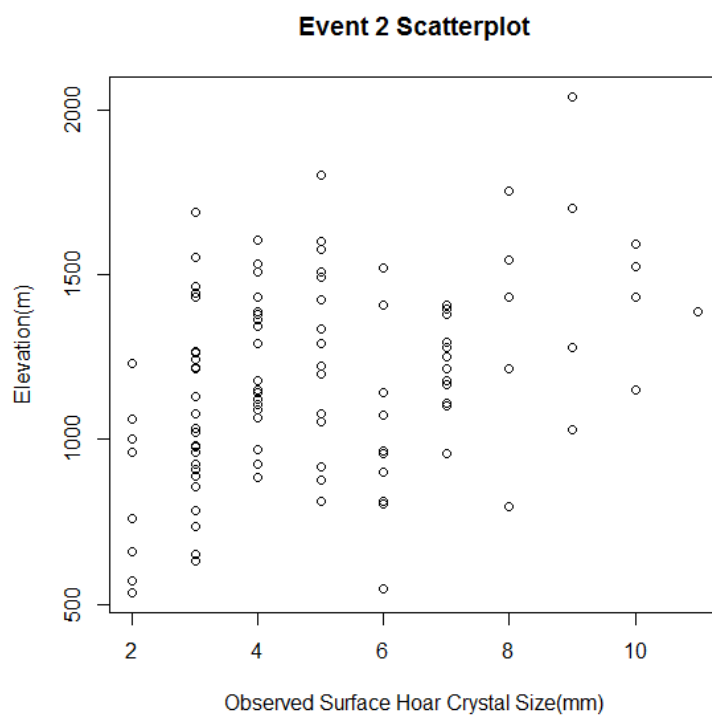


Figure 4.20: Scatterplot illustrating Event 2 surface hoar crystal size by elevation. $n=107$. Mean elevation of observed surface hoar crystals is 1178 m and standard deviation is 379 m.

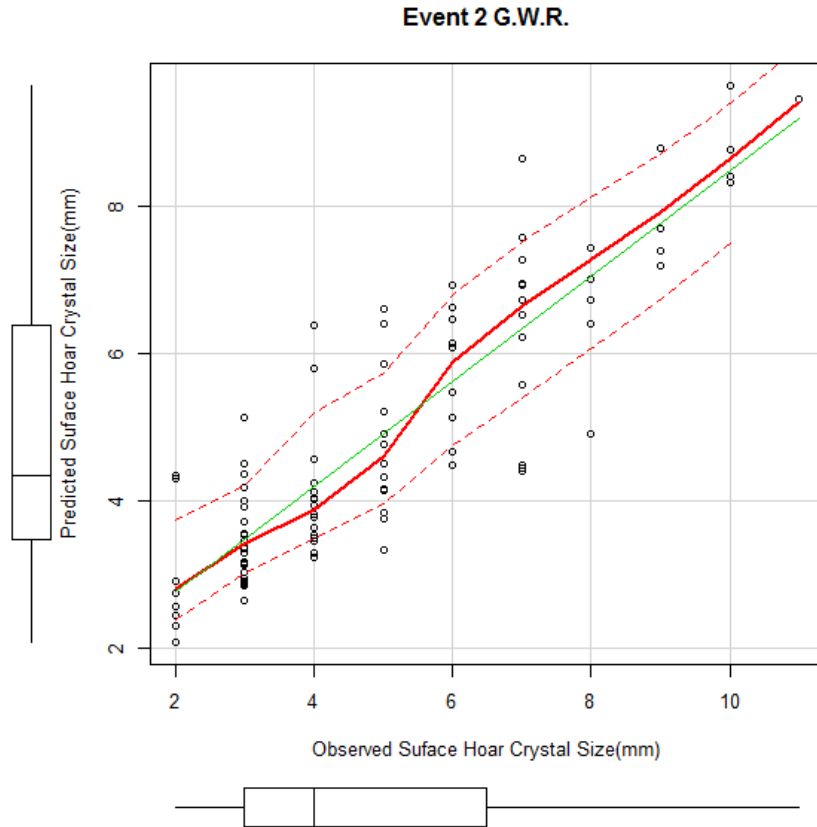


Figure 4.21: Geographically Weighted Regression with best fit lines and box plots describing 107 surface hoar observations from Event 2. This model produced the best fit of all four events. Adjusted $R^2 = 0.67$.

The Event 2 Breusch-Pagan analysis of the Geographically Weighted Regression residuals produced an $X^2(2, n=107) = 1.55$, $p > 0.05$ test statistic of 1.55 (p-value > 0.5) (Table 4.6). This result fails to reject the null hypothesis and is indicative of constant variance satisfying the linear regression assumption of homoscedasticity (Figure 4.22). The Shapiro-Wilk test statistic of 0.98 (p-value > 0.05) suggests the Event 2 G.W.R. residuals come from a normal distribution (Table 4.7 and Figure 4.22).

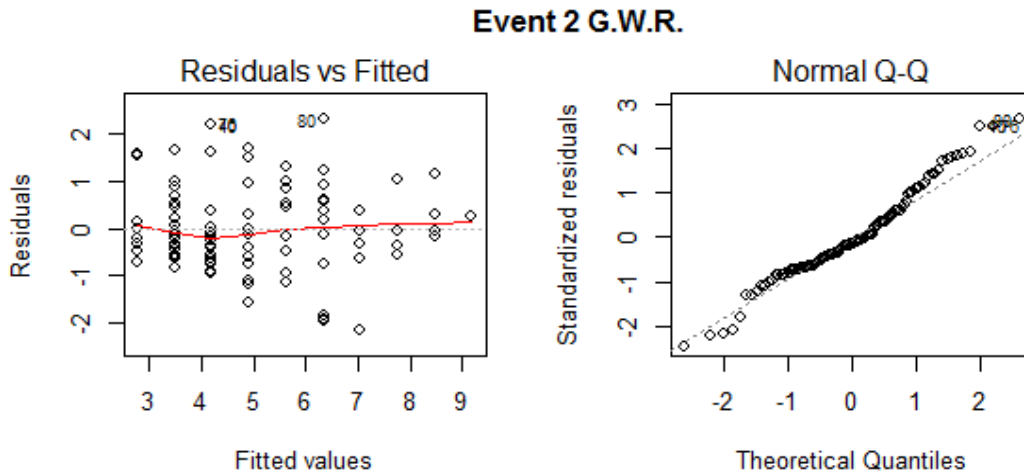


Figure 4.22: Residual versus fitted and normal quantile-quantile plots for event 2. Residual homoscedasticity and normality are depicted.

4.3 Event 3

4.3.1 Event 3 Background and Weather

March 2011 was heavily influenced by strong offshore flow. At the Haines airport both the average precipitation and temperature were far below normal for the month. Less than 1 cm of SWE fell in March while the average temperature was -2.5°C . Guides observed about 30 cm of low density snow that fell in the study area's alpine elevations directly preceding Event 3 during the 14th-16th. Relative humidity oscillated slightly around 90% on the 16th before falling to about 65% by the 17th at the alpine station (Figure 4.23).

Moderate alpine weather station E-SSE winds averaged up to 10 ms^{-1} on the 14th but lessened to around 5 ms^{-1} and shifted to the W-SW by the 16th (Figure 4.24). Guides began to observe surface hoar on March 17th and collected snow surface observations

until March 22nd. Throughout Event 3, the alpine weather station temperatures stayed consistently cold with a low of about -13°C on March 19th and a high of just above -5°C on March 20th. Relative humidity plummeted from 95% on the 17th to only 15% by the 20th. At nearly the same time the relative humidity decreased on the 17th, the prevailing winds shifted to the east for the remainder of Event 3. The average wind speed during Event 3 fluctuated from a high of approximately 9 ms^{-1} down to only 1 ms^{-1} . Shortwave radiation daily maximum values during Event 3 are consistent with mostly sunny weather (Figure 4.25). More variable values were recorded when clouds moved back into the study on the on the last day of data collection. On March 22nd, the prevailing winds shifted back to SW onshore flow, which ushered in new precipitation and ended Event 3 (Table 4.1).

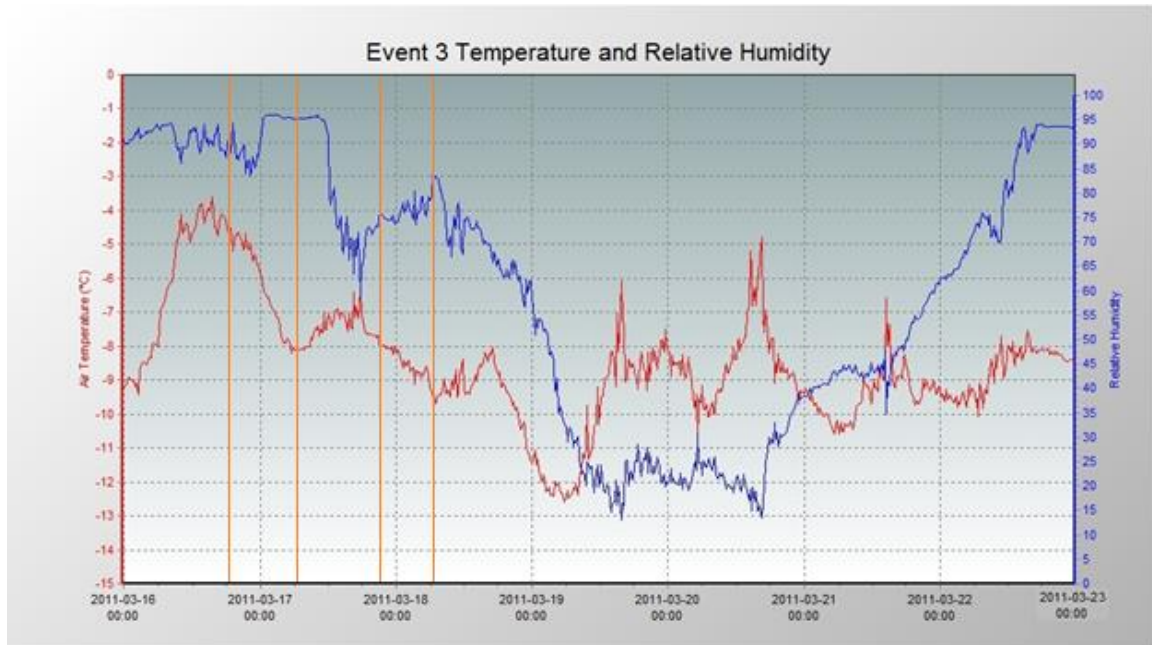


Figure 4.23: Event 3 temperature and relative humidity recorded at the Old Faithful alpine weather station. Orange lines represent estimated window of surface hoar formation. High relative humidity immediately preceding Event 3 allowed surface hoar to form at high elevations. Temperatures during Event 3 were colder than average due to the influence of offshore flow.

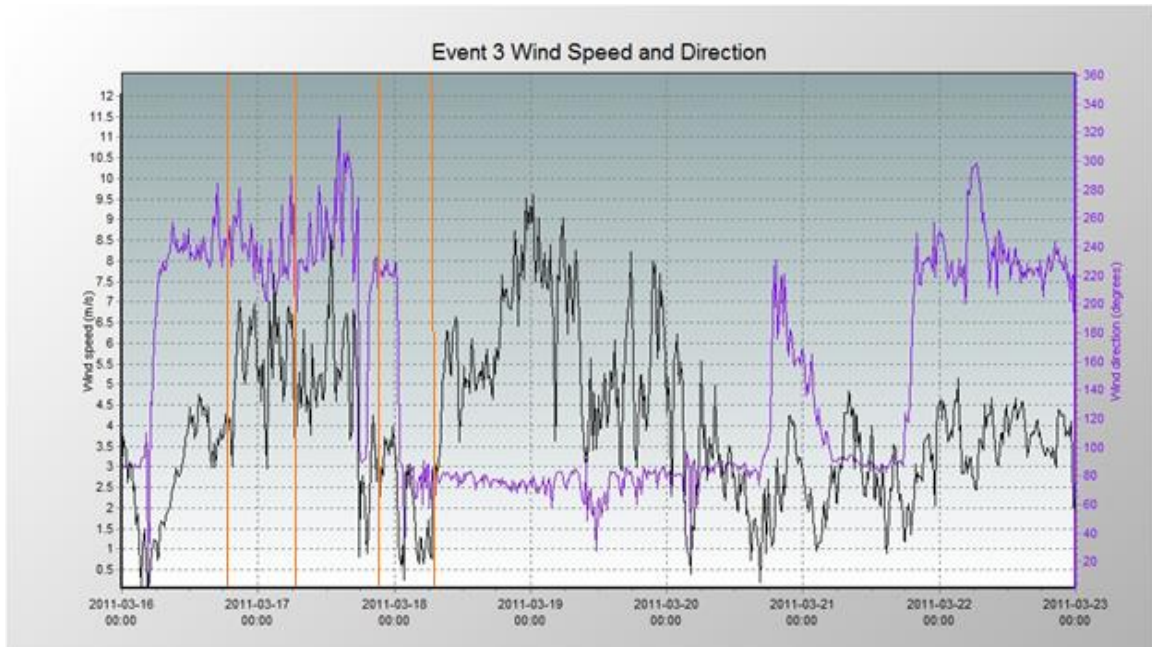


Figure 4.24: Wind speed and direction recorded at the Old Faithful alpine station during Event 3. Orange lines represent estimated window of surface hoar formation. Surface hoar growth occurred under light SW winds before the winds increased to about 10 m s^{-1} as the direction switched to predominantly east.

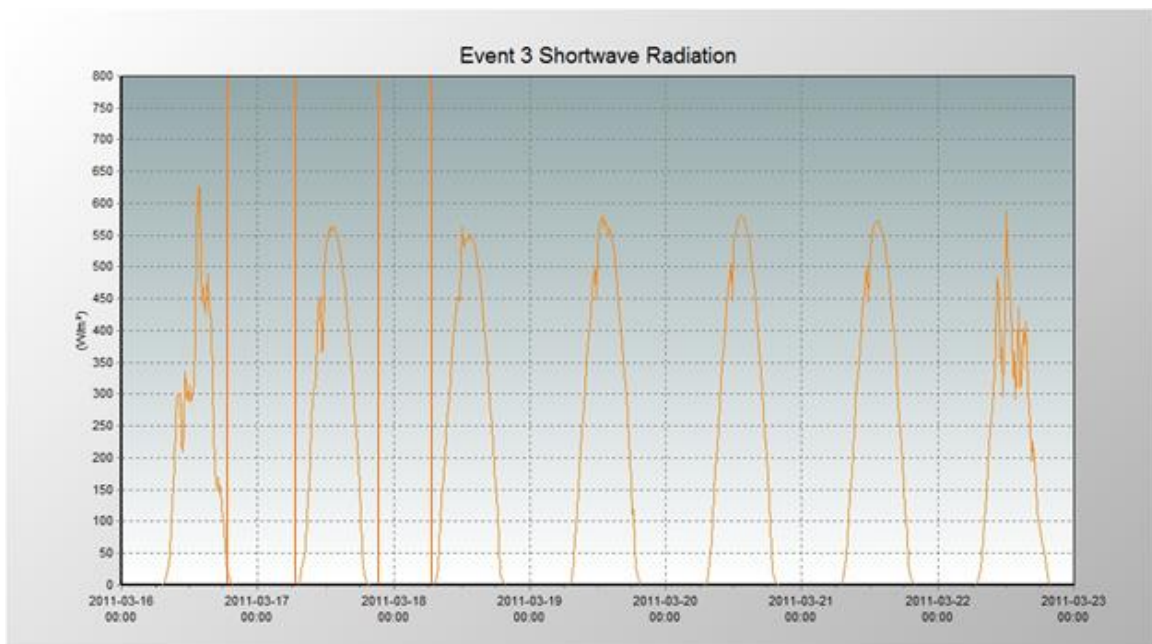


Figure 4.25: Shortwave radiation measured at the Old Faithful alpine weather station during Event 3 is indicative of mostly sunny to partly cloudy early spring weather. Orange lines represent estimated window of surface hoar formation.

4.3.2 Event 3 Spatial Distribution of Surface Hoar Presence

Guides made about 300 observations during Event 3 across a measurement extent just under 20 km. The minimum spacing between point measurements was approximately 10 m (Table 4.2). Event 3 had the lowest prevalence of surface hoar presence of the four events, with observable surface hoar at only 23% of sample sites.

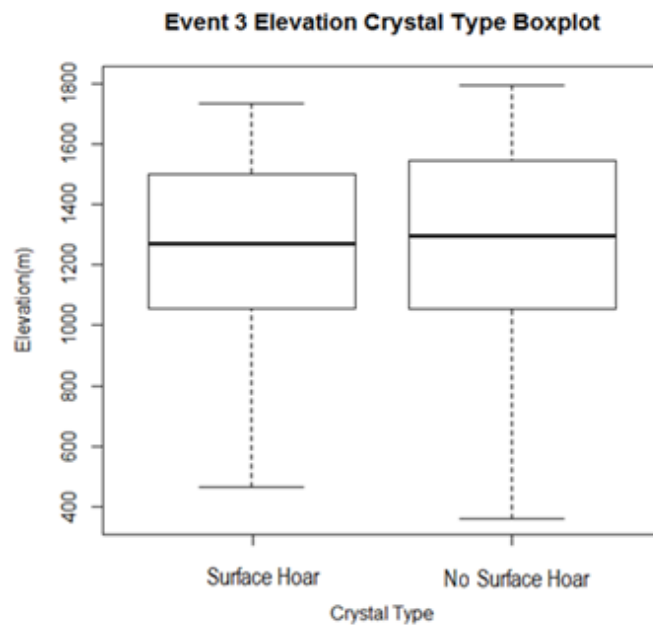


Figure 4.26: Boxplots depicting the presence or absence of surface hoar by elevation. Surface Hoar n=68. No Surface Hoar n=222.

Event 3 semivariogram modeling across a 20 km lag produced a range of 3.9 km (Figure 4.27). Event 3's semivariogram model had the largest layer nugget variance value at 0.04 with a sill value of 0.21 (Table 4.3) The calculated nugget/sill ratio was 0.19, suggesting strong spatial structure in the surface hoar observations. Kriging surface hoar presence probability was low in most areas except for wind-protected high elevation locations (Figure 4.28).

Event 3 had the spottiest observed surface hoar layer during the study. Surface hoar of Event 3 was present mostly near the tops of peaks with diurnally recrystallized near-surface facets making up the majority of the snow surface at lower elevations.

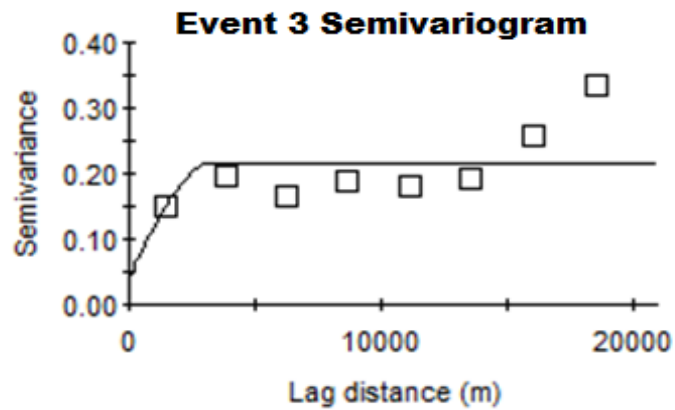


Figure 4.27: Event 3 spherical surface hoar presence or absence indicator semivariogram.

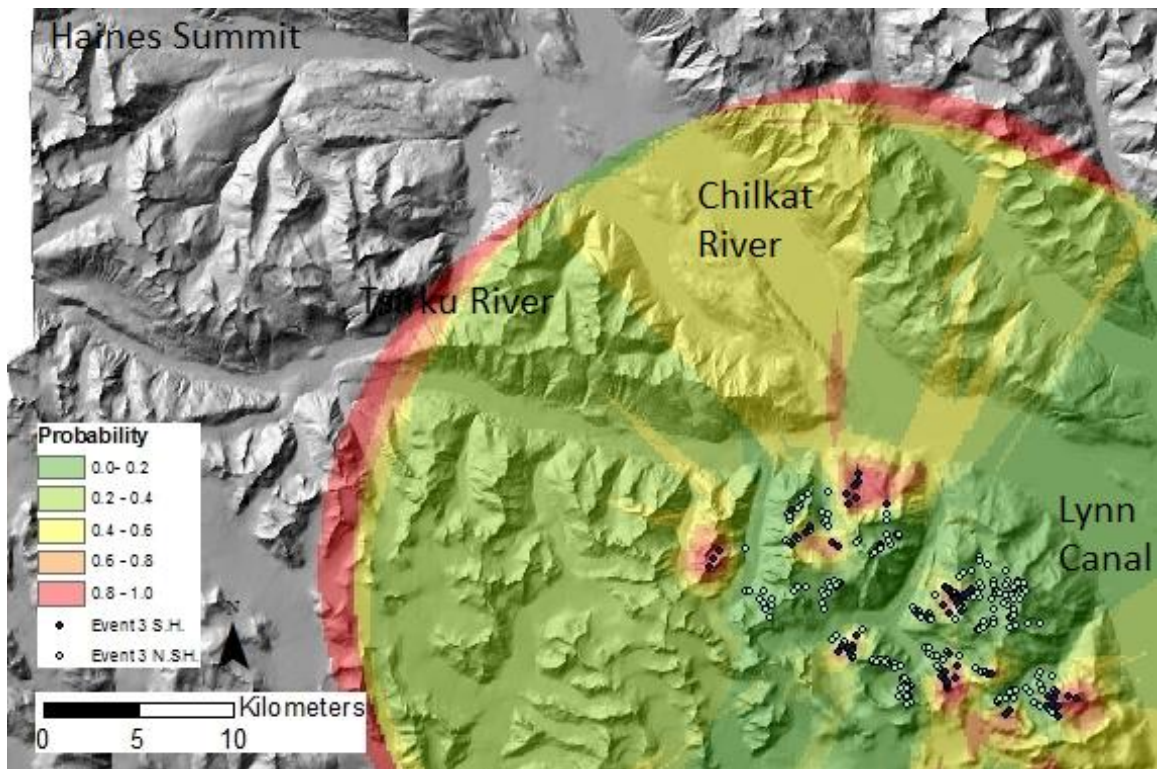


Figure 4.28: Event 3 kriging surface hoar presence probability interpolated values for Event 2. With the exception of slopes exposed to synoptic winds, surface hoar was present on many runs. However, surface hoar formation was strongly elevation dependent and was only observed near the top of runs. Interpolations are less reliable with increasing distance from sampled data and on slopes dissimilar to observation locations, which were biased toward northerly aspects (Figure 4.2).

4.3.3 Event 3 Effect of Elevation on Surface Hoar Crystal Size

The observed surface hoar crystals of Event 3 were small sector plates (Figure 4.29) not larger than 2 mm. Event 3 mean observed crystal size was 1.3 mm with a standard deviation of 0.5 mm (Figure 4.1 and Table 4.1). Due to the narrow size distribution of Event 3's surface hoar, it is difficult to visualize a linear scatterplot trend (Figure 4.30)



Figure 4.29: Small sector plate crystals from Event 3 in front of 1 and 2 mm grids.

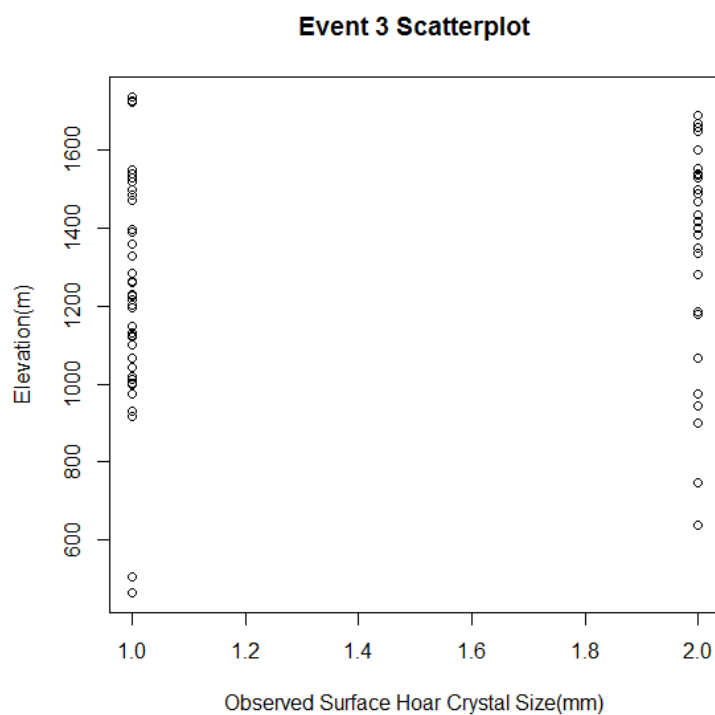


Figure 4.30: Scatterplot of Event 3 surface hoar crystal size and elevation. $n=68$. Only sizes of 1 mm or 2 mm were observed on this sampling day. Mean elevation of observed surface hoar crystals is 1268 m and standard deviation is 289 m.

Geographically Weighted Regression gave an adjusted R^2 value of 0.07 for the Event 3 surface hoar layer when describing the effect of elevation on surface hoar crystal size (Figure 4.31). The Event 3 Breusch-Pagan analysis of the Geographically

Weighted Regression residuals gave a $\chi^2(2, n=68) = 2.75$ $p > 0.05$ (Table 4.6). This result fails to reject the null hypothesis and suggests constant variance within the model, satisfying the linear regression assumption of homoscedasticity (Figure 4.32). The Shapiro-Wilk test statistic of 0.88 (p-value < 0.05) strongly suggests the Event 3 G.W.R. residuals do not come from a normal distribution (Table 4.7 and Figure 4.32).

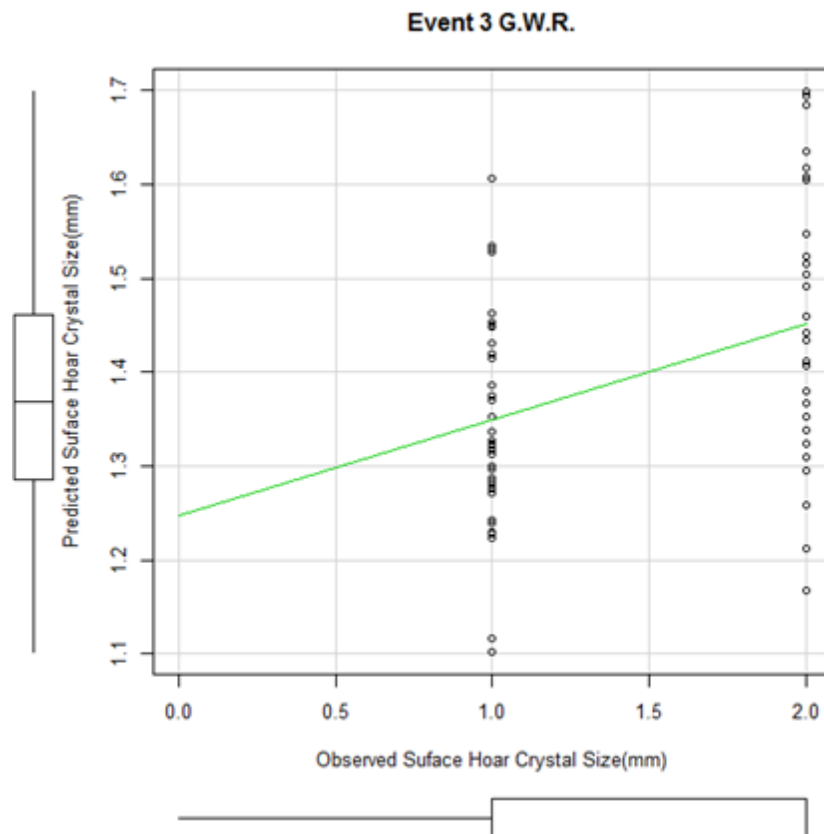


Figure 4.31: Geographically Weighted Regression and box plots describing 68 surface hoar observations from Event 3. No best fit lines are present since this model is likely invalid due to its distribution and low number of observations. Adjusted $R^2=0.07$.

Event 3 G.W.R.

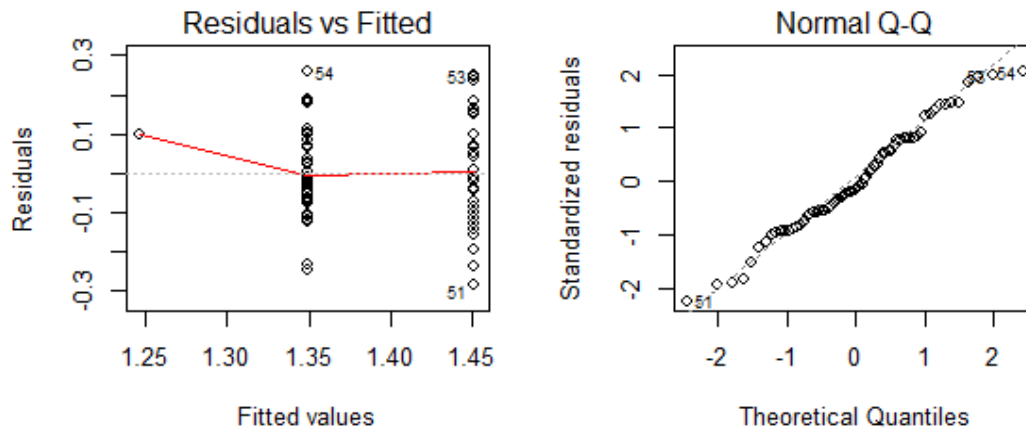


Figure 4.32: Residual versus fitted and normal quantile-quantile plots for Event 3. Residuals are homoscedastic but not normally distributed.

4.4 Event 4

4.4.1 Event 4 Background and Weather

April 2011 was also characterized by dry offshore flow which brought well below average precipitation of only 1.37 cm with a slightly below normal average monthly temperature of 4.6° C at the Haines airport (Table 3.1).

Guides observed moderate alpine snowfall from SSW flow during the last few days of March, at which time the subalpine weather station recorded a snow depth increase of about 10 cm. On April 1st the alpine weather station data shows a temperature spike nearly to the freezing point with relative humidity values between 95 and 100 percent (Figure 4.33). Unfortunately, the alpine station wind data from April 1st is missing due to suspected anemometer icing or wind velocities below the threshold requisite for recorded values. However, wind direction early on the 1st and mid-morning

on the 2nd displays SW winds with velocities ranging near 1 ms^{-1} (Figure 4.34). Subalpine temps during the Event 4 period began to reach springtime values with daytime temperatures slightly above freezing and nighttime values just below freezing (Figure 4.35).

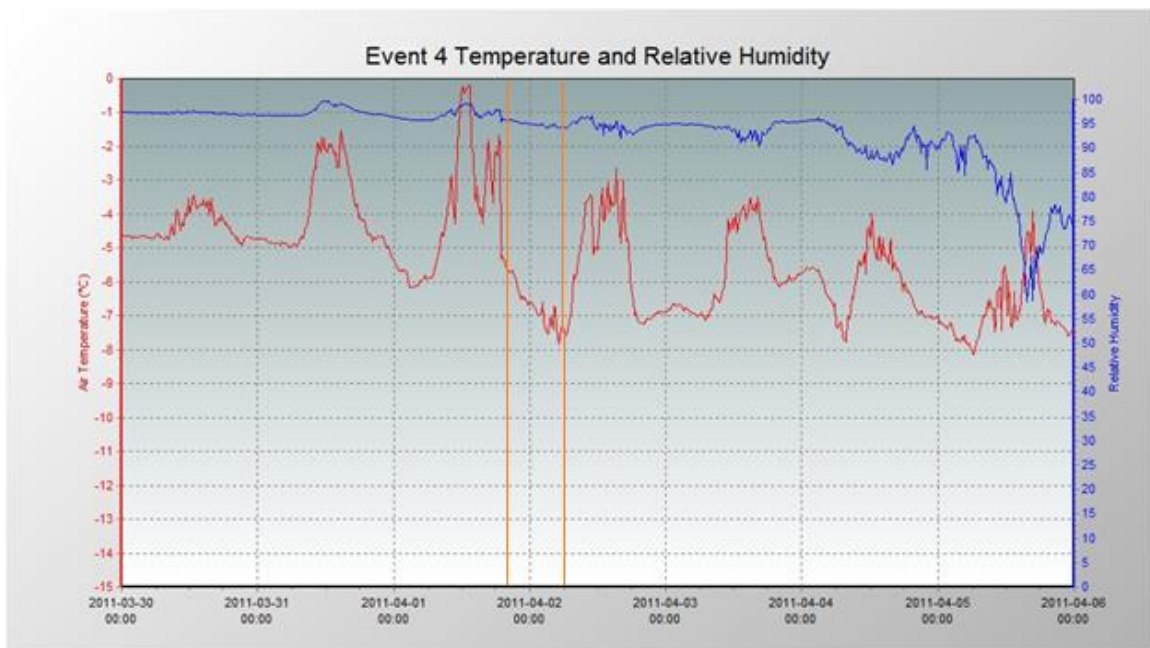


Figure 4.33: Event 4 temperature and relative humidity recorded at the Old Faithful alpine weather station. Orange lines represent estimated window of surface hoar formation. Alpine temperatures almost reach 0°C highs during the week of Event 4. Relative humidity remained high before, during, and after surface hoar was observed on April 2nd.

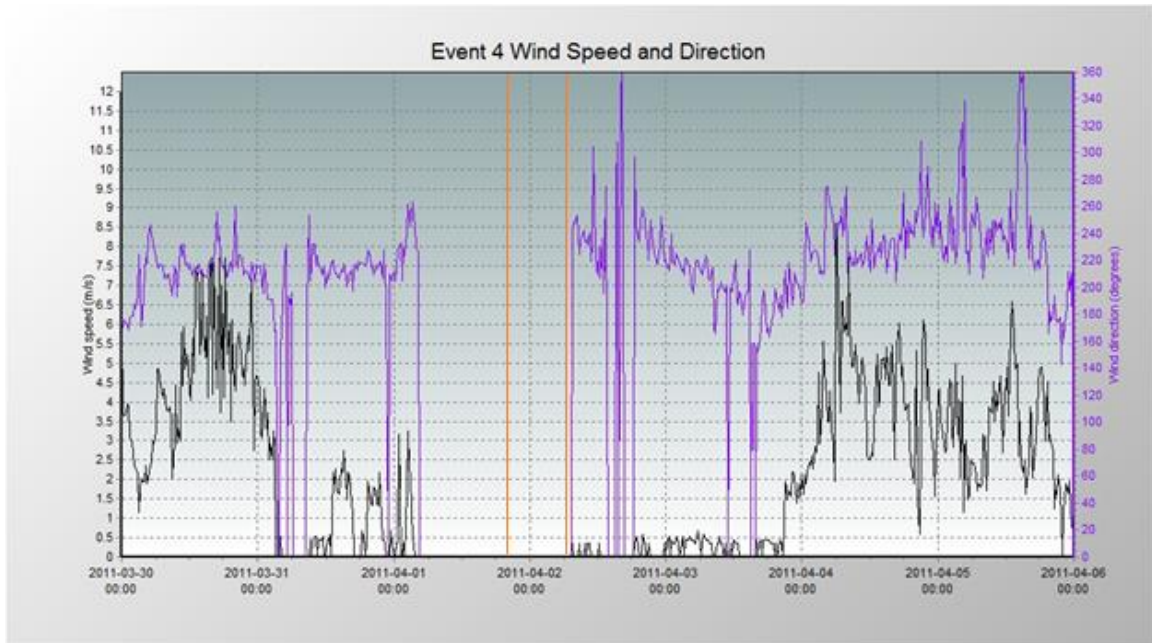


Figure 4.34: Low velocity winds out of the SW characterized the weather at the Old Faithful alpine station during Event 4. Orange lines represent estimated window of surface hoar formation.

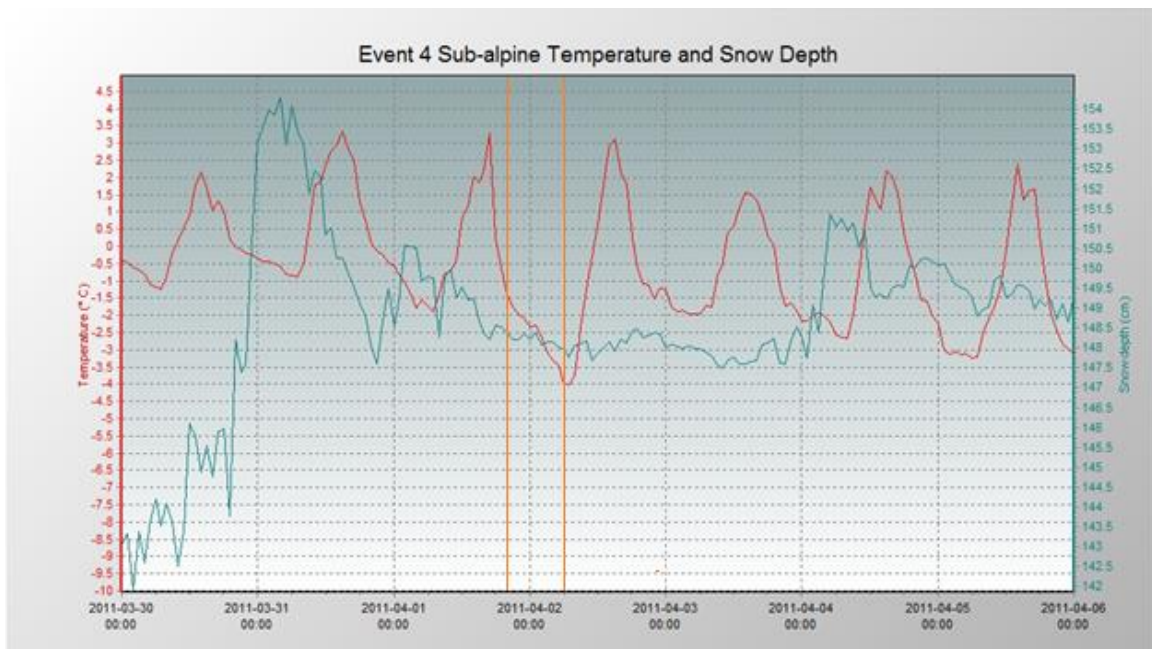


Figure 4.35: Old Faithful temperature and snowpack depth measured at the sub-alpine station. Orange lines represent estimated window of surface hoar formation. Light to moderate snowfall is evident before and after Event 4. Daytime temperatures above freezing at lower elevations signal the arrival of spring.

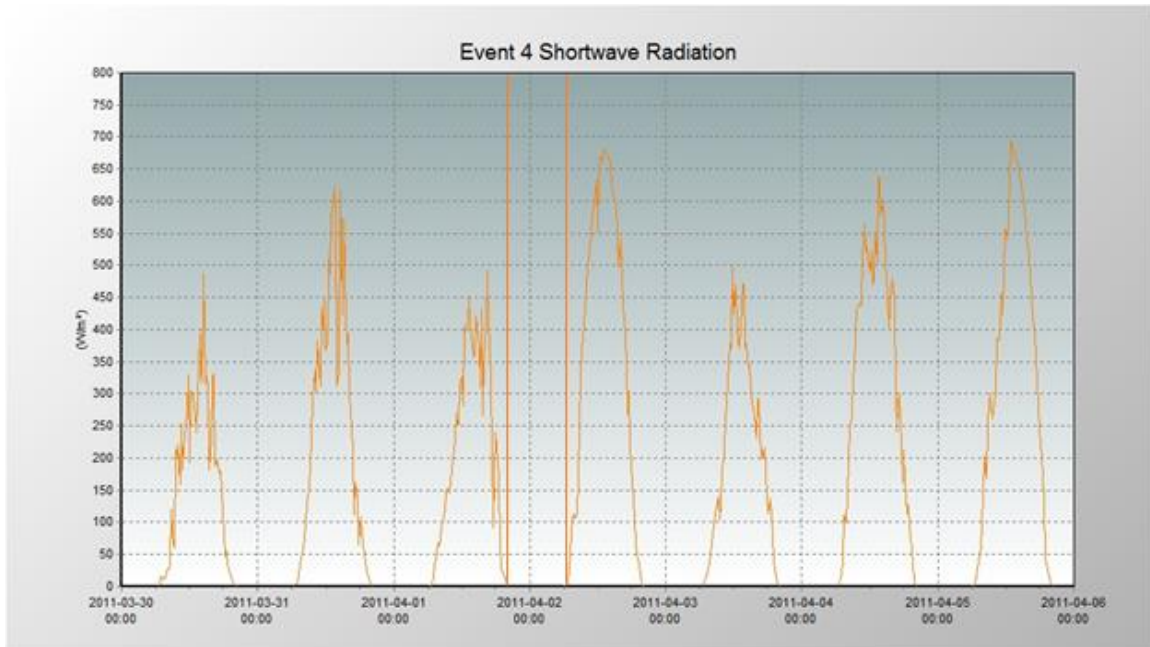


Figure 4.36: Old Faithful alpine weather station shortwave radiation during Event 4. The highest shortwave values of the week reflect the sunny weather on April 2, 2011. Orange lines represent estimated window of surface hoar formation.

All of Event 4's observations were taken on only one day. On April 2nd guides collected snow surface measurements under mostly sunny skies and light SW surface winds. Many thick stratus valley clouds with varying ceiling heights were also noted. Solar shortwave records in the alpine are consistent with the generally clear upper atmospheric weather of April 2nd, as well as the light precipitation preceding and immediately following Event 4 (Figure 4.36).

4.4.2 Event 4 Spatial Distribution of Surface Hoar Presence

Although only one day's worth of observations were taken during Event 4, guides were able to collect 87 snow surface observations (Table 4.1). Surface hoar at was present at 71% of sampling locations.

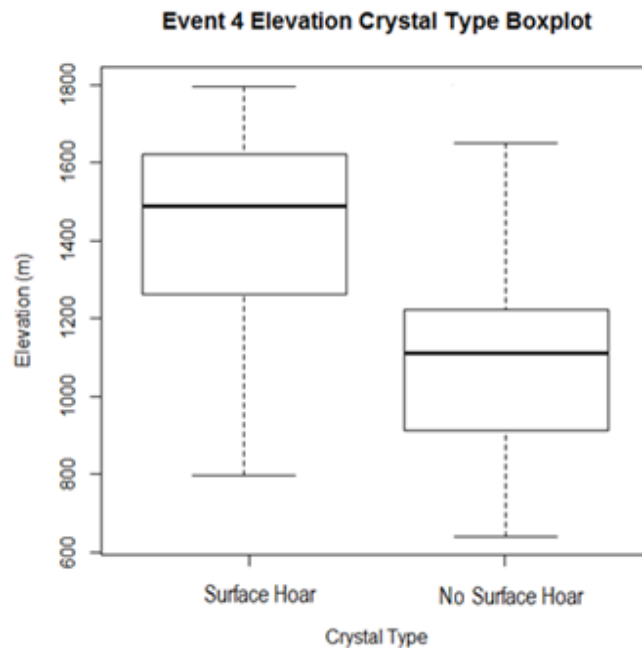


Figure 4.37: Boxplots describing presence or absence of surface hoar related to elevation. A distinct melt freeze crust observed on April 2, 2011 diminished the presence of surface hoar below about 900 m on several runs. Surface hoar n=62. No surface hoar n=25.

The extent of Event 4's data was the smallest of the study at a little more than 10 km. Event 4's minimum spacing between point measurements was approximately 50 m (Table 4.2).

Guides observations during Event 4 described the surface hoar layer to be of the sector plate variety and relatively continuous on slopes where it was present. Surface hoar presence probability was strongly elevation dependent during Event 4 (Figure

4.37). In some areas the layer ended abruptly as observers reached a freeze thaw line around 900 m.

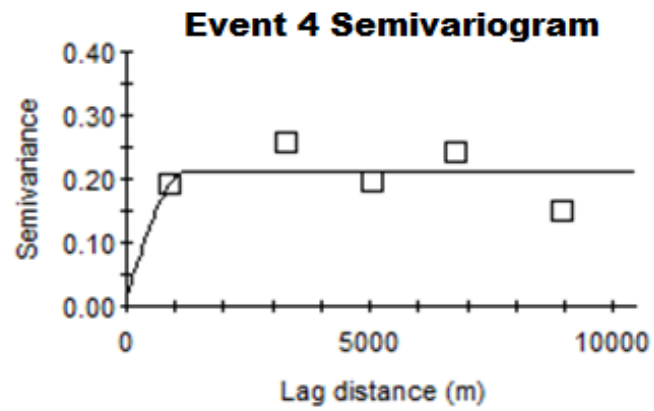


Figure 4.38: Event 4 surface hoar presence or absence indicator semivariogram.

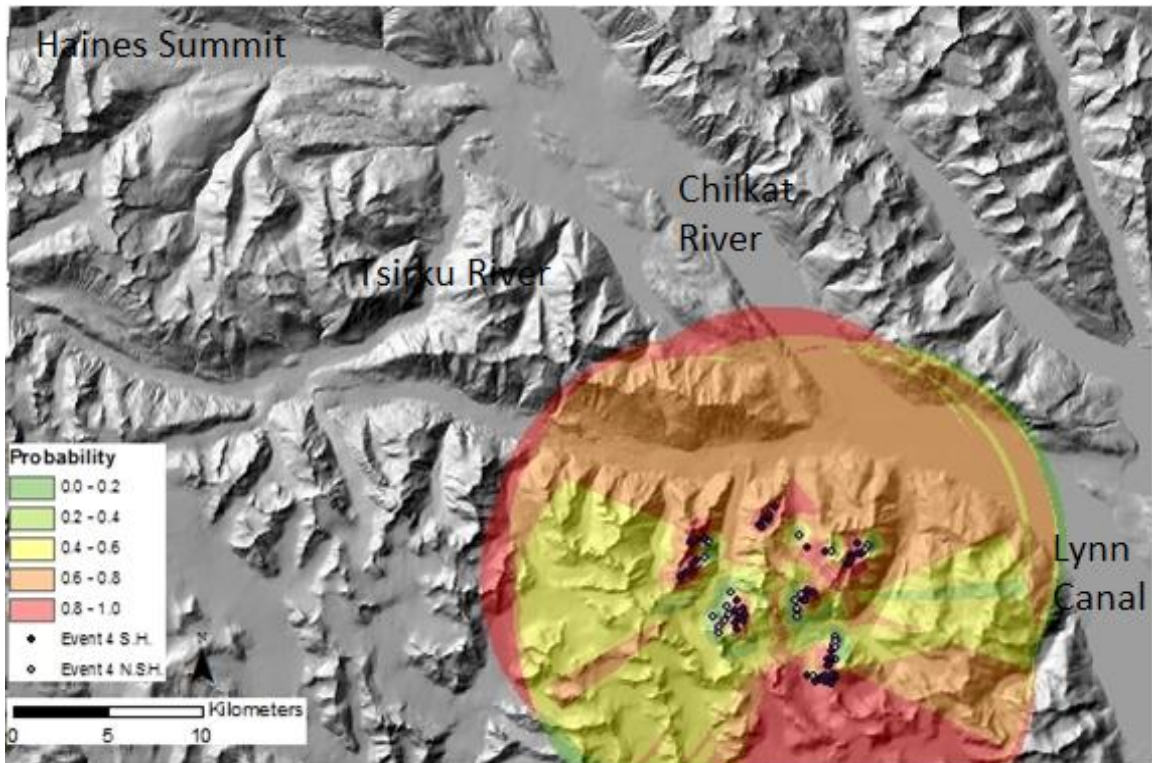


Figure 4.39: Interpolated surface hoar presence probabilities for Event 4. Despite limited observation, guides described widespread surface hoar presence above a freeze/thaw line about 2/3 way down runs at approximately 900 m elevation. Interpolations are less reliable with increasing distance from sampled data and on slopes dissimilar to observation locations, which were biased toward northerly aspects (Figure 4.2).

Event 4's data was fit to a semivariogram using a lag of about 10 km which produced a range of only 1.2 km, both of which were this study's smallest values (Figure 4.38). Nugget and sill calculations for Event 4 equaled 0.02 and 0.22 making for a nugget/sill ratio of 0.09 and indicating strong spatial structure.

4.4.3 Event 4 Effect of Elevation on Surface Hoar Crystal Size

Event 4 was characterized by sector plate crystals (Figure 4.40) between 1 mm and 4 mm which were generally smaller sizes towards the bottom of runs (Figure 4.41). Event 4 mean crystal size was 2.8 mm with a standard deviation of 0.8 mm (Table 4.1).

Using Geographically Weighted Regression produced an adjusted R^2 value of 0.44 for the Event 4 surface hoar layer (Figure 4.42).

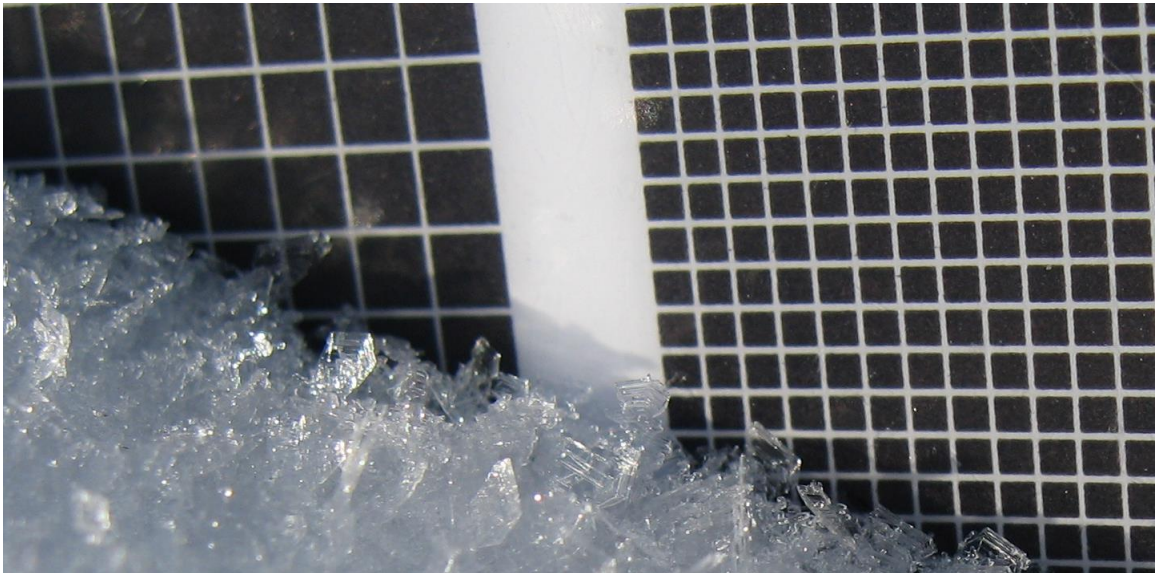


Figure 4.40: Event four sector plate crystals in front of 1 and 2 mm grids.

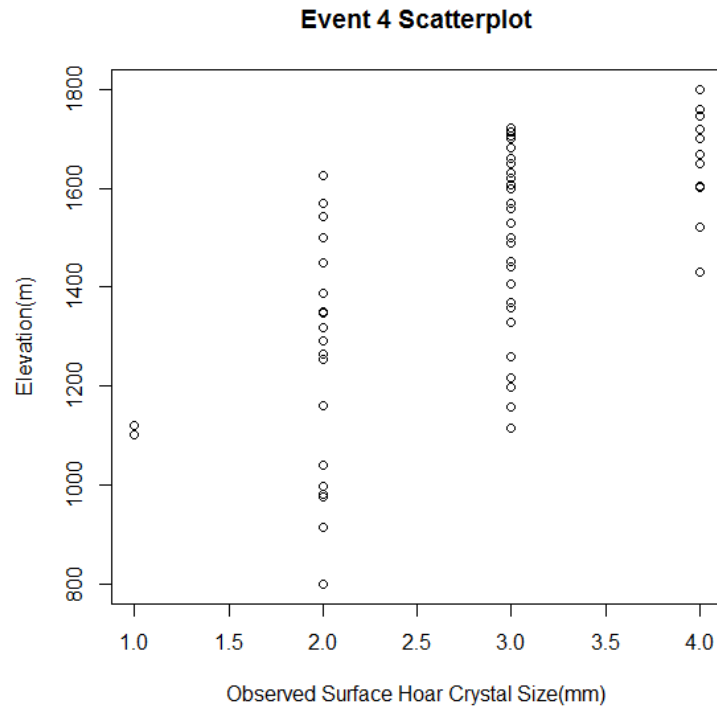


Figure 4.41: Scatterplot illustrating Event 2 surface hoar crystal size by elevation. $n = 62$. Mean elevation of observed surface hoar crystals is 1425 m and standard deviation is 244 m.

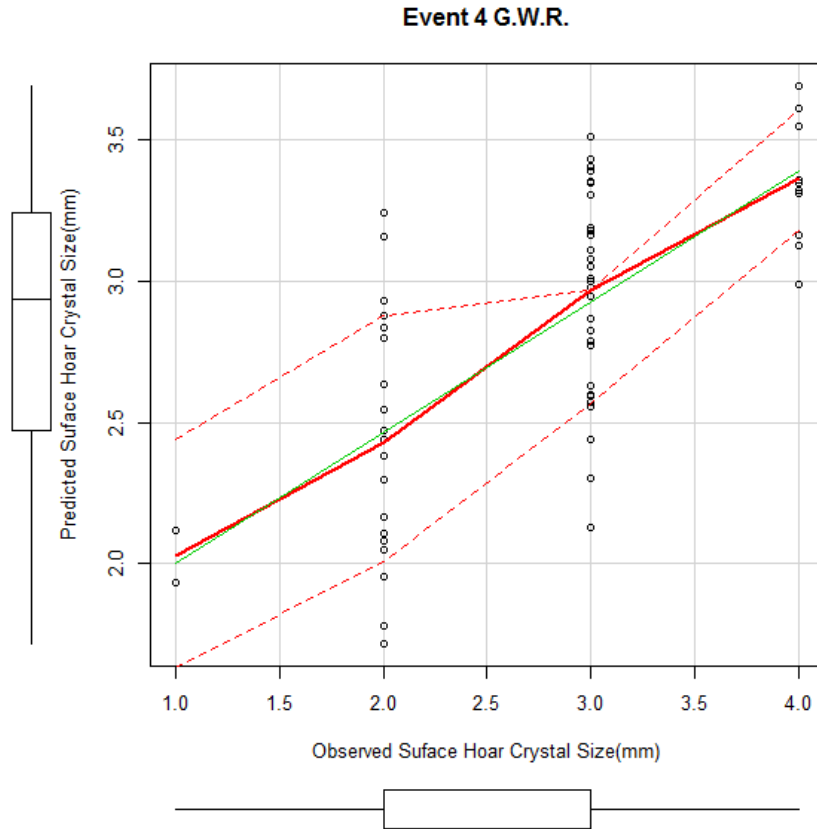


Figure 4.42 Geographically Weighted Regression with best fit lines and box plots describing 62 surface hoar observations from Event 4. Adjusted $R^2 = 0.44$.

A Breusch-Pagan Chi-squared goodness-of-fit test was calculated on the Event 4 Geographically Weighted Regression residuals produced $X^2(2, n=62) = 2.39, p > 0.05$ (Table 4.6 and Figure 4.43). This result fails to reject the null hypothesis, is indicative of constant variance, and meets the linear regression assumption of homoscedasticity. The Shapiro-Wilk test statistic of 0.9, $p > 0.05$ fails to reject the null hypothesis of normality (Table 4.7 and Figure 4.43).

Event 4 G.W.R.

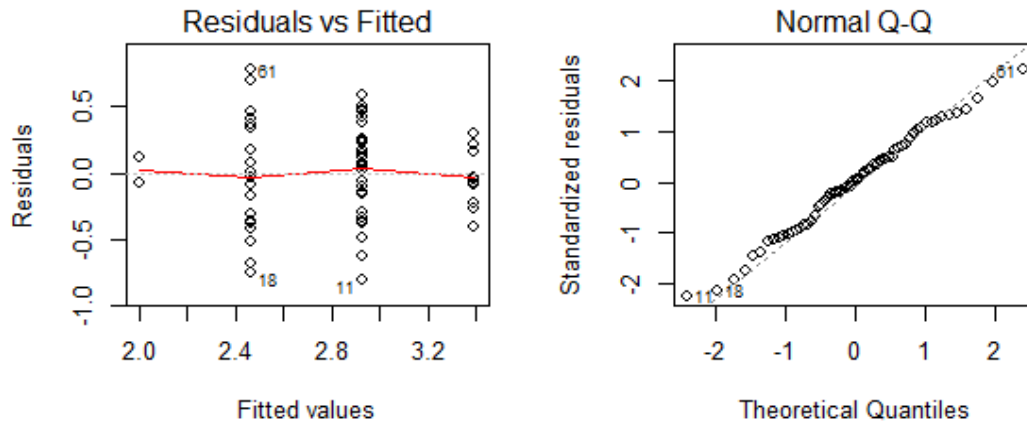


Figure 4.43 Residual versus fitted and normal quantile-quantile plots for event 4. Residuals are homoscedastic and normally distributed.

4.5 Results Summary

This section highlights important results findings via summary tables.

Information on this study's measurement scale triplet (Table 4.2), indicator semivariogram analysis (Table 4.3), Moran's I analysis of Ordinary Least Squares and Geographically Weighted Regression residuals (Table 4.4), Geographically Weighted Regression analysis (Table 4.5), and Geographically Weighted Regression assumptions tests (Tables 4.6 and 4.7) is included.

In Table 4.2 it can be seen that although the average spacing of observations was relatively uniform, the event extents varied widely. Measurement spacing stayed somewhat consistent because it was a function of guides generally taking the same number of observations per run. However, the extent was dependent on several factors. Events with longer extents resulted from situations where SEABA used multiple

helicopters at separate ends of the study area. The short extent of Event 4 arose because observations were only taken during a short weather window in a relatively small area.

Table 4.2: Summary table of study measurement scale triplet.

Event	Support (cm)	Average Spacing (m)	Extent (km)
1	5	255	59.2
2	5	368	41.9
3	5	205	20.5
4	5	238	10.0

Table 4.3 illustrates key aspects of the surface hoar presence or absence indicator semivariogram analysis. The coefficient of determination (R^2) values suggest that the models of Events 1 and 2 had the best fits. Excluding Event 2, all of the other events had relatively similar ranges which mimic the size of the basins in the study area. Event 2's range was inflated due to a strong aspect sampling bias. Event 2 took place latest in the season compared to the other events which means that the runs were for the most part on only north facing slopes where surface hoar persists best (Cooperstein, 2004; Feick et al., 2007; Lutz and Birkeland, 2011). It is also worth noting that all 4 events possessed low nugget to sill ratios (<25%) which is indicative of strong spatial structure based upon research by Cambardella et al., (as cited in Balasundram et al., 2008).

Table 4.3: Surface hoar presence spherical semivariogram summary.

Event	RSS	R ²	Range (km)	Sill (C ₀ +C)	Nugget (C ₀)	Lag (km)	Interval (km)
1	0.017	0.30	6.2	0.25	0.02	59.2	5
2	0.036	0.61	25.7	0.29	0.02	41.9	5
3	0.022	0.15	3.9	0.21	0.04	20.0	5
4	0.001	0.04	1.2	0.21	0.02	10.4	2

Table 4.4 describes the results of the Moran's I test which was used to look for spatial clustering in the regression model residuals. While both the Ordinary Least Squares Regression and Geographically Weighted Regression residuals possessed some degree of spatial autocorrelation, it was less pronounced in the G.W.R. models.

Table 4.4 Results of Moran's I test on O.L.S. and G.W.R. residuals.

	Moran's I	Z-Score	Summary
O.L.S. Residuals			
Event 1	0.19	0.66	The pattern is neither clustered nor dispersed.
Event 2	0.64	4.47	< 5% chance pattern is random
Event 3	0.14	3.46	< 5% chance pattern is random
Event4	0.41	3.46	< 5% chance pattern is random
G.W.R. Residuals			
Event 1	0.11	0.40	The pattern is neither clustered nor dispersed
Event 2	0.71	4.99	< 5% chance pattern is random
Event 3	0.03	0.03	The pattern is neither clustered nor dispersed
Event 4	0.32	4.18	< 5% chance pattern is random

The results listed in Table 4.5 describe the effect of elevation on surface hoar crystal size using Geographically Weighted Regression analysis. The coefficient of determination (R²) values suggest that elevation explains a moderate amount of variability in surface hoar crystal size within the study area. The adjusted R² values are lower than the R² values since there was only one explanatory variable (elevation). Event 3 has very low R² values since the

observations came from locally narrow ranges of elevation and had a small crystal size standard deviation (Table 4.1).

Table 4.5 Summary of surface hoar formation coefficient of determination values (R^2) from Geographically Weighted Regression models.

Event	R^2	Adjusted R^2
1	0.52	0.37
2	0.75	0.67
3	0.13	0.07
4	0.49	0.44

P-Values are not typically reported with Geographically Weighted Regressions since each regression point produces a set of parameters and potentially thousands of significance tests could be needed (Fotheringham et al., 2002).

Table 4.6 summarizes the results of the Breush-Pagan test which was used to evaluate the Geographically Weighted Regression residuals for homoscedasticity. Two Event 1 outlying surface hoar observations produced a Chi-squared test statistic that suggested residual non-constant variance. Removing the outliers insinuated a return to constant variance.

Table 4.6: Breusch-Pagan test for non-constant variance of G.W.R. residuals.

Event	Chi-squared statistic	n	p-value
1	13.55	130	2.3×10^{-5}
1 (modified)	1.22	128	0.27*
2	1.55	107	0.21*
3	2.75	68	0.10*
4	2.39	62	0.12*

* Accept null-hypothesis of constant variance.

Table 4.7 describes the results of the Shapiro-Wilk test for normality conducted on the Geographically Weighted Regression residuals. Two surface hoar outliers led to a

Shapiro-Wilk test statistic indicative of a non-normal distribution. Removing the two outliers and performing the test again produced a normal distribution.

Table 4.7: Shapiro-Wilk test for normality of G.W.R. residuals.

Event	Shapiro-Wilk statistic	n	p-value
1	0.932	130	4.50×10^{-6}
1 (modified)	0.98	128	0.05*
2	0.98	107	0.14*
3	0.88	68	6.48×10^{-6}
4	0.98	62	0.47*

* Accept null-hypothesis of normality.

5. DISCUSSION

The following chapter discusses the results of four surface hoar formation periods over the course of SEABA's 2010 and 2011 heli-skiing seasons. Its goals are to illustrate surface hoar formation and persistence patterns at regional and mountain range snow process scales, describe the effect of elevation on surface hoar crystal size, and provide insights into the phenomena that likely influenced this study's observations. In particular, this chapter will look at how these results may be unique to Alaska's Chilkat and Takhinsha Mountains.

Previous research coupled with advanced weather forecasts and automated weather stations do reasonably well at keying avalanche practitioners in on potential surface hoar formation periods. Therefore, the next logical progression is to describe the spatial patterns of these events. In other words, we would like to know where surface hoar exists within the landscape. Geostatistics provide us with tools to quantify snowpack spatial heterogeneity. These techniques assume that surface hoar variability isn't random, but is correlated over some distance which has been previously summarized for coarse spatial process scales by Schweizer and Kronholm (2007) as well as Helbig and van Herwijnen (2012).

Besides describing the location of surface hoar crystals, additional information about their size is important to consider for its effects on both the amount of time a layer may persist in the snowpack and also how it might affect avalanches after they are initiated. Existing research suggests that larger surface hoar crystals are likely to remain

in the snowpack longer than smaller crystals (Jamieson and Schweizer, 2000; Chalmers and Jamieson, 2001, Lutz and Birkeland, 2011). It is thought that surface hoar crystals penetrate into surrounding layers as they become increasingly loaded from above with additional snow, which facilitates layer thinning and bonding (Jamieson and Schweizer, 2000). The thicker weak layers created by larger crystals may also provide greater potential energy for avalanche propagation when they collapse during layer failure (Heierli et al., 2008). In consideration of such ideas, avalanche professionals are generally more concerned about rising avalanche danger when larger surface hoar crystals form and are buried.

5.1 Event 1

5.1.1 Event 1 Background and Weather

While March of 2010 brought large snowfalls to the mountains of Southeast Alaska, the weather during and immediately surrounding Event 1, a mid-season surface hoar formation period, was neither extreme nor unseasonal. Breyfogle (1987) stated that a frontal passage that leaves a highly-saturated environment makes for an ideal surface hoar development scenario. A clearing winter storm and low-wind speeds at the onset of Event 1 produced the conditions which provided the requisite moisture necessary for surface hoar deposition. During the event, mostly clear skies at night, gentle to moderate surface winds, and a relatively-low sun angle during the day led to a surface hoar layer with medium-sized crystals which was able to persist on many slopes

before being buried by about 1 m of snowfall several days after its formation. This sequence produced many more observed avalanches than any of the other 3 study layers.

5.1.2 Event 1 Spatial Distribution of Surface Hoar Presence

For event 1, surface hoar was present at 62% of observation sites across an extent of approximately 60 km (Tables 4.1 and 4.2). These data were collected from a wide variety of elevations and aspects between WSW to ESE across a large area. However, there were several basins that had much lower surface hoar presence. While it is difficult to establish causation for the observed variability, there are several phenomena which likely affected the guides' observations.

During Event 1's data collection period, I suspect that a combination of surface hoar formation impediments and destructive forces after deposition affected why we observed surface hoar in some basins, but not in others. Since temperatures were seasonal and solar shortwave radiation was still relatively weak, wind was likely the major driver of variability in Event 1's surface hoar presence observations. This is evident in Figure 4.8, where basins lacking adjacent wind-blocking mountains with large relief, exposed to synoptic outflow winds, or near major regional wind corridors (Figure 3.3) such as the Rainbow Glacier (Figure 5.1) had lesser amounts of surface hoar. The Event 1 semivariogram 6.2 km range (Table 4.3) also corroborates the idea of surface hoar presence being strongly dictated by basin location and characteristics.



Figure 5.1: Katabatic winds likely reach higher velocities in basins like the Rainbow Glacier area (directly below these skiers) which are adjacent to major onshore and offshore synoptic wind corridors such as the Lynn Canal (upper center of image). These wind interactions may prevent surface hoar from forming or destroy it if formation does occur.

5.1.3 Event 1 Effect of Elevation on Surface Hoar Crystal Size

Event 1 had the second largest mean crystal size of the study at 3.7 mm and the second lowest standard deviation in size at 1.8 mm (Table 4.1). These characteristics could therefore be interpreted to mean that the layer was well-developed, and somewhat homogenous.

Geographically Weighted Regression calculations from Event 1 produced an adjusted R^2 of 0.37 and suggest a moderate positive relationship between surface hoar crystal size as a dependent variable and elevation as an independent variable (Table

4.4). This implies that local elevation differences explain about 37% of surface hoar crystal size variance within the Event 1 observations.

Since Event 1 took place during March, at a time when many runs were still being skied to their lowest elevation pickup zones, the effect of elevation on surface hoar crystal size should be clearer than if observations were collected late in the season at which time skiers are typically picked up at higher elevations. Event 1 had the second lowest mean surface hoar observation elevation and second highest surface hoar observation elevation standard deviation which supports a high adjusted R^2 relative to the other events (Figure 4.1).

5.2 Event 2

5.2.1 Event 2 Background and Weather

Similarly to Event 1, Event 2 was preceded by precipitation in the study area which provided ambient moisture for surface hoar formation. Event 2 surface hoar deposition occurred late in the season during the beginning of a strong stretch of high-pressure and guides observed crystals across the second largest extent of the study. However, rapidly increasing seasonal solar radiation and a lack of subsequent snowfall before the layer was essentially destroyed negated the possibility of avalanche activity. Thus, no avalanches obviously associated with Event 2 surface hoar layer failure were observed.

5.2.2 Event 2 Spatial Distribution of Surface Hoar Presence

In Event 2 surface hoar was observed at 75% of observation locations which was the highest occurrence during this study (Table 4.1). Not unlike Event 1, the data were collected across a broad area with an extent of approximately 42 km (Table 4.2).

It is important to note that Event 2 took place late in the season at which time guides choose runs within a narrow aspect window generally centered on northerly facing slopes. In other words, the sampling design was biased. During the Southeast Alaskan high-latitude spring, there is a notable and rapid increase in insolation that can be seen when comparing Figures 4.24 and 4.35 which show about a 20% increase in shortwave radiation during mostly clear sky conditions over only a few weeks. Increased heating of the snow surface leads to more prevalent and stronger diurnal slope scale winds which also affect the snow surface. However, the effect of insolation is much less pervasive on north facing slopes which is where the best powder snow exists, and greatest concentration of observations took place. This likely inflated Event 2's surface hoar presence percentage and I suspect we would have observed a much lower incidence of surface hoar if the runs were equally distributed by aspect. Had we sampled a more random distribution of aspects, it is possible that the observed surface hoar presence would have been much lower largely resulting from surface hoar destruction.

Just as in Event 1, the areas which the kriging model predicted to have the largest surface hoar presence probability are clustered in areas that are relatively

protected from the influence of synoptic onshore and offshore flow (Figure 4.17). Of special note, guides stated the snow surface near the Porcupine area was very wind-affected and under the influence of heavily localized Tsirku River valley winds (Figure 3.3) which may have occurred on April 9th and 10th (Figure 4.14).

5.2.3 Event 2 Effect of Elevation on Surface Hoar Crystal Size

Event 2 had the largest mean crystal size at 4.9 mm with a standard deviation of 2.2 mm (Table 4.1). It also had the highest Geographically Weighted Regression adjusted R^2 value of the study at 0.67 (Table 4.5). There are several factors which may explain the high values. Late in the heli-skiing season, ski runs are often concentrated further inland and at higher elevations where temperatures are often lower and the mountains have greater relief. This is illustrated in Figure 4.19 where it can be seen that Event 2 had the study's lowest median surface hoar observation elevation and the highest elevation standard deviation. Furthermore, the relative humidity stayed high during the beginning of Event 2 (Figure 4.13) which facilitated prime deposition conditions before gradually lowering to values where sublimation likely occurred on and after April 11th. Hachikubo and Akitaya (1997) described a positive feedback loop where the bulk coefficient of water vapor transfer increases through increased surface aerodynamic roughness once surface hoar crystals reach several millimeters which may have led to the development of this study's largest surface hoar crystals.

5.3 Event 3

5.3.1 Event 3 Background and Weather

Event 3 was unlike the other three surface hoar events observed throughout the study due to a much greater influence of offshore flow over the 2011 heli-skiing season. Even though guides observed a moderate amount of low-density snowfall in the study area prior to Event 3 the amount of SWE that fell was miniscule. In general when compared to the other events, temperatures were colder, and drier offshore continental air masses failed to provide requisite amount of moisture for crystal growth. Consequently, only small crystals and no major avalanche cycle was observed immediately afterwards.

5.3.2 Event 3 Spatial Distribution of Surface Hoar Presence

Event 3's surface hoar observations were taken across an extent of just over 20 km (Table 4.2) which is medium-sized relative to this study's other formation periods. Surface hoar distribution was dissimilar to the other events because even though crystals were observed across the bulk of the extent boundaries, guides only recorded their presence near the tops of runs.

Event 3's spatial structure contrasts with typical surface hoar formation patterns in which peaks and ridgetops are often too windy for surface hoar formation and persistence (Schweizer and Kronholm, 2007). There are several plausible explanations for why we observed larger crystals at higher elevations. Firstly, the sky remained

relatively clear from March 17th-22nd, 2011 which theoretically provided the requisite negative heat flux from the snow surface for surface hoar growth. Previous research tells us that relative humidity needs to be greater than approximately 70% for optimal surface hoar deposition (McClung and Schaerer, 2006). Data from the alpine weather station in Figure 4.22 suggests there was ample moisture in the low-atmosphere for surface hoar formation on March 17th at the beginning of Event 3. However, by the evening of March 18th, the relative humidity began to plummet to below 15% on March 19th. This likely explains why guides observed a lull in surface hoar growth during Event 3. It is also possible that some areas may have even experienced sublimation of surface hoar into the atmosphere.

The somewhat unique mountain topography and run selection of guides may have also influenced the observation characteristics. While many mountain ranges have relatively uniform peak and ridgetop heights, the rugged mountains surrounding Haines have a large amount of variation. This allows guides to choose relatively large vertical relief runs from peaks of intermediate elevation. In fact, during periods of extended offshore flow, such as the heli-skiing season of 2011, guides often avoid the highest peaks and seek out wind-protected areas such as the sunlit slopes in Figure 5.2.



Figure 5.2: The mid-elevation wind-protected slopes of the Garrison Glacier provide plentiful places for surface hoar growth in addition to reliable powder skiing. Common ski runs are delineated with red lines.

5.3.3 Event 3 Effect of Elevation on Surface Hoar Crystal Size

Event 3 produced an artificially low Geographically Weighted Regression adjusted R^2 value of 0.07. This was likely due to almost all of the surface hoar observations coming from within a very narrow elevation band near the upper elevations of the runs skied during March 17th to 22nd, 2011. Examining the Old Faithful alpine weather station data from Event 3 provides further plausible explanation for this. Although a small amount of precipitation which began to facilitate surface hoar deposition fell prior to Event 3, weather station relative humidity plummeted on March 18th after a transition from onshore to offshore flow, which can be seen in Figures 4.22 and 4.23. Considering relative humidity generally increases adiabatically with elevation and Event 3's mean crystal size was only 1.3 mm, it is reasonable to assume there was

barely a sufficient amount of water vapor for surface hoar formation at the tops of observation ski runs, while an insufficient amount of water vapor was present at lower elevations.

5.4 Event 4

5.4.1 Event 4 Background and Weather

Event 4 surface hoar was sampled only briefly during a short break between winter storms. Although it likely existed across a wider extent than guides visited, it was not observed beyond the relatively small area that skiing occurred in on April 2nd, 2011. In spite of a short time frame with favorable surface hoar growth conditions, a good number of 1 mm to 4 mm crystals were observed before being buried by new snowfall. Guides noted numerous thick valley clouds (Figures 5.3 and 5.4) on Event 4's sole field sampling day which, in combination with passing frontal systems, provided moisture for surface hoar deposition and strongly affected its distribution and size.



Figure: 5.3: Valley stratus clouds photographed near 1100 m elevation on April 2nd, 2011 in a low-elevation section of the study area. Faceted surface hoar crystals are clearly visible in the lower right-hand corner but were absent several hundred meters lower.



Figure 5.4: Valley stratus clouds in the study area's alpine zone photographed on April 2nd from approximately 1500 m elevation. Surface hoar was observed near the top of the slope, but not present on the lower portion of the run.

5.4.2 Event 4 Spatial Distribution of Surface Hoar Presence

Previous research on valley clouds may provide some clues for the genesis of Event 4's surface hoar layer. Breyfogle (1987), Colbeck et al. (2008), and Shea and Jamieson (2008) all suggested surface hoar growth may occur at the periphery of supersaturated valley clouds. This explains an additional growth mechanism and the sudden transition from areas of widespread surface hoar to zones of melt-freeze surface crusts found when guides crossed an elevation threshold near 900 m.

Also of note, the fourth event had a very small calculated range of 1.2 km. Due to the short weather window, observations were only collected on one day, across an extent of only 10 km which was easily the study's smallest. This factor lowered the potential for calculating a larger surface hoar presence spatial autocorrelation range. Therefore, extrapolation of Event 4's results to a larger area should be done cautiously.

5.4.3 Event 4 Effect of Elevation on Surface Hoar Crystal Size

Event 4 was unique because there was a distinct freezing line observed near 900 m at which point guides noted an abrupt change between small surface hoar crystals and a thin melt-freeze crust without any overlying surface hoar. Similar to Event 3, surface hoar presence was confined to a generally distinct set of elevations. However, the elevation range of surface hoar presence was much wider for Event 4 which allowed for a relatively high adjusted 0.44 R^2 value that described the effect of elevation on surface hoar crystal size using Geographically Weighted Regression.

5.5 General Discussion

Though this study analyzed the presence of surface hoar and the effect of elevation on surface hoar crystal size separately, they are clearly related. The conditions necessary for surface hoar presence are also required for its growth, and areas where surface hoar presence is most probable are often the same places we are likely to find the largest crystals. Just as surface hoar presence and size are correlated, so are numerous other factors such as slope aspect and solar radiation which interact in complex ways to influence surface hoar layer characteristics.

Surface hoar spatial and temporal variation are difficult to quantify (Birkeland et al., 2004; Lutz and Birkeland, 2011; Schweizer and Kronholm, 2007). Undoubtedly, there were times that surface hoar formed, but was destroyed before guides were able to observe it in the field. It is also plausible that both positive and negative surface hoar growth occurred before and after field observations.

5.5.1 Spatial Distribution of Surface Hoar Presence

A multitude of factors affect surface hoar spatial variability. Early snow research suggested that wind may be the most important influencing factor of snow process spatial variability (Seligman, 1936). This sentiment was later echoed by others in specific reference to surface hoar (Schewizer and Kronholm, 2007; Feick et al., 2007).

In the Chilkat and Takhinsha Mountains near Haines, wind affects surface hoar presence and size at multiple scales. As can be seen in the aforementioned discussion

of individual events, synoptic wind regimes generally facilitate coarse scale atmospheric conditions which are either favorable or unfavorable for surface hoar formation and crystal size increases. At medium scales, katabatic winds may inhibit surface hoar formation and affect its size across individual slopes. At fine scales, wind micro-meteorology may destroy delicate snow surface temperature gradients and impede surface hoar formation, or perhaps keep supplying localized moisture needed to grow large crystals. Of course, wind also has the capacity to destroy surface hoar crystals that do form.

Aspect also has a major effect on surface hoar growth and destruction near Haines which rapidly becomes more important as the heli-skiing season progresses. Numerous studies have determined that surface hoar tends to form and persist on shaded aspects (Gubler and Rychetnik, 1991; Schweizer and Kronholm, 2007; Cooperstein, 2008; Lutz and Birkeland, 2011). Recent model simulations by Helbig and van Herwijnen (2012) support this and suggest surface hoar autocorrelation lengths decrease with increasing sun elevation angles. This is important to note since very small changes in field observation locations, for example on the shaded side of a sub-ridge, could have, dramatically influenced our results. I suspect the sampling bias during Event 2 which heavily favored north aspects inflated its semivariogram range.

Schweizer and Kronholm (2007) found slope angle to be a valuable Autologistic Regression model predictor for surface hoar presence and proposed decreased sky view associated with increasing slope angle may be responsible for lower surface hoar

presence on steep slopes. There is no shortage of steep terrain near Haines and it is not unreasonable to conclude that there may have been some occurrences where slope angle, and thus insufficient long-wave radiative cooling of the snow surface, was a primary limiting factor of surface hoar growth.

In cases where surface hoar formed on or adjacent to steep slopes, it may have been destroyed by the sometimes large loose sluff avalanches which are common near Haines. In fact, guides often take a proactive approach to “clean out” areas of unburied surface hoar on popular ski runs with controlled sluffing to prevent surface hoar burial.

Geostatistical analysis used to quantify surface hoar spatial variability yielded spherical semivariogram autocorrelation ranges from approximately 4-6 km for Events 1 and 3. Considering this, along with the aspect observation bias of Event 2 which inflated its range and the small extent of Event 4 which deflated its range, it could be said that the average surface hoar autocorrelation distance is similar in size to many of the basins and regions within the study area. Generally speaking, these results agree with both empirical and theoretical research. Semivariogram results from Schweizer and Kronholm (2007) suggested spatial autocorrelation ranges from 500 m to 1500 m for regional data with longer ranges of about 10 km at the mountain range scale. Helbig and van Herwijnen's (2012) mathematical models suggested surface hoar spatial autocorrelation to be closely related to the typical width of mountains, which translates to several kilometers when considering the terrain adjacent to Haines, Alaska.

For semivariogram modeling of a stationary random function, Webster and Oliver (1992) suggest using at least 100 data points. This requirement was easily met by all four formation period observations (Table 4.1), with the exception of Event 4, which fell slightly short of 100 ($n=87$). Therefore, its results are suspect and extra caution is advised when considering the Event 4's model.

There are several important components of semivariogram models which can be evaluated to gain insights about environmental phenomena. The semivariogram nugget is the sum of measurement error and micro variation that occurs at a finer scale than the measurement spacing. However, either of these values can be equal to zero and it isn't possible to separate the two. The sill describes the maximum amount of observed data variation.

The nugget to sill ratio ($\{C/\{C_0 + C\}\}$) gives a proportional measure of sample variance ($C_0 + C$) explained by the spatially structured variance (C). In other words, the nugget to sill ratio describes the percentage of random variation in the data, and as it increases, spatial structure in the data decreases (Srivastava, 1996). The nugget to sill ratio of all 4 events was calculated below 0.20 (Table 4.3) which is indicative of strong spatial structure.

From our knowledge of surface hoar spatial variability, it certainly seems plausible that at least some of the nugget effect arose from variation in the surface hoar layers occurring at the scale of tens to hundreds of meters, perhaps resulting from small terrain features, slope scale katabatic winds, or aspect changes. However, it is

imperative to note that this study's low nugget to sill ratios suggest that, all other things being equal, if surface hoar is found within a basin or drainage, it should be assumed that its formation was widespread within the local area.

5.5.2 Surface Hoar Kriging Interpolation

Ordinary Kriging analysis of a single variable is generally the most robust form of kriging used to model global trends across a study area (Webster and Oliver, 2007).

Upon examination of the Ordinary Kriging surface hoar maps calculated from our semivariogram analysis, several visually observable trends were elucidated. However, it must be noted that the sampling bias illustrated in Figure 4.2 affects their scope of inference.

Due to the complexity of mountain environments it is possible to encounter large amounts of variability across small distances. Therefore, even with large surface hoar spatial autocorrelation lengths, it is not appropriate to assume that observers will find similar conditions, even without traveling far, if characteristics such as slope, aspect, or elevation change significantly. In other words, the predictive ability of the kriging models is strongest in terrain that is similar to the observation locations used to construct them.

Assuming wind does have the largest influence on both surface hoar formation and destruction provides some plausible explanations for this study's results. The surface hoar presence probability values are greatest near the center of the study area, where pressure gradient winds are generally less active. Synoptic inflow and outflow

wind influences are often strongest near Lynn Canal (Figure 5.1) on the eastern boundary of the study area, along the north/south oriented Tsirku River (Figure 5.5), and adjacent to the Haines Summit mountain pass (Figure 5.6) northwest of the study area. Katabatic winds may reach greater speeds in these areas from positive feedback interactions with synoptic winds, thus impeding surface hoar growth and persistence.



Figure 5.5: A view above the Tsirku River. The area where it is oriented approximately S/N in the center-right part of the photo is the largest gap in the region's mostly E/W oriented mountains. This zone often concentrates inflow and outflow winds.



Figure 5.6: The view from the NW corner of the study area looking toward Haines Summit mountain pass. This area is one of the most favored zones for strong inflow and outflow winds.

Feick et al., (2007) hypothesized downslope katabatic winds (which occurred when a high pressure center dominated and pressure gradient winds were absent) were responsible for relative humidity decreases (via adiabatic heating), making surface hoar growth conditions less favorable. This effect is likely more pronounced in the heavily glaciated terrain surrounding Haines where there is no vegetation to disrupt katabatic winds. Additionally, there are several large massifs near the center of the study area that sometimes block prevailing flow near 800 mb which may lead to calmer conditions and therefore more favorable conditions for surface hoar formation and persistence.

5.5.3 Effect of Elevation on Surface Hoar Crystal Size

Casual observations made by SEABA guides prior to this study suggested that a positive relationship exists between surface hoar crystal size and elevation. In other

words, they often found the largest crystals near the tops of runs, with crystal size generally decreasing as they descended runs. The data collected during this research supports these observations (Figures 4.10, 4.19, 4.29, 4.40).

Geographically Weighted Regression was chosen to quantitatively analyze this study's data because it can elucidate trends where parameter estimates vary spatially and it lessens the effects of spatial autocorrelation. Using Geographically Weighted Regression to predict surface hoar crystal size using elevation produced adjusted R^2 values ranging from 0.07 to 0.68 and averaging 0.39 for all four events (Table 4.5). Although these findings suggest elevation explains about 40% of the variability in surface hoar crystal size, clearly there are other important variables to consider including temperature, aspect, slope steepness, sky visibility, moisture availability, presence or absence of vegetation, cloud cover, and micro-terrain variations.

Interestingly, this study's findings imply a greater effect of elevation on surface hoar crystal size than Schweizer and Kronholm (2007) whom only described elevation to explain about 5% of the variance in surface hoar size using univariate regression analysis. However, there are several explanations for this discrepancy. Schweizer and Kronholm found a statistically significant correlation between observation elevation and distance to ridge. It is worth noting that Schweizer and Kronholm (2007) stated the identification of major ridges was subjective and relied upon expert knowledge.

In this study, I propose in addition to ridges directly adjacent to observation locations, the surrounding ridges are also important to consider for two reasons,

especially when they differ substantially in elevation. Firstly, slopes at upper elevations are likely to have greater sky-view which has previously been suggested to increase surface hoar growth potential (Lutz and Birkeland, 2011). Second, adjacent ridges which are significantly higher than leeward terrain may block turbulent air capable of destroying strong snow surface temperature gradients necessary for surface hoar formation (Figure 5.7).



Figure 5.7: The combination of relative protection from the wind provided by higher elevation surrounding ridges, gentle slopes, and high sky visibility commonly produces large surface hoar crystals in the Kicking Horse Glacier drainage.

It is important to recognize that Geographically Weighted Regression is a localized analysis which is based upon a kernel size. This study's analysis used an adaptive kernel size which was premised upon observation density. In general, the kernel bandwidth typically calculated local Geographically Weighted Regression

equations which were contained to within several kilometers of one another. In other words this means that the effect of elevation on surface hoar crystal size may not be valuable when looking at a large area, although it may be useful to consider the elevation within an individual drainage and perhaps its neighboring terrain.

Several other factors may have been at work which could explain why bigger crystals were more often observed at upper elevations. Feick et al. (2007) described surface hoar crystals that were frequently larger within an alpine study area at a ridge top site versus an area with level terrain which was under the influence of a different local wind regime during relatively calm synoptic wind conditions. They hypothesized these spatial variability differences in crystal size came about due to the presence or absence of katabatic winds that lowered humidity levels and impeded favorable growth conditions. This effect is likely more pronounced in the mountains surrounding Haines where surface heating and cooling are not affected nearly as much by vegetation as in areas such as the Rocky Mountains of Canada.

While these findings provide an interesting first analysis of the effect of elevation on surface hoar size in the Chilkat and Takhinsha Mountains, clearly there are many other complicating factors which affect surface hoar growth. Furthermore, these observations were dictated by heli-skiing run selection and I suspect that the true relationship between elevation and crystal size may be more parabolic/polynomial than linear.

5.6 Uncertainty

As with any observational study some uncertainty exists with this study even though I tried to minimize its effects. Human error, logistical challenges, and instrument accuracy are several of the primary contributors.

Heli-ski guiding is a challenging undertaking and skier safety is by far its most important responsibility. This study was a secondary priority to both guide and client safety. In practical terms, this meant that guides were unable to spend more than a few moments at each observation location. It is therefore plausible that some observation locations were noted to be void of surface hoar where it was actually present and vice versa. Many of the runs were completed on shaded aspects where crystal identification is difficult, especially with small grain sizes.

Aspect and slope steepness information may have provided more insights from the Geographically Weighted Regression model. However, the rigorous nature of heli-ski guiding and time sensitive observation opportunities also inhibited the gathering of these data and 30 m resolution DEMs available at the time of this research were insufficient for fine-scale geographic coordinate aspect derivation and slope steepness. The relationship between aspect and crystal size has been studied previously and is somewhat well understood (Feick et al., 2007; Cooperstein 2008; Lutz and Birkeland, 2011, Hendrikx et al., 2012). Schweitzer et al. (2007) also noted that slope steepness is a valuable predictor of surface hoar presence.

While it was beneficial to have access to relatively high-elevation remote weather station data, those data provide only a very general representation of an extremely dynamic environment. Feick et al. (2007) estimated wind resolution less than or equal to 10 m is necessary to accurately predict surface hoar formation.

A final source of uncertainty with this project is locating the sampling sites. The recreational grade Garmin eTrex GPS receivers used to collect observation location are not capable of extremely precise measurements, especially in rugged terrain at the study area's high latitude. As a result of this shortcoming, guides were interviewed about their observations as soon as possible after collection and compared with topographic maps and known landmarks to filter out obviously erroneous readings.

6. CONCLUSIONS

6.1 Research Findings

This study examined four surface hoar formation periods during two winter seasons near Haines, Alaska. It provides new and valuable mountain range scale information on the spatial variability of surface hoar presence and the effect of elevation on crystal size. Work at the mountain range scale is rare because winter travel through avalanche terrain is slow. This study benefitted by taking advantage of a heli-ski operation to collect data over a large area.

In this study, semivariogram and kriging analysis described surface hoar spatial autocorrelation ranges and aided in the geographic visualization of coarse scale surface hoar formation and persistence patterns across a heli-skiing tenure. The findings of this research are consistent with observations made by guides in previous years and suggest several zones within the study area that are more likely to see buried surface hoar avalanches. Zones of higher or lower danger which sometimes mimic basin sizes may result from complex coarse scale interactions between topographic characteristics, synoptic inflow and outflow winds, and slope scale katabatic winds. This information is now considered during daily operational planning when buried surface hoar is thought to exist within the snowpack. Additionally, my results are similar to the results previous field (Feick et al. 2007; Schweizer and Krohnolm, 2007) and theoretical studies (Helbig and van Herwijnen, 2012).

Geographically Weighted Regression results suggest a positive relationship between surface hoar crystal size and elevation, with larger crystals generally found at higher elevations. In my study area, high elevations have greater sky visibility, which is conducive to longwave radiational cooling and surface hoar growth. Increased wind speeds (due to katabatic winds) at lower elevations during surface hoar formation events might inhibit surface hoar growth rates. It is important to realize that these conditions may be unique to the alpine terrain above treeline sampled in this study. With larger surface hoar at upper elevations, we expect more dangerous conditions higher in the starting zones because of the tendency of larger crystals to persist longer in the snowpack (Jamieson and Schweizer, 2000; Schweizer and Kronholm, 2007) and provide more potential energy for avalanche propagation (Heierli et al., 2008).

Avalanche prediction must account for many complex interactions between snowpack, terrain, and weather variables. Though avalanche practitioners do their best to take all factors into consideration, Kronholm (2004) observed that stability – which is ultimately what we are concerned with – is even more variable than layer characteristics. As such, when buried surface hoar exists within the snow pack, smaller surface hoar autocorrelation ranges and larger crystals should dictate a more cautious approach when travelling through avalanche terrain. The smaller autocorrelation ranges mean that surface hoar presence will be more “spotty”, which could result in certain slopes being safe, while others may have dangerous avalanche conditions.

6.1 Future Work

While this research highlighted findings relevant to guides and backcountry avalanche forecasters, additional data are needed to more completely understand of why surface hoar forms in some areas, but not others during relatively similar atmospheric conditions. Further studies focusing on the effect of factors such as aspect, slope angle, sky visibility, temperature, humidity, and radiation balance on surface hoar formation may bring us closer to this goal. Perhaps more importantly, precise quantification of destructive forces such as wind and incoming solar radiation might help us to more accurately describe surface hoar layer persistence and size. Finding the balance between natural snowpack processes and efficient modeling scales should become more feasible in the future as our field observation database grows along with improving weather measurements.

Collecting a large amount of data across a vast area during a timeframe with minimal snow metamorphism and destruction remains difficult. However, emerging technologies may soon make sampling much more efficient. Unmanned aerial vehicles (UAVs) are now relatively inexpensive and widely available. Advanced airframes, flight control, and navigation systems coupled with remote sensing instruments are capable of collecting high-quality data much more cheaply than traditional human-based field campaign methods currently allow. Still, at this time a method to remotely sense surface hoar presence and size would be needed for this work to be replicated with a UAV.

Remote LiDAR data might someday be a way to quantify surface hoar size.

Deems et al. (2013) used LiDAR to map snow depth and found snow reflectance to be highly dependent upon grain size. In a glaciology focused study, Arnold et al. (2006) were able to distinguish between different types of surfaces using LiDAR intensity which is a measure of the laser pulse return strength. Much more work is needed to remotely assess the presence and size of surface hoar, but, LiDAR data in conjunction with ground truthing observations might provide maps with levels of previously unseen detail.

Until further advances are made for remote sensing of snow surface crystals, we will continue to rely on field measurements. Further, efficient field sampling at the mountain range scale will be limited to helicopter assisted data collection. Thus, this work forms a valuable baseline for future work on the coarse scale spatial variability of surface hoar.

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APPENDIX A

FIELD DATA

Ob.	Type	Size (mm)	Elev. (m)	Zone	Easting	Northing	Date
1	no surface hoar	-	1652	UTM 8N	467724	6553123	20100320
2	no surface hoar	-	1468	UTM 8N	467677	6553385	20100320
3	no surface hoar	-	1336	UTM 8N	445660	6573264	20100320
4	no surface hoar	-	1130	UTM 8N	445245	6573816	20100320
5	no surface hoar	-	1603	UTM 8N	445695	6572885	20100320
6	no surface hoar	-	1042	UTM 8N	443640	6573518	20100320
7	no surface hoar	-	807	UTM 8N	443279	6573715	20100320
8	no surface hoar	-	1385	UTM 8N	441657	6577850	20100320
9	no surface hoar	-	1217	UTM 8N	441339	6577750	20100320
10	no surface hoar	-	1003	UTM 8N	440995	6577631	20100320
11	no surface hoar	-	857	UTM 8N	440616	6577352	20100320
12	no surface hoar	-	1265	UTM 8N	468074	6560696	20100320
13	no surface hoar	-	1751	UTM 8N	462130	6553647	20100320
14	no surface hoar	-	1269	UTM 8N	449836	6571019	20100320
15	no surface hoar	-	908	UTM 8N	449748	6571424	20100320
16	no surface hoar	-	666	UTM 8N	449659	6571824	20100320
17	no surface hoar	-	494	UTM 8N	449533	6572137	20100320
18	no surface hoar	-	1578	UTM 8N	445647	6572890	20100320
19	no surface hoar	-	1429	UTM 8N	445632	6573123	20100320
20	no surface hoar	-	1276	UTM 8N	445569	6573429	20100320
21	no surface hoar	-	1134	UTM 8N	445249	6573751	20100320
22	no surface hoar	-	1311	UTM 8N	441599	6577922	20100320
23	no surface hoar	-	963	UTM 8N	441043	6577764	20100320
24	no surface hoar	-	842	UTM 8N	440577	6577330	20100320
25	no surface hoar	-	1563	UTM 8N	468294	6559755	20100320
26	no surface hoar	-	1349	UTM 8N	467650	6560298	20100320
27	no surface hoar	-	1195	UTM 8N	467070	6560705	20100320
28	no surface hoar	-	944	UTM 8N	466376	6560985	20100320
29	no surface hoar	-	691	UTM 8N	466022	6561464	20100320
30	surface hoar	3	1713	UTM 8N	464298	6554563	20100320
31	surface hoar	3	1572	UTM 8N	464116	6554797	20100320
32	surface hoar	4	1438	UTM 8N	464199	6555187	20100320
33	surface hoar	4	1250	UTM 8N	463844	6555770	20100320
34	surface hoar	2	1084	UTM 8N	463600	6556092	20100320
35	surface hoar	1	844	UTM 8N	463277	6556533	20100320
36	surface hoar	1	754	UTM 8N	462845	6556661	20100320
37	surface hoar	3	1706	UTM 8N	467755	6552973	20100320
38	surface hoar	10	1074	UTM 8N	450038	6571136	20100320
39	surface hoar	8	862	UTM 8N	449909	6571549	20100320
40	surface hoar	6	465	UTM 8N	449765	6572240	20100320

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42	surface hoar	4	900	UTM 8N	458675	6557023	20100320
43	surface hoar	3	855	UTM 8N	458564	6557383	20100320
44	surface hoar	5	1579	UTM 8N	461742	6554152	20100320
45	surface hoar	5	1341	UTM 8N	461780	6554459	20100320
46	surface hoar	5	1189	UTM 8N	461785	6554798	20100320
47	surface hoar	4	1171	UTM 8N	461790	6555031	20100320
48	surface hoar	6	1787	UTM 8N	462055	6553642	20100320
49	surface hoar	7	1663	UTM 8N	462189	6553932	20100320
50	surface hoar	7	1484	UTM 8N	462237	6554260	20100320
51	surface hoar	7	1296	UTM 8N	462256	6554804	20100320
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53	surface hoar	4	1435	UTM 8N	466079	6558117	20100320
54	surface hoar	4	1304	UTM 8N	466045	6558280	20100320
55	surface hoar	2	1131	UTM 8N	468083	6560900	20100320
56	surface hoar	3	1492	UTM 8N	459062	6556156	20100320
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58	surface hoar	2	1079	UTM 8N	458530	6556315	20100320
59	surface hoar	2	913	UTM 8N	458151	6556734	20100320
60	surface hoar	3	1501	UTM 8N	461695	6554126	20100320
61	surface hoar	3	1392	UTM 8N	461721	6554377	20100320
62	surface hoar	2	1223	UTM 8N	461708	6554820	20100320
63	surface hoar	6	1699	UTM 8N	462116	6553838	20100320
64	surface hoar	6	1558	UTM 8N	462165	6554111	20100320
65	surface hoar	6	1346	UTM 8N	462203	6554532	20100320
66	surface hoar	5	1212	UTM 8N	462168	6554960	20100320
67	surface hoar	3	1170	UTM 8N	461967	6555090	20100320
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71	surface hoar	10	1284	UTM 8N	439378	6572631	20100320
72	surface hoar	8	962	UTM 8N	439466	6573320	20100320
73	surface hoar	7	669	UTM 8N	439302	6574091	20100320
74	surface hoar	3	162	UTM 8N	438457	6574623	20100320
75	surface hoar	7	1713	UTM 8N	462224	6553699	20100320
76	surface hoar	6	1690	UTM 8N	462275	6553852	20100320
77	surface hoar	6	1391	UTM 8N	462313	6554531	20100320
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92	no surface hoar	-	1276	UTM 8N	458789	6556217	20100321
93	no surface hoar	-	1557	UTM 8N	468290	6559794	20100321
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122	surface hoar	8	1349	UTM 8N	441433	6572201	20100321
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128	surface hoar	5	1289	UTM 8N	435292	6566890	20100321
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130	surface hoar	5	1362	UTM 8N	435138	6566980	20100321
131	surface hoar	4	1256	UTM 8N	435234	6567053	20100321
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156	surface hoar	3	925	UTM 8N	469796	6554703	20100321
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159	surface hoar	2	1228	UTM 8N	469203	6554444	20100321
160	surface hoar	2	1051	UTM 8N	468949	6554620	20100321
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162	surface hoar	1	732	UTM 8N	468668	6555210	20100321
163	surface hoar	3	1630	UTM 8N	459558	6556351	20100321
164	surface hoar	3	1377	UTM 8N	459625	6556730	20100321
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171	surface hoar		3	1254	UTM 8N	459543	6556899	20100321
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174	surface hoar		4	1625	UTM 8N	459296	6556131	20100321
175	surface hoar		4	1455	UTM 8N	459190	6556473	20100321
176	surface hoar		3	1190	UTM 8N	459031	6556834	20100321
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187	no surface hoar	-		1309	UTM 8N	449720	6561093	20100322
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189	no surface hoar	-		1042	UTM 8N	450584	6560866	20100322
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195	no surface hoar	-		1260	UTM 8N	421362	6581520	20100322
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206	surface hoar		3	1763	UTM 8N	422330	6568971	20100322
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211	surface hoar	3	1748	UTM 8N	422069	6581186	20100322

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3	no surface hoar	-	1536	UTM 8N	468198	6559813	20100408
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19	surface hoar	2	1060	UTM 8N	467956	6560993	20100408
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21	surface hoar	5	1599	UTM 8N	464990	6558474	20100408
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27	no surface hoar	-	1307	UTM 8N	468672	6557731	20100409
28	no surface hoar	-	990	UTM 8N	469343	6557760	20100409
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34	surface hoar	5	918	UTM 8N	442646	6572851	20100409
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36	surface hoar	4	1142	UTM 8N	445669	6565341	20100409
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38	surface hoar	3	633	UTM 8N	445366	6566410	20100409
39	surface hoar	5	1493	UTM 8N	446378	6562023	20100409
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41	surface hoar	4	1090	UTM 8N	446536	6563001	20100409
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43	surface hoar	4	1509	UTM 8N	444604	6565173	20100409
44	surface hoar	4	1380	UTM 8N	444709	6565335	20100409
45	surface hoar	3	1033	UTM 8N	445077	6565716	20100409
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47	surface hoar	3	1443	UTM 8N	445445	6562914	20100409
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51	surface hoar	7	1409	UTM 8N	447701	6564113	20100409
52	surface hoar	7	1295	UTM 8N	447800	6564251	20100409
53	surface hoar	5	1077	UTM 8N	448082	6564417	20100409
54	surface hoar	5	814	UTM 8N	448347	6565018	20100409
55	surface hoar	10	1591	UTM 8N	445654	6572889	20100409
56	surface hoar	7	1395	UTM 8N	445654	6573185	20100409
57	surface hoar	7	1252	UTM 8N	445598	6573554	20100409
58	surface hoar	5	1197	UTM 8N	445440	6573721	20100409
59	surface hoar	4	1067	UTM 8N	444974	6573801	20100409
60	surface hoar	7	1378	UTM 8N	444180	6573292	20100409
61	surface hoar	7	1108	UTM 8N	443749	6573387	20100409
62	surface hoar	6	964	UTM 8N	443421	6573534	20100409
63	surface hoar	6	814	UTM 8N	443213	6573821	20100409
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65	surface hoar	3	1213	UTM 8N	444865	6565514	20100409
66	surface hoar	3	889	UTM 8N	445132	6566001	20100409
67	surface hoar	4	1604	UTM 8N	445653	6563933	20100409
68	surface hoar	4	1364	UTM 8N	445594	6564644	20100409
69	surface hoar	3	1034	UTM 8N	445445	6565447	20100409
70	surface hoar	3	653	UTM 8N	445370	6566341	20100409
71	surface hoar	3	1690	UTM 8N	448272	6562630	20100409
72	surface hoar	4	1432	UTM 8N	447662	6562793	20100409
73	surface hoar	4	1290	UTM 8N	447320	6562993	20100409
74	surface hoar	2	1002	UTM 8N	446695	6563495	20100409

75	surface hoar	8	1432	UTM 8N	448034	6563984	20100409
76	surface hoar	7	1165	UTM 8N	448108	6564221	20100409
77	surface hoar	4	885	UTM 8N	448168	6564730	20100409
78	surface hoar	4	1389	UTM 8N	445802	6564494	20100409
79	surface hoar	4	1106	UTM 8N	446100	6564626	20100409
80	surface hoar	3	960	UTM 8N	446338	6564740	20100409
81	surface hoar	2	761	UTM 8N	446784	6564790	20100409
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83	surface hoar	8	1754	UTM 8N	436696	6565162	20100409
84	surface hoar	5	1578	UTM 8N	436785	6565958	20100409
85	surface hoar	5	1221	UTM 8N	436250	6566421	20100409
86	surface hoar	4	926	UTM 8N	435625	6567303	20100409
87	surface hoar	9	1701	UTM 8N	437172	6566162	20100409
88	surface hoar	4	1531	UTM 8N	437068	6566393	20100409
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90	surface hoar	3	1023	UTM 8N	436145	6566841	20100409
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92	surface hoar	7	1279	UTM 8N	448120	6571171	20100409
93	surface hoar	9	1029	UTM 8N	448179	6571593	20100409
94	surface hoar	6	806	UTM 8N	448387	6571934	20100409
95	surface hoar	11	1387	UTM 8N	449310	6570681	20100409
96	surface hoar	10	1149	UTM 8N	449176	6570993	20100409
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98	surface hoar	6	546	UTM 8N	449206	6571995	20100409
99	surface hoar	4	1179	UTM 8N	446170	6565319	20100409
100	surface hoar	4	968	UTM 8N	446349	6565341	20100409
101	surface hoar	3	736	UTM 8N	446572	6565333	20100409
102	surface hoar	2	570	UTM 8N	446855	6565360	20100409
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115	surface hoar	6	1406	UTM 8N	440559	6566142	20100410
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123	surface hoar		2	659	UTM 8N	450382	6562771	20100410
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135	no surface hoar	-		1492	UTM 8N	435368	6575436	20100411
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141	surface hoar		6	901	UTM 8N	442948	6573183	20100411
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12	surface hoar		1	1541	UTM 8N	466340	6555281	20110317
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15	surface hoar		1	1723	UTM 8N	464269	6554527	20110317
16	surface hoar		1	1518	UTM 8N	464097	6554927	20110317
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18	no surface hoar	-		876	UTM 8N	463314	6556297	20110317
19	no surface hoar	-		1602	UTM 8N	461704	6554117	20110317
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21	no surface hoar	-		1172	UTM 8N	461936	6555095	20110317
22	surface hoar		1	1131	UTM 8N	464554	6559327	20110317
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51	no surface hoar	-		1115	UTM 8N	464631	6559523	20110317
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54	surface hoar		1	1260	UTM 8N	464844	6559085	20110317
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83	no surface hoar	-	694	UTM 8N	469035	6555115	20110318
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92	no surface hoar	-	1730	UTM 8N	467509	6557657	20110318
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137	no surface hoar	-		1675	UTM 8N	460425	6561652	20110319
138	no surface hoar	-		1356	UTM 8N	460734	6562054	20110319
139	no surface hoar	-		1200	UTM 8N	461061	6562550	20110319
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143	no surface hoar	-		780	UTM 8N	459744	6557644	20110319
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165	no surface hoar	-		1300	UTM 8N	463296	6558143	20110319
166	no surface hoar	-		1062	UTM 8N	462882	6558253	20110319
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182	no surface hoar	-		1596	UTM 8N	459561	6562209	20110320

183	surface hoar		1	1100	UTM 8N	458478	6561949	20110320
184	no surface hoar	-		495	UTM 8N	458023	6563639	20110320
185	no surface hoar	-		365	UTM 8N	458017	6564784	20110320
186	surface hoar		2	1538	UTM 8N	456130	6562012	20110320
187	surface hoar		1	1125	UTM 8N	456785	6562628	20110320
188	no surface hoar	-		600	UTM 8N	457747	6563167	20110320
189	no surface hoar	-		1758	UTM 8N	458588	6559994	20110320
190	no surface hoar	-		1711	UTM 8N	458384	6559832	20110320
191	no surface hoar	-		1370	UTM 8N	458027	6559499	20110320
192	no surface hoar	-		1036	UTM 8N	457799	6558678	20110320
193	no surface hoar	-		1610	UTM 8N	459441	6562148	20110320
194	surface hoar		1	917	UTM 8N	458238	6562165	20110320
195	no surface hoar	-		630	UTM 8N	458011	6563042	20110320
196	no surface hoar	-		515	UTM 8N	457690	6563738	20110320
197	surface hoar		1	930	UTM 8N	457068	6563001	20110320
198	surface hoar		2	1435	UTM 8N	456288	6562481	20110320
199	no surface hoar	-		1560	UTM 8N	455811	6562264	20110320
200	no surface hoar	-		1564	UTM 8N	458036	6560050	20110320
201	no surface hoar	-		1600	UTM 8N	458354	6560151	20110320
202	no surface hoar	-		1291	UTM 8N	457690	6559631	20110320
203	no surface hoar	-		1167	UTM 8N	457718	6559024	20110320
204	surface hoar		2	945	UTM 8N	458961	6564689	20110320
205	surface hoar		2	639	UTM 8N	459337	6565065	20110320
206	surface hoar		1	465	UTM 8N	459568	6565700	20110320
207	no surface hoar	-		1655	UTM 8N	460453	6561596	20110321
208	no surface hoar	-		1440	UTM 8N	460743	6561813	20110321
209	no surface hoar	-		1244	UTM 8N	461133	6562239	20110321
210	no surface hoar	-		1060	UTM 8N	461650	6562520	20110321
211	surface hoar		2	1650	UTM 8N	451720	6560873	20110321
212	surface hoar		1	1500	UTM 8N	451926	6561272	20110321
213	surface hoar		1	1230	UTM 8N	452264	6561683	20110321
214	no surface hoar	-		626	UTM 8N	453618	6561804	20110321
215	no surface hoar	-		1338	UTM 8N	461023	6563327	20110321
216	no surface hoar	-		1165	UTM 8N	461087	6563618	20110321
217	surface hoar		1	960	UTM 8N	461006	6564166	20110321
218	no surface hoar	-		1166	UTM 8N	455818	6563656	20110321
219	no surface hoar	-		1050	UTM 8N	456103	6563803	20110321
220	no surface hoar	-		940	UTM 8N	456492	6564097	20110321
221	no surface hoar	-		615	UTM 8N	456881	6564675	20110321
222	no surface hoar	-		1760	UTM 8N	454870	6558247	20110321
223	no surface hoar	-		1661	UTM 8N	454734	6558625	20110321
224	no surface hoar	-		1490	UTM 8N	454549	6558921	20110321

225	no surface hoar	-	1185	UTM 8N	454348	6559138	20110321
226	no surface hoar	-	843	UTM 8N	453610	6559604	20110321
227	no surface hoar	-	1657	UTM 8N	456155	6559645	20110321
228	no surface hoar	-	1443	UTM 8N	456364	6559831	20110321
229	no surface hoar	-	1300	UTM 8N	456829	6559798	20110321
230	no surface hoar	-	1687	UTM 8N	458540	6560055	20110321
231	no surface hoar	-	1721	UTM 8N	458459	6559975	20110321
232	no surface hoar	-	1555	UTM 8N	458082	6559854	20110321
233	no surface hoar	-	1250	UTM 8N	457777	6559445	20110321
234	surface hoar	1	1020	UTM 8N	459016	6564187	20110321
235	surface hoar	2	748	UTM 8N	459448	6564492	20110321
236	surface hoar	1	506	UTM 8N	459574	6565354	20110321
237	no surface hoar	-	1570	UTM 8N	456012	6562094	20110321
238	no surface hoar	-	1389	UTM 8N	456381	6562331	20110321
239	no surface hoar	-	1016	UTM 8N	457019	6562789	20110321
240	no surface hoar	-	553	UTM 8N	457853	6563346	20110321
241	no surface hoar	-	1334	UTM 8N	455932	6563290	20110321
242	no surface hoar	-	1250	UTM 8N	455987	6563530	20110321
243	no surface hoar	-	970	UTM 8N	456401	6563945	20110321
244	no surface hoar	-	815	UTM 8N	456630	6564501	20110321
245	no surface hoar	-	1615	UTM 8N	455062	6558824	20110321
246	no surface hoar	-	1481	UTM 8N	455029	6559195	20110321
247	no surface hoar	-	1100	UTM 8N	454558	6559638	20110321
248	no surface hoar	-	885	UTM 8N	453899	6559599	20110321
249	surface hoar	2	1335	UTM 8N	465038	6559362	20110322
250	surface hoar	2	1280	UTM 8N	465245	6559548	20110322
251	surface hoar	1	1130	UTM 8N	465493	6559702	20110322
252	no surface hoar	-	916	UTM 8N	465936	6560074	20110322
253	no surface hoar	-	1511	UTM 8N	468202	6560041	20110322
254	no surface hoar	-	1450	UTM 8N	467887	6560002	20110322
255	no surface hoar	-	1300	UTM 8N	467443	6560115	20110322
256	no surface hoar	-	995	UTM 8N	466638	6560115	20110322
257	no surface hoar	-	1675	UTM 8N	467577	6558226	20110322
258	no surface hoar	-	1484	UTM 8N	467691	6558392	20110322
259	no surface hoar	-	1165	UTM 8N	467237	6558970	20110322
260	no surface hoar	-	1586	UTM 8N	468331	6559645	20110322
261	no surface hoar	-	1415	UTM 8N	467732	6559810	20110322
262	no surface hoar	-	1228	UTM 8N	467299	6559892	20110322
263	no surface hoar	-	1015	UTM 8N	466669	6559913	20110322
264	no surface hoar	-	1530	UTM 8N	464966	6558540	20110322
265	no surface hoar	-	1318	UTM 8N	464863	6558922	20110322
266	surface hoar	1	1011	UTM 8N	464326	6559655	20110322

267	no surface hoar	-	1317	UTM 8N	463356	6558148	20110322
268	surface hoar	2	1185	UTM 8N	463129	6558293	20110322
269	surface hoar	2	901	UTM 8N	462665	6558489	20110322
270	no surface hoar	-	1070	UTM 8N	466899	6559589	20110322
271	no surface hoar	-	1305	UTM 8N	467625	6559371	20110322
272	no surface hoar	-	1590	UTM 8N	466899	6559589	20110322
273	no surface hoar	-	1014	UTM 8N	465860	6559492	20110322
274	no surface hoar	-	1192	UTM 8N	465618	6559251	20110322
275	no surface hoar	-	1350	UTM 8N	465255	6559251	20110322
276	no surface hoar	-	1776	UTM 8N	465874	6557613	20110322
277	no surface hoar	-	1580	UTM 8N	466129	6557695	20110322
278	no surface hoar	-	1387	UTM 8N	466680	6557919	20110322
279	no surface hoar	-	1185	UTM 8N	466629	6558654	20110322
280	no surface hoar	-	1618	UTM 8N	467598	6558235	20110322
281	no surface hoar	-	1500	UTM 8N	467731	6558337	20110322
282	no surface hoar	-	1370	UTM 8N	467680	6558613	20110322
283	no surface hoar	-	1596	UTM 8N	468037	6559153	20110322
284	no surface hoar	-	1410	UTM 8N	467751	6559225	20110322
285	no surface hoar	-	1153	UTM 8N	467343	6559419	20110322
286	no surface hoar	-	1100	UTM 8N	466996	6559470	20110322
287	no surface hoar	-	1554	UTM 8N	464946	6558521	20110322
288	no surface hoar	-	1400	UTM 8N	464824	6558766	20110322
289	surface hoar	1	1203	UTM 8N	464681	6559184	20110322
290	surface hoar	1	1001	UTM 8N	464211	6559684	20110322
1	surface hoar	4	1720	UTM 8N	460396	6561479	20110402
2	surface hoar	4	1430	UTM 8N	460661	6561898	20110402
3	surface hoar	3	1328	UTM 8N	461131	6562061	20110402
4	no surface hoar	-	1125	UTM 8N	461508	6562499	20110402
5	no surface hoar	-	1587	UTM 8N	459570	6562153	20110402
6	surface hoar	2	1500	UTM 8N	459223	6562112	20110402
7	surface hoar	2	915	UTM 8N	458295	6562336	20110402
8	no surface hoar	-	641	UTM 8N	457917	6562979	20110402
9	surface hoar	4	1799	UTM 8N	458621	6560031	20110402
10	surface hoar	3	1713	UTM 8N	458356	6559878	20110402
11	surface hoar	3	1500	UTM 8N	458070	6559602	20110402
12	no surface hoar	-	1191	UTM 8N	457764	6559062	20110402
13	no surface hoar	-	1067	UTM 8N	457785	6558776	20110402
14	surface hoar	4	1650	UTM 8N	459366	6556226	20110402
15	surface hoar	3	1452	UTM 8N	459366	6556562	20110402
16	surface hoar	3	1157	UTM 8N	459549	6557011	20110402
17	no surface hoar	-	955	UTM 8N	459733	6557276	20110402

18	no surface hoar	-		780	UTM 8N	459764	6557674	20110402
19	surface hoar		3	1723	UTM 8N	454928	6558552	20110402
20	surface hoar		3	1600	UTM 8N	454745	6558796	20110402
21	surface hoar		2	1317	UTM 8N	454479	6559051	20110402
22	no surface hoar	-		980	UTM 8N	454061	6559286	20110402
23	no surface hoar	-		1135	UTM 8N	453317	6558776	20110402
24	no surface hoar	-		1222	UTM 8N	453939	6558501	20110402
25	no surface hoar	-		1460	UTM 8N	453674	6558215	20110402
26	no surface hoar	-		1650	UTM 8N	453612	6557888	20110402
27	surface hoar		4	1760	UTM 8N	458570	6560010	20110402
28	surface hoar		3	1558	UTM 8N	458172	6559643	20110402
29	no surface hoar	-		1215	UTM 8N	457815	6559215	20110402
30	surface hoar		3	1650	UTM 8N	459794	6555583	20110402
31	surface hoar		2	1039	UTM 8N	458356	6555644	20110402
32	surface hoar		2	1255	UTM 8N	459039	6555563	20110402
33	surface hoar		3	1440	UTM 8N	459407	6555542	20110402
34	surface hoar		3	1683	UTM 8N	459754	6555685	20110402
35	surface hoar		2	1450	UTM 8N	459294	6555675	20110402
36	no surface hoar	-		1090	UTM 8N	458631	6555705	20110402
37	surface hoar		4	1747	UTM 8N	459478	6556175	20110402
38	surface hoar		3	1600	UTM 8N	459539	6556389	20110402
39	no surface hoar	-		1423	UTM 8N	459774	6556583	20110402
40	no surface hoar	-		1080	UTM 8N	459825	6557215	20110402
41	surface hoar		4	1700	UTM 8N	454612	6558103	20110402
42	surface hoar		3	1370	UTM 8N	454469	6558450	20110402
43	no surface hoar	-		1112	UTM 8N	454143	6558858	20110402
44	surface hoar		3	1705	UTM 8N	451592	6560745	20110402
45	surface hoar		3	1600	UTM 8N	451888	6560949	20110402
46	surface hoar		2	1569	UTM 8N	452174	6561183	20110402
47	surface hoar		1	1100	UTM 8N	452500	6561673	20110402
48	surface hoar		3	1607	UTM 8N	452215	6562591	20110402
49	surface hoar		2	1265	UTM 8N	452511	6562775	20110402
50	no surface hoar	-		869	UTM 8N	453051	6562703	20110402
51	surface hoar		3	1197	UTM 8N	455795	6563560	20110402
52	surface hoar		2	996	UTM 8N	456265	6563846	20110402
53	surface hoar		2	800	UTM 8N	456652	6564448	20110402
54	surface hoar		4	1604	UTM 8N	460498	6561615	20110402
55	surface hoar		3	1407	UTM 8N	460777	6561939	20110402
56	surface hoar		3	1217	UTM 8N	460954	6562558	20110402
57	surface hoar		3	1530	UTM 8N	459599	6555270	20110402
58	surface hoar		2	1388	UTM 8N	459246	6555388	20110402
59	surface hoar		1	1120	UTM 8N	458716	6555402	20110402

60	surface hoar		4	1601	UTM 8N	455049	6558848	20110402
61	surface hoar		3	1488	UTM 8N	454931	6559187	20110402
62	surface hoar		2	1160	UTM 8N	454651	6559570	20110402
63	no surface hoar	-		894	UTM 8N	454254	6560041	20110402
64	surface hoar		3	1660	UTM 8N	451633	6560866	20110402
65	surface hoar		2	1543	UTM 8N	451942	6561116	20110402
66	surface hoar		2	1348	UTM 8N	452222	6561514	20110402
67	no surface hoar	-		912	UTM 8N	452855	6561823	20110402
68	surface hoar		3	1570	UTM 8N	452207	6562662	20110402
69	surface hoar		3	1357	UTM 8N	452369	6562780	20110402
70	surface hoar		2	975	UTM 8N	452899	6562795	20110402
71	no surface hoar	-		830	UTM 8N	453120	6562662	20110402
72	surface hoar		3	1260	UTM 8N	455877	6563450	20110402
73	surface hoar		3	1114	UTM 8N	455944	6563759	20110402
74	surface hoar		2	980	UTM 8N	456275	6564013	20110402
75	surface hoar		3	1620	UTM 8N	460505	6561562	20110402
76	surface hoar		4	1520	UTM 8N	460582	6561749	20110402
77	surface hoar		2	1350	UTM 8N	460991	6562025	20110402
78	no surface hoar	-		1150	UTM 8N	461389	6562268	20110402
79	surface hoar		3	1630	UTM 8N	458318	6560148	20110402
80	no surface hoar	-		1570	UTM 8N	458009	6559949	20110402
81	no surface hoar	-		1257	UTM 8N	457656	6559585	20110402
82	surface hoar		4	1669	UTM 8N	459456	6556216	20110402
83	surface hoar		3	1370	UTM 8N	459555	6556669	20110402
84	no surface hoar	-		831	UTM 8N	459754	6557530	20110402
85	surface hoar		3	1700	UTM 8N	459820	6555741	20110402
86	surface hoar		2	1625	UTM 8N	459599	6555664	20110402
87	surface hoar		2	1290	UTM 8N	459058	6555432	20110402