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Philip Bonnaventure

AUTEUR DE LA THÈSE / AUTHOR OF THESIS

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**Validation of the Basal Temperature of Snow (BTS) Method to Map Permafrost in Complex
Mountainous Terrain, Ruby Range Y.T. & Haines Summit B.C.**

TITRE DE LA THÈSE / TITLE OF THESIS

Antoni Lewkowicz

DIRECTEUR (DIRECTRICE) DE LA THÈSE / THESIS SUPERVISOR

CO-DIRECTEUR (CO-DIRECTRICE) DE LA THÈSE / THESIS CO-SUPERVISOR

EXAMINATEURS (EXAMINATRICES) DE LA THÈSE / THESIS EXAMINERS

Sharon Smith

Mike Sawada

Gary W. Slater

Le Doyen de la Faculté des études supérieures et postdoctorales / Dean of the Faculty of Graduate and Postdoctoral Studies

M.Sc. Thesis

Validation of the Basal Temperature of Snow (BTS)
Method to Map Permafrost in Complex Mountainous
Terrain, Ruby Range Y.T. & Haines Summit B.C.

Completed By:
Philip P. Bonnaventure
Department of Geography
University of Ottawa

Supervisor: Dr. A. G. Lewkowicz

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Abstract:

This study is the second attempt to use the Basal Temperature of Snow (BTS) method to map permafrost in mountainous regions of northwestern Canada. It differs from the first study which took place in Wolf Creek in terms of (1) the methodology used to evaluate BTS, (2) the strategy used to avoid spatial autocorrelation in residuals, and (3) the climatic regions investigated. Two study areas, part of the Ruby Range ($61^{\circ} 12' \text{ N}$, $138^{\circ} 19' \text{ W}$) and Haines Summit ($59^{\circ} 37' \text{ N}$, $136^{\circ} 27' \text{ W}$) were selected for BTS sampling based on differing climatic conditions and previous knowledge of permafrost elevations from active rock glaciers.

A total of 30 BTS measurements were made in the Ruby Range in the winter of 2006 and a total of 77 BTS values were obtained in the Haines Summit area during 2005 and 2006. From these results, modeled BTS surfaces were created using elevation and potential incoming solar radiation as independent variables in a multiple linear regression. At Haines Summit, potential incoming solar radiation was not significant in the model and thus was dropped. The surface of modeled BTS was then combined with a physical validation of permafrost presence completed during the late-summer of 2005 in a logistic regression. The modeled results produced permafrost probability maps for both study areas. Based on modeled results, permafrost underlies an estimated 282 km^2 or 66% of the Ruby Range study area and $230 - 236 \text{ km}^2$ or 43 - 44 % of the Haines Summit study area.

An attempt was made to use the linear model derived in the Ruby Range at Haines Summit in order to examine the possibility of expanding predictions into new areas. Although the results produced similar total amounts of permafrost, the spatial distribution

differed: permafrost probabilities were reduced at high elevations while lower elevation sites exhibited increased probabilities. The results of the model transfer illustrate the importance of the pit data in determining the total amount of permafrost, while knowledge of BTS ranges contributes to the spatial distribution of permafrost. With further study it is likely that generic models can be derived for areas of similar climate.

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1.0 Introduction and Background:

1.1 Introduction:

Permafrost is defined as earth materials which remain at a temperature of 0 °C or below for two or more consecutive years (ACGR, 1988; Washburn, 1979). Permafrost is further classified into regions or zones including continuous, discontinuous, sub-sea and alpine or mountain permafrost (French, 1996). Mountain permafrost refers to the occurrence of cryotic conditions in mountain regions where permafrost is absent from adjacent lowlands and valleys (Harris and Corte, 1992). Although complex in all permafrost zones, the existence of mountain permafrost is not exclusively determined by mean annual air temperature. Many factors, including elevation, depth of snow cover, slope, aspect, geology and vegetation can be extremely important contributors to the existence of permafrost in mountain environments.

The study of the distribution of alpine permafrost in the discontinuous zone is becoming increasingly important. With the effects of climate change being felt most in the arctic and sub-arctic, evaluations of these areas must be done today (IPCC, 2001). Warming climatic conditions in sub-arctic mountain areas will likely have a significant impact on the distribution, and potentially on the existence, of mountain permafrost (Haeberli et al., 1993).

The potential effects of climate change on permafrost areas include increasing active layer thickness, basal melt resulting in permafrost thinning, hydrological changes, and increased likelihood of a thicker snow cover accompanied by warming of surface temperatures (Haeberli et al., 1993; Harris et al., 2001; Woo et al., 1992). Climate change will likely have a great effect on permafrost slopes, possibly generating or enhancing

mass movements, such as creep-related processes, rockslides, rock falls, mudslides, and active layer detachment failures (Evans & Clague, 1994; Harris *et al.*, 2001). An evaluation of mountain permafrost distribution is also important for infrastructure development, such as pipelines, roads or railways. Climate change potentially threatens the structural stability of infrastructure making an accurate evaluation of mountain permafrost conditions a necessary planning aid. In order to accurately measure and map areas of mountain permafrost in North America, a reliable and cost effective method must be developed.

1.2 Permafrost Modeling:

Mountain permafrost detection can be undertaken using direct or indirect techniques. Direct methods involve physically observing frozen ground, measuring the temperature of permafrost by digging, drilling, taking temperature measurements inside boreholes, or by locating landforms with high concentrations of ground ice (e.g. active rock glaciers). Indirect methods include measurement of the Basal Temperature of Snow (BTS) as well as interpretation of geophysical data (Etzelmüller *et al.*, 2001).

In order to generate accurate permafrost maps for mountainous areas, both direct and indirect methods of permafrost detection should be used. Using this information it is possible to map and spatially model the distribution of permafrost in alpine regions. A model is a simplified version of reality that allows the user to input conditions to achieve an extrapolated result. Models predicting mountain permafrost are classified based on the number and type of inputs measured. Common types include empirical-statistical and process-oriented models (Etzelmüller *et al.*, 2001).

1.2.1 Empirical-Statistical Models:

Empirical-statistical models do not directly measure energy exchanges that take place between the ground and the atmosphere but use calculated climate factors as proxies. These models make use of indirect influences on permafrost, including slope, aspect, elevation, snow cover, potential incoming solar radiation, and land cover dynamics. Empirical-statistical models have used freezing and thawing indexes (Nelson & Outcalt, 1987), Potential Incoming Solar Radiation (PISR) (Hoelzle, 1992) as well as mean annual air temperature (Etzelmüller et al., 1998) as inputs.

Empirical-statistical models view complex energy exchanges at the surface and in the upper portion of the active layer as a grey box. From this vantage point, permafrost influencing factors are selected based on order of importance with the aid of field observations or satellite imagery (Hoelzle, et al., 2001). The advantage of these types of models is that they do not necessarily require climate data in order to complete the model, thus allowing remote locations with no climate recording infrastructure to be more easily modeled.

Empirical-statistical models use regression functions based on attributes that affect permafrost such as elevation and Potential Incoming Solar Radiation (PISR) to predict the probability of permafrost in each grid cell of a Digital Elevation Model (DEM). The models generate a surface of values such as Basal Temperature of Snow (BTS) which can then be validated by collecting actual BTS measurements. The advantage of such a method is that it allows a surface to be calculated effectively and can be altered to extrapolate the effects of climate change relatively easily (Lugon & Delaloye, 2001; Lewkowicz & Ednie, 2004).

1.2.2 Process-Oriented Models:

Process-oriented models examine exchanges between the surface and the atmosphere in detail. These models usually use a combination of an energy balance approach and a thermal offset approach (Hoelzle, et. al., 2001). In an energy balance model the presence of permafrost is an outcome of exchanges between the atmosphere and the surface of short-wave and long-wave radiation, turbulent fluxes and snow distribution. Energy balance models require an extensive set of input parameters which are often difficult to collect, especially in mountainous terrain.

A continuous surface of modeled ground temperatures can be used in a thermal offset model. The values from this surface can then be used to examine and predict values of the mean annual ground temperatures (MAGT) and mean annual temperature at the permafrost table (MAPT) (Burn & Smith, 1988; Smith & Riseborough, 2002). A thermal offset model works on the assumption that the relationship between the ground surface temperature and the top of the permafrost is mainly determined by conductive heat flow (Smith & Riseborough, 2002). Common Thermal offset models include TTOP (Smith & Riseborough, 1996), and TONE (Wright et al., 2003). Thermal offset models can be used to examine the impact of climate change on permafrost distribution (e.g. Smith & Riseborough, 1993, 2002), but are limited by the high degree of microclimatic variability in alpine regions (Hoelzle et al., 2001).

1.3 Permafrost Sampling Techniques:

Various techniques exist to detect the presence of alpine permafrost, including probing using a metal rod in late summer, DC resistivity, Ground Penetrating Radar (GPR), hot needle probing, seismic techniques, radiometry, transient electromagnetic

method and the Basal Temperature of Snow method (BTS) (Vonder Mühill, et al., 2000; Putkonen, 2003). Although all of these techniques have been verified, it is important to note that only the BTS method and probing can be used on more than a local scale.

1.3.1 The Basal Temperature of Snow (BTS) Method:

The Basal Temperature of Snow (BTS) method was first devised by Haeberli (1973) for the detection of alpine permafrost in the Swiss Alps. The BTS method has since been refined and verified in different locations, including central Europe (e.g. Gruber & Hoelzle, 2001; Lugon & Delaloye, 2001; Gardaz, 1997; Hoelzle et al., 1999; Imhof et al., 2000; Hoelzle, 1992; King, 1992; Dobinski, 1998), Scandinavia (e.g. Isaksen et al., 2002; Jeckel, 1988; Ødegard et al., 1996), Japan (e.g. Ishikawa & Hirakawa, 2000), and most recently in North America (Lewkowicz & Ednie, 2004). The BTS method is principally based on the fact that deep snow cover (> 0.8 m) has a low heat transfer capacity allowing the ground to be insulated from diurnal and other short-term surface energy balance changes (Hoelzle et al., 1993). As a result, equilibrium temperatures that develop at the snow-ground interface in mid to late-winter, reflect thermal conditions within the ground. Low temperatures at the snow-ground interface indicate the presence of permafrost while higher temperatures correspond to non-permafrost conditions. BTS measurements must be taken in mid to late-winter allowing the snow-ground interface to be in thermal equilibrium (Imhof et al., 2000). BTS measurements are then classified into categories based on 'rules-of-thumb': values < -3 °C indicate probable permafrost, values of -2 °C to -3 °C indicate possible permafrost and values > -2 °C indicate that permafrost is improbable (Hoelzle, 1992). It is important to understand that these 'rules of thumb'

serve as indicators of permafrost and do not reflect 100% likelihood for the probable category or 0% for the improbable category (Lewkowicz & Ednie, 2004).

BTS measurements provide point indications of permafrost likelihood that can be related statistically with factors such as elevation, slope, aspect and Potential Incoming Solar Radiation (PISR). When incorporated into a Geographic Information System (GIS), the BTS method requires limited inputs and provides a predictive model that is easily applied and cost effective (Hoelzle et al. 2001). Other advantages of the BTS method include the fact that models generated in a GIS can be locally calibrated using the same thresholds for different alpine locations (e.g. Dobinski, 1998; Ishikawa & Hirakawa, 2000; Jeckel, 1988; Lewkowicz & Ednie, 2004), and that models can be used to predict the effect of climate change scenarios (Lugon & Delaloye, 2001).

A major potential limitation of the BTS method is that it requires a snow depth of at least 80 cm in order to achieve equilibrium temperatures at the snow-ground interface. Due to the uneven nature of surfaces in alpine areas, snow cover is not uniform. This causes snow to accumulate in certain areas and be wind-swept in others. Uneven snow packs results in BTS measurements only being able to be collected in deep-snow locations which are often the warmest parts of the landscape. Another drawback is that the location and depth of snow can vary inter-annually causing different readings from year to year. Inter-annual variations can also be caused by the timing of snow cover in autumn and early winter. If the snow cover is established early, ground temperatures are insulated at relatively high values. If snow cover is established later, ground temperatures are considerably colder (Imhof et al., 2000; Vonder Muhll et al., 1998; Brenning et al., 2005, Keller & Grubler, 1993). A final drawback includes the collection of BTS and the

potential of encountering the adverse affects of spatial autocorrelation (e.g. Lewkowicz & Ednie, 2004). Spatial autocorrelation refers to the idea that spatial data from nearby locations are more likely to be similar than data from distant locations. If data points display significant spatial autocorrelation the independence of each point is compromised due to the fact that the value at one point is locally dependent on the values of neighbouring localities (Sokal & Oden, 1978). It is usually possible to avoid the adverse effects of spatial autocorrelation by locating BTS points at least 150 m apart (Brenning et al., 2005).

2.0 Objectives and Goals:

2.1 Central Research Objective:

The goal of this research is to determine whether BTS-based probability models, can be generated, locally calibrated and transferred between the areas of the Ruby Range, Yukon Territory and Haines Summit, British Columbia.

2.2 Associated Research Objectives:

- 1) To develop a map of Potential Incoming Solar Radiation (PISR) for the study areas of the Ruby Range Yukon Territory and Haines Summit British Columbia in order to perform a multiple regression analysis using PISR and elevation.
- 2) To verify the presence of permafrost in the two study areas by digging pits and probing.
- 3) To create a logistic regression model to predict the distribution of frozen ground (from the ground truthing validations) using modeled BTS values.
- 4) To investigate whether cold air drainage effects exist for the Ruby Range and Haines Summit as seen in Wolf Creek (Lewkowicz & Ednie, 2004), and if so to develop a method to incorporate them into a permafrost probability model.
- 5) To produce permafrost probability maps for the Ruby Range and Haines Summit study locations.

This study differs from previous research conducted in Wolf Creek (Lewkowicz and Ednie, 2004) in terms of (1) the methodology used to evaluate BTS, (2) the strategy used to avoid spatial autocorrelation in residuals, and (3) in the climatic regions investigated.

3.0 Study Areas:

The areas of the Ruby Range and Haines Summit (Figures 1 and 2) were selected for this thesis because they illustrate differing climatic and permafrost conditions. Haines Summit is classified as a maritime climate with isolated patches of permafrost whereas the Ruby Range is a continental location with sporadic discontinuous permafrost. In addition the Ruby Range is classified as part of the Upper Yukon Stikine Basin, an area known to be of the most arid in the southern Yukon with particularly strong winds (Wahl et al., 1987). Haines Summit is part of the St. Elias-Coast Mountains an area known to be particularly cloudy with very high precipitation levels (Wahl et al., 1987).

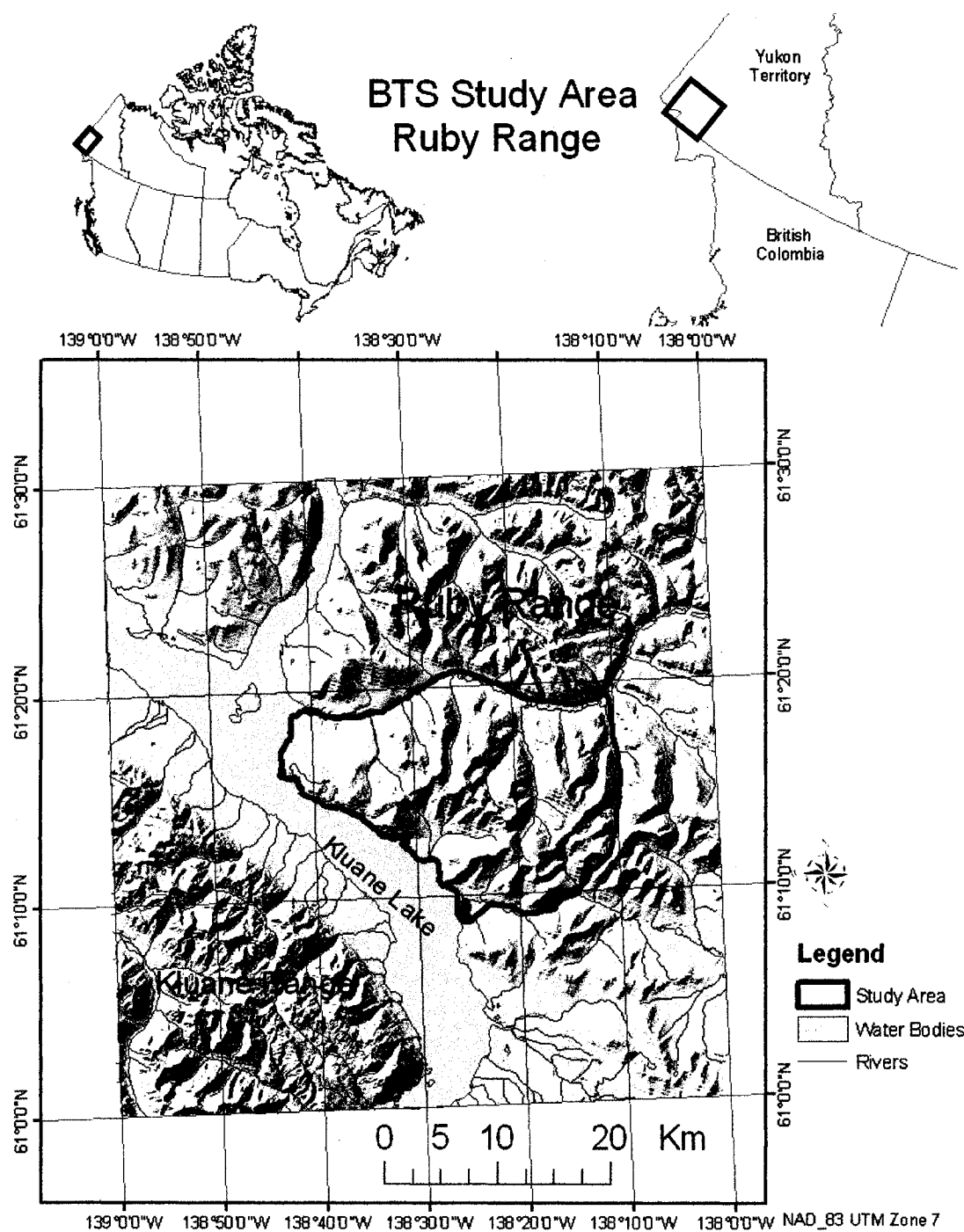


Figure 1: Location map of the Ruby Range study area (Geobase, 2006).

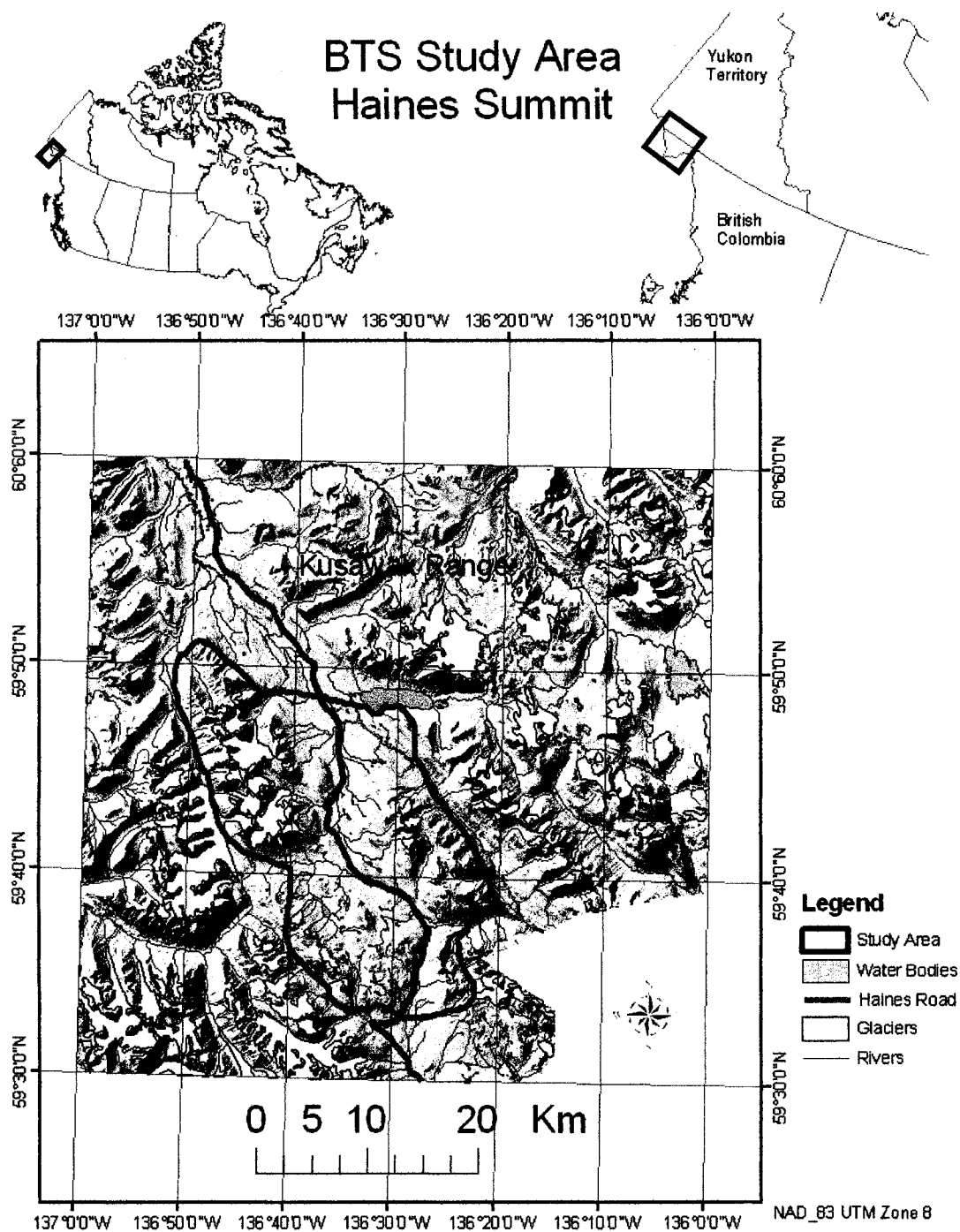


Figure 2: Location map of the Haines Summit study area (Geobase, 2006).

3.1 The Ruby Range:

The Ruby Range ($61^{\circ} 12' \text{ N } 138^{\circ} 19' \text{ W}$), is a chain of mountains in the Yukon Territory located east of the St. Elias Mountains and Kluane Lake (Figure 1). It lies to the northeast of a major thrust fault separating the two chains known as the Shikwak Trench (Bostock, 1952). This area was largely ice-covered during the last glaciation but is relatively non-glaciated today. The area is made up of a granite plateau (Bostock, 1952). Soil profiles were developed during the Holocene and include all four subdivisions of Cryosols as well as glacial tills (Canada Soil Survey Committee, 1978). Landforms currently active in this area include mass-movement features such as mudflows and solifluction lobes, while patterned ground and rock glaciers are common in areas of high elevation (Johnson, 1984).

The closest climate station to the Ruby Range study area is located at Burwash Landings ($61^{\circ} 22' \text{ N } 139^{\circ} 3' \text{ W}$), some 60 km to the north-west at an elevation of 805 meters a.s.l. The Mean Annual Air Temperature (MAAT) in this location is about -4°C , with approximately 280 mm of precipitation, 40% of which falls as snow (Environment Canada, 2005). As a result of the air temperature, this site is located within the zone of sporadic discontinuous permafrost (Heginbottom & Radburn, 1992). Elevation increases permafrost likelihood with the lower limit ranging from 1050 – 1300 meters (established by examining local rock glaciers). The main air-stream comes from the Pacific Ocean, but due to the presence of the St. Elias Mountains, the Ruby Range is within a rain shadow. The characteristics of this area classify it as a region of continental climate.

Vegetation in the Ruby Range is strongly controlled by elevation with northern boreal forest in the valleys and lowlands and alpine tundra on higher mountainous areas.

Vegetation consists of various species of coniferous trees including spruce and balsam fir in lowlands. Shrubs and krumholtz forms as well as alpine tundra replace the trees as elevations increase and cryotic conditions become more widespread (Harris, 1987).

3.2 Haines Summit:

The Haines Summit area (59° 37' N, 136° 27' W) is located south of Haines Junction Y.T. and North of Pleasant Camp B.C. along the Haines Road (Figure 2). This area is part of the Alsek Range of the St. Elias Mountains. The area was largely ice-covered during the last glaciation and today contains a mixture of glaciated and non-glaciated terrain. The study area is located in non-glaciated terrain constituting part of the zone of isolated patches of permafrost (Heginbottom & Radburn, 1992). Bedrock in this area is largely made up of quartz diorite of Cretaceous and Tertiary age with slopes having a mixture of exposed bedrock outcrop or talus (Energy, Mines and Resources Canada, 1974). Vegetation varies with elevation: sparse coniferous trees and deciduous shrubs occur in the lowlands and these change to alpine tundra around 1100 m a.s.l.

The closest meteorological station to the Haines Summit is located at Pleasant Camp, British Columbia. Although the meteorological station is relatively close to the study location, there is considerable elevation difference between the two areas. The elevation at the meteorological station is 274 m a.s.l. whereas the elevation of the road at Haines Summit is 1060 m a.s.l. Due to this difference in elevation, there is certainly a substantial difference in temperature and probably precipitation between the meteorological station and the study area. Given the Mean Annual Air Temperature (MAAT) at Pleasant Camp of 2.7 °C (Environment Canada) and using a lapse rate of 6.5 °C/km, a calculated mean annual air temperature of -2.4 °C is obtained for Haines

Summit. Precipitation values recorded at Pleasant Camp are 1416 mm/yr (Environment Canada), with 52% of the precipitation falling as snow. Precipitation values are unknown for the study site but a higher percentage of snow can be expected due to decreased mean temperatures.

4.0 Methodology:

This section contains an overview list of the major steps involved in validating the BTS method in the Ruby Range and Haines Summit areas. It is followed by more a detailed description of each step.

- 1) Conduct winter BTS measurements for the two study areas.
- 2) Conduct ground truthing by verifying the presence of frozen ground in late-summer by probing and digging pits.
- 3) Obtain a high resolution Digital Elevation Model (DEM) (30 m or better), in order to derive slope, aspect and elevation for the study areas.
- 4) Develop a map of Potential Incoming Solar Radiation (PISR), for the two study areas using the Solar Analyst extension in an Arcview 3.2 environment (Fu & Rich, 1999).
- 5) Perform a multiple linear regression based on elevation and Potential Incoming Solar Radiation (PISR) in order to develop a model predicting BTS values for the two study areas.
- 6) Examine the modeled and actual BTS values for valley bottoms in order to determine if cold air drainage is affecting results.
- 7) Perform a logistic regression between modeled BTS values and the actual distribution of frozen ground to develop a model to predict the probability of permafrost within the two study sites.
- 8) Compare the logistic regression models for the two primary study areas in order to determine if BTS values correspond to the same permafrost probability as shown by the Wolf Creek model (Lewkowicz and Ednie, 2004).

- 9) Examine whether the derived models can be calibrated to allow them to be interchanged or used in other study areas.

4.1 Expanded Methodology:

1) Conduct winter BTS measurements for the two study areas.

To evaluate BTS in the Haines Summit and the Ruby Range areas, modified methodologies were created from Lewkowicz and Ednie (2004) as well as Brenning et al. (2005). Initial data collection was conducted in March 2005 for the Haines Summit area with additional collection in March 2006. The collection of BTS points in the Ruby Range occurred only in March of 2006 as readings were not possible during the winter of 2005 due to unseasonably warm temperatures and a lack of snow in low-lying areas which prevented access.

To take meaningful BTS measurements it is first important to have an idea of the lower limit of alpine permafrost. In order to obtain this information, secondary sources such as the location of rock glaciers were examined. For both study areas, rock glaciers were identified on maps and aerial photographs and a lower limit of permafrost of between 1100 and 1300 meters was established. The range in values is the result of different aspects and microclimates which affect the lower permafrost limit.

Once the lower limit of permafrost was established, a sampling procedure was developed which would be representative of the area and its microclimates. Slope aspect greatly affects the amount of solar radiation that a surface receives. It is thus important to evenly distribute or at least make sure all major aspects (north, south, east, west and valley bottoms) are represented in BTS sampling.

BTS sampling was concentrated around the lower permafrost limit (Brenning et al., 2005) to allow for a detailed study of the transition from seasonally frozen to perennially frozen ground. The aim was for roughly 60% of the points to fall within the 1100 to 1300 meter level with the remaining 40% were to be collected equally above and below the window. In addition to aspect, it was important to sample in valley bottoms in order to examine whether BTS values are affected by the potential for cold air drainage. Finally the possibility of spatial autocorrelation was minimized by sampling each set of points at least 150 to 200 meters away from each other (Brenning et al., 2005).

In order to ensure a high quality BTS value at each sampling site while minimizing the potential of an outlier value being obtained, four measurements were made within a ten meter radius at each site and averaged. For each measurement the BTS rod with thermistor inside was inserted in the snow until the ground was struck. The thermistor was then connected to a multimeter and resistance was recorded in $k\Omega$ every minute at one minute intervals for five minutes or if resistance continued to change after five minutes until change equaled $0.02 k\Omega/\text{minute}$ or less (equivalent to $0.07 ^\circ\text{C}/\text{minute}$ or less). Resistance was converted into temperature using a second order polynomial function. Temperature values for each BTS site were determined by fitting the recorded values to an exponential curve and calculating an equilibrium temperature after 30 minutes. These values are expected to have an accuracy of better than $\pm 0.5 ^\circ\text{C}$. Supplementary observations at each site, included gradient, depth of snow, aspect, UTM coordinates and elevation using a hand held GPS unit (Garmin Etrek Summit, WGS 84 Datum).

2) Conduct ground truthing by verifying the presence or absence of frozen ground in late-summer by probing and digging pits.

Physical verification of permafrost was accomplished by probing, augering holes and or digging pits in a series of locations for the two study sites during August 2005. Pits were excavated in areas reflecting the spatial distribution of BTS measurements collected in March 2005 for Haines Summit with a similar pattern used for the Ruby Range. Verification in both areas took place over a range of elevations, aspects and valley bottoms. Physical validation was performed in the month of August in order to avoid misidentifying late-lying seasonal frost as permafrost.

Wherever possible, two checks on permafrost were made at each site, one in an inferred low-snow location (convex break-of-slope) and the second in a high-snow location (concave break-of-slope). At each site the presence of frozen ground was verified using various techniques depending on the concentration of clasts in the soil. Techniques included a combination of probing, augering when probing was not possible, pit-digging and recording temperature profiles if frozen ground was not encountered in the top 1.5 meters. Temperatures within the excavated sites were measured using a probe and thermistor similar to the one used during winter BTS measurements. Pits were dug to a maximum depth of 1.5 meters where a temperature reading of $< 0.5^{\circ}\text{C}$ was taken as an indicator of the presence of permafrost. If temperatures $< 0.5^{\circ}\text{C}$ were not encountered either through measurement or direct observation (i.e. observation of ground ice) within a depth of 1.5 - 2 meters, the site was taken to be permafrost free. In locations where clast-rich sediments did not allow for the digging of deep pits (>80 cm), temperature profiles were taken at depths of 10, 20, 40, 60, and 80 centimetres as well as in the bottom within

the pit. The presence of a strong temperature gradient with low ground temperatures indicates that permafrost is likely present at depth, while a weak gradient and higher temperatures indicate that permafrost is unlikely. In addition, each permafrost verification site included observations regarding vegetation cover, shading, organic mat thickness, and soil characteristics.

3) Obtain a high resolution Digital Elevation Model (DEM) (30 m or better), in order to derive slope, aspect and elevation for the study areas.

Digital Elevation Models (DEMs) were obtained from Geobase for the Ruby Range and Haines Summit areas and projected in an ArcGIS environment where the necessary attributes for each area could be calculated. A DEM contains pixels which represent elevation information for each cell. Using a raster calculation program, attributes including aspect and slope can be identified. Aspect is calculated by the raster program by identifying the steepest downslope direction for each cell in the DEM in relation to the closest cells. As a result an aspect grid is generated with each cell in the field containing a numeric aspect value. Slope is also determined using a raster calculation program by identifying the maximum rate of change for each pixel and its neighbouring pixels in the field of view.

4) Develop a map of Potential Incoming Solar Radiation (PISR), for the two study areas using the Solar Analyst extension in an Arcview 3.2 environment (Fu & Rich, 1999).

This step involved generating maps of Potential Incoming Solar Radiation (PISR) for both the Ruby Range and Haines Summit study areas. PISR was calculated for the two areas using the Solar Analyst extension within an Arcview 3.2 GIS environment (Fu

& Rich, 1999). The aforementioned program generates an upward-looking hemispherical viewshed known as a fisheye view for every location on the DEM. A map of PISR is then produced by merging the hemispherical viewsheds calculated for each pixel on the DEM. PISR was calculated for the two study areas for the portion of the year when albedo is low and snow does not interfere with the radiation balance (May 15th – Oct 15th in both locations). Unique grids were created based on specific solar attributes of the area including site latitude, topographic shading, transmittivity and the diffuse proportion based on cloud cover. The proportion of cloud cover greatly influences the amount of solar radiation reaching the surface. Using a combination of meteorological data (Environment Canada, 2005) and recorded ground and air temperature offsets throughout the day, cloud cover percentages were estimated. Diffuse proportions representing cloud cover percentages of 0.65 and 0.7 were used for the Ruby Range and Haines Summit respectively while an atmospheric transmittivity of 0.5 was used in both areas.

5) Perform a multiple linear regression based on elevation and Potential Incoming Solar Radiation (PISR) in order to develop a model predicting BTS values for the two study areas.

This portion of the study involved performing a multiple linear regression in S-Plus for the two study areas based on Potential Incoming Solar Radiation (PISR) and elevation. The results from the regression were used to develop a model predicting BTS values.

6) Examine the modeled and actual BTS values for valley bottoms in order to determine if cold air drainage is occurring for the two study areas.

Cold air drainage refers to the presence of atmospheric temperature inversions in mountain environments. Few studies have been done on cold air drainage, but it is known to occur in northern Alberta, British Columbia and the southern Yukon Territory (Harris, 1982; Taylor et al., 1998; Lewkowicz & Ednie, 2004).

Cold air drainage if present will be recognized for the Ruby Range and Haines Summit by identifying valley bottom locations in a 1:1 plot of actual and modeled BTS values. If valley bottom temperatures generally lie above the 1:1 line, it is likely that cold air drainage is affecting the results. Work-around solutions for this issue include creating a separate model for valley bottom locations (Lewkowicz & Ednie, 2004) or potentially increasing the elevation by a constant for all valley bottom points, effectively lowering predicted values temperature values.

7) Perform a logistic regression between modeled BTS values and the actual distribution of frozen ground to develop a model to predict the probability of permafrost within the two study sites.

This portion of the study makes use of logistic regression (e.g. Lewkowicz & Ednie, 2004), to predict the probability of permafrost at a given location using the modeled BTS values and the actual distribution of frozen ground. Logistic regression estimates the probability of a certain condition occurring by calculating changes in log odds of the independent variable, not changes in the dependent variable itself (Lewkowicz & Ednie, 2004). The logistic regression analysis was performed in the statistical software package S-Plus and then incorporated into the GIS environment.

8) Compare the logistic regression models for the two primary study areas in order to determine if BTS values correspond to the same permafrost probability as shown by the Wolf Creek model.

In order to determine if modeled BTS values in the study areas of the Ruby Range and Haines Summit represent the same probability of permafrost as those for Wolf Creek (Lewkowicz & Ednie, 2004), all three logistic regression models can be compared. Comparison involves plotting all of the logistic regression models for the respective locations on the same axis and determining the probability at critical temperature values. It is likely that modelled values close to 0°C could be very similar in probability for all three models. This is due to the fact that the presence of permafrost indicated by a BTS value close to 0°C should show a very low probability of permafrost. The same reasoning can be used for modelled BTS values below -6 °C as permafrost is very likely present. The comparison focuses on the probability of the three logistic regression models for BTS values between -2 and -6 °C. These values were selected by examining the shape of the curve generated from the logistic regression model for Wolf Creek (Figure 3) (Lewkowicz & Ednie, 2004).

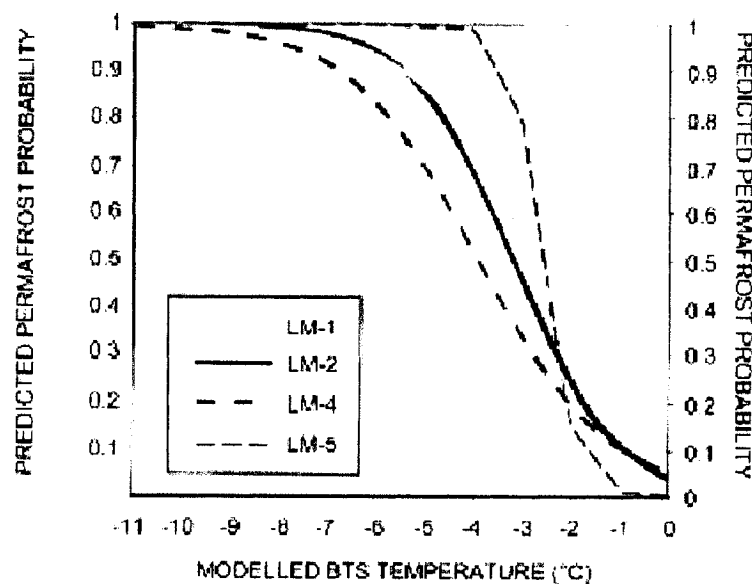


Figure 3: Graph illustrating the logistic regression model for Wolf Creek from which values are quoted (LM-2, Solid black line) (Lewkowicz & Ednie, 2004). Grey boxes represent the BTS ‘rules of thumb’ value ranges.

9) Examine whether the derived models can be calibrated for use interchangeably and at other study areas.

If the results from step 8 show that a given modelled BTS temperature represents a given permafrost probability, then the only calibration between areas that will be needed is in relation to the coefficients in the multiple linear equations (Step 5). This calibration is likely to be needed because of different mean annual air temperatures, different lapse rates, different radiation regimes and different snowpacks. Regional calibration of BTS models was also necessary in Switzerland (Gruber and Hoelzle, 2001).

5.0 Results:

5.1 Collection of BTS points for the Ruby Range and Haines Summit:

A total of 30 measurements were taken in March of 2006 in the Ruby Range (Figure 4). Due to insufficient snow depths in low lying areas, BTS points for this region were collected between the altitudinal ranges of 1100 – 1800 m. BTS measurements recorded in these areas all displayed temperatures lower than -3°C .

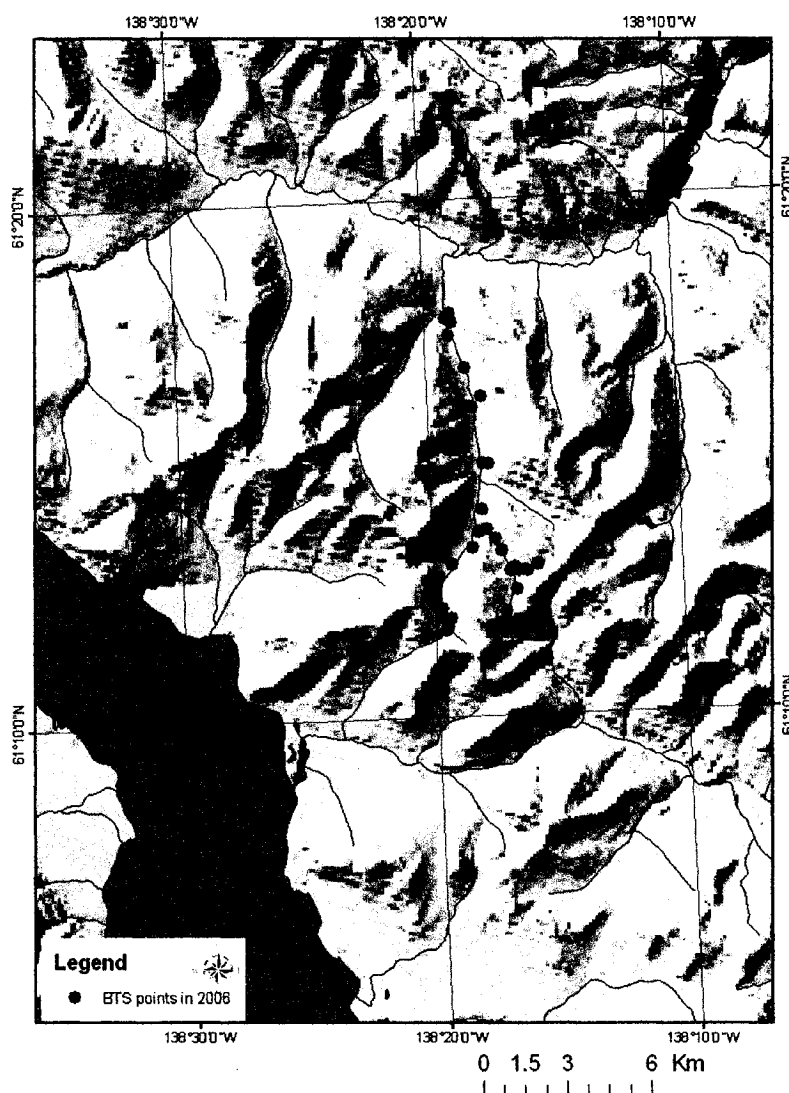


Figure 4: Map showing BTS measurement sites for the Ruby Range collected in March 2006.

BTS points were collected at 60 sites in the Haines Summit area during March 2005 (Figure 4) for different aspects and elevation ranges using the method outlined in step one of section three. The results from the four sampled locations at each site were averaged after reaching equilibrium to counter potential problems caused by the nugget effect (Brenning et al., 2005). Of the 60 sites, four had temperatures $< -3^{\circ}\text{C}$ representing probable permafrost according to the “BTS rules of thumb”. Four of the sites showed temperature values between -2 and -3°C indicating possible permafrost. The remaining 52 sites displayed temperatures $> -2^{\circ}\text{C}$ indicating improbable permafrost. BTS temperatures ranged from 0°C and -4.5°C with an average of -0.8°C .

An additional 17 BTS points were collected in the Haines Summit area during the winter of 2006 (Figure 5). Following the experience of 2005 the second set of points focused on obtaining higher elevation points ($> 1400\text{ m}$), as well as several measurements to compare BTS inter-annual variation between the two seasons. Of the 17 sites, eight showed temperatures below -3°C , three had temperatures between -3 and -2°C and the remainder were between -1 and 0°C .

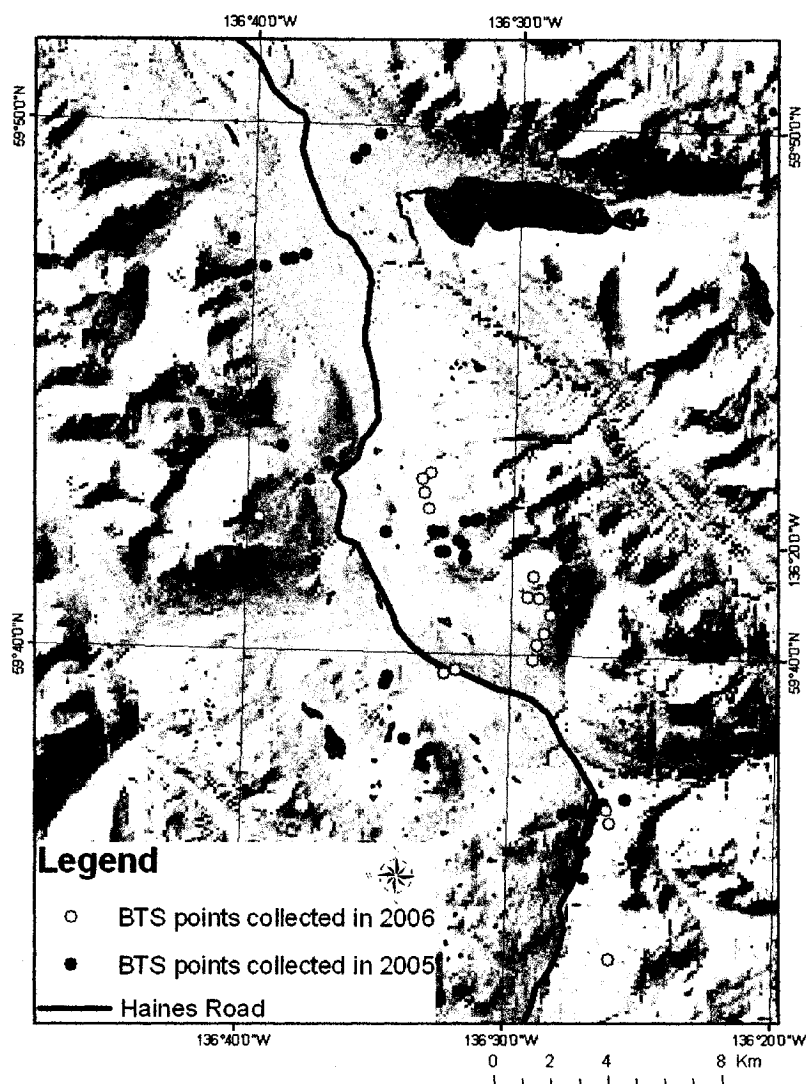


Figure 5: Map showing BTS measurement sites for Haines Summit in March 2005 and 2006.

5.1.2 BTS Sampling Periods:

Many issues in the data collection process can affect the accuracy and quality of both BTS measurements and ground truthing sites. It is thus important to examine not only the data but also the sampling procedure. The procedure for BTS sampling is outlined in step 1 of the methodology and this system was employed over the two winter

seasons of March 2005 and 2006. BTS point collection can be temporally sensitive and it is thus important to attempt to plan a field season with the best possible information. In order to collect meaningful BTS data the temperature at the ground surface interface must be relatively constant. Finding the optimal time can be difficult and must include the examination of temperature logger information collected over several seasons.

A total of four air and ground temperature monitoring stations exist in the Ruby Range recording data from the summer of 2004 to the summer of 2006.

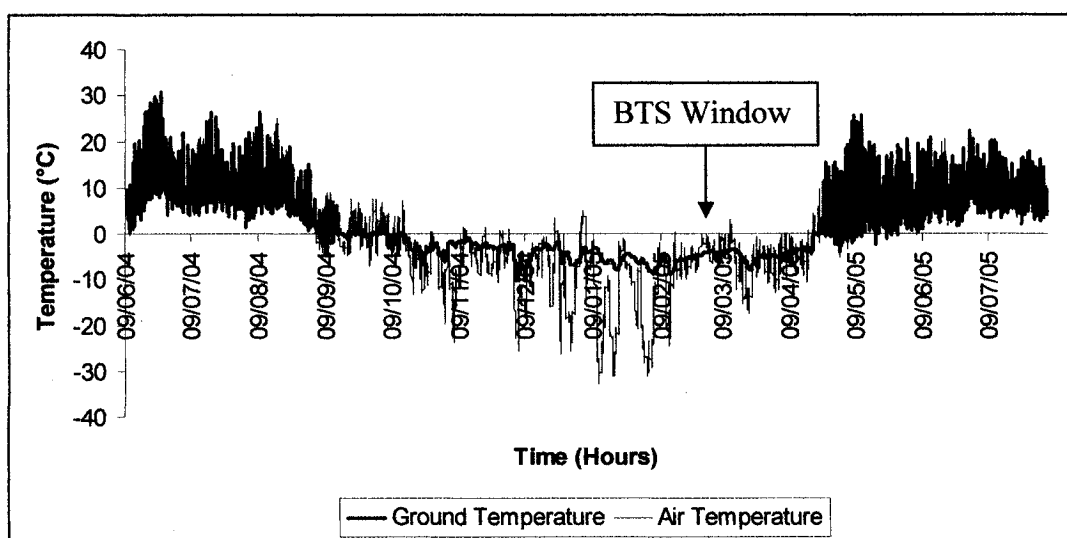


Figure 6: Air and ground temperature data for March 2005 from Swanson Creek in the Ruby Range

Although the attempt to collect BTS data in the Ruby Range was not successful in March of 2005 due to a lack of snow in the lower elevation portions of the study area, Figure 6 indicates that a March sampling period would have been appropriate. BTS sampling for both study areas in 2006 proceeded at the same time as in the previous year.

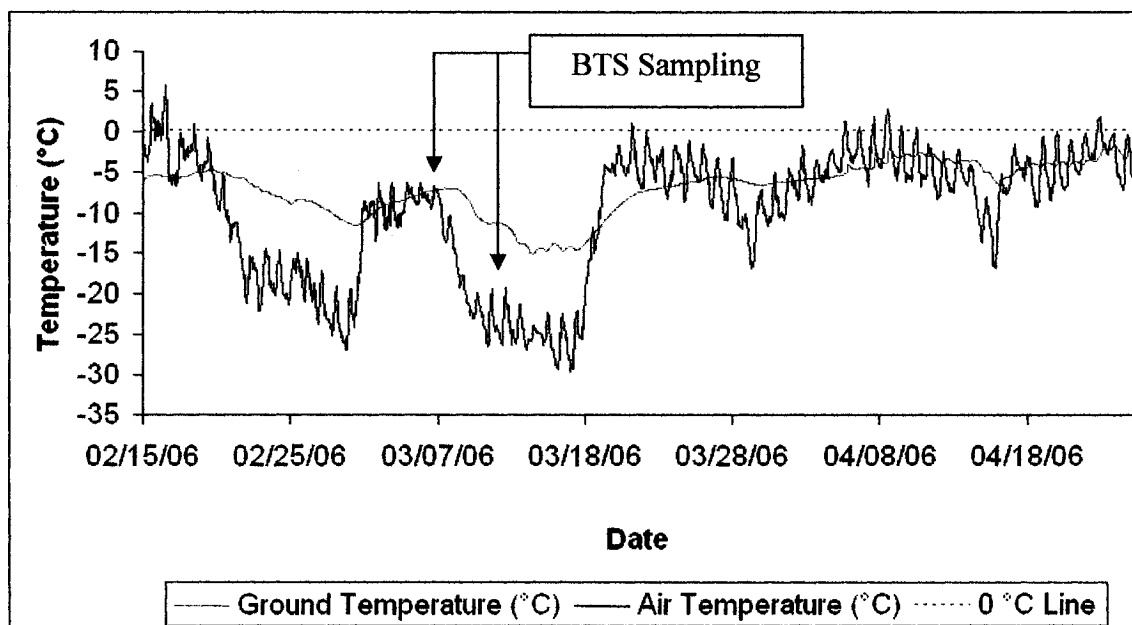


Figure 7: Air and ground temperature data for March 2006 from Swanson Creek in the Ruby Range. BTS temperatures were made at this location from March 6 – 10, 2006.

The 2006 logger data indicates that although ground temperatures were temporarily stable at the time of sampling (Figure 7), it appears that sampling was performed before equilibrium was reached in late March and early April. A later season ground temperature stabilization date could be the result of the establishment of snow cover later than in the previous year, an idea suspected for Haines Summit as well.

In Haines Summit there are four air and ground temperature monitoring stations recording summer and winter temperatures. At the beginning of this study, data was available for 2003 and 2004 at one of the stations. Examination of this data prompted the decision that an early to mid-March collection season would be most suitable for this area.

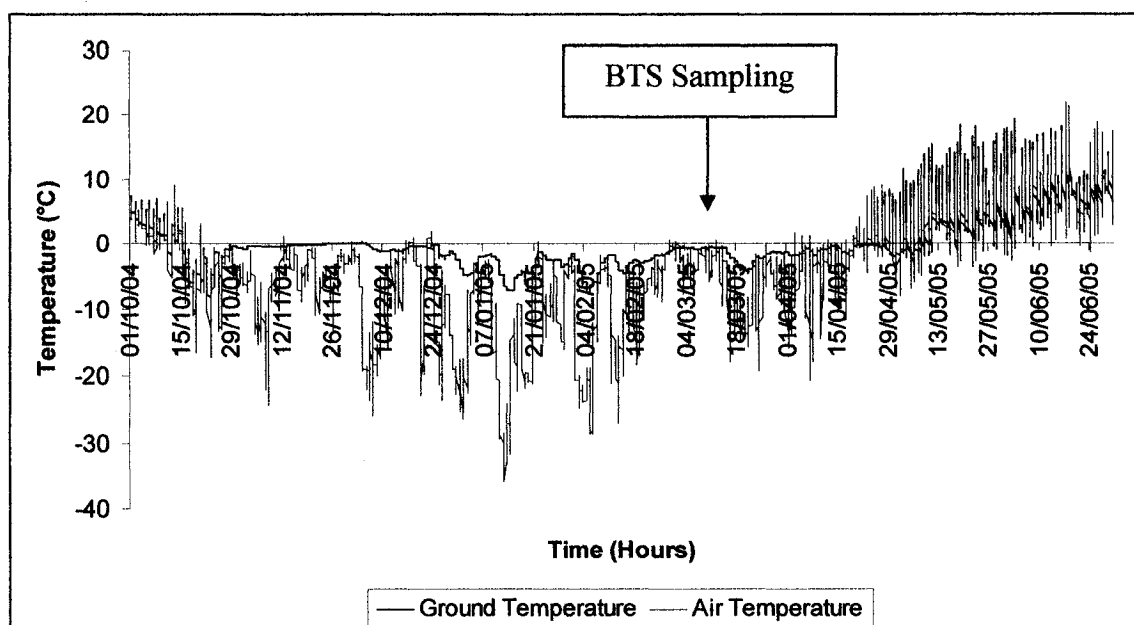


Figure 8: Graph of ground and air temperature data from Mosquito Flats in Haines Summit displaying stabilization of ground temperatures in late winter. BTS temperatures were made at this location from March 9 – 16, 2005. Since the ground surface temperature at the site was stable, this represents a BTS sample that indicates that permafrost is not present at this site.

Data were later retrieved for the time of the 2005 and 2006 sample in Haines Summit (Figure 8). They show that the sampling was done during the correct period in 2005. The 2006 logger data indicates that although ground temperatures were temporarily stable at the time of sampling, it is likely that sampling was performed before equilibrium was reached, giving colder temperatures (Figure 9). A later season ground temperature stabilization date could be the result of a snow cover established later than in the previous year.

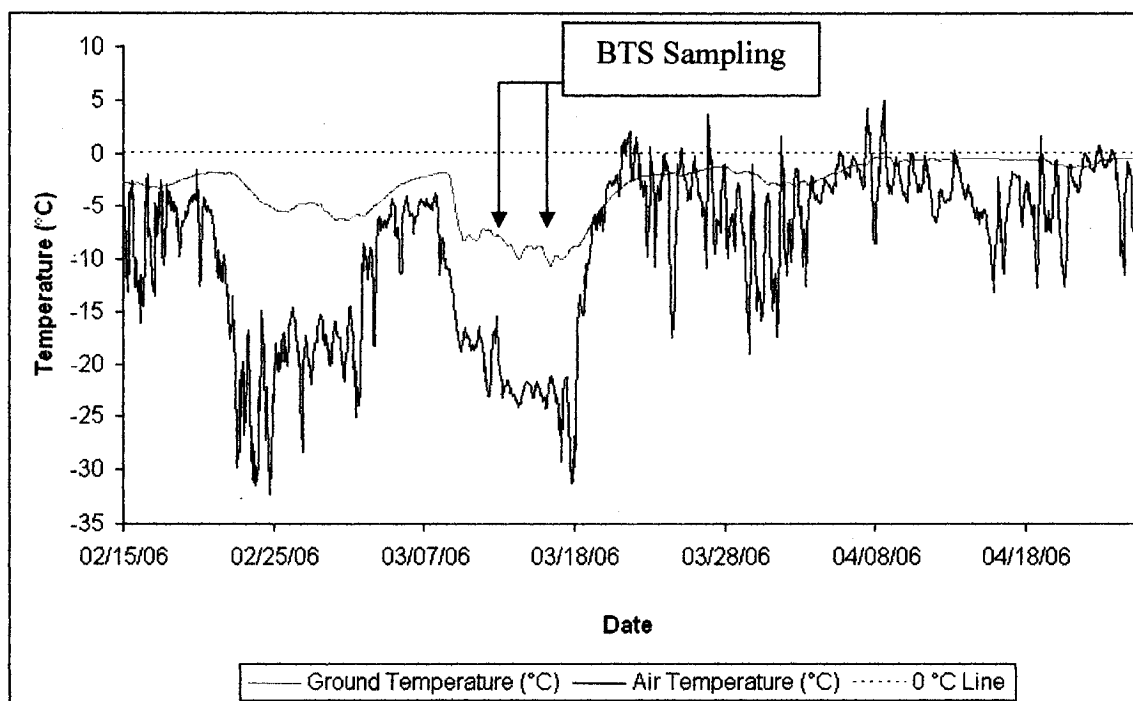


Figure 9: Graph of ground and air temperature data from Mosquito Flats in Haines Summit. BTS temperatures were collected from March 12 – 16, 2006.

The air and ground temperature data was also examined at the Three Guardsmen logger (Figure 10), this location is approximately 250 vertical meters higher than Mosquito flats and thus more representative of the 2006 sampling plan. The data in Figure 10 indicates that at this location ground temperatures were stable at the time of sampling, indicating BTS was preformed at the correct time.

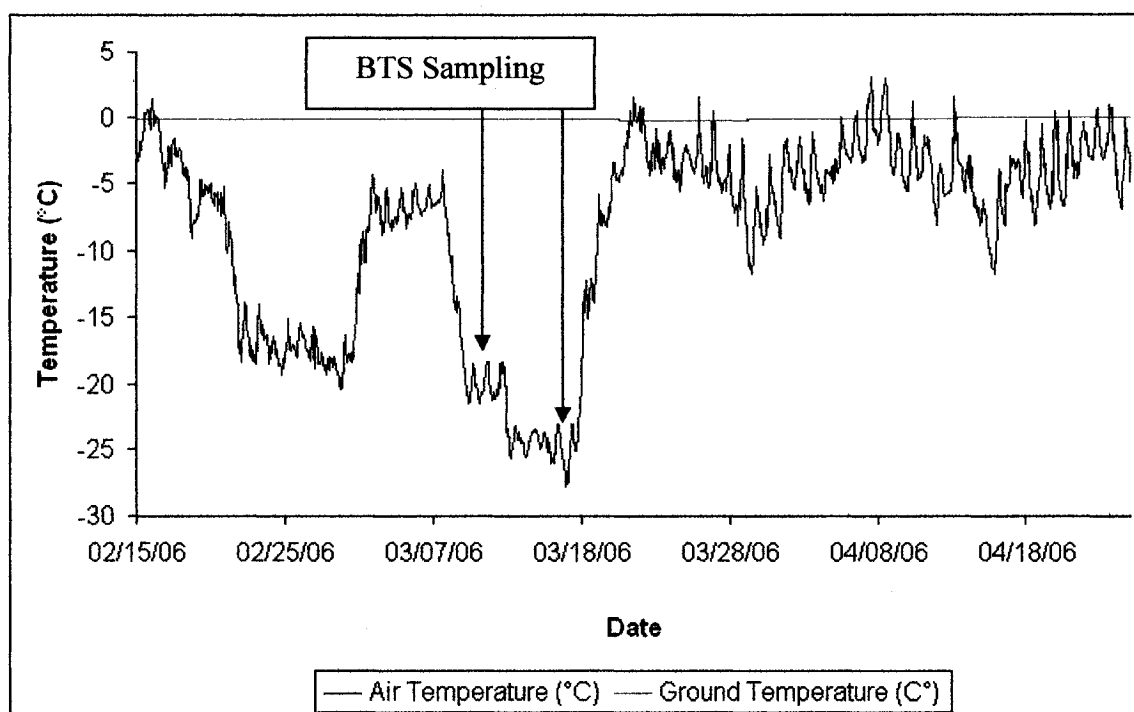


Figure 10: Graph of ground and air temperature data from Three Guardsmen in Haines Summit. BTS temperatures were collected from March 12 – 16, 2006.

5.2 Potential Incoming Solar Radiation (PISR) modeling:

Using a 30 meter resolution digital elevation model for each of the study areas, maps of potential incoming solar radiation (Figures 11 and 12) were created for snow free periods using the Arc view 3.2 extension solar analyst.

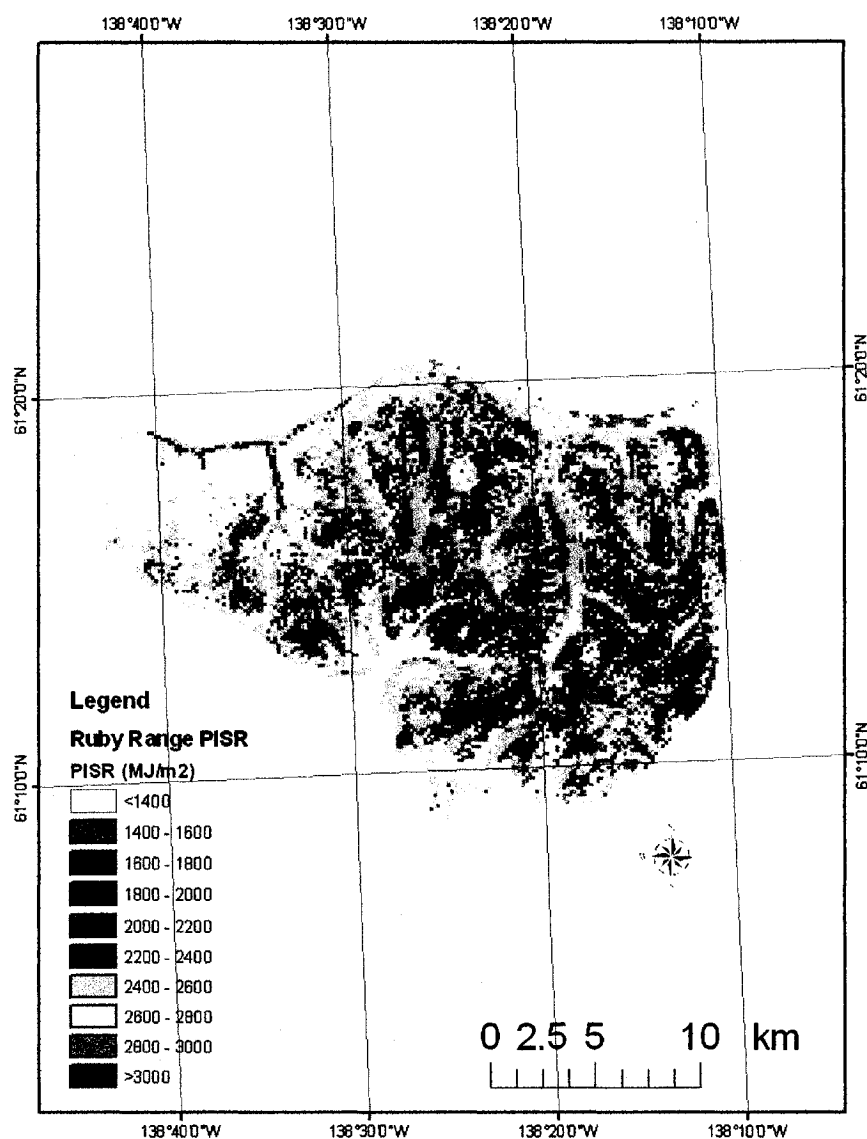


Figure 11: Map of potential incoming solar radiation for the period of May 15th to October 15th for the Ruby Range.

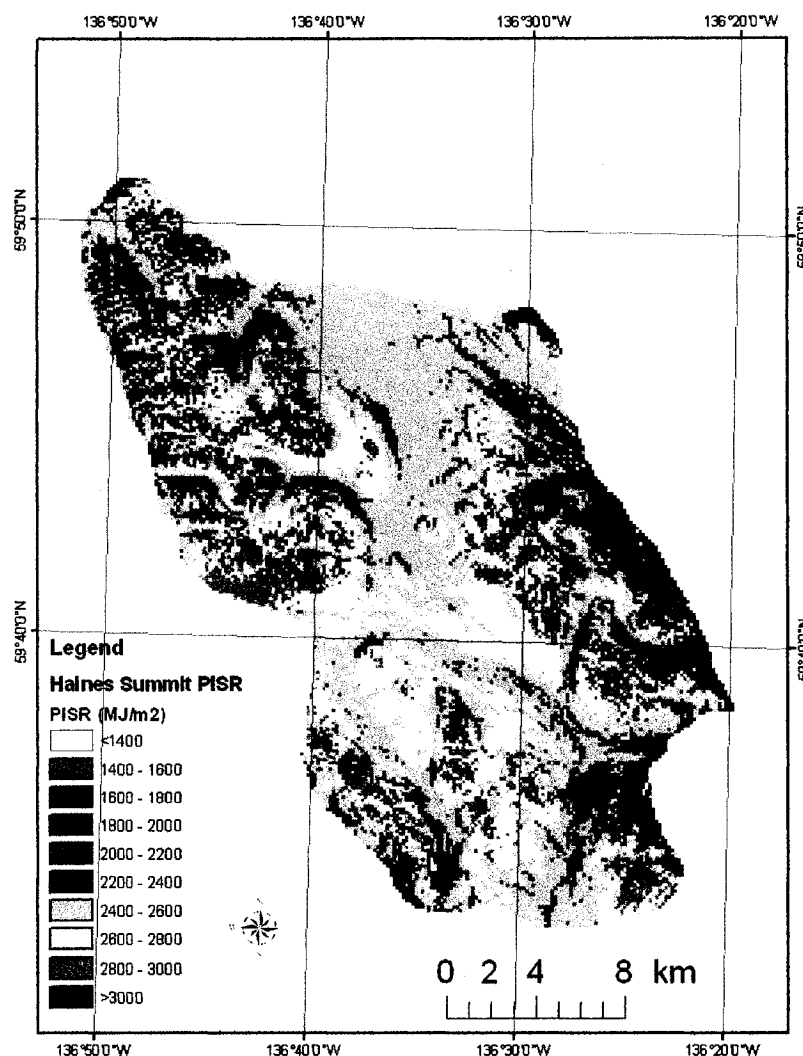


Figure 12: Map of potential incoming solar radiation for the period of May 15th to October 15th for Haines Summit.

The extension calculated solar radiation intensity in MJ/m² for May 15th to October 15th using a cloud cover proportion of 70 % (Haines Summit) and 65 % (Ruby Range). Solar radiation intensities are highly dependent on aspect and slope gradient and thus range greatly across terrain. In the Haines Summit area, PISR ranged from 400 - 3600 MJ/m² with a mean of 2500 MJ/m² and a standard deviation of 340. Solar radiation

intensity in the Ruby Range ranged from 900 – 4100 MJ/m² with a mean of 2650 MJ/m² and a standard deviation of 330.

5.3 Regression analysis to determine modeled BTS values:

As outlined in the methodology a linear regression model was developed for each of the study areas in order to predict BTS values based on elevation and PISR. Before the model was run, the measured BTS data were tested for normality and spatial autocorrelation.

5.3.1 Linear Regression for the Ruby Range:

A test for normality was conducted on the dependent and independent variables for the Ruby Range using a QQ plot with normality line (Figure 13). Each of the variables was tested independently and showed only slight deviations from normality, and thus did not require transformation.

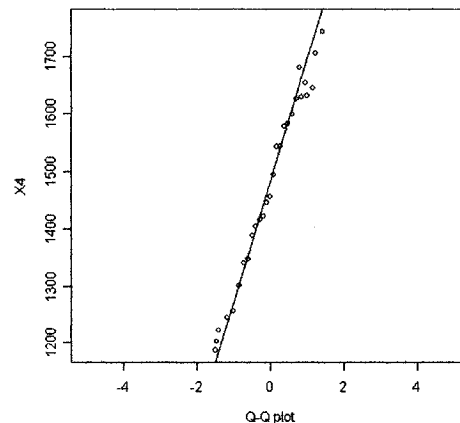


Figure 13: QQ-plot with normality line for elevation data in the Ruby Range.

In addition the variables were also tested for normality to a 95% confidence interval using a Kolmogorov-Smirnov normality test. The results indicated that values of BTS,

elevation and Potential Incoming Solar Radiation (PISR) did not significantly differ from a normal distribution.

The presence of spatial autocorrelation in the linear regression residuals was tested before the model was used. If data display significant spatial autocorrelation among linear regression residuals it likely reflects a flaw in the data collection process. The effects of spatial autocorrelation can potentially create spatially dependent trends in the data thus violating basic assumptions of linear regression modeling (Kerr et al., 2001). The test for spatial autocorrelation was conducted using global Moran's I in the Excel add-in program Rookcase (Sawada, 1999). Global Moran's I examines the residual values within a user-defined radius surrounding each point referred to as a lag distance. Within the lag distance all residual values encountered are compared and examined for similarity. Global Moran's I values range from 1 to -1 with positive values indicating positive dependence and negative values illustrating negative dependence, while a value of 0 indicates totally independent data. For this particular test a lag distance of 460 meters representing the mean nearest neighbour distance was used. When executed, the test yielded a global Moran's I value of -0.0714 with a p-value of 0.1470 indicating that spatial autocorrelation was not significant in this data set.

Using the 30 BTS points collected in the Ruby Range during March 2006 an initial linear regression model was created. The initial model produced a statistically significant fit (Table 1) with a multiple r^2 value of 0.255 and the following equation:

$$\text{BTS} = -0.0059(\text{elevation}) + 0.0043 (\text{PISR}) - 8.27 \quad (1)$$

$r^2 = 0.255$	Coefficient	P – value	Standard Error
Intercept	-8.27	0.042	3.87
Elevation	-0.0059	0.009	0.002
PISR	0.0043	0.019	0.0017

Table 1: Initial BTS linear model statistics for the Ruby Range.

The residual plot of the initial model indicated one particularly large residual (Figure 14) which was then examined in greater detail.

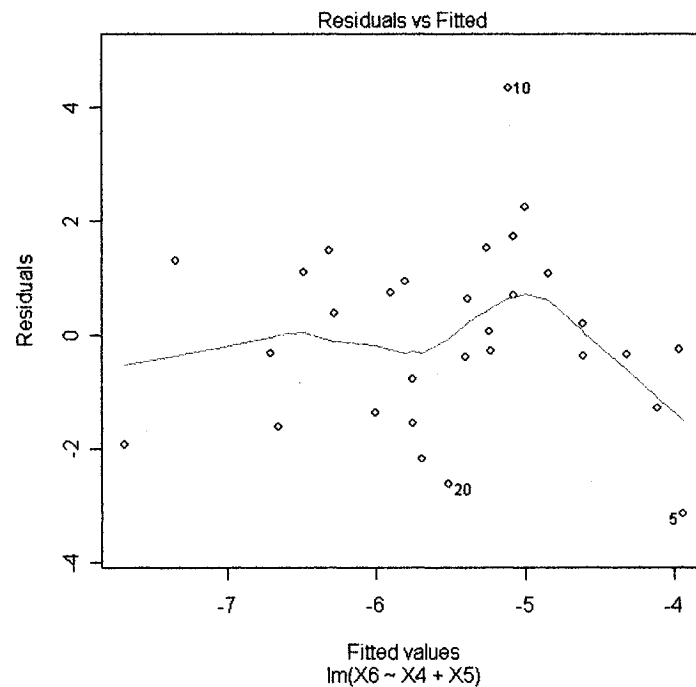


Figure 14: Plot of initial residuals for linear model of modeled BTS in the Ruby Range highlighting residual 10 as an outlier.

Of the thirty points collected in the Ruby Range during March 2006, the average observed temperature was approximately -5.5°C ; this particular point had an average temperature of -0.8°C . Spatially, this point was close to a major creek and showed a much higher BTS value than all surrounding points. It was concluded that this point was likely taken on ice and not at the snow ground interface. Consequently, it was eliminated and the model re-run to yield the following.

$$\text{BTS} = -0.0052 (\text{elevation}) + 0.0043(\text{PISR}) - 9.39 \quad (2)$$

$r^2 = 0.290$	Coefficient	P – value	Standard Error
Intercept	-9.39	0.01	3.39
Elevation	-0.0052	0.008	0.0019
PISR	0.0043	0.008	0.0015

Table 2: BTS linear model statistics for the Ruby Range.

The Ruby Range site is adjacent to Kluane Lake which is a major water body. Distance to the lake needed to be tested because very low BTS temperatures were predicted on steep slopes within one kilometre of the lake and appeared to contradict other data. BTS temperatures were not collected on these slopes due to a lack of snow in both the winters of 2005 and 2006; however, direct observations of late summer frozen ground were made in these areas (see section 5.4) and only one of the nine sites excavated close to the lake showed frozen conditions (Figure 15).

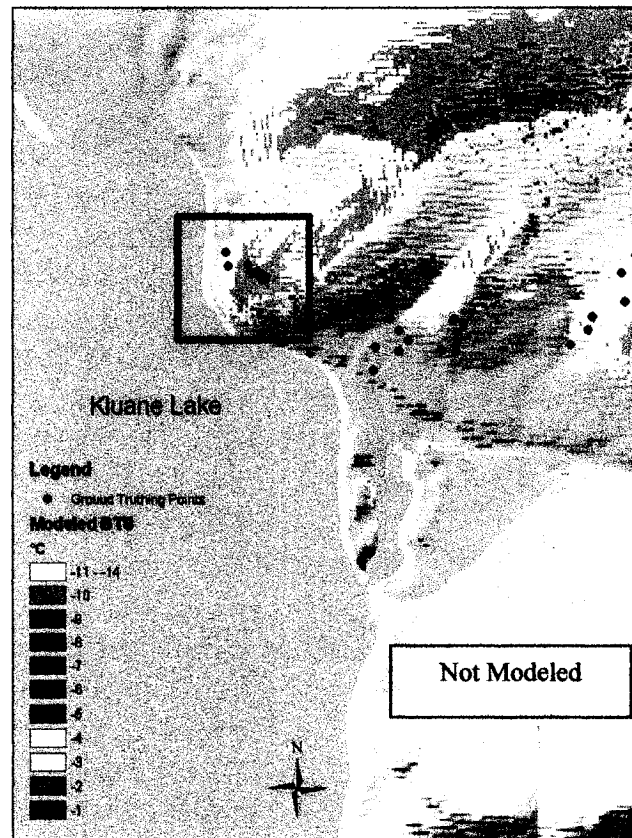


Figure 15: Map illustrating observations of late-summer frozen ground sites on steep slopes with close to Kluane Lake. Of the nine sites in the box, only one exhibited frozen conditions.

To explore its effect, the shortest distance to the lake (in meters) was calculated for each BTS point using the measurement tool in ArcGIS with the results square-rooted and added to the linear model as a third independent variable. Re-running the model determined that there was not a statistically significant relationship between BTS and the “distance to the lake” variable.

$$\text{BTS} = -0.007 (\text{elevation}) + 0.005 (\text{PISR}) - 0.03 (\sqrt{\text{distance}}) \quad (3)$$

$r^2 = 0.3212$	Coefficient	P – value	Standard Error
Intercept	-5.47	0.37	6.0
Elevation	-0.007	0.025	0.003
PISR	0.005	0.008	0.0017
Distance from Lake	-0.03	0.43	0.0037

Table 3: BTS linear model statistics for the Ruby Range with distance from Kluane Lake added.

As Figure 15 illustrates the highlighted late-summer observation points represent modeled BTS values ranging between -3.3 to -7.3°C. Due to the fact that only the highest elevation points displayed frozen conditions this suggests a flaw in the linear model.

In order to determine the strength of the linear regression model (Equation 2), several plots of the residuals versus the modeled fitted values were examined (Figures 16 & 17). Figure 16 plots the distribution of residuals and fitted values. The graph illustrates the distribution of residuals and does not show any evident clustering with roughly the same number of points located above and below the zero line between 2 and -2. S-Plus identifies outlying points whenever such a graph is created. In Figure 16, points 5, 12 and 19 are identified as outliers and were thus examined. Each of these points displayed greater residuals than average but, no evidence that could justify eliminating these points from the model could be found.

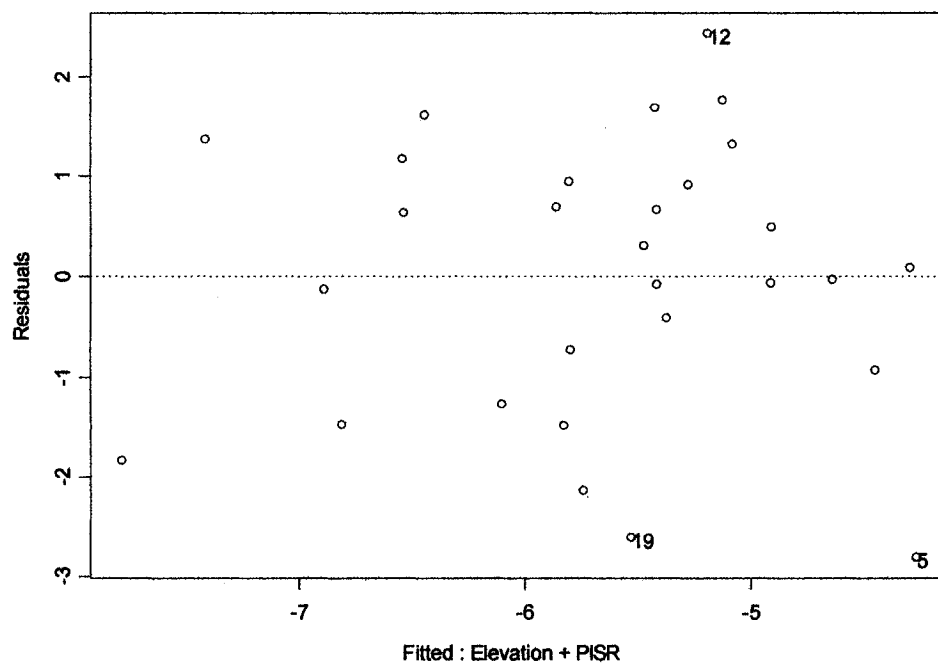


Figure 16: Plot of residuals for Ruby Range linear regression model (Equation 2).

Figure 17 was also examined to test the model's robustness and shows that the residual standard error is close to being normally distributed following the 1:1 plot line.

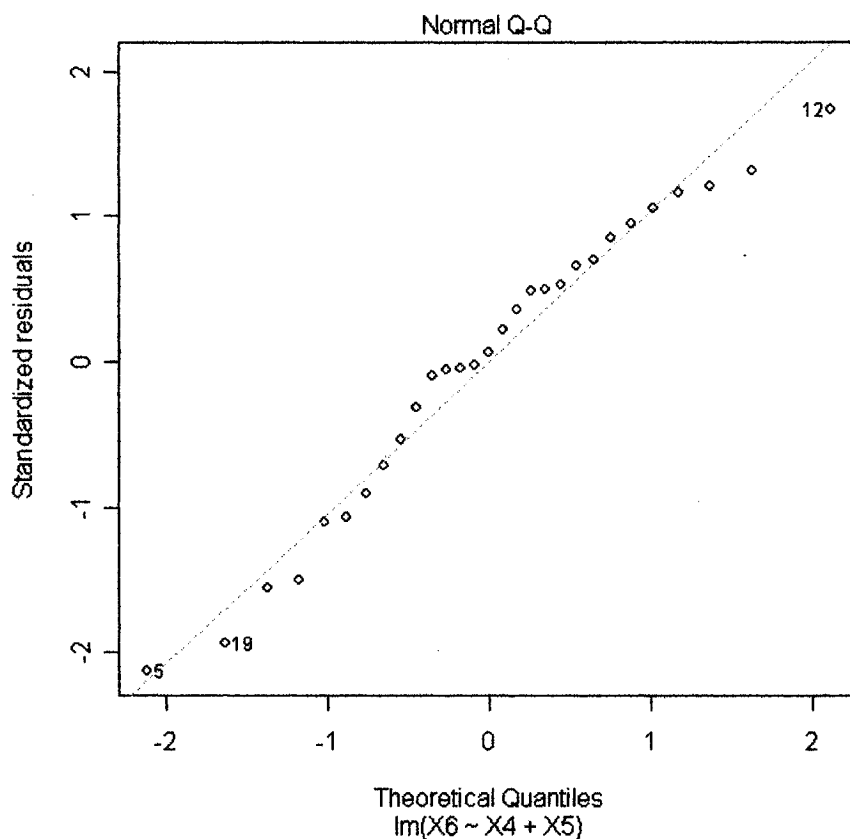


Figure 17: Distribution of Ruby Range linear model residuals in a Q-Q plot to examine normality.

Figure 18 compares measured and modeled BTS values for the Ruby Range. This line differs significantly from the 1:1 but is adequate for modeling purposes because the relationship between modelled BTS and permafrost is evaluated separately. Equation 2 was used directly in ArcGIS to develop a map of modeled BTS temperatures (figure 19).

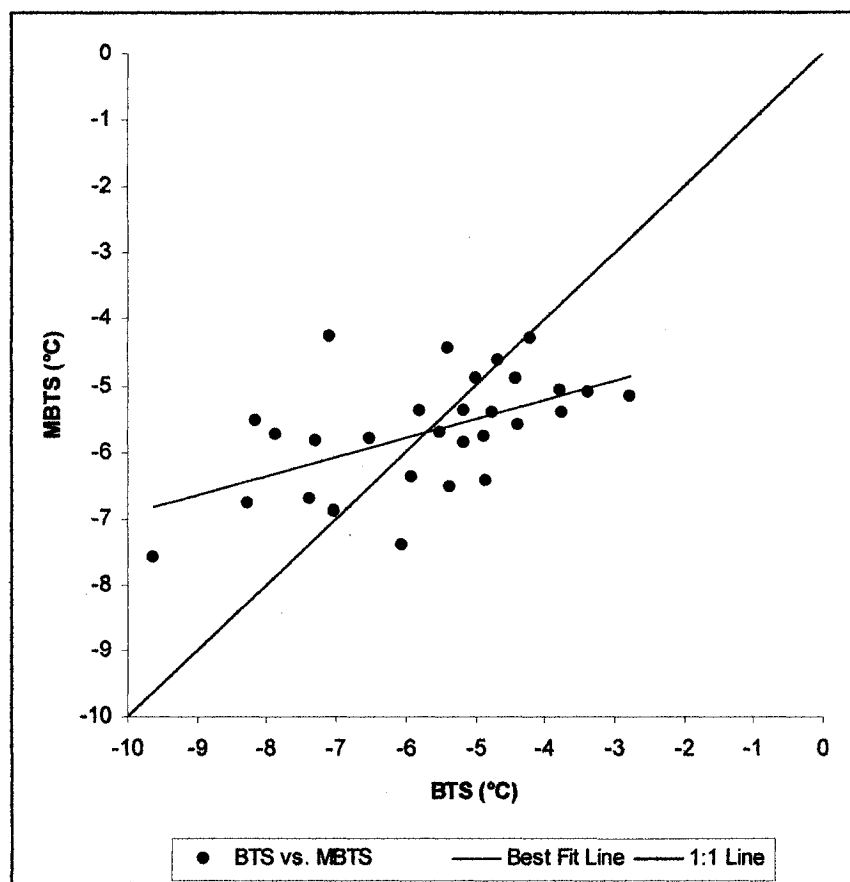


Figure 18: 1:1 plot of modeled BTS (MBTS) values versus measured BTS values. Modeled using equation 2.

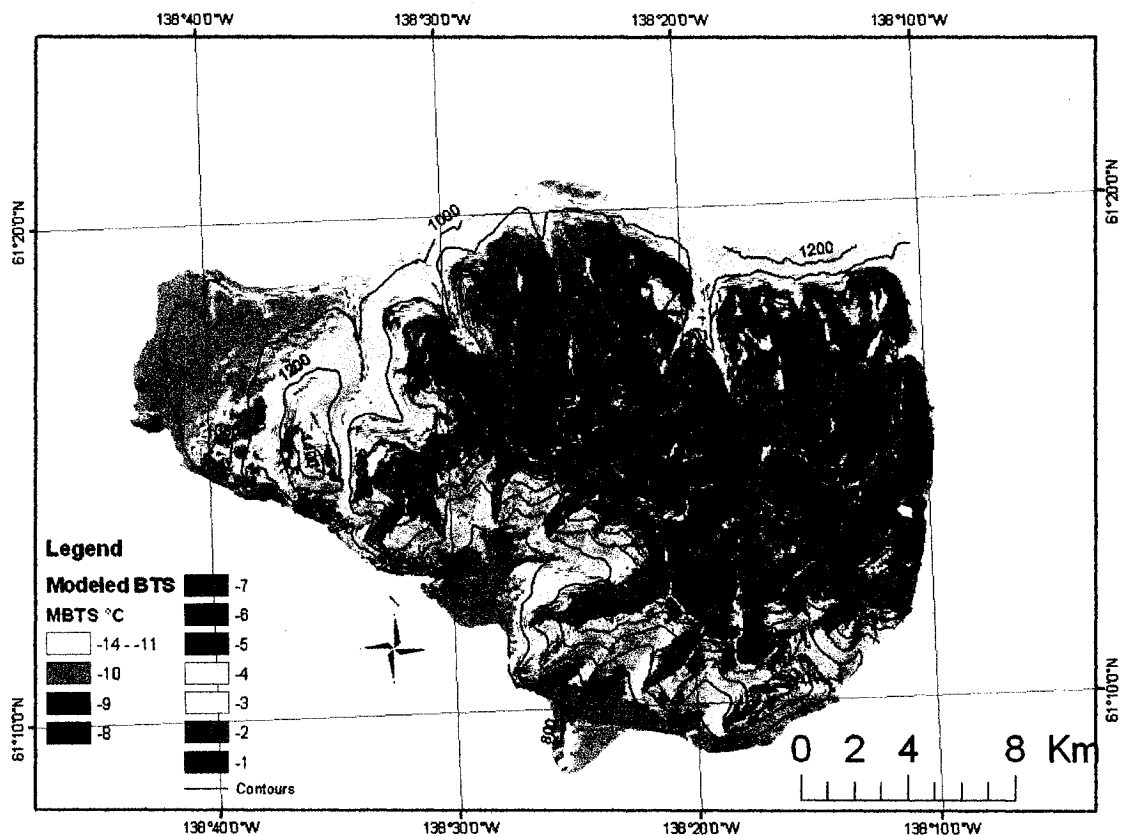


Figure 19: Map of modeled BTS values for the Ruby Range study area. The contour interval is 200 m.

5.3.2 Linear Regression for Haines Summit:

A test for normality was conducted on the dependent and independent variables for Haines Summit using a QQ plot with normality line as well as a Kolmogorov-Smirnov normality test. The dependent and independent variables were tested independently and showed no significant deviations from normality, and thus did not require transformation.

Spatial autocorrelation was tested as well using the same method outlined for the Ruby Range. The test of spatial autocorrelation was performed using global Moran's I on a total of 77 BTS point residuals collected in Haines Summit during the winters of 2005

and 2006. When executed, the test yielded a global Moran's I value of -0.05 with a P-value of 0.2238 indicating that spatial autocorrelation was not significant over a lag distance of 520 m.

Using the two-year data set for Haines Summit an initial linear model was created from 77 measurements. Model construction was accomplished using the same dependent and independent variables as in the Ruby Range. The initial model yielded a multiple r^2 value of 0.31 however, only elevation was statistically significant according to the model summary (Table 4). Results of this model produced the following equation and coefficients:

$$\text{BTS} = -0.0037(\text{Elevation}) + 0.0004(\text{PISR}) + 2.1593 \quad (4)$$

$r^2 = 0.311$	Coefficient	P – value	Standard Error
Intercept	2.16	0.243	1.83
Elevation	-0.0037	0.0000	0.0008
PISR	0.0004	0.633	0.0009

Table 4: Initial linear model coefficients for Haines Summit.

Although the PISR coefficient and intercept were not statistically significant, plots of the residuals were examined. These revealed significant clustering of residual data with values collected in 2005 displaying mostly positive residuals and data collected in 2006 exhibiting almost exclusively negative residuals (Figure 20).

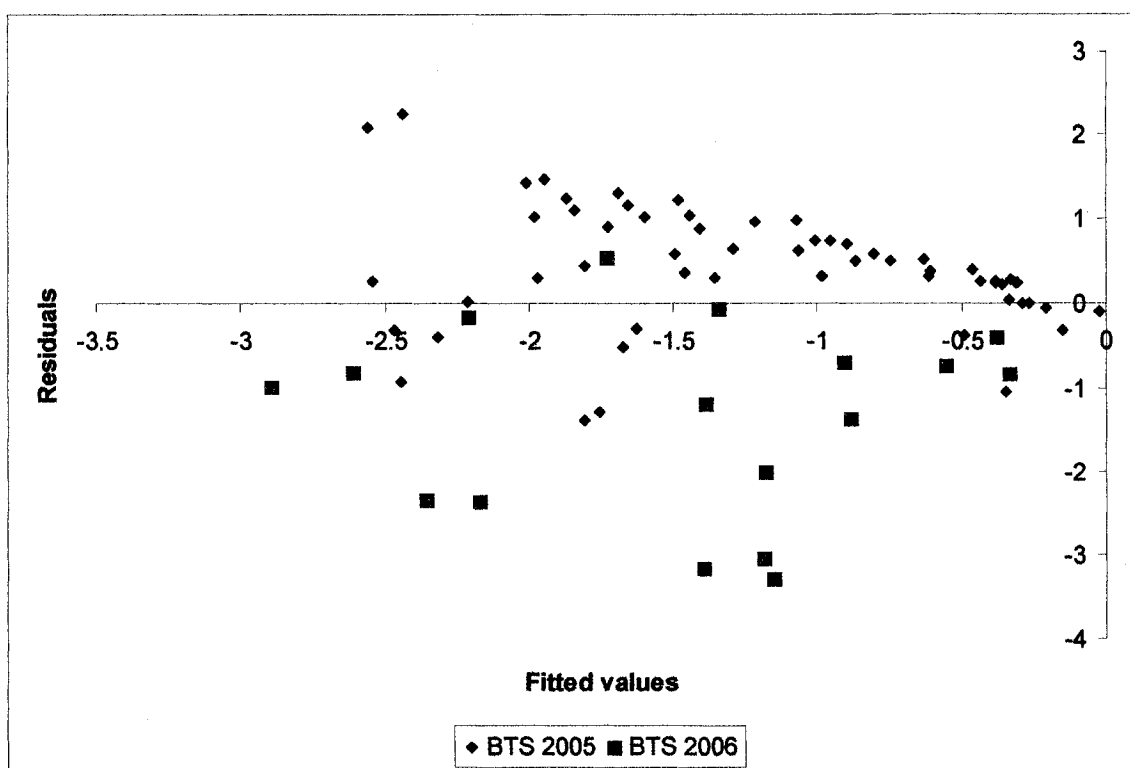


Figure 20: Plot of residuals for initial linear model for Haines Summit displaying temporal autocorrelation in residual data.

The key to these differences appears to be the arrival of snow in the fall. Personal communication with snow removal teams in the area revealed that snow was late to arrive in the fall of 2005 exposing the ground to cold winter air temperatures. The 2005 BTS measurements averaged -0.84°C while the 2006 ones averaged -2.40°C . Part of this difference may be because the 2006 sampling was focused on higher elevation sites. However, Figures 8, 9 and 20 suggest a systematic difference between the two seasons. This was examined by subtracting 0.5°C , 1°C and 1.5°C from the 2005 data until the best fit was found for the combined 2005 and 2006 data. Subtraction from the 2005 data rather than addition to the 2006 data was chosen because of results from the Ruby Range,

where only data from 2006 was available. The best results for Haines Summit were obtained by subtracting 1°C from the 2005 data.

Re-running the model with the adjusted 2005 values yielded the following equation and a higher r^2 value of 0.37. However, once again, only elevation was significant (Table 5).

$$\text{BTS} = -0.0035(\text{Elevation}) + 0.0006(\text{PISR}) + 0.77 \quad (5)$$

$r^2 = 0.369$	Coefficient	P – value	Standard Error
Intercept	0.77	0.6073	1.50
Elevation	-0.0035	0.0000	0.0007
PISR	0.0006	0.43	0.0006

Table 5: Coefficients for Haines Summit linear model after reducing BTS temperatures for 2005 by 1°C.

In both of the previous attempts to model BTS at Haines Summit, PISR was not significant and thus this variable was excluded in the third version of the model. The resultant equation was statistically significant (Table 6).

$$\text{BTS} = -0.0032(\text{Elevation}) + 1.87 \quad (6)$$

$r^2 = 0.363$	Coefficient	P – value	Standard Error
Intercept	1.87	0.0030	0.608
Elevation	-0.0032	0.0000	0.0005

Table 6: Coefficients for Haines Summit linear model excluding PISR and after reducing BTS temperatures for 2005 by 1°C.

In order to determine the strength of this linear regression model several plots of the residuals versus the modeled fitted values were examined (Figure 21).

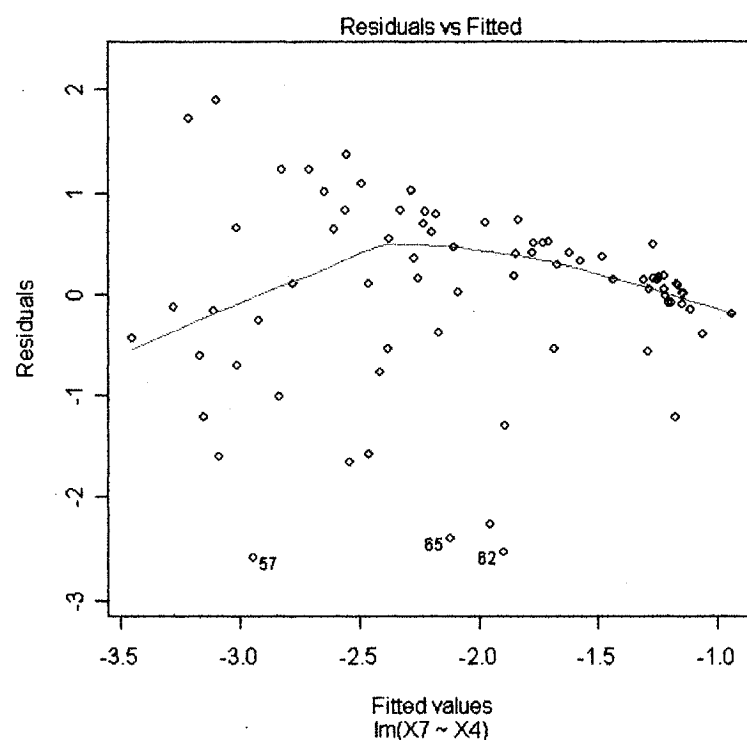


Figure 21: Plot of residuals versus fitted values for Haines Summit. Numbered points are large residuals.

S-Plus identified three highly negative outlying residuals which can be seen in Figure 21.

Each highlighted point was identified in the raw data and examined but, no reason to exclude them from the dataset could be found.

Grids of modeled BTS values for Haines Summit were produced using the same techniques as for the Ruby Range. 1:1 plots and maps were produced using linear models which included elevation as the sole independent variable (Figures 22 and 23) as well as a combination of elevation and PISR (Figures 24 and 25). Although a statistically significant relationship was not found when including the PISR variable, it is believed by some that even non-significant variables can be important to a models fit and thus this was examined on an exploratory basis. The examination of PISR for this study area was the result of successful BTS modeling in the past (e.g. Lewkowitz and Ednie, 2004).

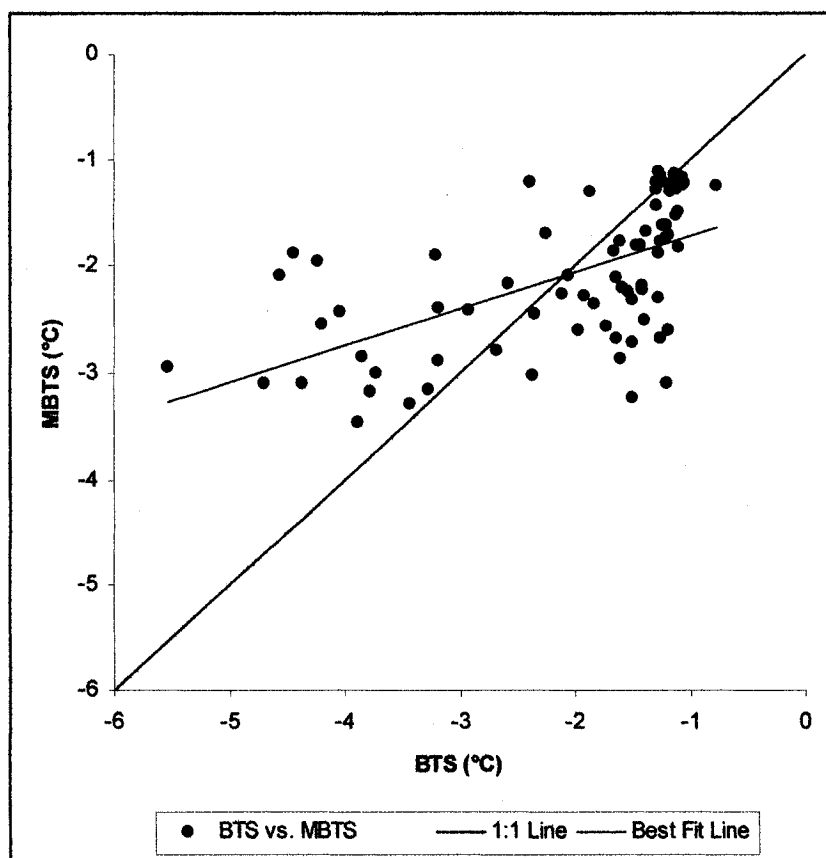


Figure 22: BTS vs. Modeled BTS (MBTS) values for Haines Summit using elevation only (equation 6) to generate MBTS.

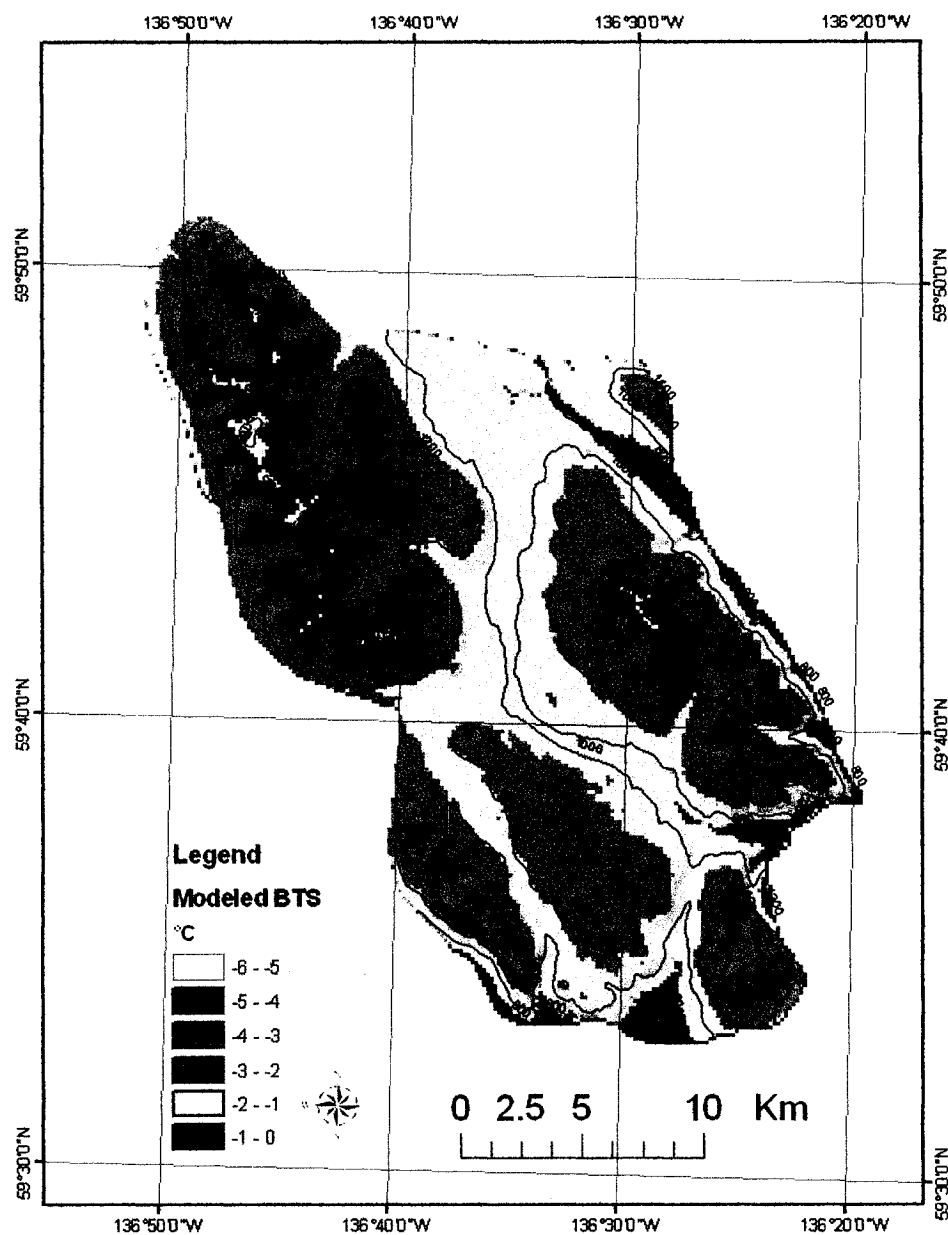


Figure 23: Map of modeled BTS values using equation 6 for the Haines Summit study area. Contour interval is 200 m.

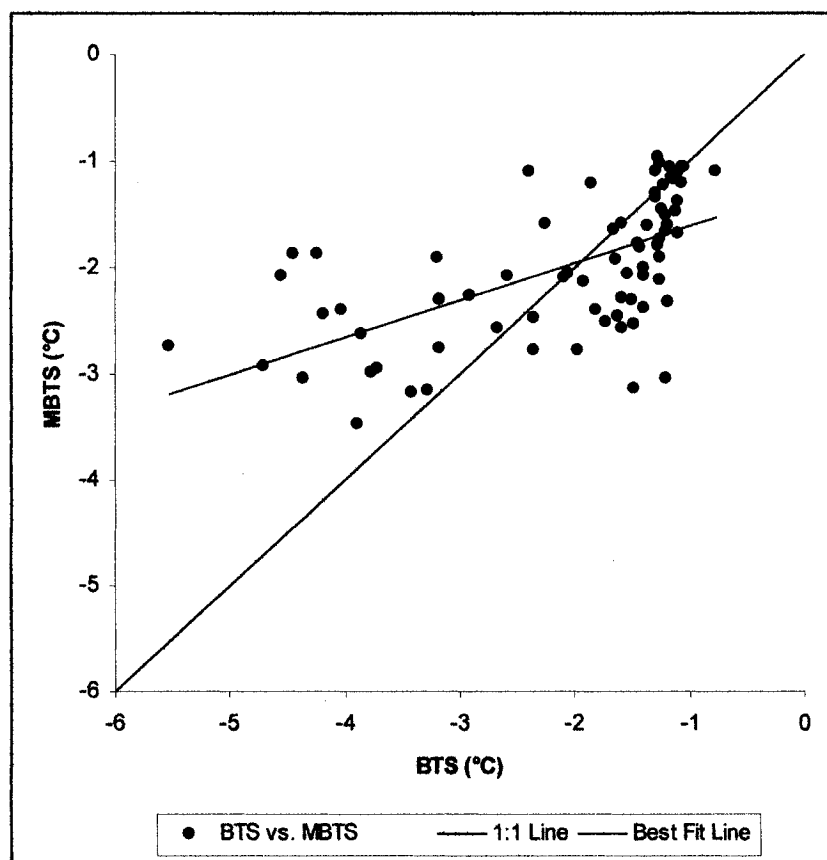


Figure 24: BTS vs. Modeled BTS (MBTS) values for Haines Summit using elevation and PISR to generate MBTS (equation 5).

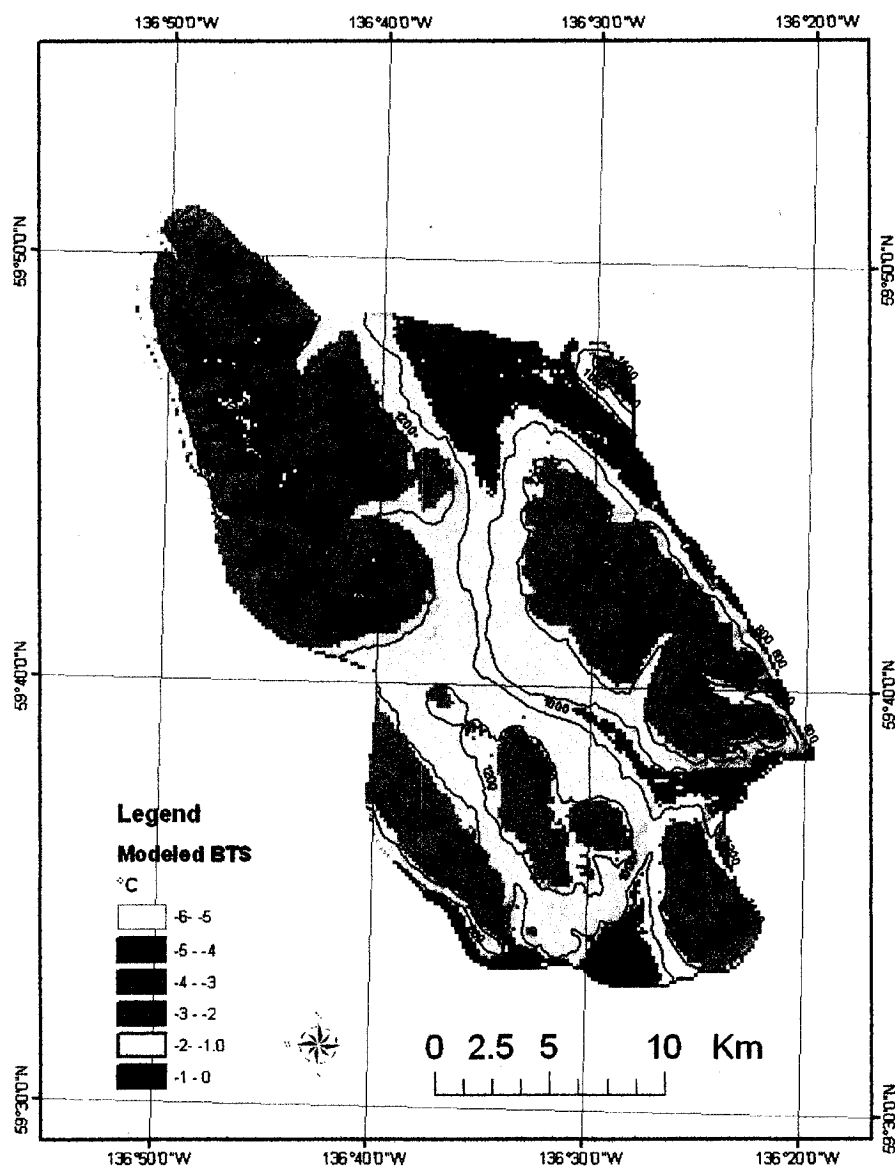


Figure 25: Map of modeled BTS values using elevation and PISR as independent variables (equation 5) for the Haines Summit study area. Contour interval is 200 m.

Examination of the modeled BTS surfaces produced from equations 5 and 6 show limited differences. BTS values are slightly warmer in areas where south-facing slopes dominate when PISR is included; however, differences never exceed 0.25 °C. This indicates that the modeling is relatively robust.

5.4 Direct observation of late-summer frozen ground (Ground Truthing):

Between July 30th and August 27th 2005, 85 pits in the Ruby Range and 95 pits in the Haines Summit study area were excavated. The detection of frozen ground was made using a combination of techniques including probing, digging and direct temperature measurement (Figure 26).



Figure 26: Pit showing the presence of frozen ground in the Ruby Range at a depth of 60 cm on August 3, 2005. The multimeter reading of 7.45 k Ω is equivalent to a temperature of +0.4 °C.

Section 5.4.1: Observation of late summer frozen ground in the Ruby Range:

Of the 85 pits excavated in the Ruby Range, 56 exhibited frozen ground conditions (Figure 27), with measured and estimated active layers ranging from 41 – 147 cm over an elevation range of 1100 – 1800 m. Most of the pits dug in the Ruby Range

had elevations of 1000 – 1400 m as this range provided the greatest likelihood of finding both frozen and unfrozen conditions.

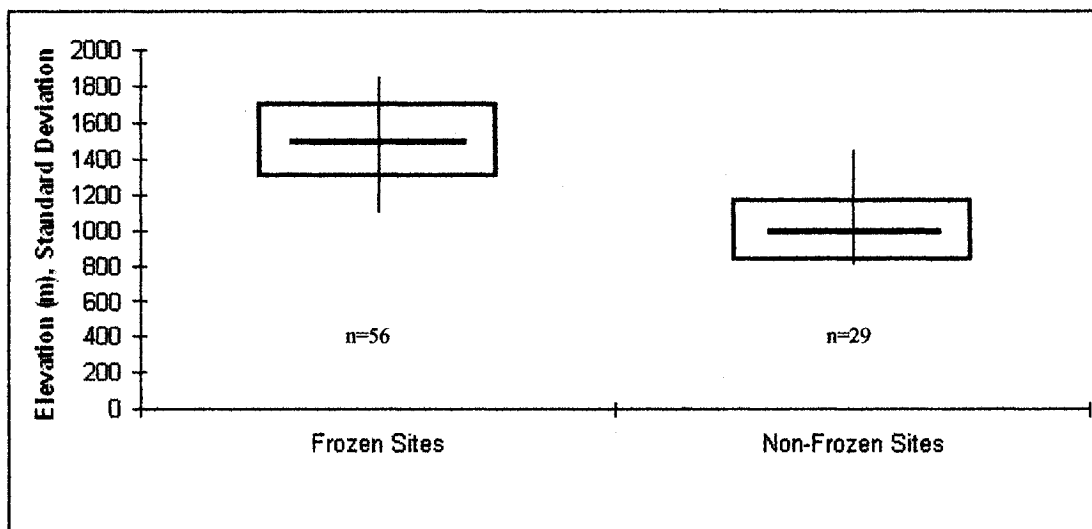


Figure 27: A graph illustrating the elevations of frozen and non-frozen sites in the Ruby Range. Horizontal lines represent elevation means vertical lines represent the highest and lowest elevations of each category. Open boxes represent plus or minus one standard deviation.

Pits were excavated and compared to BTS values produced by the linear regression model described in section 5.3.1. Modeled BTS values for excavation sites varied from -2.2 °C to -8.7 °C with an average value of -5 °C (Figure 28).

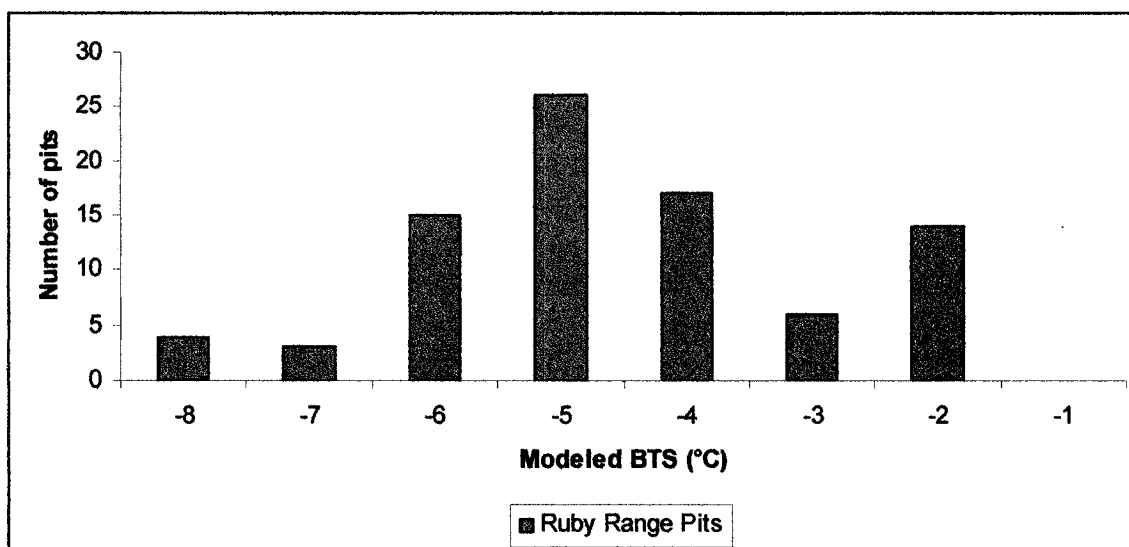


Figure 28: Histogram of ground truthing pits and modeled BTS values. Note: modeled values shown represent a 1 °C range of temperature (e.g. -1 °C represents -1 °C to -1.999 °C).

During pit excavation the thickness of the organic mat was recorded in order to examine whether a relationship existed between its thickness and the presence or absence of permafrost. For the Ruby Range, there were 29 ground truthing points not displaying frozen characteristics. At these locations, a minimum organic mat thickness of 0 cm was recorded with a maximum of 20 cm and an average thickness of 3.8 cm (Figure 29). Permafrost present sites showed a minimum organic mat depth of 0 cm with a maximum of 30 cm and a higher average of 11.5 cm. A differences of means test was performed on the results of the frozen and non-frozen sites, revealing that the means of each group were statistically different.

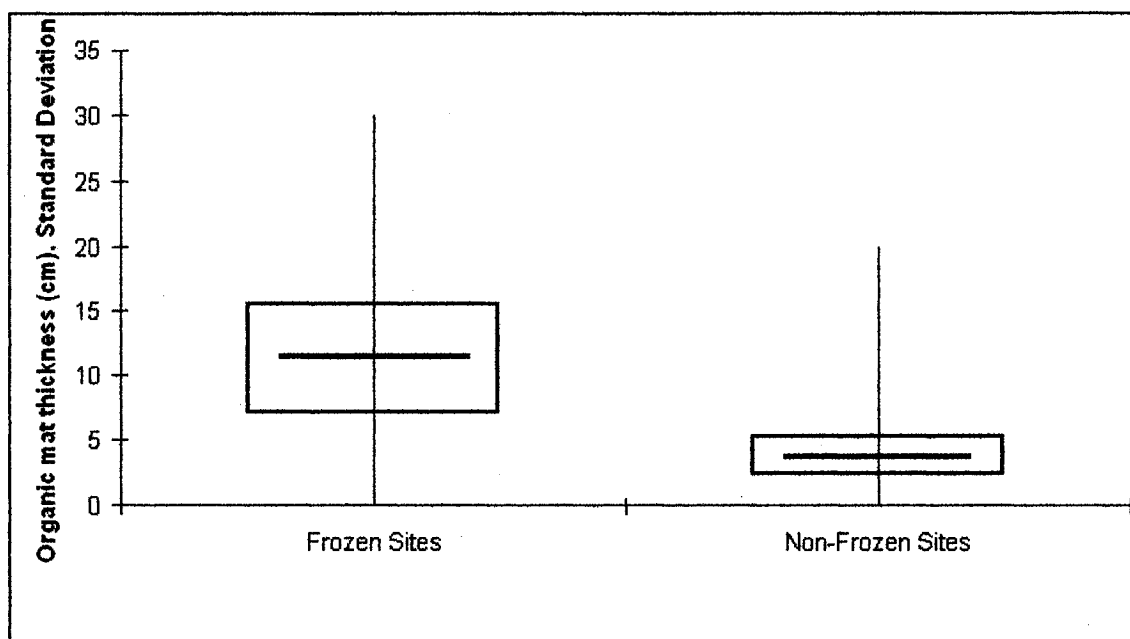


Figure 29: Graph illustrating the organic mat thickness at frozen and non frozen sites in the Ruby Range. Horizontal lines represent elevation means vertical lines represent the highest and lowest elevations of each category. Open boxes represent plus or minus one standard deviation.

Although not exclusively the case, organic mat thickness at many frozen sites contained thicker layers of sphagnum, lichen and other mosses. Organic mat thickness appeared particularly important on south-facing slopes which showed frozen ground conditions when greater than 6 cm of organics were present whereas at comparable elevations containing thinner organic layers, no permafrost existed. It would seem from this examination that although a thicker organic layer is often found at permafrost sites in the Ruby Range it cannot be used as an indicator of permafrost by itself. This variable would theoretically work well if integrated into the initial multiple linear regressions, but this is not possible as it is not realistic to collect organic mat depths and BTS points at the same time in the year.

Section 5.5 Permafrost Probability Predicted by Logistic Regression for the Ruby Range:

The probability of permafrost within the study area was calculated from the modeled BTS values (section 5.3.1) and the results of the late-summer examination of frozen ground using logistic regression analysis. This type of regression follows a logistic curve relating the independent variable to the rolling mean of the dependent variable (Hosmer and Lemeshow, 1989). The regression follows the following equation:

$$P = 1 / (1 + \exp (-Y)) \quad (7)$$

Where P is the probability of permafrost ranging from 0 – 1 and Y is a constant developed from the independent variable in the regression (Modeled BTS).

Using the above approach a logistic model was created for the Ruby Range entitled LM-RR which generated the following equation:

$$Y = -4.84 - 1.17 (\text{MBTS}) \quad (8)$$

The Y term was then substituted into the probability equation and calculated for the entire area. Table 7 was generated from the results of the logistic model.

LM-RR	β Coefficient	Standard Error	Wald ¹ Statistic	Degrees of Freedom	Significance
Constant	-4.84	1.19	16.54	1	< 0.01
MBTS	-1.17	0.25	21.9	1	< 0.01

Table 7: Summary of coefficients in the logistic model for the Ruby Range LM-RR

¹ A Wald Statistic is obtained by comparing the maximum likelihood estimate of the slope to an estimate of its standard error (Hosmer and Lemeshow, 1989).

Both of the β coefficients are considered significant at the 99% confidence level and allow for the generation of a permafrost probability curve (Figure 30).

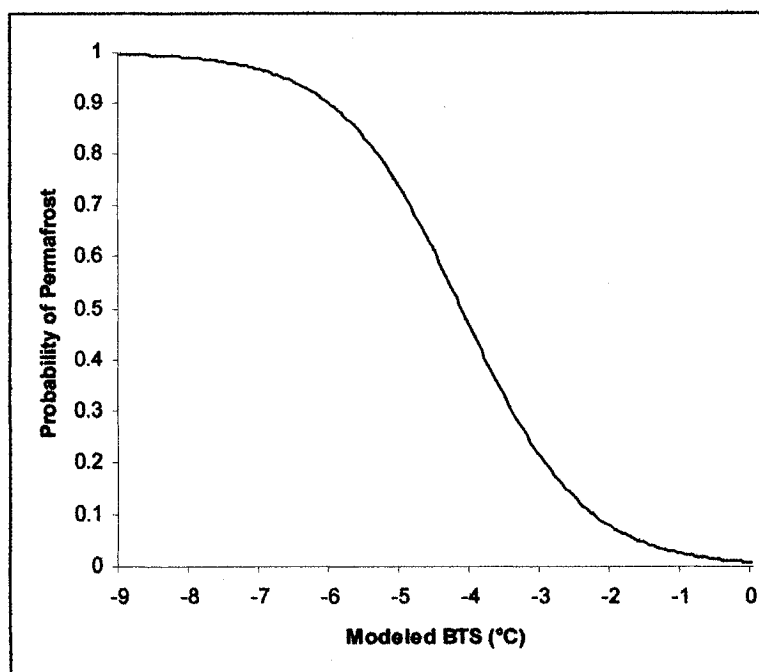


Figure 30: Permafrost probability curve for the logistic regression model (LM-RR) for the Ruby Range.

Examination of the permafrost probability curve for LM-RR indicates that there is a 10 % chance of encountering permafrost at a modeled BTS temperature of -2.3°C . Areas with $<10\%$ permafrost coverage are classified as isolated patches of permafrost (Heginbottom et. al 1995). Permafrost coverage between 10 – 50 % corresponds to sporadic discontinuous permafrost, with LM-RR temperatures between -2.3°C and -4.15°C . A 50 - 90 % likelihood of permafrost occurs from -4.15°C to -6°C making up the widespread discontinuous permafrost with probabilities $> 90\%$ representing the continuous permafrost which occurs at temperatures $< -6^{\circ}\text{C}$.

In order to test the accuracy of the logistic regression model (LM-RR) the modeled probability of permafrost was compared to the actual presence of permafrost observed in the late-summer ground truthing. Modeled BTS values were grouped into one degree categories from -1 to -8°C . A percentage was then calculated from the number of

pits containing permafrost in a category divided by the number of pits excavated. This was compared to the probability of permafrost for that particular temperature range (Table 8 and Figure 31).

LM-RR	0	-1	-2	-3	-4	-5	-6	-7	-8
Number of Pits	0	0	14	6	17	26	15	3	4
Number of Pits with PF	0	0	0	2	12	23	13	2	4
% of PF	0	0	0	33.3	70.5	88.46	86.7	66.6	100
Range of Probabilities from Logistic Model (%)	0.08 - 2.5	2.5 - 7.6	7.6 - 20	20 - 46	46 - 73	73 - 89	89 - 96	96 - 98.9	98.9 - 99.9

Table 8: A tabular comparison between the percentage of permafrost detected from ground truthing and the probability determined by the logistic model (LM-RR). Note: the categories above include the full range of the value (i.e. -1 covers -1 to -1.999 °C).

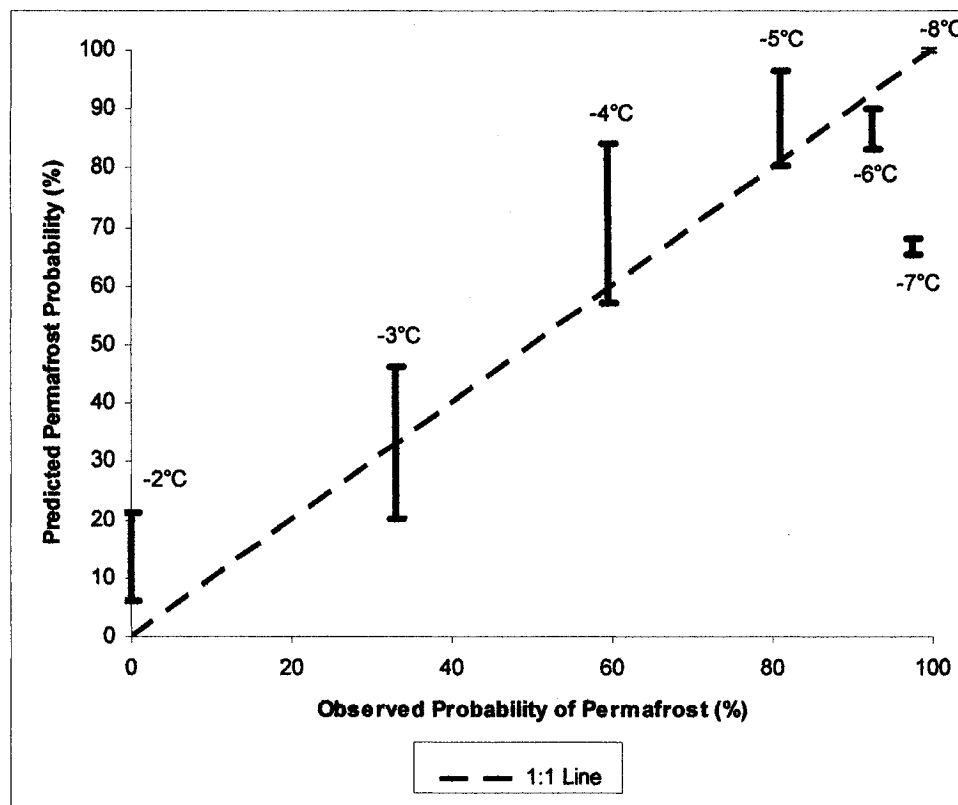


Figure 31: Graph showing observed predicted permafrost percentages according to LM-RR versus measured values. The bars represent the range of predicted probability for a 1 °C range of modeled BTS values.

Using the raster calculator in Arc GIS the logistic regression model LM-RR was used to produce a surface of permafrost probabilities for the Ruby Range (Figure 32). LM-RR generated permafrost probabilities ranging from 0.06 to 1.0 for the study area with a mean probability of 0.66. The highest probabilities are on high mountain peaks and upper elevation north-facing slopes. Low probabilities of permafrost are predicted for lower elevations and in areas where solar radiation inputs are greater.

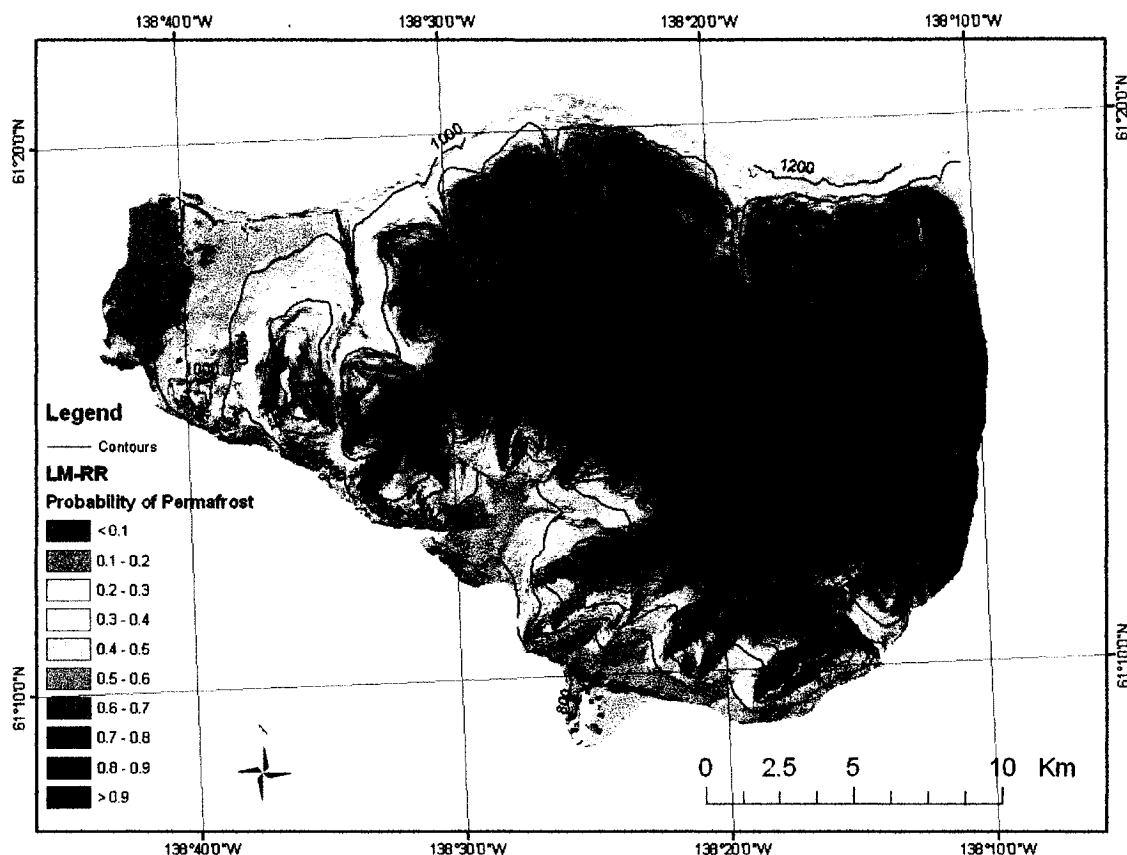


Figure 32: Map of Permafrost Probability for the Ruby Range created from LM-RR (equation 8).

The information in Figure 32 can be converted into units of percentage and area in order to fully understand the dimensions of permafrost in the Ruby Range. In this conversion, it is assumed that because of the large sample size, there is a direct relationship between probability and percentage of area underlain by permafrost. For example, it is assumed that for grid cells with a probability of 0.5, half are underlain by permafrost and half are not. Using ArcGIS, elevation zones in the study area were reclassified into 100 meter zones ranging from 700 – 800 to 2300 – 2400 m. Zonal statistics were then applied to the re-classed grid using a mean function to determine the amount of permafrost in each elevation zone (Figure 33).

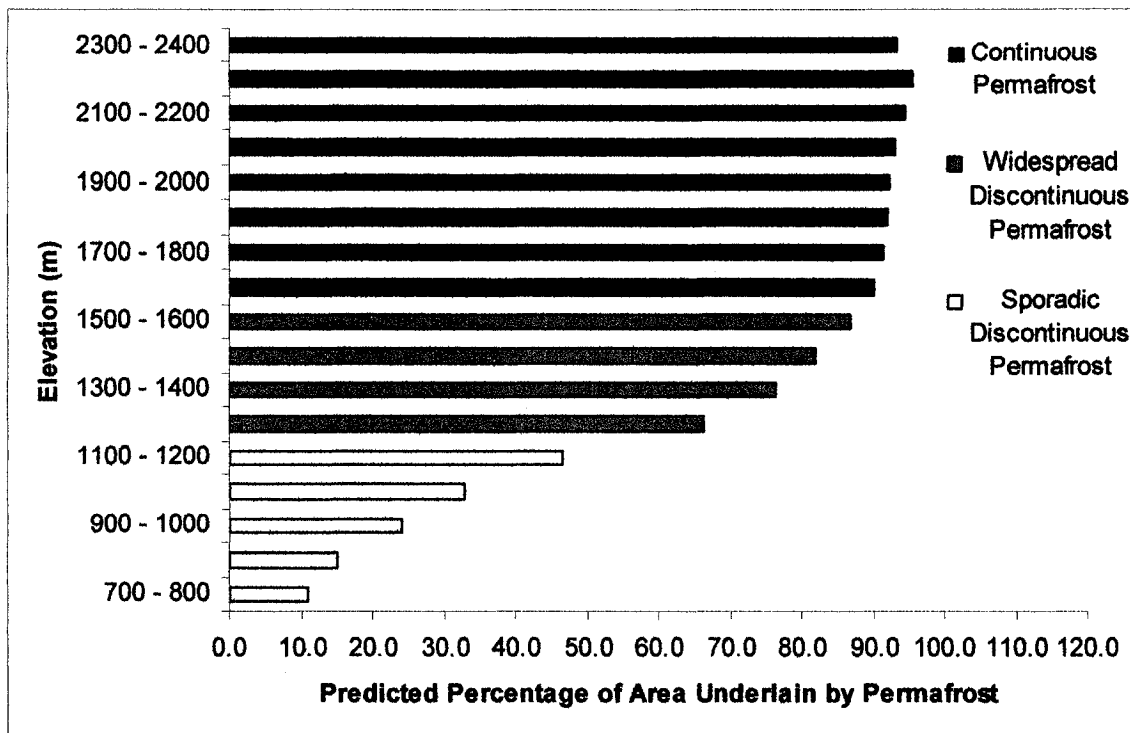


Figure 33: Graph illustrating the predicted percentage of area underlain by permafrost for each 100 m elevation band in the Ruby Range based on LM-RR

Permafrost percentage in the Ruby Range increases dramatically as elevation increases reaching a maximum of 96 % in the 2200 – 2300 m elevation band. Using a conventional permafrost classification according to Heginbottom et al. (1995), elevations of 700 – 1200 m fit into the sporadic discontinuous permafrost zone (10 – 50% permafrost), 1200 – 1600 m elevations fall into the widespread discontinuous permafrost zone (50 – 90% permafrost) and all elevations above into the continuous permafrost zone (>90% permafrost). It is interesting to note that no complete elevation bands in the study area belong to the isolated patches of permafrost (<10% permafrost) but a few areas do have probabilities <10 % (notably in the northwest). The study area as a whole is conventionally classified as a zone of sporadic discontinuous permafrost zone (Heginbottom 1995).

The Ruby Range study area is approximately 425 km² and ranges in elevation from 700 – 2400 m. A total of 282 km² of the area or 66 % is underlain by permafrost according to LM-RR. Much of this occurs in the elevation range of 1000 – 2000 m where the greatest landscape area exists.

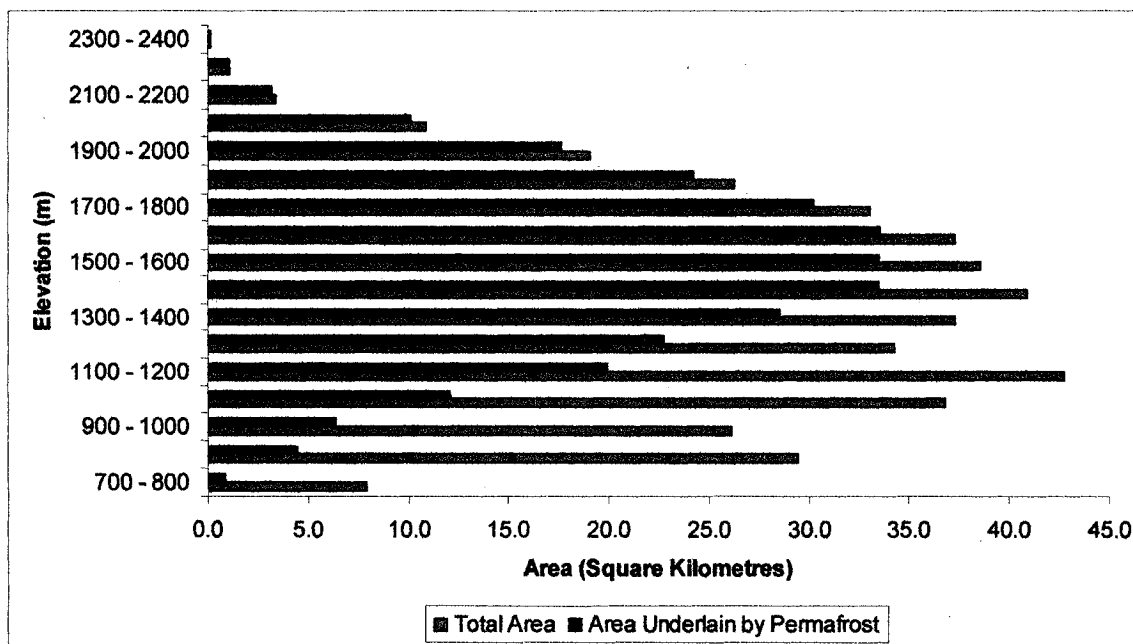


Figure 34: Graph illustrating the amount of area in each elevation band underlain by permafrost versus the total area in that elevation class for the Ruby Range.

Section 5.6: Observation of late summer frozen ground in Haines Summit:

A total of 95 pits were excavated in Haines Summit during the late summer of 2005. Of the excavated sites a total of 28 exhibited permafrost conditions with the remaining 67 sites showing no indication of frozen ground (Figure 35). Active layer depths in the frozen sites measured from a minimum of 59 cm to a maximum of 149 cm over an elevation range of 1100 – 1600 m. The majority of pits in Haines Summit were excavated between 1100 – 1400 m in order to sample within the expected transition area between permafrost and non-permafrost terrain.

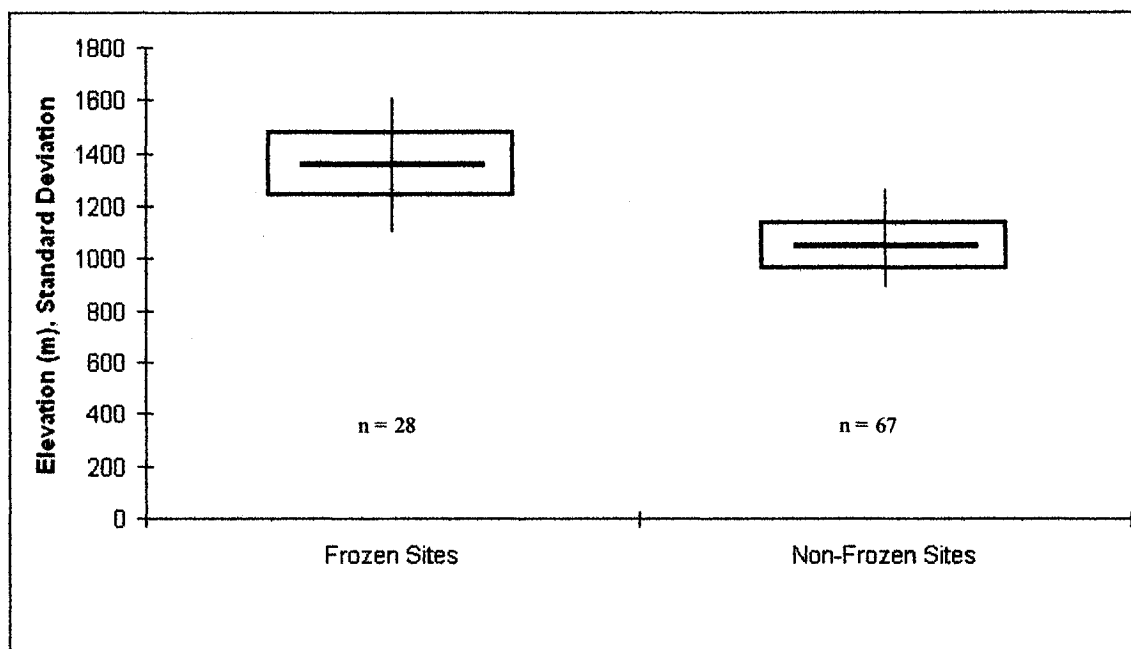


Figure 35: A graph illustrating the elevations of frozen and non-frozen sites in the Haines Summit Study Area. Horizontal lines represent elevation means, vertical lines represent the highest and lowest elevations of each category, and open boxes represent plus or minus one standard error.

Pit data was compared to BTS values produced by both linear regression models developed in section 5.3.2 (equations 5 and 6). Excavated sites spanned a temperature range of -1.1 to -3 °C with an average of -1.8 °C for modeled BTS values from the elevation only linear regression (Figure 36). The pit location resulting temperatures from the regression involving both terms varied slightly more, ranging from -0.95 to -3 °C with an average of -1.7 °C (Figure 36).

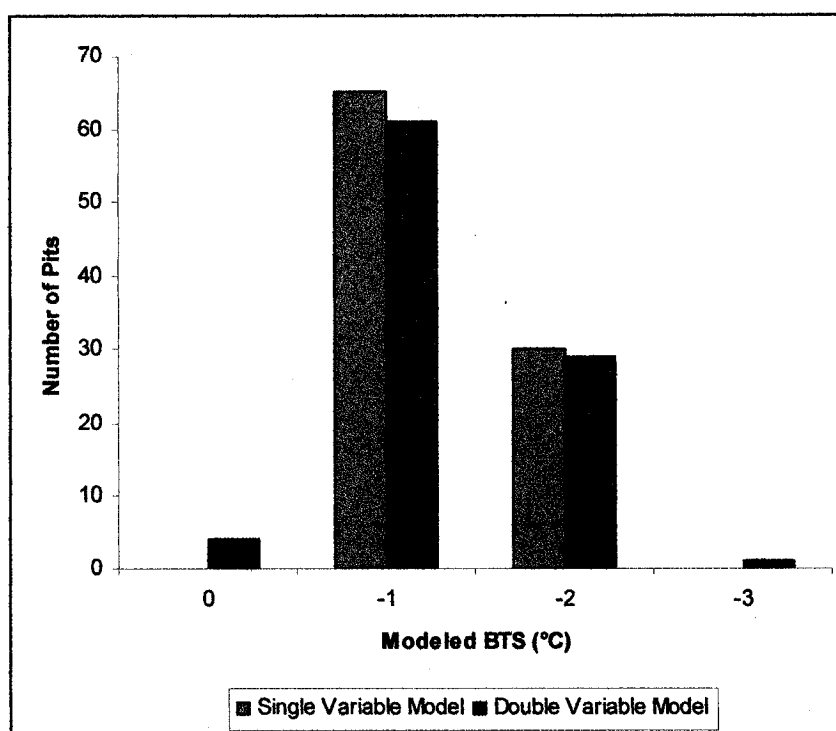


Figure 36: Histogram of ground truthing pits and modeled BTS values for the Haines Summit study area. Note: modeled values shown represent a 1 °C range of temperature (e.g. -1 °C represents -1 °C to -1.999)

As in the Ruby Range the organic mat thickness was measured at each of the excavated sites in order to determine whether this factor was related to the presence or absence of permafrost. Of the 28 sites where permafrost conditions were encountered organic mat thicknesses ranged from a minimum of 0 cm to a maximum of 9 cm with an average of 2.1 cm. Organic mat thicknesses in non-permafrost sites ranged from a minimum of 0 cm to a maximum of 14 cm with an average thickness of 5.6 cm. Thus unlike the Ruby Range, permafrost sites have average organic mat thicknesses less than those of non-frozen sites.

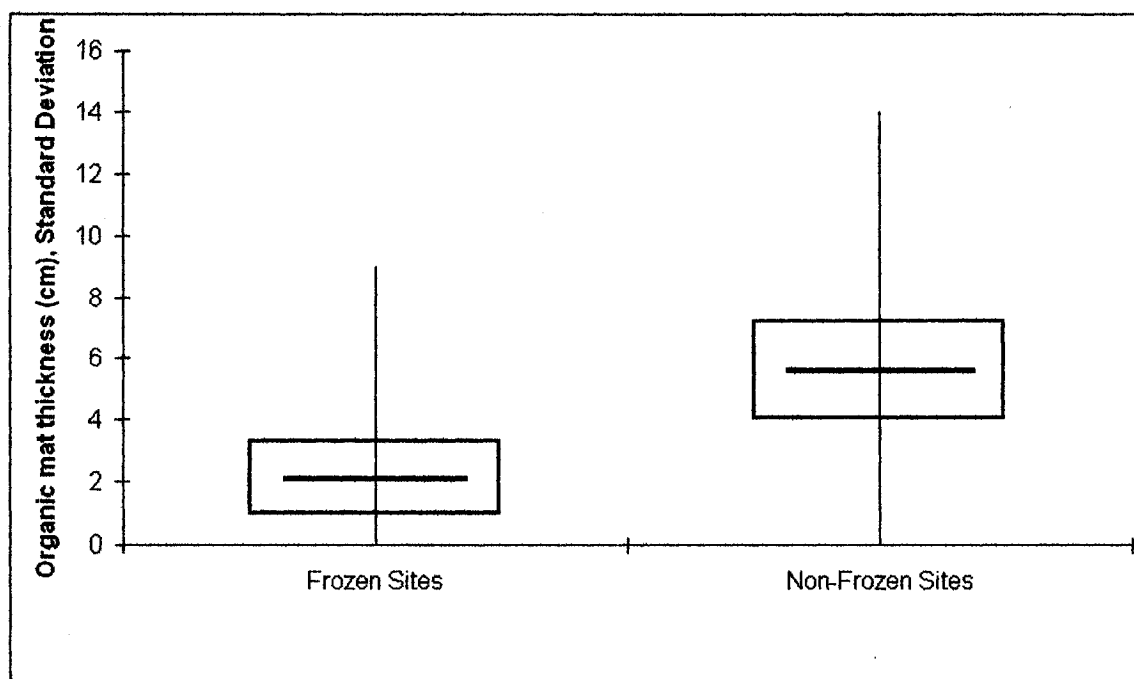


Figure 37: Graph illustrating the organic mat thickness at frozen and non frozen sites in Haines Summit. Horizontal lines represent elevation means, vertical lines represent the highest and lowest elevations of each category, and open boxes represent plus or minus one standard error.

From the data collected for the Haines Summit area, there appears to be either an inverse relationship between organic mat thicknesses and the presence of permafrost or no relationship at all. The Haines Summit area displays very different vegetation conditions than that of the Ruby Range. Lower parts of the Ruby Range are predominantly covered by boreal forest and elevation-induced tundra exists above 1500 m. In contrast, lower parts of Haines Summit are covered with shrubs and grasses with tundra at higher elevations studied. In terms of organic mat, the shrub-covered areas without permafrost have thicker organic mats on average, whereas high elevations are mostly associated with thin lichen cover or exposed rock surfaces (Figure 38). Given these patterns, organic mat thickness does not discriminate between permafrost and non-permafrost sites.

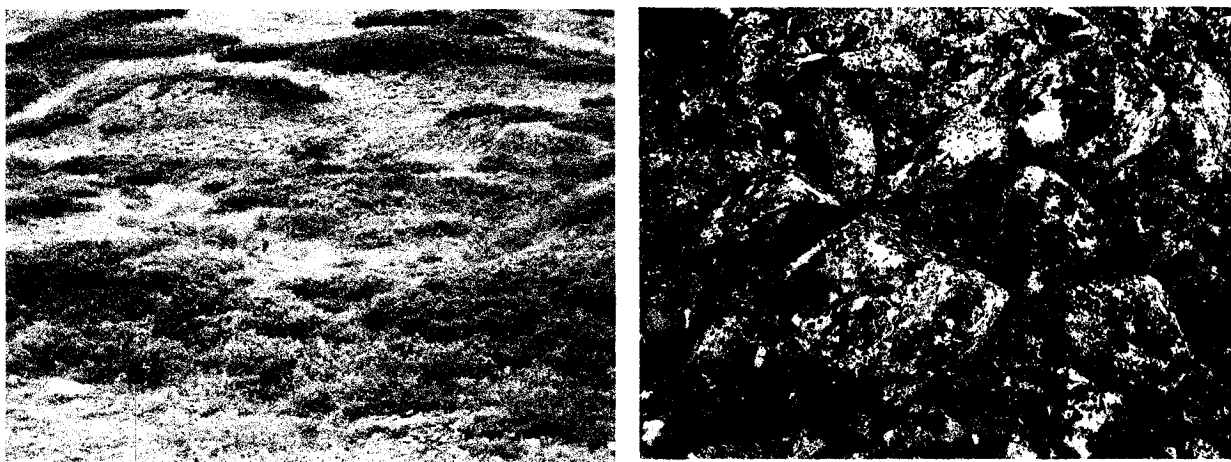


Figure 38: Photos of the Haines Summit area illustrating the difference in tundra vegetation between high elevation sites and low elevation sites. The left photo shows dense shrubs at an elevation of 950 m whereas the right photo shows a much rockier and less vegetation-rich terrain at 1250 m.

Section 5.7: Permafrost Probability Predicted by Logistic Regression for Haines Summit

The probability of permafrost was calculated using the modeled BTS information from both linear models in Haines Summit, utilizing the same methodology as for the Ruby Range (section 5.5).

Two logistic models were created using the information collected from the late-summer observation of frozen ground and both the modeled BTS values using the single and multiple independent variable approaches. The results of the logistic regression using the single independent variable approach yielded a model entitled LM-HS1 with the following Y coefficient:

$$Y = -12.2 - 5.8 (\text{single independent variable MBTS}) \quad (9)$$

The result of the Y term is then substituted into the probability equation and calculated for the entire area. The following table was generated from the results of the logistic model:

LM-HS1	β Coefficient	Standard Error	Wald Statistic	Degrees of Freedom	Significance
Constant	-12.2	2.38	26.1	1	< 0.01
MBTS	-5.8	1.17	24.6	1	< 0.01

Table 9: Summary of coefficients in the logistic model for Haines Summit LM-HS1

Both of the β coefficients are considered significant at the 99% confidence level and allow for the generation of a permafrost probability curve (Figure 39).

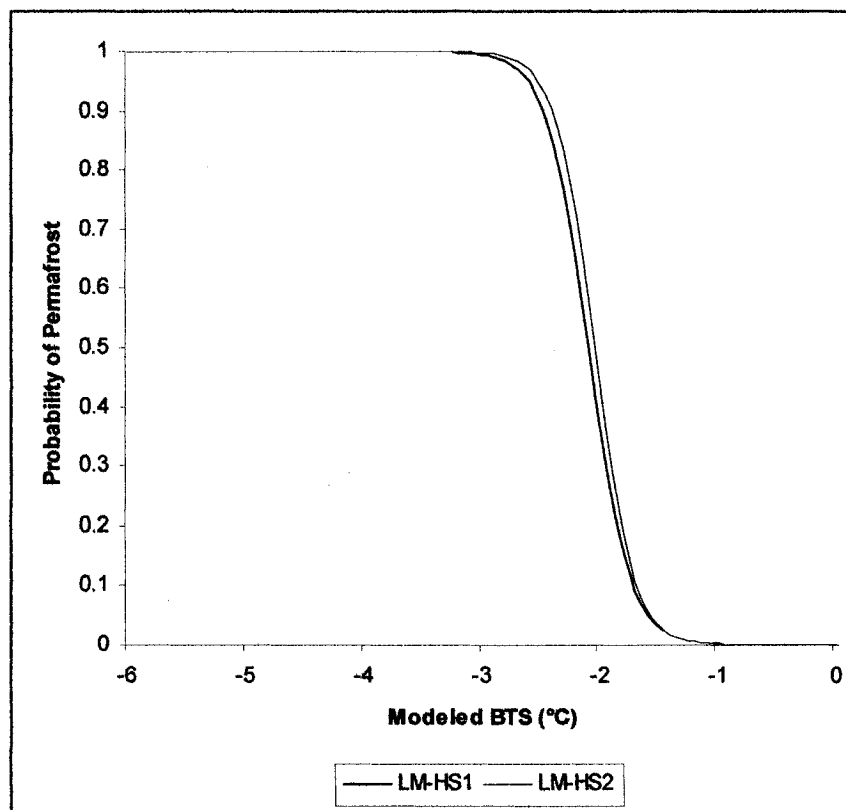


Figure 39: Permafrost probability curve for the logistic regression model LM-HS1 and LM-HS2 for Haines Summit.

Using the surface of modeled BTS created using both elevation and PISR as independent variables, a second logistic regression model for Haines Summit titled LM-HS2 was developed. LM-HS2 yielded the following slightly different coefficients and equation:

$$Y = -12.65 - 6.2 (\text{double independent variable MBTS}) \quad (10)$$

LM-HS2	β Coefficient	Standard Error	Wald Statistic	Degrees of Freedom	Significance
Constant	-12.65	2.6	23.1	1	< 0.01
MBTS	-6.2	1.3	22.2	1	< 0.01

Table 10: Summary of coefficients in the logistic model for Haines Summit LM-HS2

Both of the β coefficients are considered significant at the 99% confidence level and allow for the generation of a permafrost probability curve (see Figure 39).

Examination of the logistic model LM-HS1 shows a very steep curve changing from a very low probability of permafrost between 0 °C and -1 °C to a probability close to 100% at -3 °C. LM-HS1 reaches a value of 0.1 at -1.7 °C classifying warmer modeled BTS values as areas of isolated patches of permafrost. A value of 0.5 is seen at a modeled BTS value of -2.1 °C with a value of 0.9 occurring at -2.5 °C. According to Heginbottom et. al 1995, this would classify modeled BTS values from -1.7 °C to -2.1 °C as sporadic discontinuous permafrost, values ranging from -2.1 °C to -2.5 °C as widespread discontinuous permafrost and values < -2.5 °C as continuous permafrost. The logistic model LM-HS2 generated very similar classification thresholds.

An identical test of accuracy for the logistic regression models (LM-HS1 and LM-HS2) was completed as seen for the Ruby Range in section 5.5. Due to the fact that modeled BTS temperatures for the pits at Haines Summit occurred over a much smaller range (0 to -3 °C) categories were separated by 0.5 °C intervals rather than 1 °C intervals. The results of the analysis for LM-HS1 can be seen in Table 11 and Figure 40.

LM-HS1	0	-0.5	-1	-1.5	-2	-2.5	-3
Number of Pits	0	0	32	33	17	13	0
Number of Pits with PF	0	0	0	0	10	13	0
% of PF	0	0	0	0	58.8	100	0
Range of Probabilities from Logistic Model (%)	0.0005 – 0.009	0.009 – 0.17	0.17 – 3.03	3.03 – 36.1	36.1 – 91.1	91.1 – 99.46	99.46 – 99.97

Table 11: A tabular comparison between the percentage of permafrost detected from ground truthing and the probability determined by the logistic model (LM-HS1). Note the categories labelled above include the full range of the value (i.e. -1 = -1 to -1.4,999 °C).

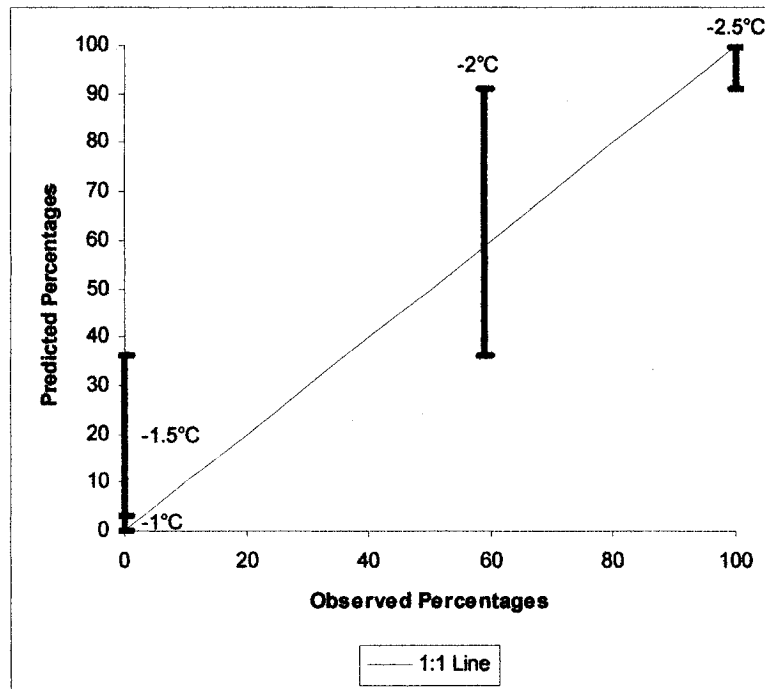


Figure 40: Graph showing observed permafrost percentages versus predicted permafrost probabilities according to LM-HS1.

The results of the analysis for LM-HS2 can be seen in Table 12 and Figure 41.

LM-HS2	0	-0.5	-1	-1.5	-2	-2.5	-3
Number of Pits	0	4	37	24	16	13	1
Number of Pits with PF	0	0	0	0	9	13	1
% of PF	0	0	0	0	56.3	100	100
Range of Probabilities from Logistic Model (%)	0.0003 – 0.007	0.007 – 0.15	0.15 – 3.30	3.30 – 43.3	43.3 – 94.4	94.4 – 99.7	99.7 – 99.98

Table 12: A tabular comparison between the percentage of permafrost detected from ground truthing and the probability determined by the logistic model (LM-HS2). Note the categories labelled above include the full range of the value (e.g. -1 = -1 to -1.4.999 °C).

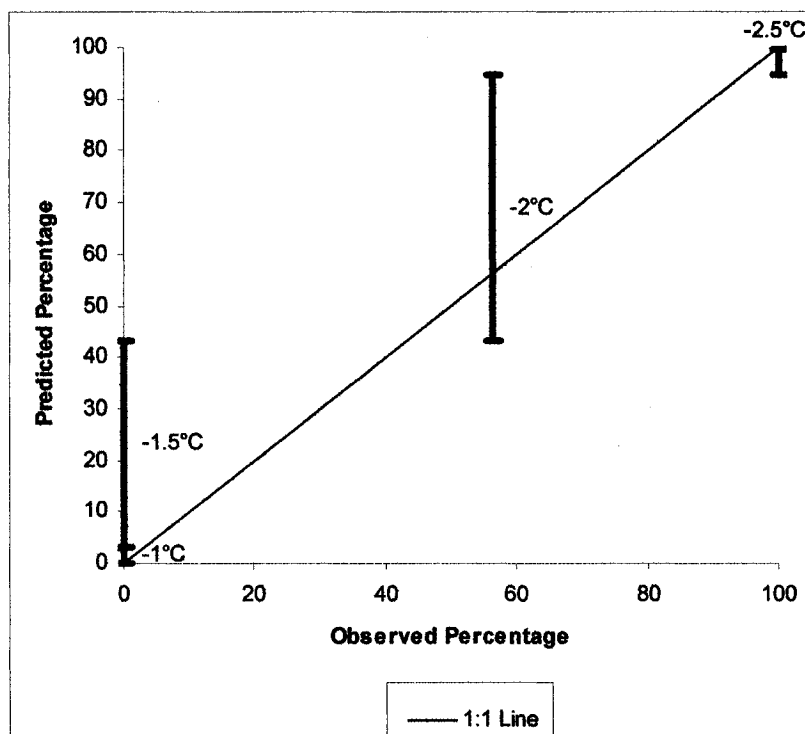


Figure 41: Graph showing observed permafrost percentages versus predicted permafrost probabilities according to LM-HS2.

Using the raster calculator in ArcGIS the logistic regression models LM-HS1 and LM-HS2 were used to produce surfaces of permafrost probabilities for Haines Summit (Figures 42 and 43). LM-HS1 generated permafrost probabilities ranging from <0.01 to

>0.99 with a mean probability of 0.43 for the study area. The LM-HS1 permafrost probability map shows a rapid transition in the probability of permafrost between low lying areas to mountain peaks. Probability values displayed in this map parallel the contour lines as a result of the single variable modeled BTS. The LM-HS2 logistic model has a similar mean probability of 0.44 but shows a more complex transition between high probability permafrost areas and low probability permafrost areas (Figure 43). This transition is best-developed in areas of south facing aspect where PISR has the maximum influence.

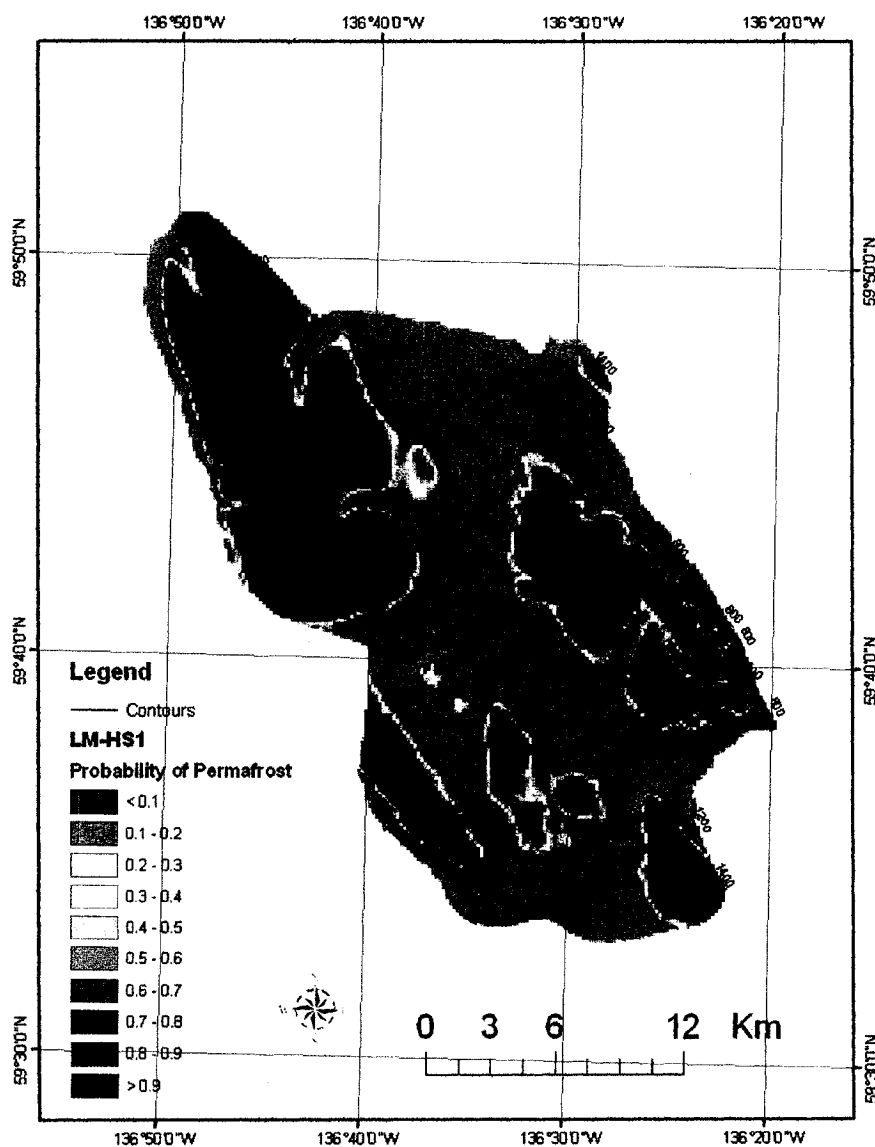


Figure 42: Map of Permafrost Probability for Haines Summit created from LM-HS1 (equation 9). Contour interval is 200 m.

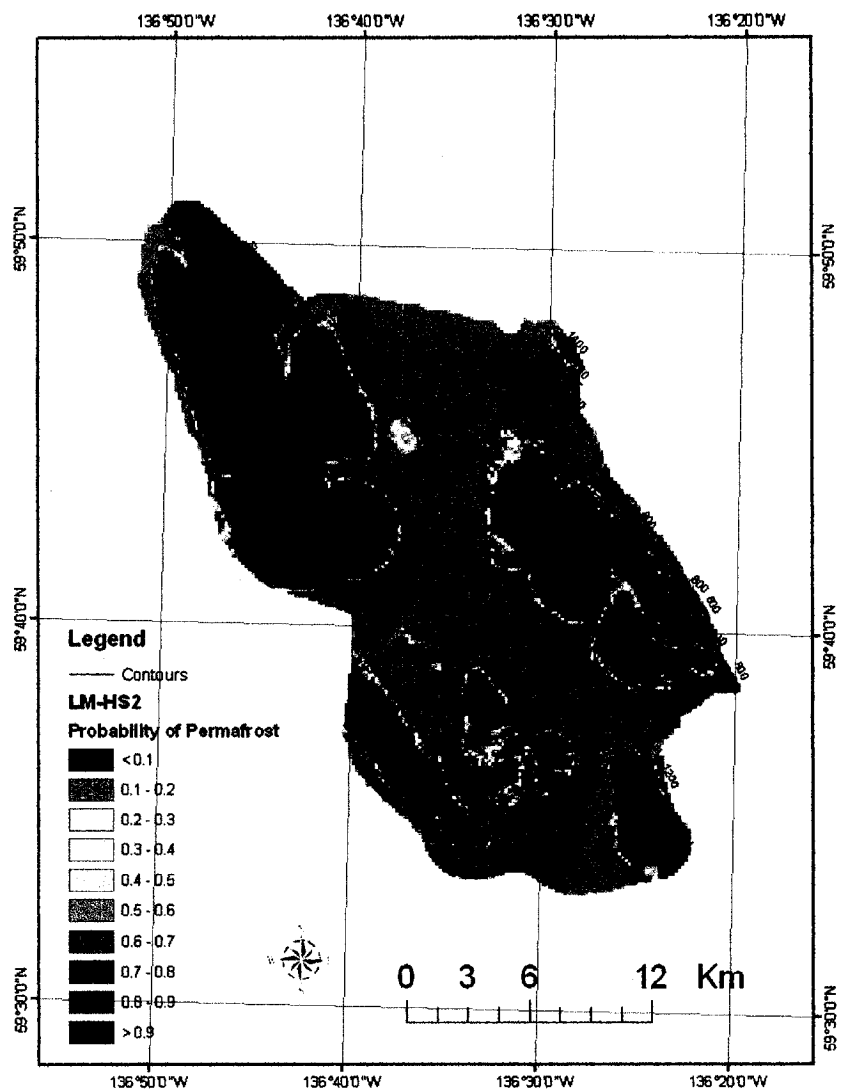


Figure 43: Map of Permafrost Probability for Haines Summit created from LM-HS2 (equation 10). Contour interval is 200 m.

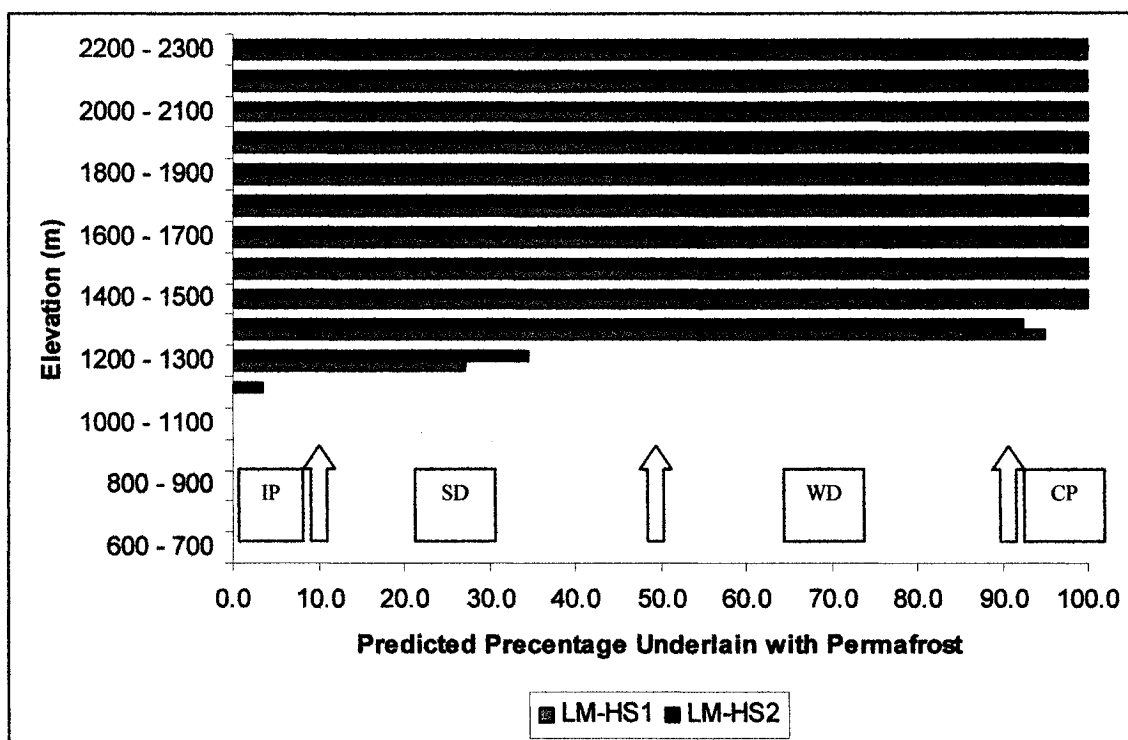


Figure 44: Graph illustrating the predicted percentage area underlain by permafrost by 100 m elevation bands in Haines Summit using the permafrost probability models LM-HS1 and LM-HS2. Areas within the box “IP” represent isolated patches of permafrost (<10%), “SD” represents sporadic discontinuous permafrost (10 – 50%), “WD” represents widespread discontinuous permafrost (50 – 90%) and “CP” represents continuous permafrost.

Predicted permafrost extent at Haines Summit increases dramatically with elevation and effectively becomes 100 % in both models in the 1400 - 1500 m elevation band. The models predict relatively similar values within the elevation bands, but LM-HS2 suggests the existence of permafrost at slightly lower elevations, including the 1100 – 1200 m band.

The Haines Summit study area is approximately 536 km² and ranges in elevation from 600 – 2300 m. A total of 230 km² of the area or 43 % is predicted to be underlain with permafrost according to LM-HS1. LM-HS2 classified a total of 236 km² as permafrost, representing 44 % of the study area.

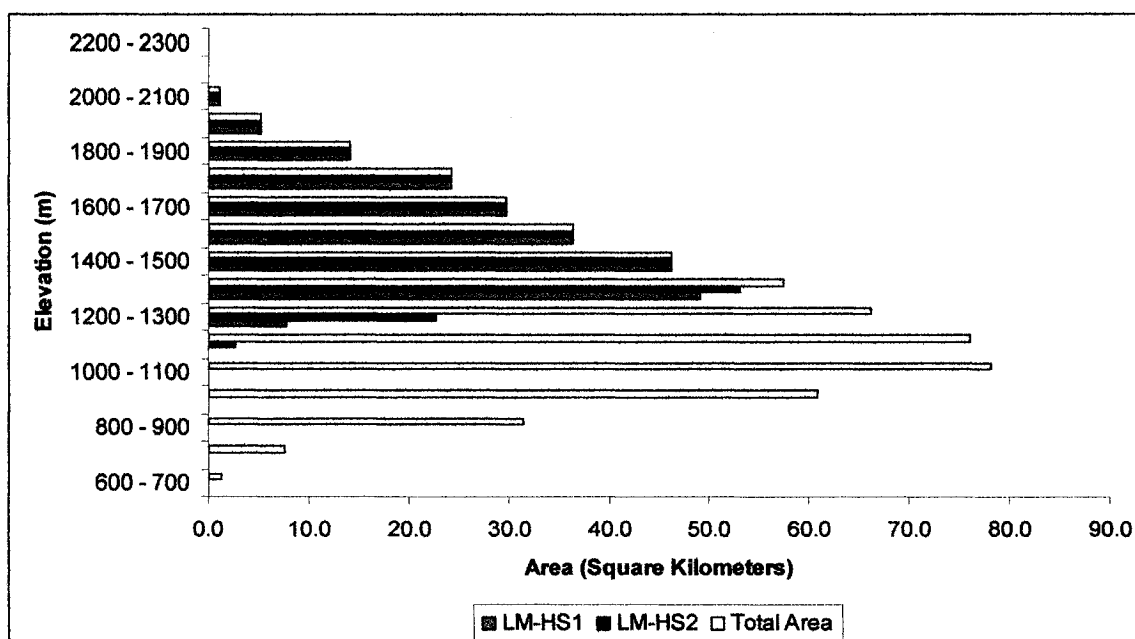


Figure 45: Graph illustrating the amount of area in each elevation band underlain with permafrost for LM-HS1 and LM-HS2 versus the total area in that elevation class.

Section 6.0 Discussion:**Section 6.1 Cold Air Drainage:**

In the description of expanded methodology (section 4.1) step 6 describes a methodology to determine whether cold air drainage is occurring in the two study areas. The existence of atmospheric temperature inversions in Wolf Creek presented a modeling problem for Lewkowicz and Ednie (2004) because in certain valley bottom locations more pits contained permafrost than the prediction of the linear model. Cold air drainage in certain locations in the Wolf Creek Basin violated the assumption that the presence of permafrost can be linearly related to elevation. The result of this issue forced a second model to be created dealing specifically with valley bottom locations. It is thus important to determine whether issues such as that of cold air drainage exist in the new study areas. In order to examine this issue, valley bottom points were identified on a graph of BTS versus modeled BTS to determine if any clustering existed (Figure 46). The valley-bottom points did not exhibit a tendency to lie above or below the 1:1 line or the best fit lines. Consequently, this data-set does not suggest major cold-air drainage impacts.

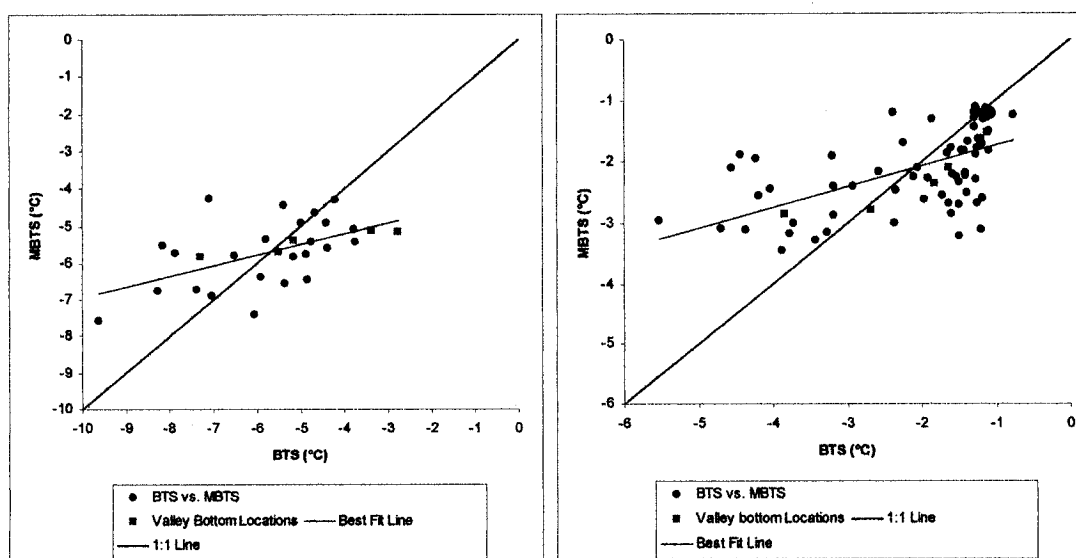


Figure 46: Graphs for the Ruby Range (left) and Haines Summit (right) illustrating valley bottom locations in order to examine whether cold air drainage is significantly present in these study areas. Data is presented in a scatter plot of BTS vs. MBTS.

Section 6.2 Micro-scale Variability in Permafrost Distribution:

Although elevation and PISR were considered the two leading factors contributing to the existence of permafrost at a given location, additional factors may be significant. One of these factors is the depth of winter snow cover. Snow is an excellent insulator that minimizes the effects of cold winter temperatures on the ground (Ishikawa and Sawagaki, 2001). The thermal characteristics of the snow, snow amount and time of arrival in the fall can all affect whether permafrost will be present or absent and therefore what BTS results will be observed (Brenning et al., 2005).

One of the drawbacks of the BTS method is that sampling can only take place in > 80 cm of snow. In the Haines Summit study area this was not an issue whereas in the Ruby Range a lack of snow greatly constrained the accessible sampling area in 2006 and prevented all sampling in 2005. Low-snow areas, especially wind-swept crests at high

elevations are much more likely to develop permafrost due to relatively direct heat exchange between the ground and extremely cold winter air. Although these areas are likely to be permafrost sites, they cannot be sampled in the winter.

Differentiation between potentially high and low snow sites was accomplished during the late-summer observation of frozen ground. During this period all ground truthing locations were categorized into concave, convex slopes, or "other". Concave areas may act as accumulation sites for fallen and wind-blown snow, whereas convex areas likely promote wind scouring and the redistribution of snow. An attempt to collect ground truthing measurements in close proximity to one another with opposite characteristics was made. However, due to logistical difficulties and unsuitable ground truthing locations, the micro variability idea could not be tested. All sites were, however, still assessed, allowing for a large-scale comparative study of concavity and elevation.

Of the 85 excavated pits in the Ruby Range, 30 were classified as concave with 47 convex locations and 8 displaying no tendency toward either. The type of classification assigned to each location was then compared to others at similar elevations in order to see if any trend existed with respect to the presence or absence of permafrost.

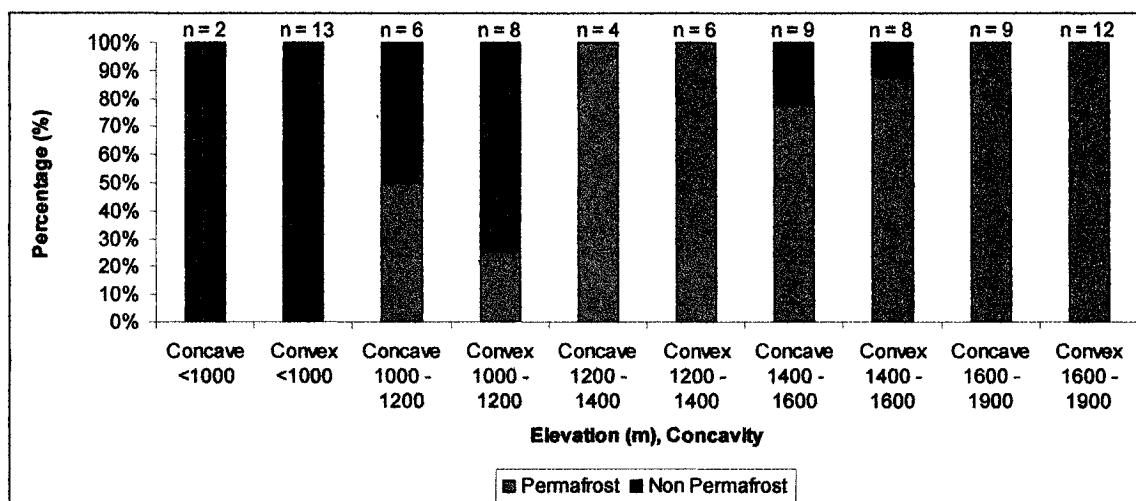


Figure 47: Graph illustrating the percentage of concave and convex pits containing permafrost at specified elevations for the Ruby Range.

Slope classifications were examined at different elevation bands including below 1000 m, 1000 – 1200 m, 1200 – 1400 m, 1400 – 1600 m and 1600 – 1900. The results can be seen in Figure 47. The pits in the elevation bands of 1200 – 1400 m and 1600 – 1900 m were of limited use since all contained permafrost whereas none of the pits below 1000 m contained permafrost. Of the remaining elevation bands the 1000 – 1200 m band contained 14 pits mostly located in boreal forest. 50 percent of the concave pits contained permafrost whereas only 25 percent of the convex pits contained permafrost. These results would not be expected if relationships between concavity / convexity and snow depth were simple. However, vegetation in the area is complex and although surfaces are convex, thick shrubs and or trees still allow snow to be trapped. In the 1400 – 1600 m elevation band a total of 17 sites were excavated, of which 77 % of the concave sites and 88 % of convex sites exhibited permafrost. It is possible that the assumption regarding snow depth has greater merit in this elevation band as vegetation is less complex and wind scouring is maximized. However, the difference is very slight.

Logistic models were created for the Ruby Range from the concave and convex data. The models were titled LM-RRcave (Table 13) and LM-RRvex (Table 14) and generated the following equations respectively:

$$Y = -7.0 - 1.8 (\text{MBTS}) \quad (11)$$

$$Y = -4.5 - 1.0 (\text{MBTS}) \quad (12)$$

LM-RRcave	β Coefficient	Standard Error	Wald Statistic	Degrees of Freedom	Significance
Constant	-7.0	3.1	5.1	1	< 0.01
MBTS	-1.8	0.7	6.6	1	< 0.01

Table 13: Summary of coefficients in the logistic model for the Ruby Range LM-RRcave.

LM-RRvex	β Coefficient	Standard Error	Wald Statistic	Degrees of Freedom	Significance
Constant	-4.5	1.32	11.6	1	< 0.01
MBTS	-1.0	0.27	13.7	1	< 0.01

Table 14: Summary of coefficients in the logistic model for the Ruby Range LM-RRvex.

All β coefficients are considered significant at the 99% confidence level and allow for the generation of permafrost probability curves (Figure 48).

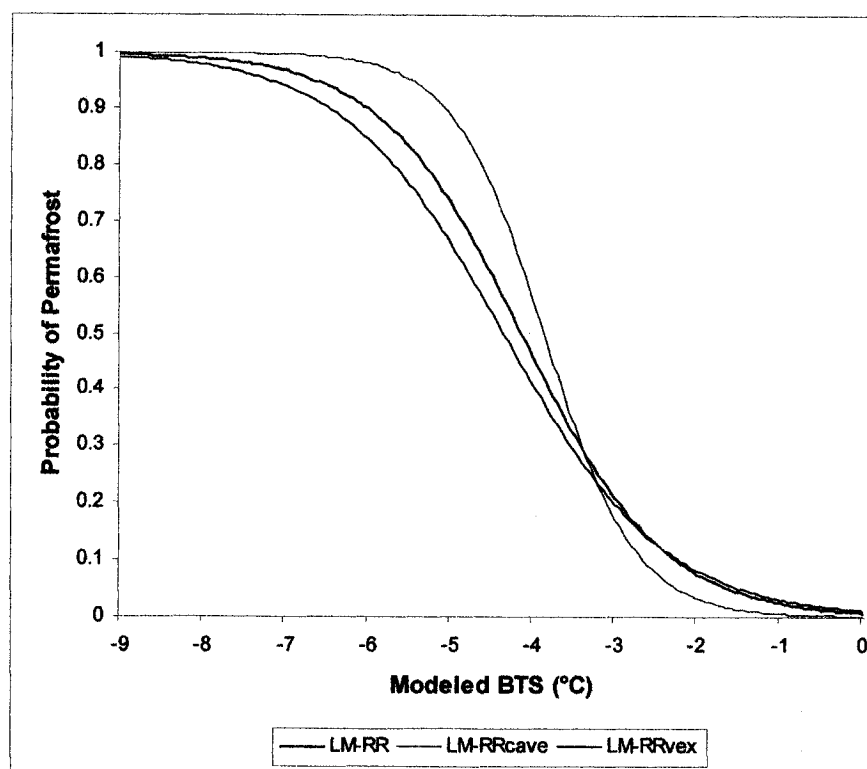


Figure 48: Permafrost probability curves for the logistic regression models LM-RR, LM-RRcave potentially representing deep snow locations and LM-RRvex potentially representing shallow snow locations for the Ruby Range.

Table 15 highlights the different permafrost zones and at what temperature ranges they occur in each model.

Model	Isolated Patches	Sporadic Discontinuous	Widespread Discontinuous	Continuous
LM-RR	$> -2.3^{\circ}\text{C}$	-2.3°C to -4.15°C	-4.15°C to -6°C	$< -6^{\circ}\text{C}$
LM-RRcave	$> -2.7^{\circ}\text{C}$	-2.7°C to -3.9°C	-3.9°C to -5.1°C	$< -5.1^{\circ}\text{C}$
LM-RRvex	$> -2.3^{\circ}\text{C}$	-2.3°C to -4.4°C	-4.4°C to -6.5°C	$< -6.5^{\circ}\text{C}$

Table 15: Predicted BTS temperatures for labelled permafrost zones according to models LM-RR, LM-RRcave and LM-RRvex for the Ruby Range.

Using the raster calculator in ArcGIS the logistic regression model LM-RRcave was used to produce a surface of permafrost probabilities for the Ruby Range (Figure 49).

LM-RRcave generated permafrost probabilities ranging from 0.02 to 1.0 for the study area with a mean probability of 0.7. The major difference in the results from this model opposed to LM-RR (see Figure 32) is that there is a much larger area with probability <0.1. It is important to note that the mean probability is slightly higher in this model than in the original.

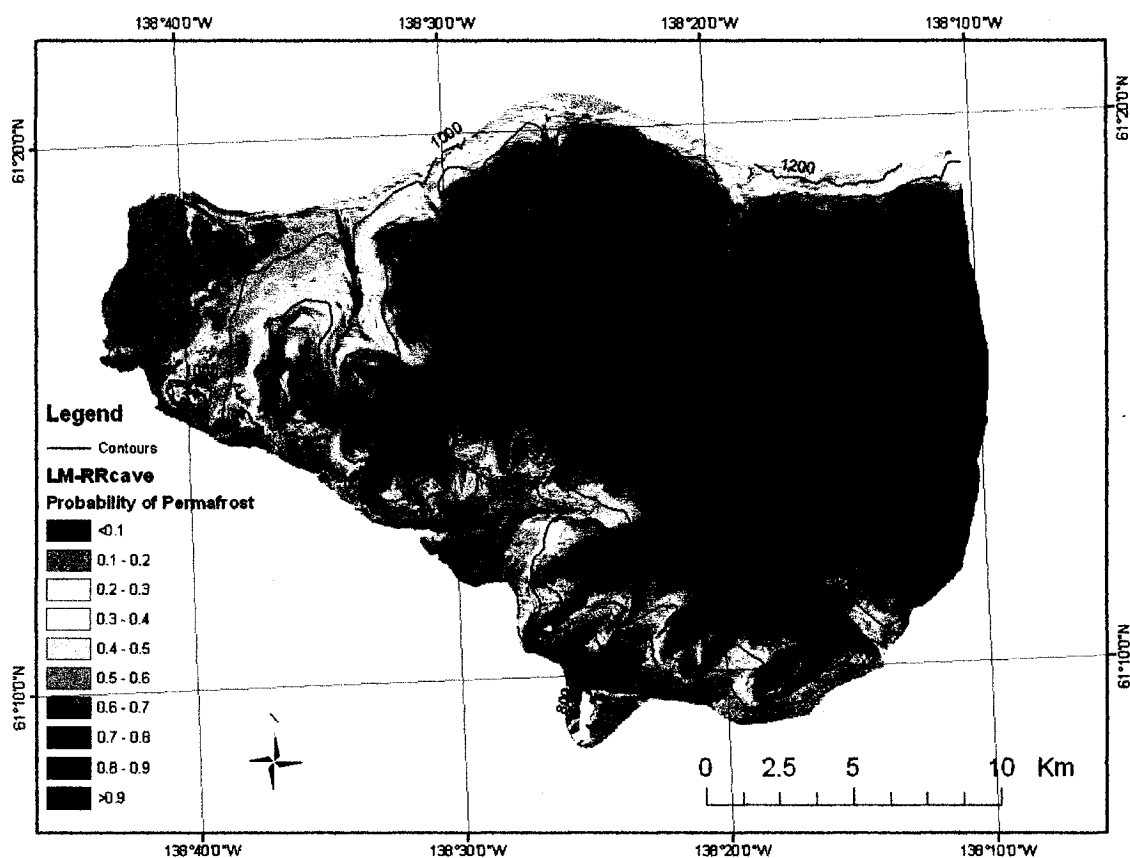


Figure 49: Map of Permafrost Probability for the Ruby Range created from LM-RRcave (equation 11).

The information in Figure 49 can be converted into units of percentage and area in order to fully understand the dimensions of permafrost in the Ruby Range under a potentially deep snow model. Using ArcGIS, elevation zones in the study area were reclassified with Zonal statistics applied to the re-classed grid in the same manner as LM-RR (Figure 50).

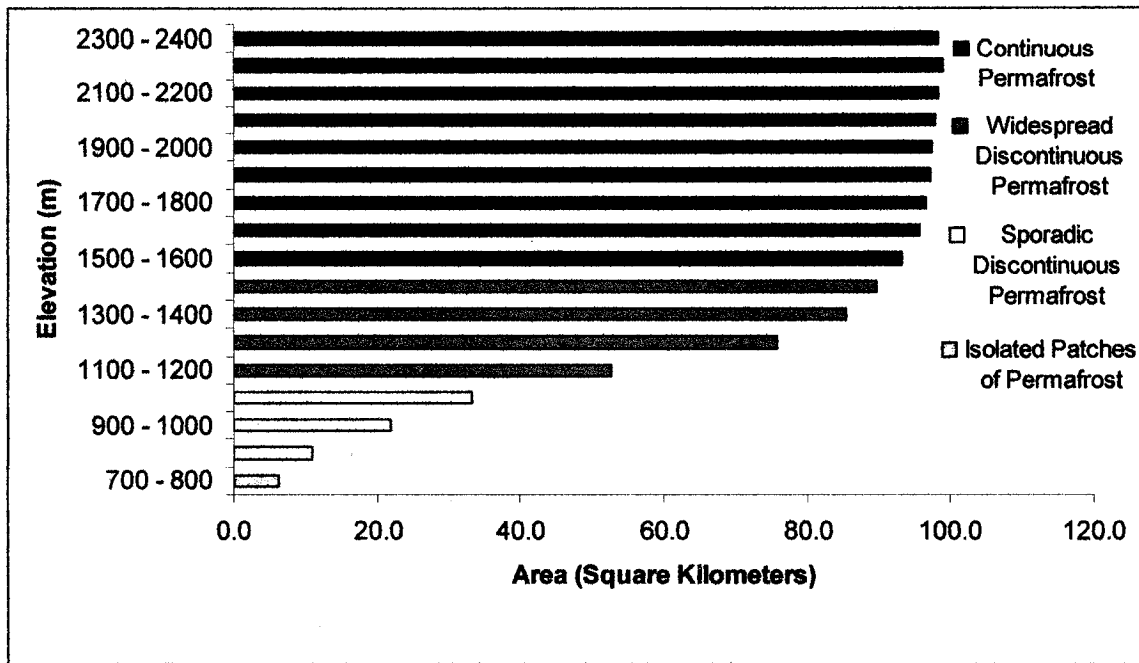


Figure 50: Graph illustrating the predicted percentage of area underlain by permafrost at each 100 m elevation band in the Ruby Range based on LM-RRcave (equation 11).

Permafrost percentage in the Ruby Range under LM-RRcave reaches a maximum of 95 % in the 2200 – 2300 m elevation band. Using a conventional permafrost classification according to Heginbottom et al. (1995), elevations of 700 – 800 m fit into the isolated patches of permafrost (< 10%). Sporadic discontinuous permafrost (10 – 50% permafrost), occurs in the elevation bands of 800 – 1100 m, with widespread discontinuous permafrost (50 – 90% permafrost) spanning from 1100 – 1500 m. All elevations above 1500 m should be continuous permafrost (>90% permafrost).

A total of 300 km² of the area or 71 % is underlain by permafrost according to LM-RRcave (Figure 51). This model marginally increases the total amount of permafrost in the Ruby Range. However, it is important to note that the lowest elevation bands (700 – 1000 m) saw decreased amounts of permafrost under LM-RRcave.

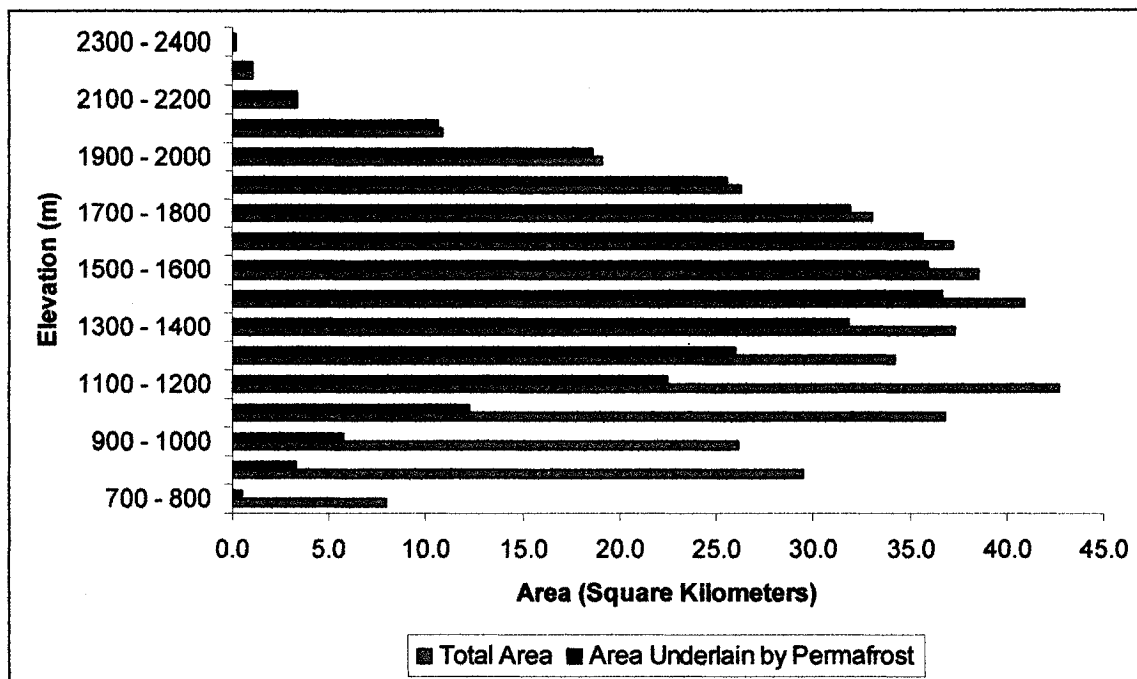


Figure 51: Graph illustrating the amount of area in each elevation band underlain by permafrost versus the total area in that elevation class for the Ruby Range under LM-RRcave (equation 11).

Using the raster calculator in ArcGIS the logistic regression model LM-RRvex was used to produce a surface of permafrost probabilities for the Ruby Range (Figure 52). LM-RRvex generated permafrost probabilities ranging from 0.06 to 1.0 for the study area with a mean probability of 0.6.

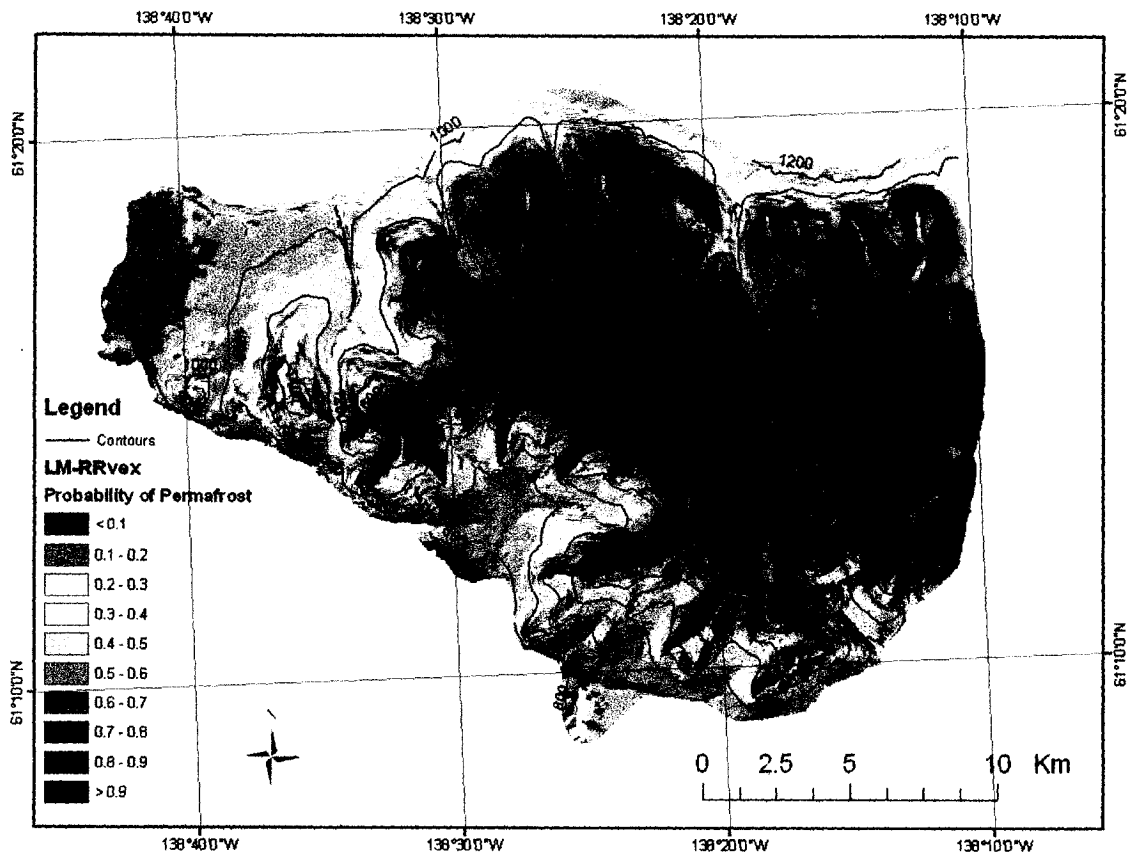


Figure 52: Map of Permafrost Probability for the Ruby Range created from LM-RRvex (equation 12).

LM-RRvex predicts virtually identical permafrost probabilities to LM-RR for values between 0 – 0.4, with slightly lower probabilities between 0.4 and 1. The largest difference between LM-RRvex and the two other models is that the area underlain by permafrost is less. LM-RRvex predicts a total of 255 km² or 60%, 6% less than LM-RR and 10% lower than LM-RRcave.

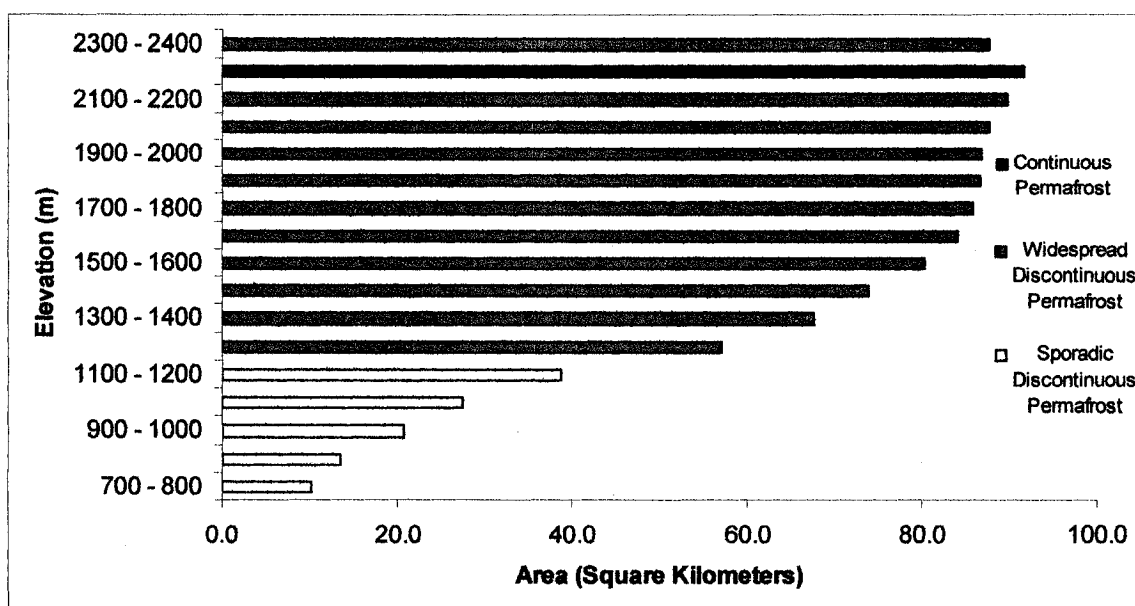


Figure 53: Graph illustrating the predicted percentage of area underlain by permafrost at each 100 m elevation band in the Ruby Range based on LM-RRvex (equation 11).

Another significant difference concerns the classification of permafrost zones according to LM-RRvex. The 2200 – 2300 m elevation band is the only one considered to be continuous permafrost (Figure 53). Elevations ranging from 700 – 1200 m are considered part of the sporadic discontinuous permafrost zone with all remaining elevations with the exception of (2200 – 2300) viewed as widespread discontinuous permafrost.

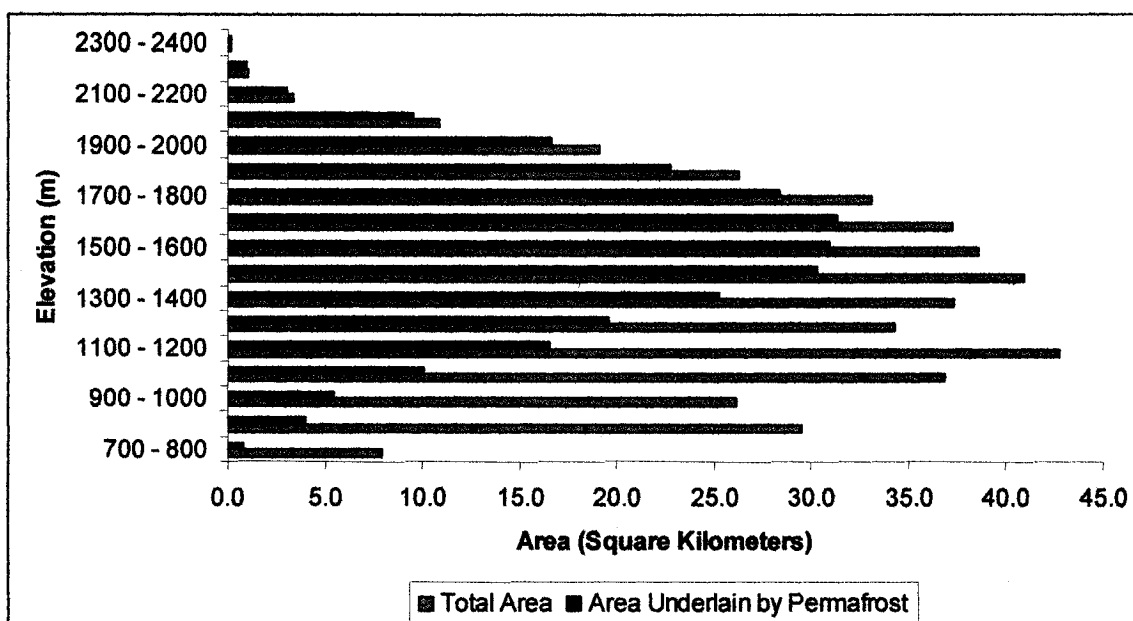


Figure 54: Graph illustrating the amount of area in each elevation band underlain by permafrost versus the total area in that elevation class for the Ruby Range under LM-RRcave (equation 10).

The results of LM-RRcave and LM-RRvex would suggest that should the study area be covered in deep snow, permafrost extent would be increased by 4 % relative to actual conditions. This result is contrary to our understanding of the impact of snow and may be due to confounding effects by vegetation, especially near to or below tree-line. In other words, LM-RRcave does not necessarily represent high snow conditions, but rather concave slope segments, some of which may possess deep snow while others may not.

In Haines Summit a total of 95 pits were excavated, 29 categorized as concave, 63 as convex and 3 displayed no tendency towards either. The type of classification assigned to each location was then compared with elevation (Figure 55) in an identical way to the Ruby Range analysis.

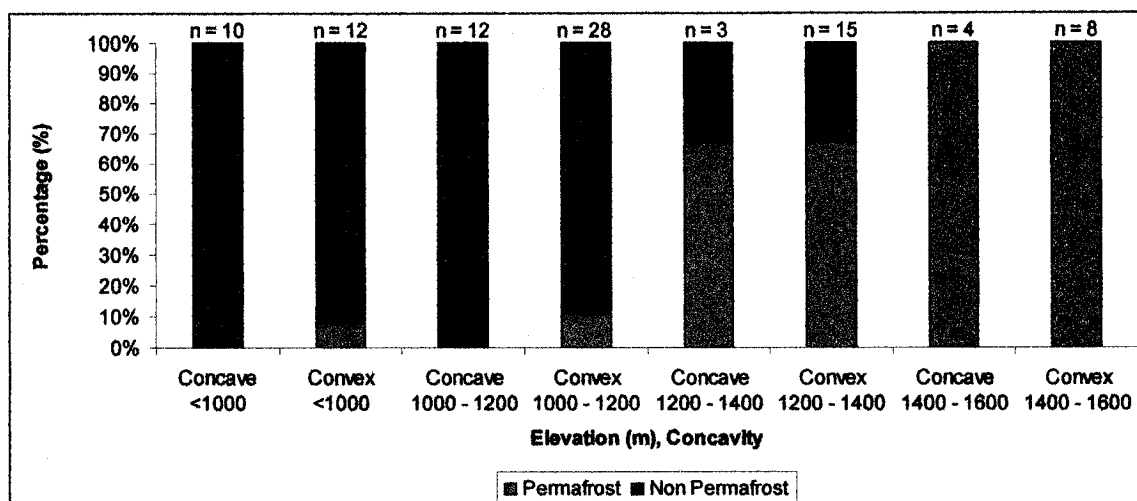


Figure 55: Graph illustrating the percentage of concave and convex pits containing permafrost at specified elevations for Haines Summit.

The analysis of slope classification and elevation was completed using the same elevation bands as for the Ruby Range. The results support the assumptions made regarding slope classification, snow depth and the presence of permafrost. It is likely that slope concavity / convexity has an effect in determining the presence of permafrost in Haines Summit because of the area's shrubs and tundra vegetation. In the Ruby Range, slope classification was most significant in the uppermost elevation bands where tundra conditions prevailed. In tundra areas, vegetation grows closer to the ground, and when covered by snow, this creates a smooth surface which promotes wind scouring and snow redistribution. With such a large amount of the Haines Summit study area classified as tundra this creates a possible explanation as to why slope classification is more significant to the existence of permafrost than in the Ruby Range.

Logistic models were created for Haines Summit from the concave and convex data. The models were entitled LM-HScave and LM-HSvex (Tables 16 and 17) which generated the following equations respectively:

$$Y = -9.4 - 4.5 (\text{MBTS}) \quad (13)$$

$$Y = -14.5 - 6.8 (\text{MBTS}) \quad (14)$$

LM-RRcave	β Coefficient	Standard Error	Wald Statistic	Degrees of Freedom	Significance
Constant	-9.4	3.0	9.8	1	< 0.01
MBTS	-4.5	1.6	7.9	1	< 0.01

Table 16: Summary of coefficients in the logistic model for Haines Summit LM-HScave.

LM-RRvex	β Coefficient	Standard Error	Wald Statistic	Degrees of Freedom	Significance
Constant	-14.5	3.65	15.8	1	< 0.01
MBTS	-6.8	1.8	14.3	1	< 0.01

Table 17: Summary of coefficients in the logistic model for Haines Summit LM-HSvex.

All β coefficients are considered significant at the 99% confidence level and allow for the generation of permafrost probability curves (Figure 56).

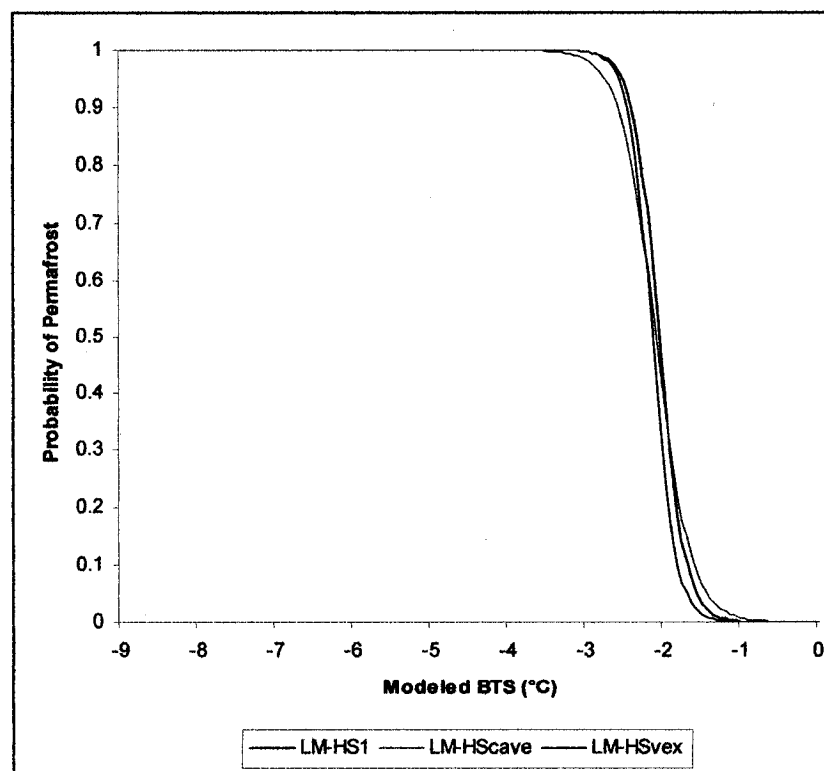


Figure 56: Permafrost probability curves for the logistic regression models LM-HS1, LM-HScave and LM-HSvex for Haines Summit.

Table 18 highlights the different permafrost zones and at what temperature ranges they occur in each model.

Model	Isolated Patches	Sporadic Discontinuous	Widespread Discontinuous	Continuous
LM-HS1	>-1.7 °C	-1.7 °C to -2.0 °C	-2.0 °C to -2.4 °C	< -2.4 °C
LM-HScave	>-1.6 °C	-1.6 °C to -2.1 °C	-2.1 °C to -2.6 °C	< -2.6 °C
LM-HSvex	>-1.8 °C	-1.8 °C to -2.1 °C	-2.1 °C to -2.5 °C	< -2.5 °C

Table 18: Predicted BTS temperatures for labelled permafrost zones according to models LM-HS1, LM-HScave and LM-HSvex for the Ruby Range.

Using the raster calculator in ArcGIS the logistic regression model LM-HScave was used to produce a surface of permafrost probabilities for Haines Summit (Figure 57). LM-HScave generated permafrost probabilities ranging from 0 to 1.0 for the study area with a mean probability of 0.5. The major difference in the results from this model compared to LM-HS is the presence of larger transitions zones from very low to very high probabilities of permafrost. It is important to note that although transition zones are more pronounced, the mean probability is slightly higher for this model than the original because decreases in probability at higher elevations are more than compensated by higher probabilities at lower elevations.

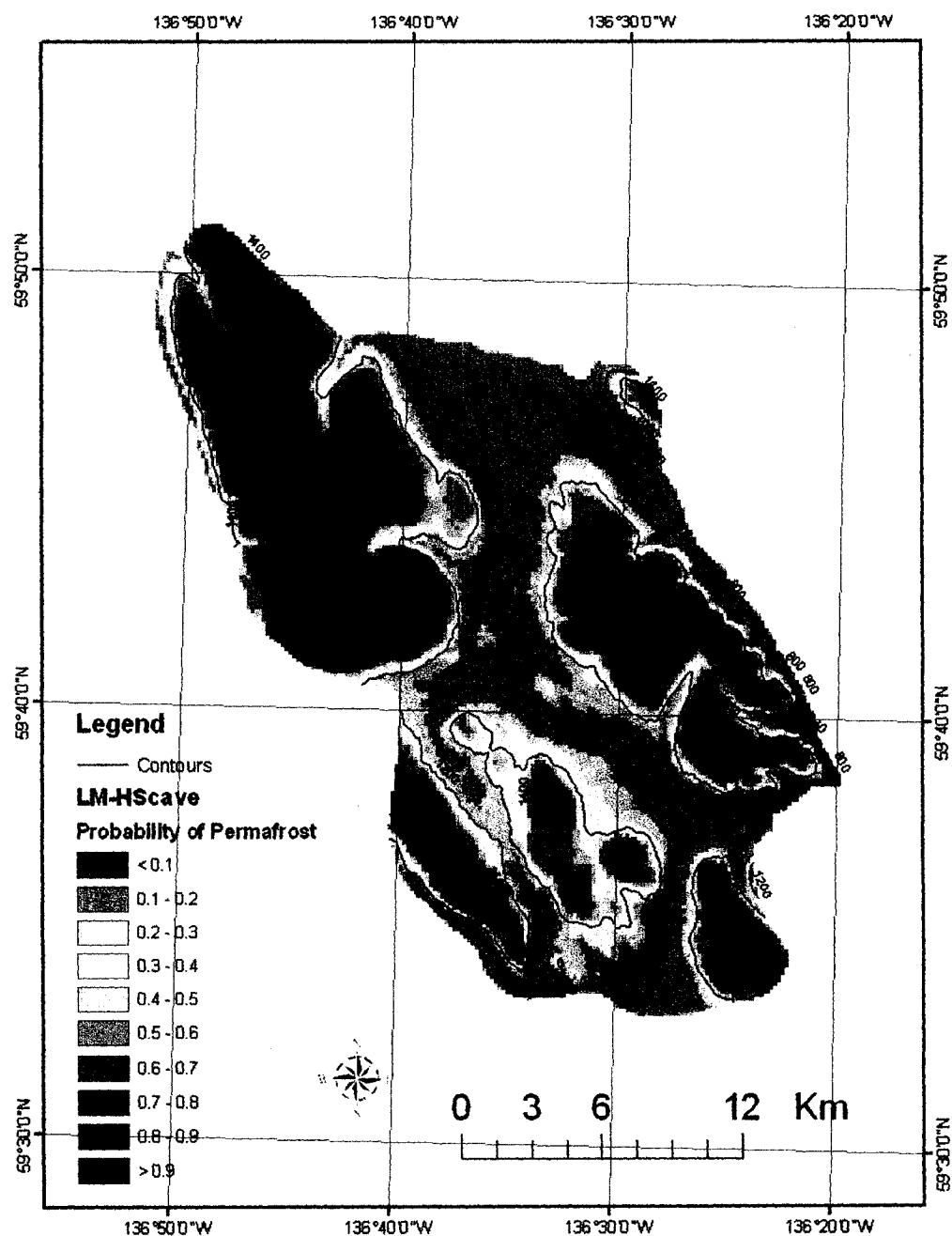


Figure 57: Map of Permafrost Probability for Haines Summit created from LM-HScave (equation 13).

The information in Figure 57 was converted into units of percentage and area.

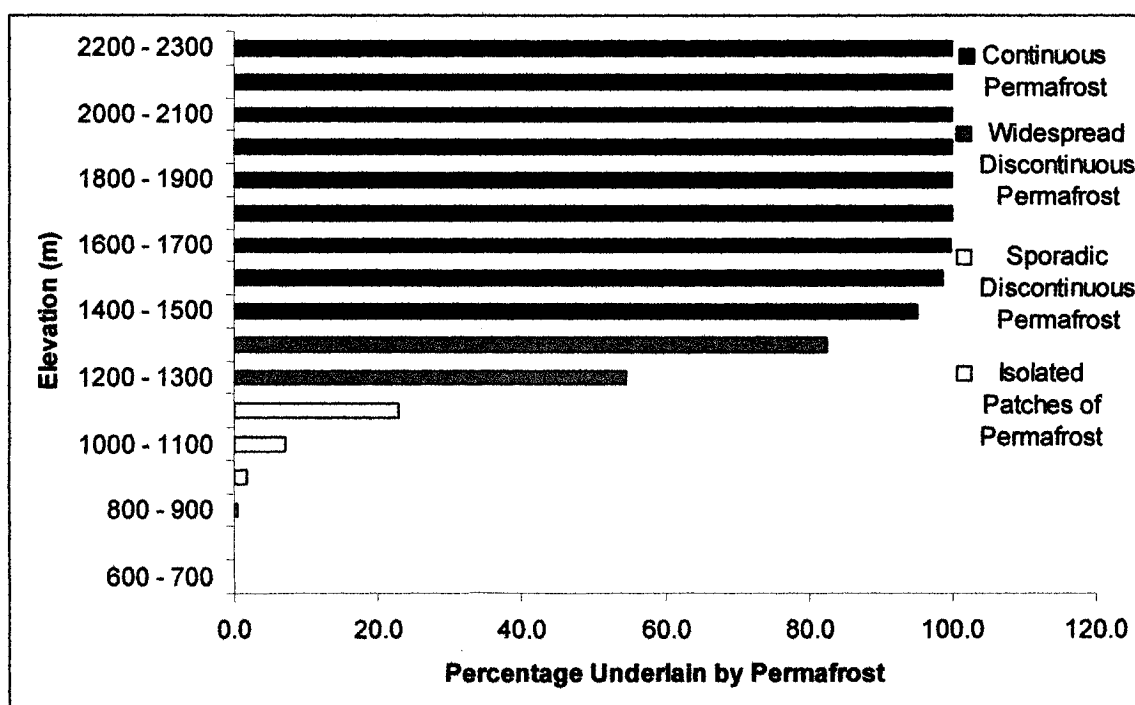


Figure 58: Graph illustrating the predicted percentage of area underlain by permafrost at each 100 m elevation band in Haines Summit based on LM-HScave (equation 13).

Permafrost percentage in Haines Summit under LM-HScave reaches a maximum of 100 % through 1800 – 2300 m elevation band. Using a conventional permafrost classification according to Heginbottom et al. (1995), elevations of 600 – 1100 m fit into the isolated patches of permafrost (< 10%) (Figure 58). The sporadic discontinuous permafrost (10 – 50% permafrost) occurs in the elevation bands of 1100 – 1200 m, with widespread discontinuous permafrost (50 – 90% permafrost) spanning from 1200 – 1400 m. All elevations above this are continuous permafrost (>90% permafrost).

A total of 260 km² of the area or 50 % is underlain by permafrost according to LM-HScave, (Figure 59) an increase of 7 % compared to LM-HS1.

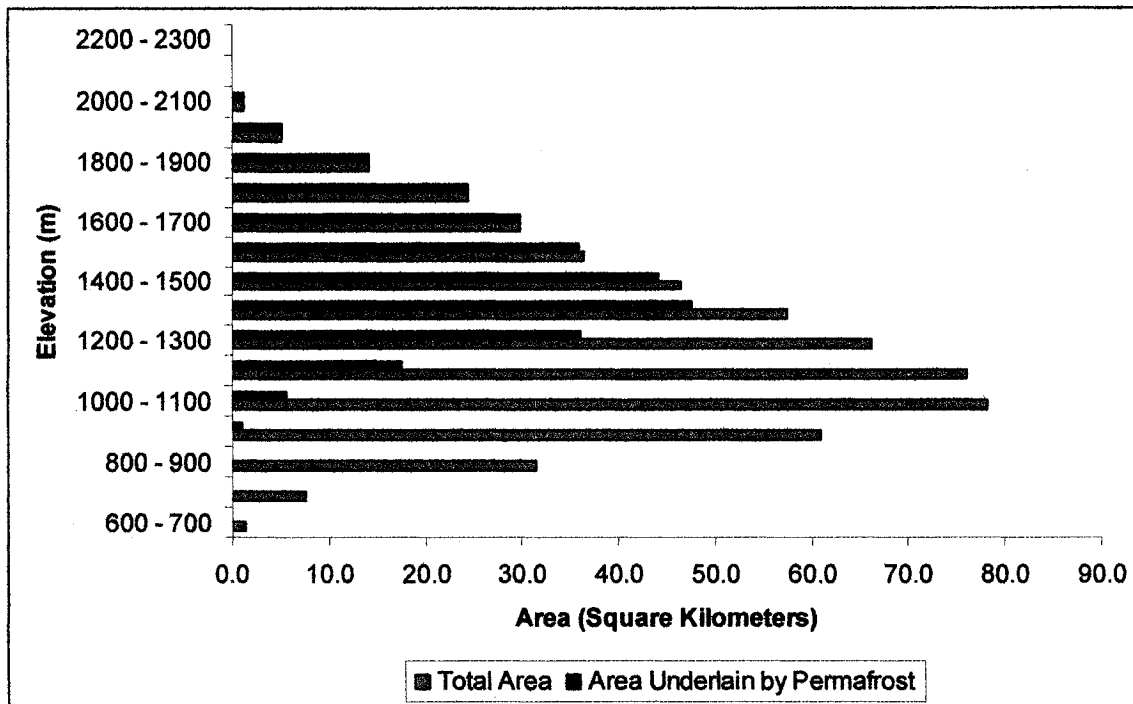


Figure 59: Graph illustrating the amount of area in each elevation band underlain by permafrost versus the total area in that elevation class for Haines Summit under LM-HScave (equation 13).

The logistic regression model LM-HSvex was used to produce a surface of permafrost probabilities under shallow snow conditions for Haines Summit (Figure 60). LM-HSvex generated permafrost probabilities ranging from 0 to 1.0 for the study area with a mean probability of 0.46.

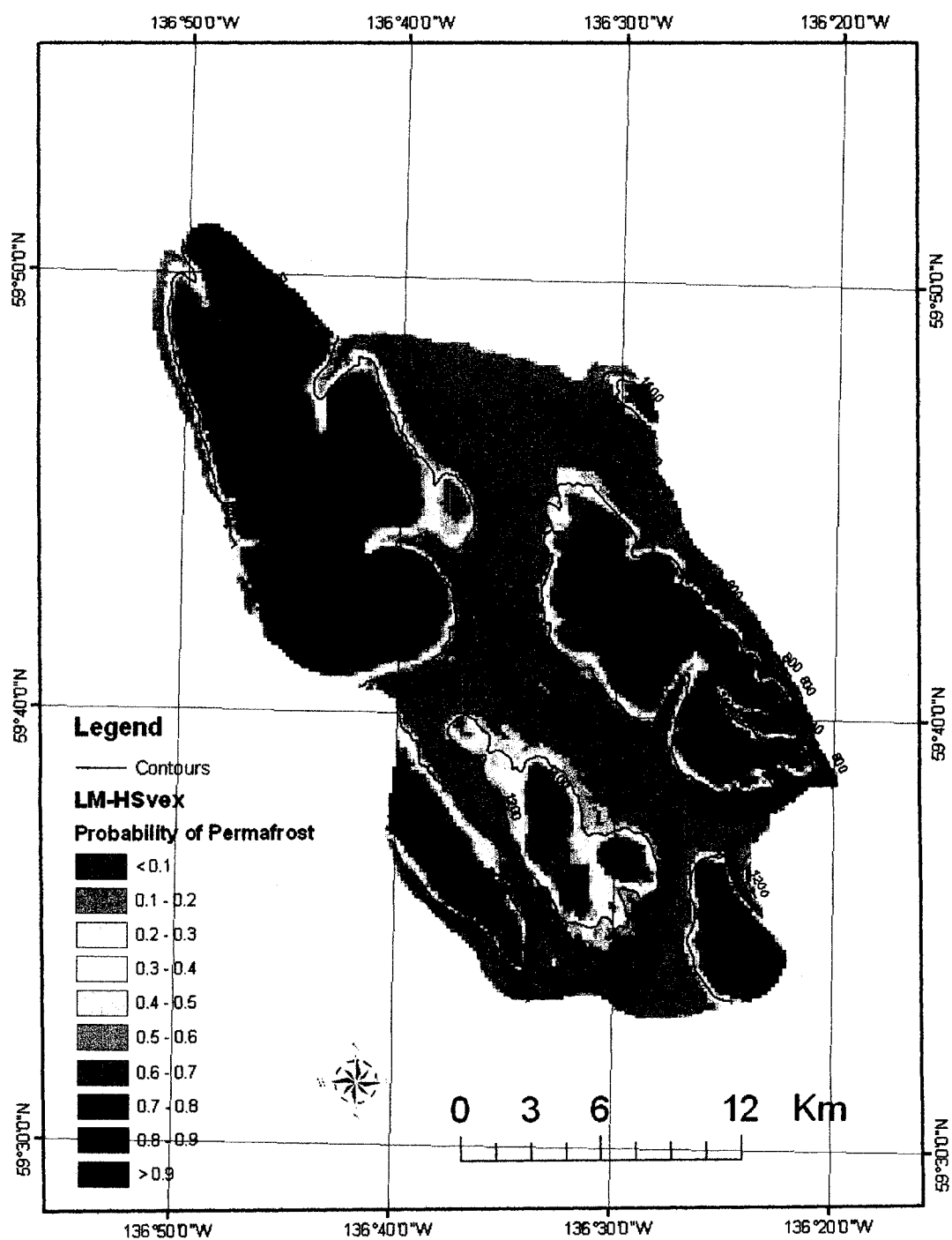


Figure 60: Map of Permafrost Probability for Haines Summit created from LM-HSvex (equation 14).

The information in Figure 60 was converted into units of percentage and area (Figure 61).

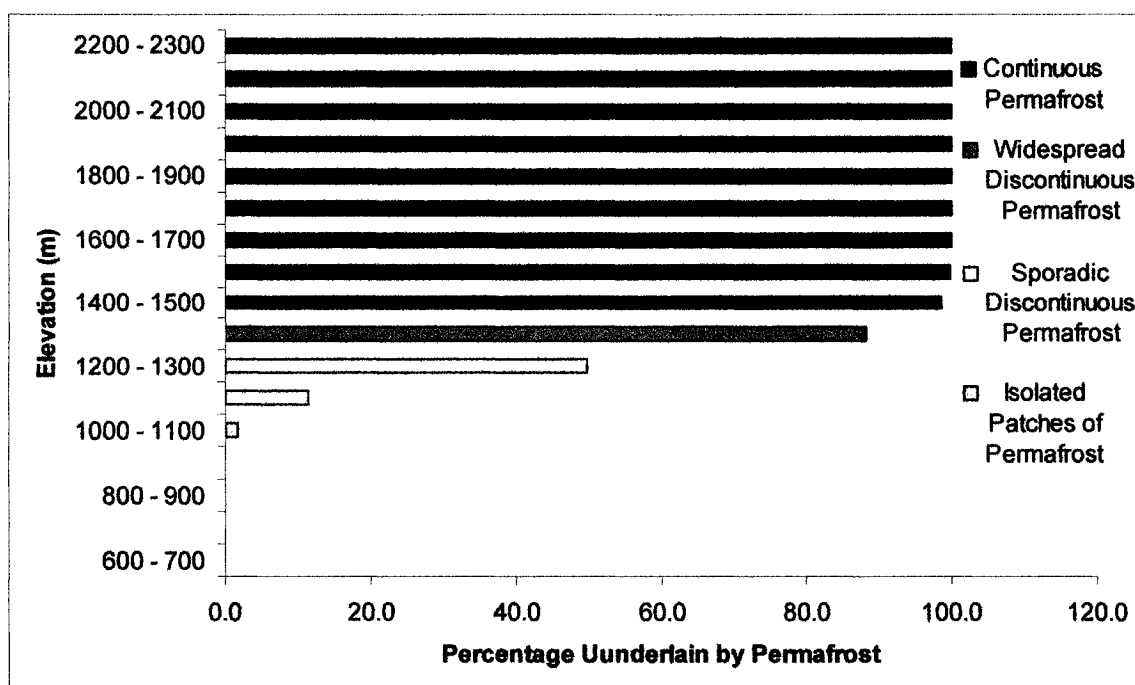


Figure 61: Graph illustrating the predicted percentage of area underlain by permafrost at each 100 m elevation band in Haines Summit based on LM-HSvex (equation 14).

Permafrost percentage in Haines Summit under LM-HSvex reaches a maximum of 100 % through the 1500 – 2300 m elevation bands. Using a conventional permafrost classification according to Heginbottom et al. (1995), elevations of 600 – 1100 m isolated patches of permafrost (< 10%). Sporadic discontinuous permafrost (10 – 50% permafrost), occurs in the elevation bands of 1100 – 1300 m, with widespread discontinuous permafrost (50 – 90% permafrost), spanning from 1300 – 1400 m. All elevations above this are continuous permafrost (>90% permafrost).

A total of 250 km² of the area or 47 % is underlain by permafrost according to LM-HSvex (Figure 62).

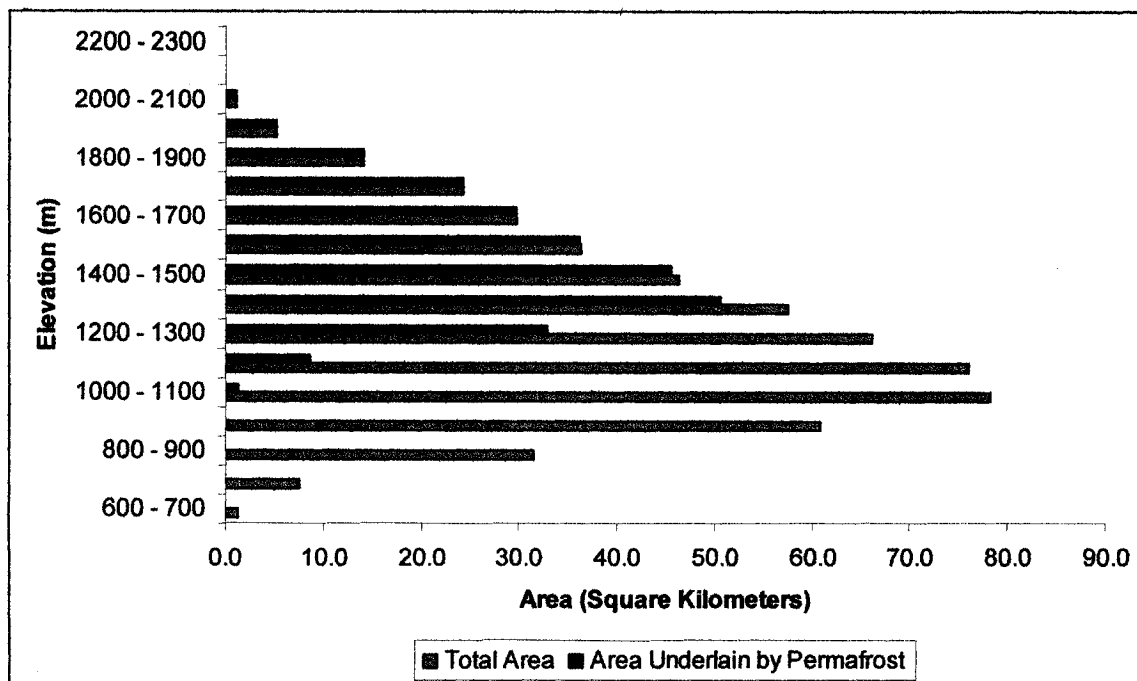


Figure 62: Graph illustrating the amount of area in each elevation band underlain by permafrost versus the total area in that elevation class for Haines Summit under LM-HSvex (equation 13).

The results of LM-HScave and LM-HSvex show that there are only slight differences between the three models. The results of this exploratory analysis indicate that this area is potentially more resilient to changes in snow depth than the Ruby Range, perhaps because snow depths are very great throughout the region.

Section 6.3 Sampling and Inter-Annual Variation:

Inter-annual variation can be a significant source of uncertainty in the creation of a permafrost probability model using the BTS method (Brenning et al., 2005, Etzelmüller et al., 2001). It is important in any modeling to attempt to collect as many years of data as possible in order to truly ascertain the dynamics of an area. BTS values are highly dependent on the intensity of winter and the timing in which it is brought on (Brenning et al., 2005). Snow is perhaps the most important factor in the BTS method with greater

amounts of snow insulating the ground from cold winter temperatures. However, in years where snow is late to arrive, lower BTS values could be recorded. Meteorological conditions with respect to the onset of temperatures below 0 °C and the arrival of snow in the fall before a BTS field season are classified as R1 and R2 winters (Brenning et al., 2005). An R1 winter refers to a season where temperatures do not drop well below 0 °C for long periods of time before the seasonal winter snow cover is established. An R2 winter is observed when the seasonal winter snow cover is late to arrive and is coupled with sub-zero air interacting with the ground during the snow-free period. Depending on the attributes of any particular winter, BTS temperatures in R1 versus R2 winters can differ by as much as 1 °C (Brenning et al., 2005). In order to conclusively identify a winter as an R1 or R2 temperature data for the site must be examined and related to local snow information.

BTS values at Haines Summit differed greatly in 2005 and 2006 with average values of -0.84 °C and -2.4 °C respectively. Although the direct observation of snow depths are not available an R2 winter is likely to have occurred for both study areas in 2006. During the fall and early winter, local people in the study areas reported cold conditions with a continuous seasonal permanent snow cover not being developed until late November at Haines Summit and in early January in the Ruby Range. Although this does not confirm the existence of an R2 type winter it does provide a partial explanation as to why BTS values were colder in Haines Summit.

With only one year of BTS data in the Ruby Range it is possible to see how permafrost conditions and extent could be overestimated if the 2006 BTS values were indeed obtained during an R2 winter. It can be assumed that BTS conditions would be

about 1 °C warmer during an R1 winter (Brenning et al., 2005). In order to determine the change in permafrost extent all of the BTS values collected in March 2006 were increased by 1 °C and a new modeled BTS surface (Figure 63) and a probability model entitled LM-RR-R1 were developed.

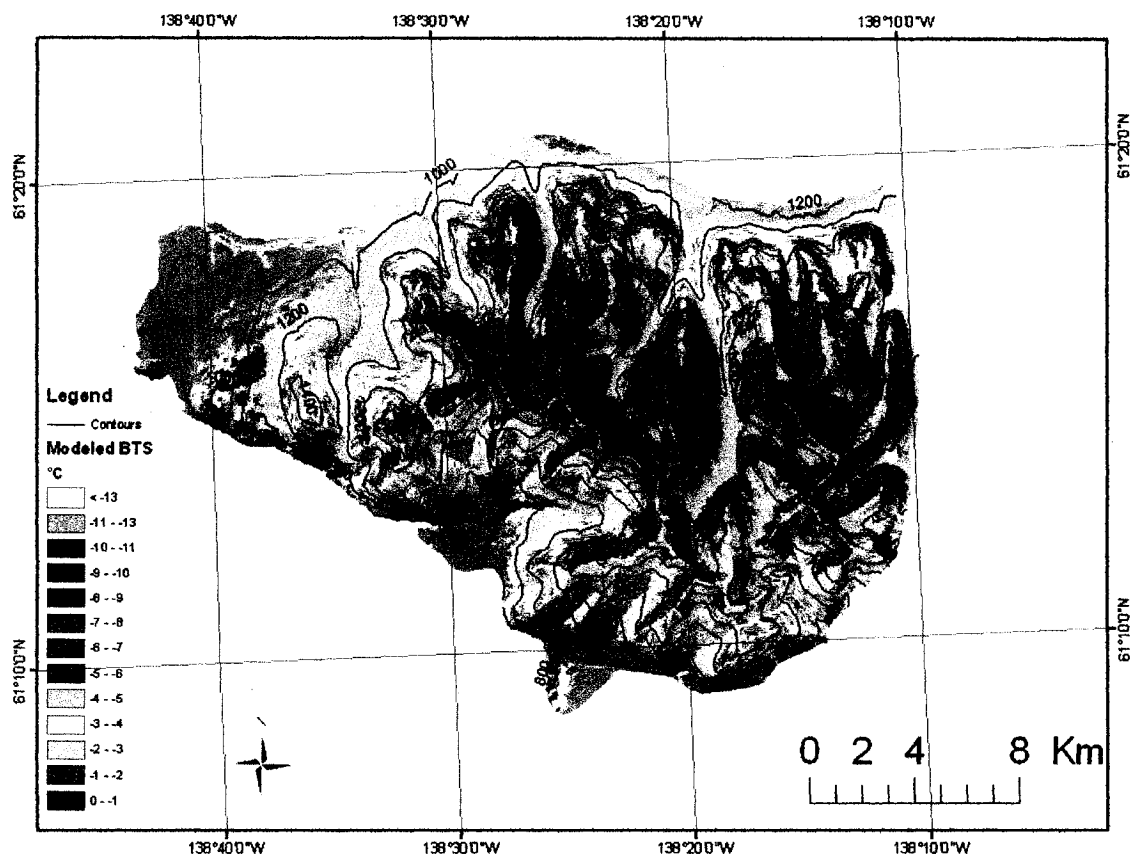


Figure 63: Map illustrating a surface of modeled BTS values under a possible scenario for an R1 type winter in the Ruby Range.

Modeled BTS conditions using the 1 °C increase in recorded BTS values predictably increases the mean, minimum and maximum values by 1 °C giving values of -4.3 °C, -13.3 °C and -0.8 °C respectively.

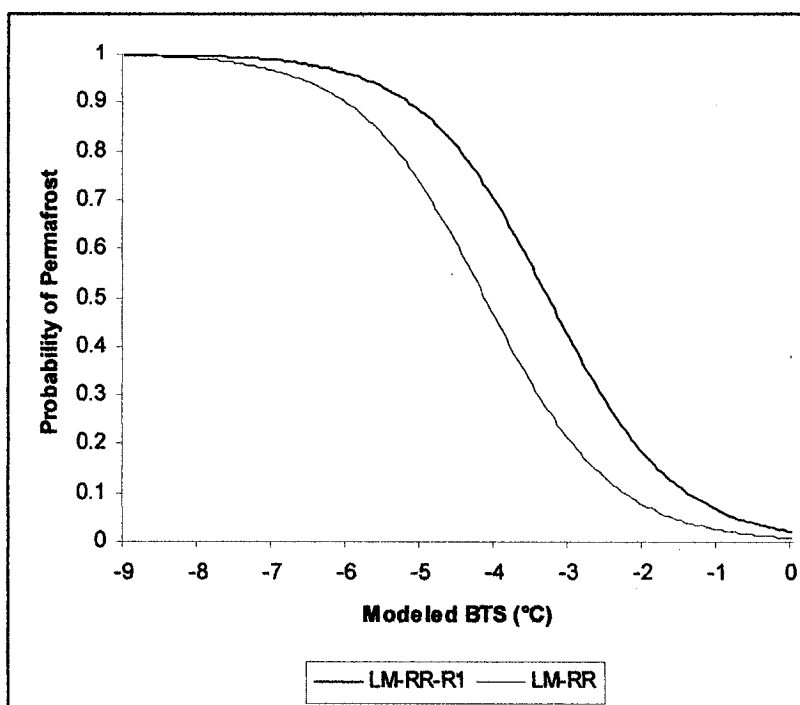


Figure 64: Probability curve illustrating the initial probability model for the Ruby Range (LM-RR) and LM-RR-R1, a model designed to show potential affects of an R1 winter in the Ruby Range.

LM-RR-R1 is very similar to LM-RR with the only difference being that the curve has been translated 1°C to the right. Under these conditions sites with modeled BTS closer to 0 °C contain slightly more permafrost; however, the mean value in the study area is slightly lower at 0.64 and the minimum value is 0.05 and the maximum probability is 1.

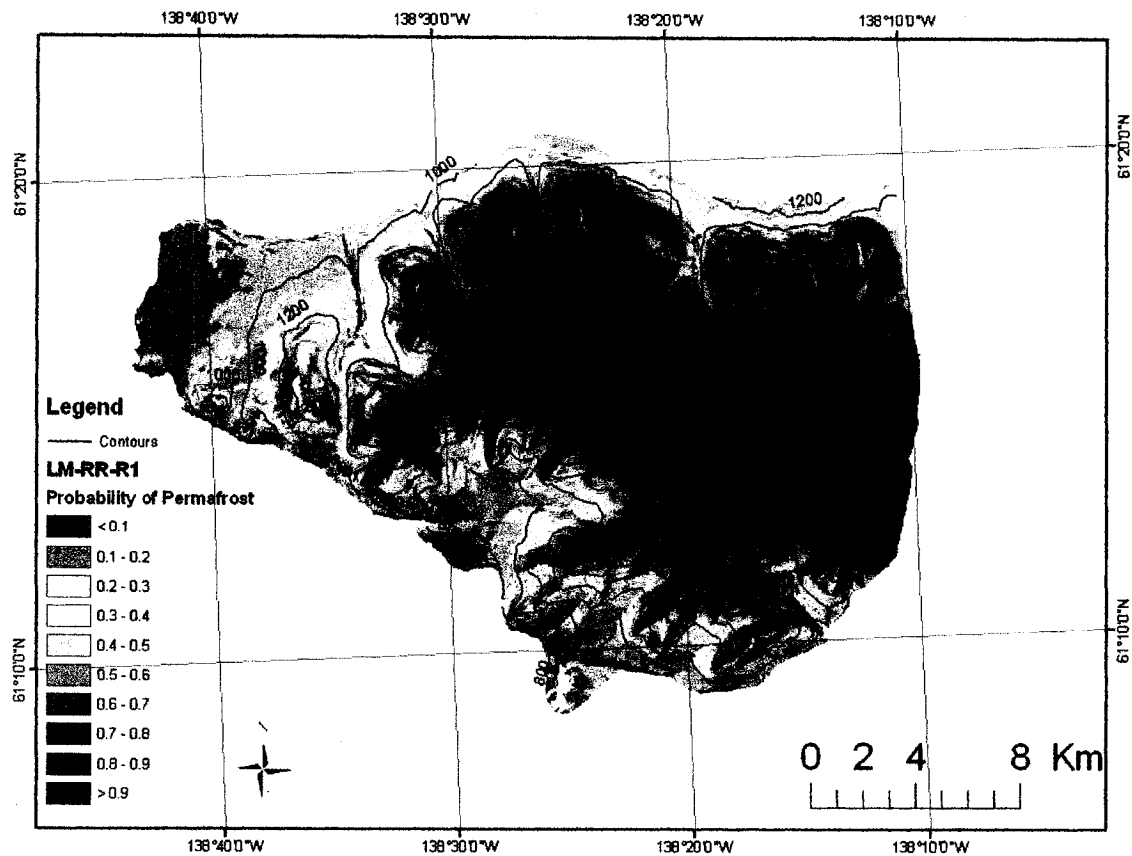


Figure 65: Permafrost probability map created from the probability model LM-RR-R1 in order to display a potential R1 BTS scenario.

Permafrost probabilities in the Ruby Range under LM-RR-R1 increase as elevation increases in an identical pattern to LM-RR, with minor changes only in the highest and lowest probability areas. A maximum value of 95 % is recorded in the 2200 – 2300 m elevation band representing approximately 1 percent less permafrost at this elevation than with LM-RR. Under LM-RR-R1, the area in the 700 – 800 m elevation band is considered as isolated patches of permafrost (<10% permafrost) whereas elevations ranging between 800 – 1200 m are sporadic discontinuous permafrost (10 – 50%). Widespread discontinuous permafrost zone (50 – 90% permafrost) exists between

elevations of 1200 – 1800 in LM-RR-R1 and continuous permafrost (>90% permafrost) at elevations greater than 1800 m (Figure 66).

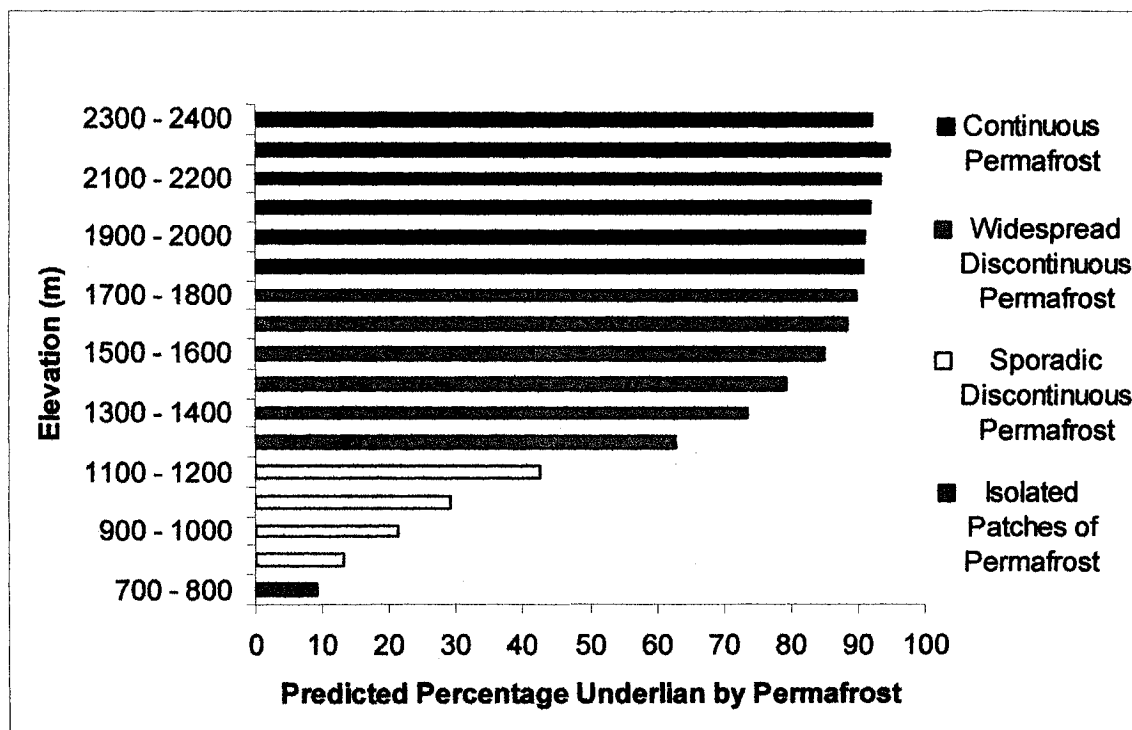


Figure 66: Graph illustrating the predicted percentage of area underlain by permafrost at each 100 m elevation band in the Ruby Range based on LM-RR-R1

A total of 282 km² of the area or 66% was determined to be underlain with permafrost according to LM-RR. The corresponding values using LM-RR-R1 were 271 km² or 64 % of the study area. The difference in the total area predicted as permafrost in the two models is approximately 11 km², or 2.5 % of the total study area. Nevertheless, this example shows the need for BTS sampling in as many years and types of winters as possible since assumptions about temperature changes were very simple. It is probable that differences between BTS values in R1 and R2 winters would not be entirely uniform.

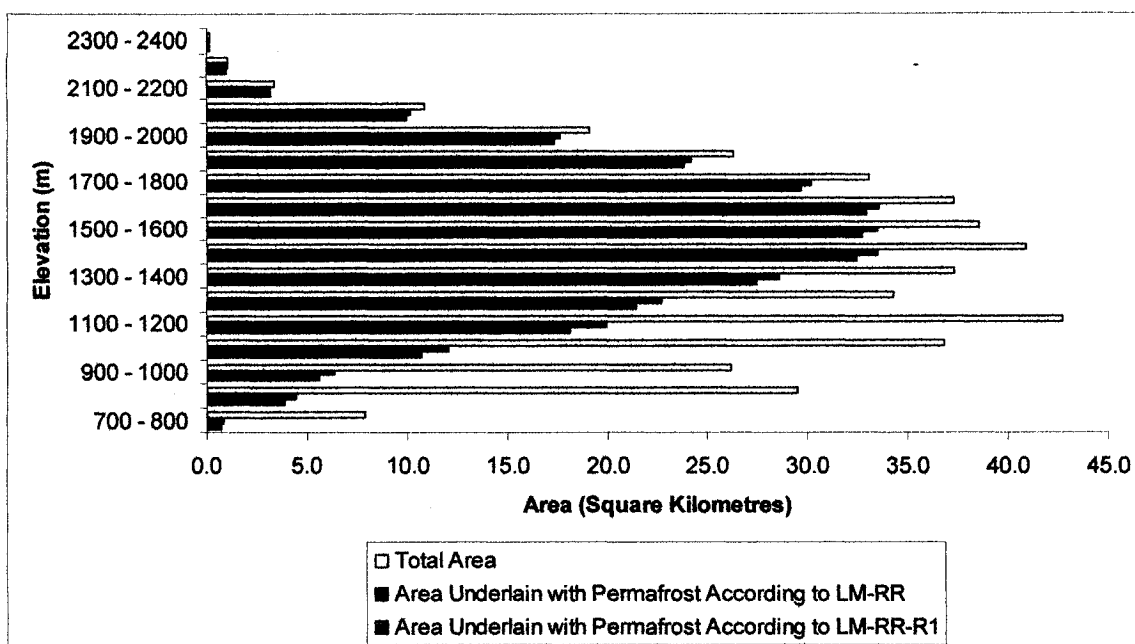


Figure 67: Graph illustrating the amount of area in each elevation band underlain by permafrost using both LM-RR and LM-RR-R1 permafrost probability models versus the total area in each elevation class.

Section 6.4 Model Transferability:

Perhaps one of the greatest challenges in empirical-statistical permafrost modeling comes when a user wishes to transfer an existing permafrost probability model to a different location. Including the current sites a total of three study areas have been sampled for BTS and ground-truthed in the southwest Yukon Territory and northwest British Columbia. The resulting permafrost probability models are shown in Figure 68.

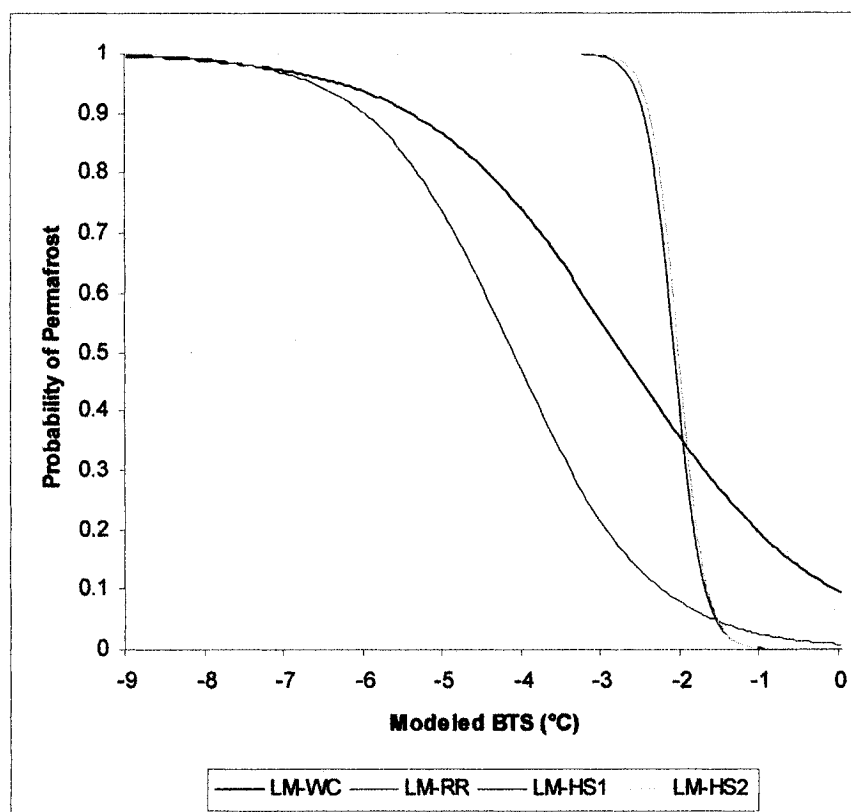


Figure 68: Graph illustrating the different permafrost probability models generated for Wolf Creek (Lewkowicz and Ednie, 2004), the Ruby Range and Haines Summit.

As Figure 68 illustrates, the probability models for the three areas show very different results with BTS values for the different areas not corresponding to the same probability of permafrost (Table 19).

	0	-1	-2	-3	-4	-5	-6	-7	-8	-9
LM-WC	0.093	0.19	0.349	0.55	0.735	0.863	0.935	0.97	0.986	0.994
LM-RR	0.007	0.024	0.075	0.209	0.46	0.733	0.898	0.966	0.989	0.996
LM-HS1	<0.001	0.002	0.361	0.994	0.999	1	1	1	1	1
LM-HS2	<0.001	0.002	0.432	0.997	0.999	1	1	1	1	1

Table 19: Probability of permafrost values for listed models at critical temperatures values.

The idea of model transference into different areas has been discussed in various studies with no clear consensus, and only in the context of multiple linear regression models

(Gruber and Hoelzle, 2001, Lugon and Delaloye, 2001, Etzelmüller et al., 2001, Tanarro et al., 2001). The collection of BTS values can be laborious and expensive, and the advantage of a transferable model would be the flexibility offered, especially if the model could be moved between areas where climatic characteristics are different.

Climatic differences are one of the leading factors preventing model transferral. Both the Ruby Range and Wolf Creek (Lewkowicz and Ednie, 2004) are areas of continental climate whereas Haines Summit is a maritime environment. Although there is significant differences in the Ruby Range model and the one from Wolf Creek the curves and coefficients have greater similarities than the ones for Haines Summit. It is however, important to note that although similarities exist in curve shape, the curves were obtained in different ways. The Wolf Creek model used elevation cubed in the completion of the linear regression model, whereas LM-RR did not weight the elevation term. This suggests a need for climatic calibration before a model can be transferred. However, the transfer process is unclear and in need of further study and research.

In order to investigate the effects of a direct model transfer, the multiple linear regression equation from the Ruby Range (Equation 2) which included elevation and PISR, was applied to Haines Summit. The results of this transfer produced a surface of modeled BTS values (Figure 69) ranging from -2.3°C to -13.8°C with a mean value of -5°C .

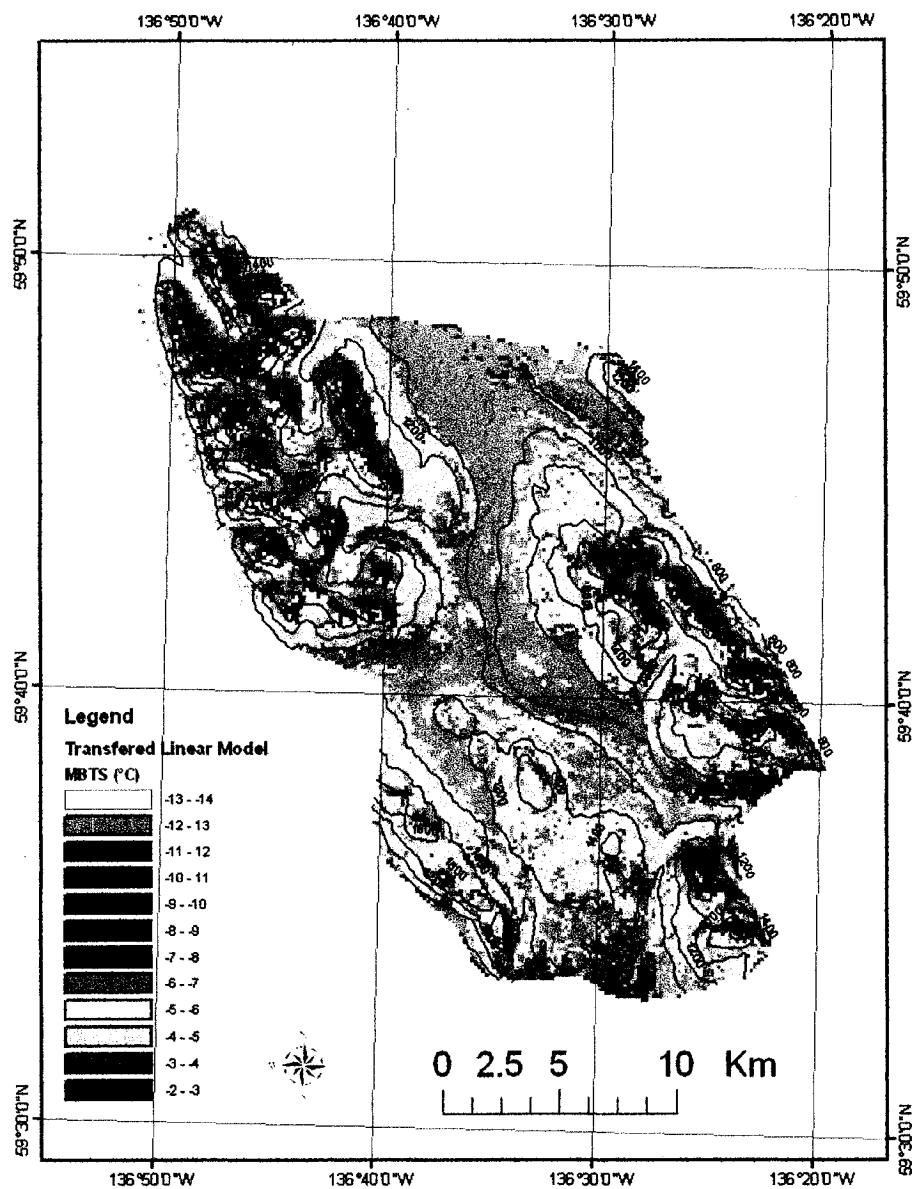


Figure 69: Map illustrating the results of transferring the linear model developed for the Ruby Range to Haines Summit.

Applying the equation from the Ruby Range to Haines Summit and the existing ground truthing information, a transfer model titled LM-HST was created based on the following equation and coefficients:

$$Y = -5.55 - 0.99 (\text{MBTS}) \quad (15)$$

LM-HST	β Coefficient	Standard Error	Wald Statistic	Degrees of Freedom	Significance
Constant	-5.55	1.35	16.8	1	< 0.01
MBTS	-0.99	0.28	11.8	1	< 0.01

Table 20: Summary of coefficients in the logistic model for Haines Summit using the linear model developed for the Ruby Range LM-HST.

Both of the β coefficients are considered significant at the 99% confidence level and allow for the generation of a permafrost probability curve (Figure 70).

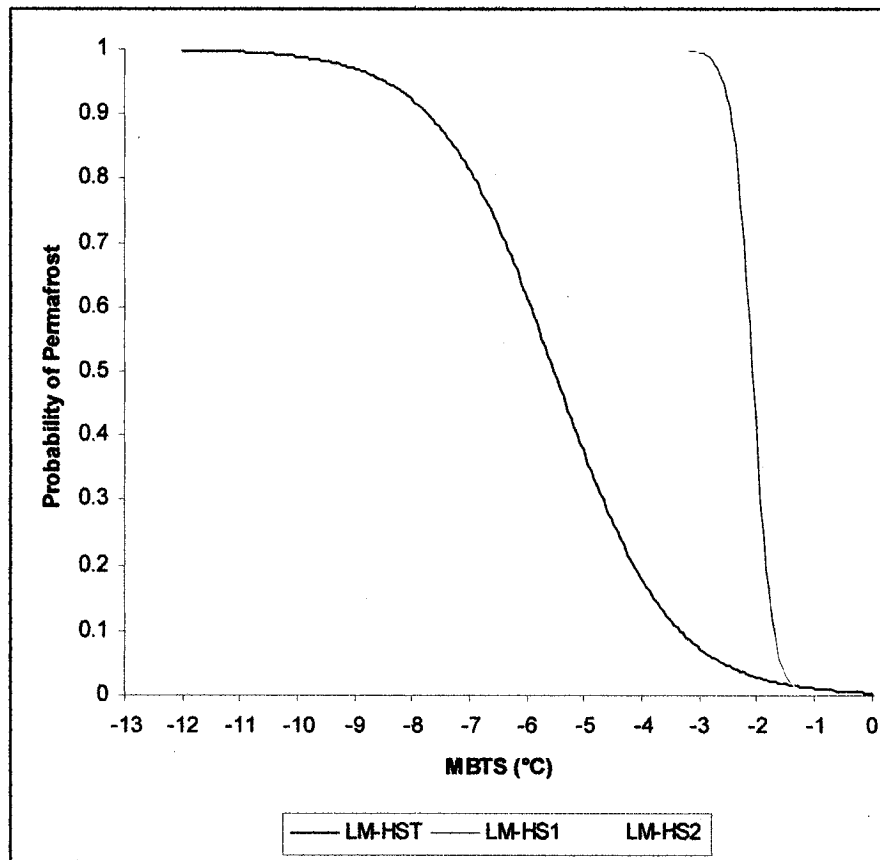


Figure 70: Permafrost probability curves showing the logistic regression models LM-HS1, LM-HS2 and the transfer model LM-HST for Haines Summit.

LM-HST has a much less steep curve than the actual Haines Summit models.

Permafrost probability reaches a value of 0.1 at a BTS temperature of -3.4 °C, a value of 0.5 at -5.5 °C and a value of 1 at around -13 °C.

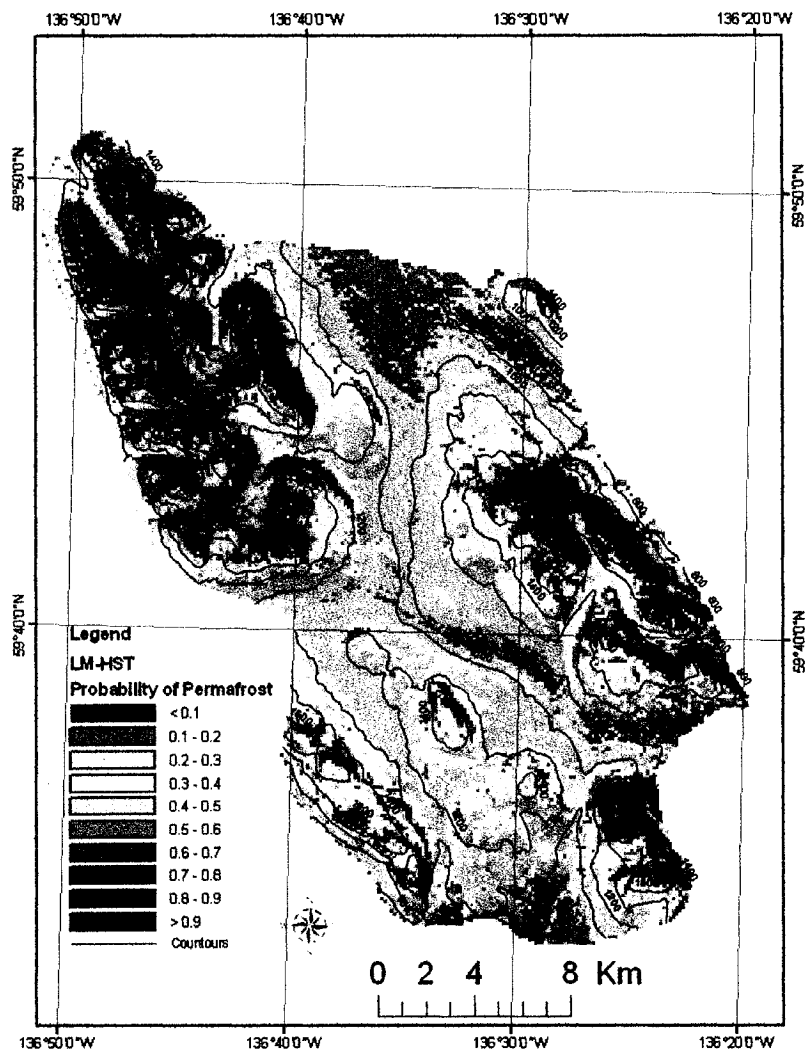


Figure 71: Map illustrating the probability of permafrost according to the transfer model LM-HST for Haines Summit. Contour interval is 200 m.

The application of the LM-HST model to the Haines Summit study area produces a probability of permafrost surface with mean value of 0.4 a minimum value of 0.04 and maximum value approaching 1 (Figure 71). Using the same procedure as the preceding models the percentage area and amount of permafrost in each elevation band was calculated (Figure 72).

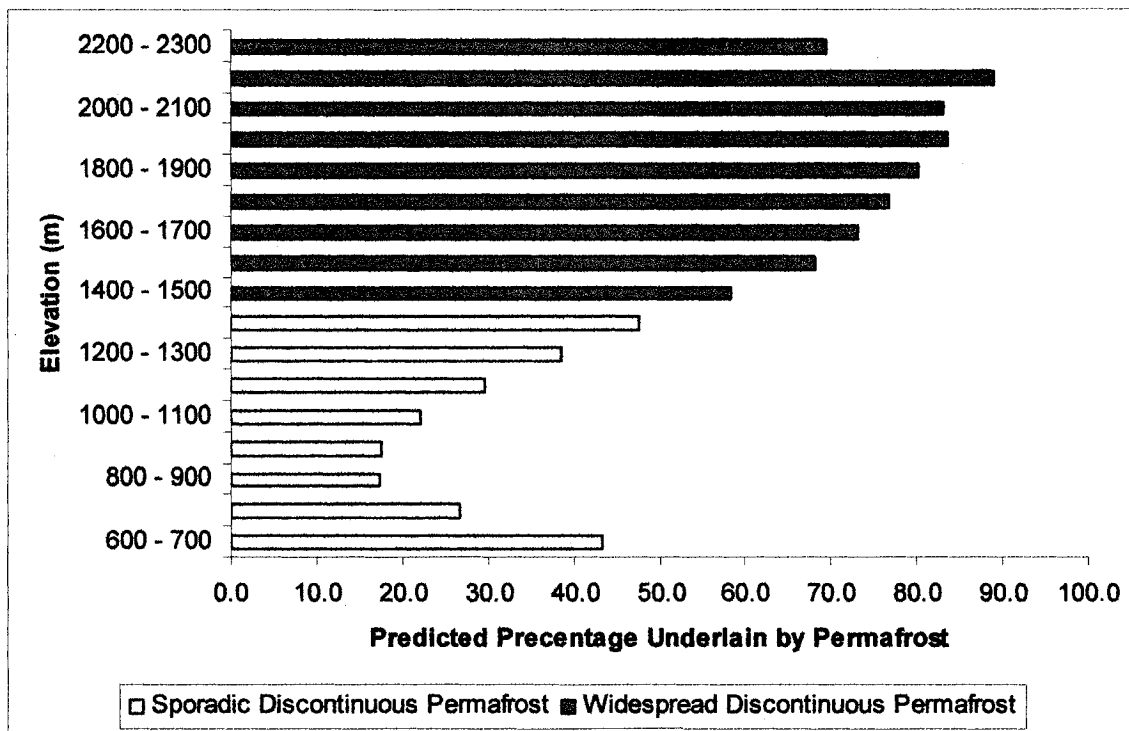


Figure 72: Graph illustrating the predicted percentage of area underlain by permafrost in each 100 m elevation band in the Haines Summit study area based on LM-HST.

According to Figure 72 only the sporadic discontinuous and widespread discontinuous permafrost classes are present in the Haines Summit study area when LM-HST is applied.

Another notable detail in the transfer model includes the fact that the two lowest elevation classes in the study area contain a higher percentage of area underlain by permafrost than the two subsequent classes above. This result is likely the result of PISR having an impact on the Ruby Range and the results of this impact being transferred to the Haines Summit study area.

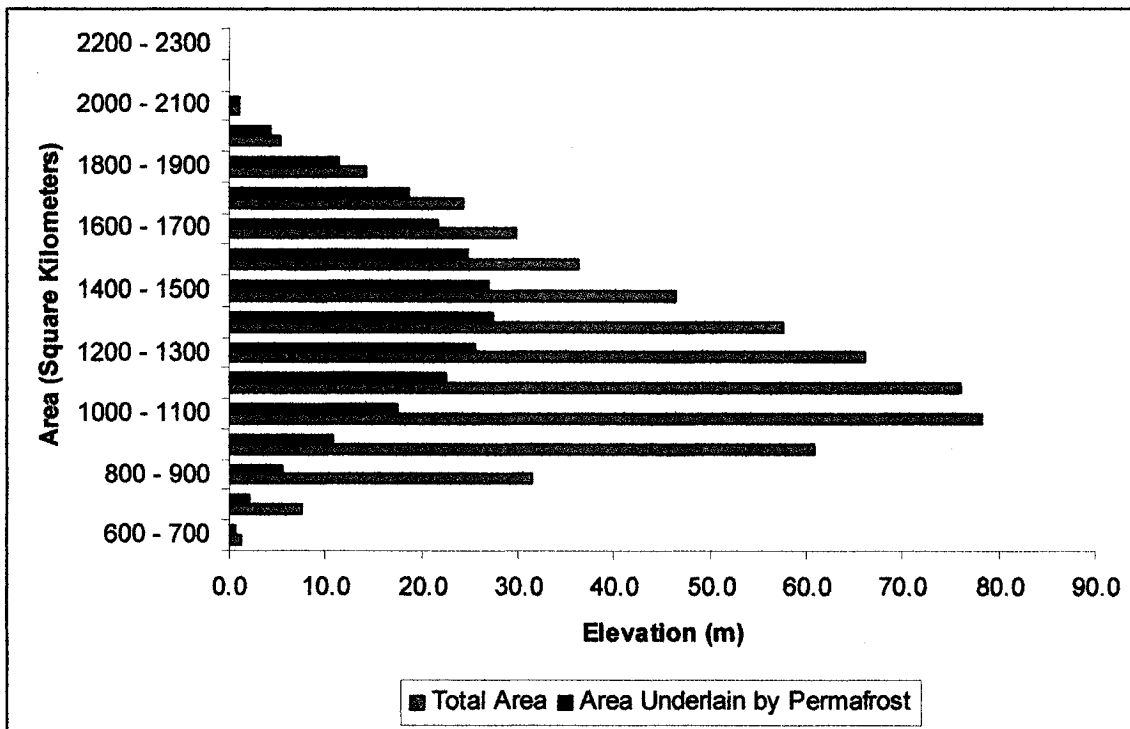


Figure 73: Graph illustrating the amount of area in each elevation band underlain with permafrost according to the transfer model LM-HST.

A total of 220 km² of area is predicted to be underlain by permafrost in Haines Summit using the transfer model LM-HST. Although the total amount of permafrost area is similar to LM-HS1 (230 km²) and LM-HS2 (236 km²) it is important to note that the spatial distribution is different (Figure 74). HS-LM1 has an extremely small transition zone separating permafrost and non permafrost terrain. Due to the nature of the transitional area, > 95 % of permafrost predicted by LM-HS1 is located above the 1200 – 1300 m elevation band. In contrast LM-HST predicts only 60 % of all permafrost lie above the same elevation band. Another key difference in the spatial distribution of permafrost is that LM-HST includes aspect effects (Figure 74). These arise from the inclusion of PISR within the Ruby Range and its transfer to this area in LM-HST.

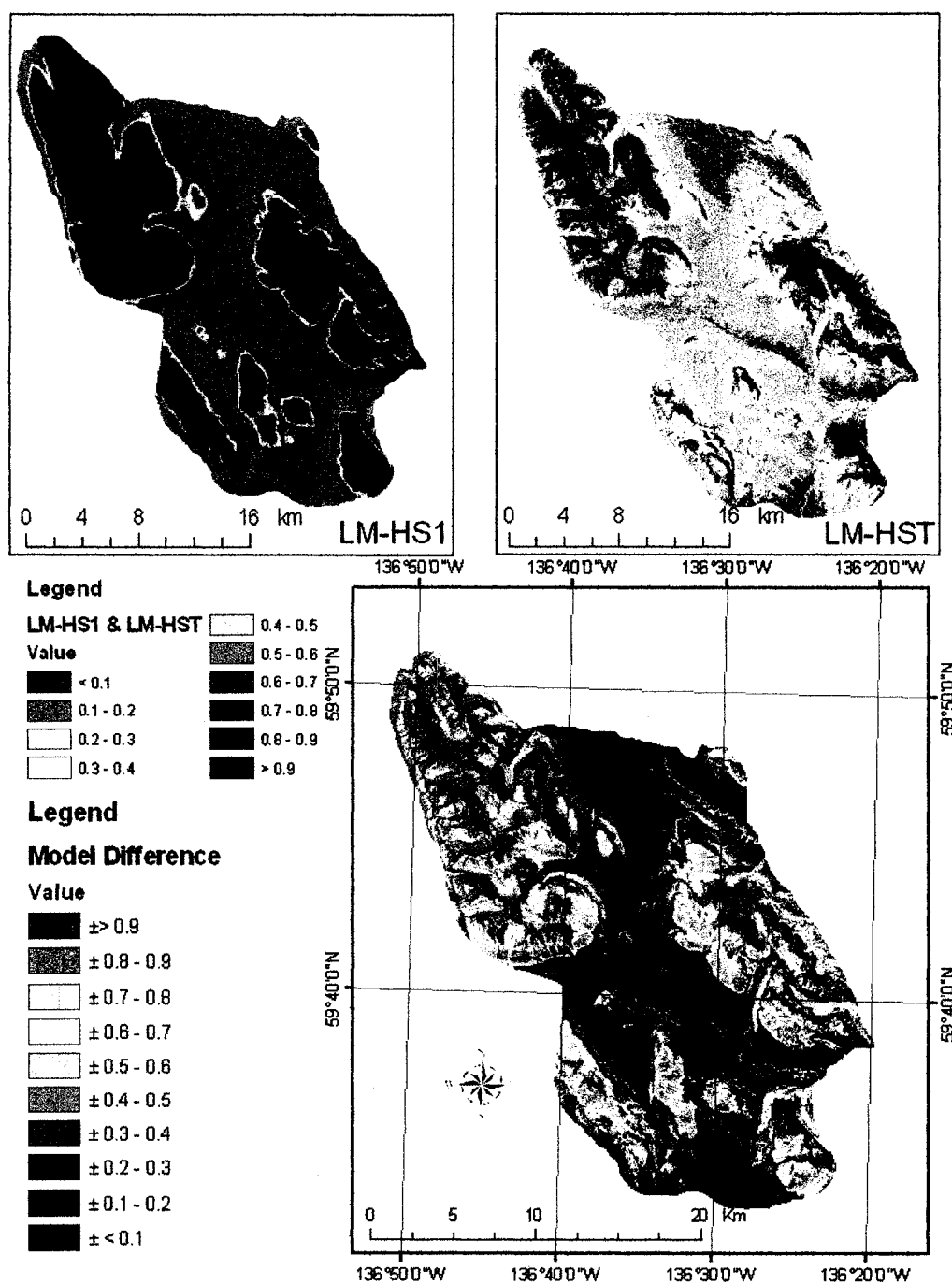


Figure 74: Maps displaying the spatial distribution of permafrost probabilities according to LM-HS1 & LM-HST as well as the spatial distribution and magnitude of difference between LM-HS1 and LM-HST for the Haines Summit study area.

The largest differences between LM-HS1 and LM-HST (Figure 74) are seen in areas of high elevation and south-facing slopes as well as in the size of transition zones. Figure 75 illustrates the intensity of differences between LM-HS1 and LM-HST across the Haines Summit study area.

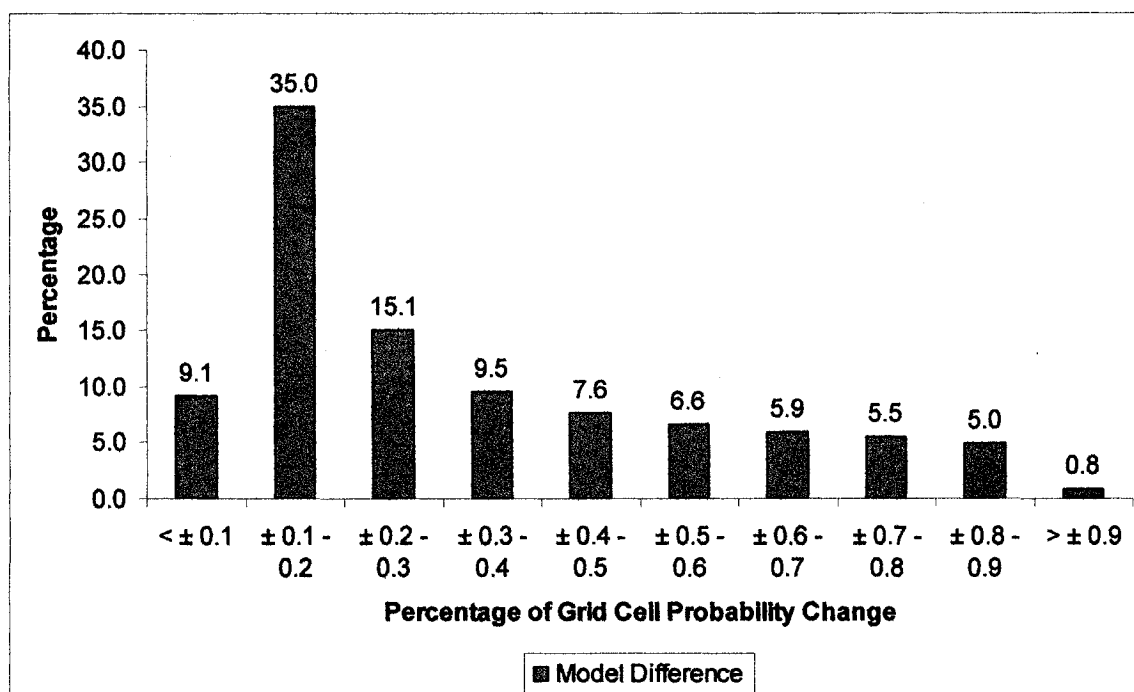


Figure 75: Percentage of pixels for the Haines Summit study area located in each band of magnitude change. This figure compares LM-HS1 to LM-HST.

Figure 75 reveals that the majority of grid cells changed probabilities by less than ± 0.3 between the two models, with the modal value being $\pm 0.1 - 0.2$.

The explanation for the redistribution of probabilities is that LM-HST was created from BTS data collected in the Ruby Range. BTS data in the Ruby Range occurred over a larger numeric range than those from Haines Summit. Consequently, when the linear model was transferred to Haines Summit, the range of modeled BTS greatly increased. The creation of this model used trends in lapse rates and PISR from the Ruby Range which were calibrated to the Haines Summit area using the pit data. The Ruby Range data

produced a larger variety of modeled BTS values at any given elevation. This made the pit data less definitive in the logistic regression model resulting in an altered spatial distribution while preserving the total amount of permafrost in the area. It would seem from the results of the transfer model LM-HST that the linear model developed in the Ruby Range is not directly transferable to Haines Summit.

It is important to note, however, that although a direct transfer without prior knowledge of BTS temperature ranges would not be advisable, the pit data appear to control the outcome of the permafrost modeling, including predictions of the overall permafrost amount. It is possible that areas with similar climate produce similar BTS temperatures and ranges thus allowing both the permafrost amount and spatial distribution to be more easily transferable. The advantage of this approach would be to allow for a simpler transfer in areas that had been properly climatically classified. Although the process of transferring a model from one region to another is not yet clear, the potential benefits of such a process are great, showing the need for further study and research.

7.0 Conclusion:

7.1 Conclusions:

The following conclusions can be reached as a result of this research:

- 1) From the analysis presented for the Ruby Range and Haines Summit the BTS method is effective in predicting the spatial distribution of mountain permafrost in different climatic areas than Wolf Creek (Lewkowicz and Ednie, 2004).
- 2) Linear modeling using elevation and PISR resulted in the generation of a surface of modeled BTS values for the Ruby Range. The Haines Summit study area used the same procedure without the PISR component which was not significant, likely due to increased levels of cloud cover.
- 3) Modeled BTS values coupled with the results of the late-summer observation of frozen ground led to the production of probability of permafrost models for both study areas (Table 21). The LM-RR model of the Ruby Range indicated that permafrost underlies approximately 282 km² or 66 % of the study area. LM-HS1 and LM-HS2 for Haines Summit indicate that 230 km² or 43 % and 236 km² or 44 %, respectively, have permafrost conditions.

Model	Variables	% IP	%SDP	% WDP	%CU	% study area
LM-RR	Elevation, PISR	3.8	28.6	32.6	34.9	66
LM-RRcave	Elevation, PISR	9.3	19.5	19.4	51.7	71
LM-RRvex	Elevation, PISR	4.5	33.7	38.2	23.6	60
LM-RR-R1	Elevation, PISR	5.9	29.1	33.2	31.8	64
LM-HS1	Elevation	52.2	4.9	4.9	37.9	43
LM-HS2	Elevation, PISR	52.3	3.7	3.6	40.3	44
LM-HScave	Elevation	30.9	21.4	17.3	30.4	50
LM-HSvex	Elevation	40.7	13.2	11.8	34.3	47
LM-HST	Elevation, PISR from RR	7.3	58.5	25.1	9.0	41

Table 21: Summary of model predictions, showing percentage of study area falling into permafrost categories and for the study areas in total.

- 4) Models were created for both study areas using pit data collected in concave and convex locations respectively which were expected to show the impact of deep and shallow snow. The results for both locations showed that the concave models exhibit slightly more permafrost overall than the convex snow models; the opposite was found in Wolf Creek (Lewkowicz and Ednie, 2004). For the Ruby Range, LM-RRcave predicted 300 km² or 71 % of the area to be underlain by permafrost, (5 % more than LM-RR). The shallow snow model (LM-RRvex), predicted 255 km² or 60 % to be underlain by permafrost (6 % less than LM-RR). For the Haines Summit study area, LM-HScave predicted 260 km² or 50 % was underlain by permafrost (7 % more than LM-HS1 and 6 % more than LM-HS2). LM-HSvex predicted 250 km² or

47 % of Haines Summit was underlain by permafrost (4 % more than LM-HS1 and 3 % more than LH-HS2).

- 5) The depth of snow and the timing of its arrival can affect the value of BTS readings thus illustrating the need to monitor temperature and snow depth in a BTS sampling area. It is postulated that sampling during the winter of 2006 took place during an R2 type (late snow) winter thus lowering the BTS values at both locations. Due to inter-annual variation, more than one year of data must be collected whenever possible.
- 6) The idea of model transference between two study areas was explored through applying the linear model for the Ruby Range, to Haines Summit. The modeled BTS surface was then calibrated using the area's pit data. Similar total amounts of permafrost were predicted (Table 21) but the spatial distribution was very different. This is possibly the result of large ranges in the transferred modeled BTS data which cause the pit data to be less definitive in the logistic regression. However, the pit data results preserve the value for the total amount of permafrost.

7.2 Future Research:

Improvements to the modeling process are necessary and might be achieved by incorporating additional independent variables into the multiple linear regression modeling. It is important to determine what factors contribute to the existence of permafrost in North American mountain environments as well as how measurements of this information can be determined and incorporated. Potential variables include indexes

of wetness, remotely sensed vegetation data, as well as the degree to which mountain landscapes are prone to atmospheric temperature inversions.

Additional effort must also be put into collecting temperature, cloud cover and snow cover data in order to increase model accuracy and improve the understanding of inter-annual variation. For multi-year sites a series of temperature control points would allow the intensity of inter-annual variation to be studied while providing certain calibration points for a study area. The installation of photo/light loggers to measure light intensity would also greatly improve cloud cover prediction in remote mountain environments.

In addition climatically similar areas must be identified and studied in order to test the idea of model transferability. The ability to predict the permafrost conditions of larger more remote areas is the overall goal of this research. Studies have shown that the BTS method will work in northwestern Canada and that there is relationship between BTS, elevation and PISR. With additional research it is likely that this relationship can be better understood resulting in the generation of more versatile and transferable models.

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