Probability Modelling of Alpine Permafrost Distribution in Tarfala Valley, Sweden

Sannolikhetsmodellering av alpin permafrost i Tarfaladalen, Sverige

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Sammanfattning

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Datainsamling har genomförts i Tarfaladalen under 5 dagar vid månadsskiftet mellan mars och april 2017. Insamlingen resulterade i 36 BTS-mätningar (Bottom Temperature of Snow cover) som därefter har använts tillsammans med data från tidigare insamlingar, till att skapa en sammanställd modell över förekomsten av permafrost omkring Tarfala. En statistisk undersökning syftade till att identifiera meningsfulla parametrar som permafrost beror av, genom att testa de oberoende variablerna mot BTS i en stegvis regression. De oberoende faktorerna höjd över havet, aspekt, solinstrålning, vinkel och gradient hos sluttningar producerades för varje undersökt BTS-punkt i ett geografiskt informationssystem.

Den stegvisa regressionen valde enbart höjden som signifikant variabel, höjden användes i en logistisk regression för att modellera permafrostens utbredning. Den slutliga modellen visade att permafrostens sannolikhet ökar med höjden. För att skilja mellan kontinuerlig, diskontinuerlig och sporadisk permafrost delades modellen in i tre zoner med olika sannolikhetsspann. Den kontinuerliga permafrosten är högst belägen och därav den zon där sannolikheten för permafrost är störst, denna zon gränsar till den diskontinuerliga permafrosten vid en höjd på 1523 m. Den diskontinuerliga permafrosten har en sannolikhet mellan 50–80 % och dess undre gräns ligger på 1108 m.ö.h. separerar den diskontinuerliga zonen från den sporadiska permafrosten.

Nyckelord: Alpin permafrost, BTS, stepwise regression, logistic regression, Tarfala

Abstract

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A field data collection has been carried out in Tarfala valley at the turn of March to April 2017. The collection resulted in 36 BTS-measurements (Bottom Temperature of Snow cover) that has been used in combination with data from earlier surveys, to create a model of the occurrence of permafrost around Tarfala. To identify meaningful parameters that permafrost relies on, independent variables were tested against BTS in a stepwise regression. The independent variables elevation, aspect, solar radiation, slope angle and curvature were produced for each investigated BTS-point in a geographic information system.

   The stepwise regression selected elevation as the only significant variable, elevation was applied to a logistic regression to model the permafrost occurrence. The final model showed that the probability of permafrost increases with height. To distinguish between continuous, discontinuous and sporadic permafrost, the model was divided into three zones with intervals of probability. The continuous permafrost is the highest located zone and therefore has the highest likelihood, this zone delimits the discontinuous permafrost at 1523 m a.s.l. The discontinuous permafrost has probabilities between 50-80 % and its lower limit at 1108 m a.s.l. separates the discontinuous zone from the sporadic permafrost.

Key words: Alpine permafrost, BTS, stepwise regression, logistic regression, Tarfala

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1   Introduction

The ground in permafrost areas consists of different sections, which react to temperature fluctuations at different timescales. The section immediately below the surface thaws and freezes according to seasonal changes in atmospheric conditions, this is called the active layer. The thickness of the active layer and the duration it is thawed is heterogeneous, but generally brief and shallow in the Arctic and thicker and prolonged farther south. Below the active layer lies a perennially frozen section of permafrost, which in some places is several hundred meters thick. The perennial permafrost requires long term temperature changes to thaw because it is located at a depth which is unaffected by short term changes in the atmospheric conditions. Permafrost is defined as ground that stays at freezing point or below for a period of at least two years, with or without water (National Research Council of Canada, 1988). When permafrost is present in middle to low latitudes and at high elevation, it is referred to as Alpine permafrost (IPA, 1998). The spatial distribution of permafrost in the subarctic regions is sporadic or discontinuous and hard to predict (Symon, Arris & Heal, 2007). Permafrost has been observed to be sensitive to climate changes, such as global warming (Lemke et al., 2007)

Permafrost degradation in respect to rising temperatures may increase hazards caused by reduced stability, such as debris flow, landslides, and rock fall. To help increase the safety in areas where the stability of permafrost is important, information about permafrost distribution is meaningful.

The difficulty of detecting permafrost is particularly problematic, which often leads to that permafrost is disregarded as a concern when constructing in high altitude areas (e.g. Haeberli, 1992; Keller, 1992).

The bottom temperature of snow cover (BTS) can be used to confirm permafrost in a measured point. A BTS below -3°C show that permafrost occurrence is probable, a BTS below -2°C that permafrost is possible and lastly that permafrost possibility decreases to improbable when the BTS is above -2°C (Hoezle, 1992). Logistic regression can then evaluate the connection between a dependent variable such as BTS, and one or more independent variables such as topographical parameters. The logistic regression estimates the probability of a chosen temperature to occur spatially, according to the relationship between the dependent and independent variables (Lewkowicz & Ednie, 2004).

1.1 Objective

The goal with this project is to make a model of the permafrost occurrence in the Tarfala valley, and to study the relevance of each independent variable (elevation, slope angle, aspect, curvature, solar radiation) against the dependent variable, BTS.

BTS measurements are measured in Tarfala valley. The collected data will be tested with stepwise regression before being modelled with logistic regression to gain a probability map of permafrost occurrence. The logistic regression creates an empirical-statistical model showing the spatial distribution in the chosen region. The model will include BTS-points from field collections in 2002, 2011 and 2017. The 64 measurements from 2002 were given to us by our supervisor (R. Pettersson, unpublished data), and the 56 BTS-points from 2011 were measured by a previous student (Marklund, 2011). The locations for previously measured points featured in this study are shown in *figure 1*.
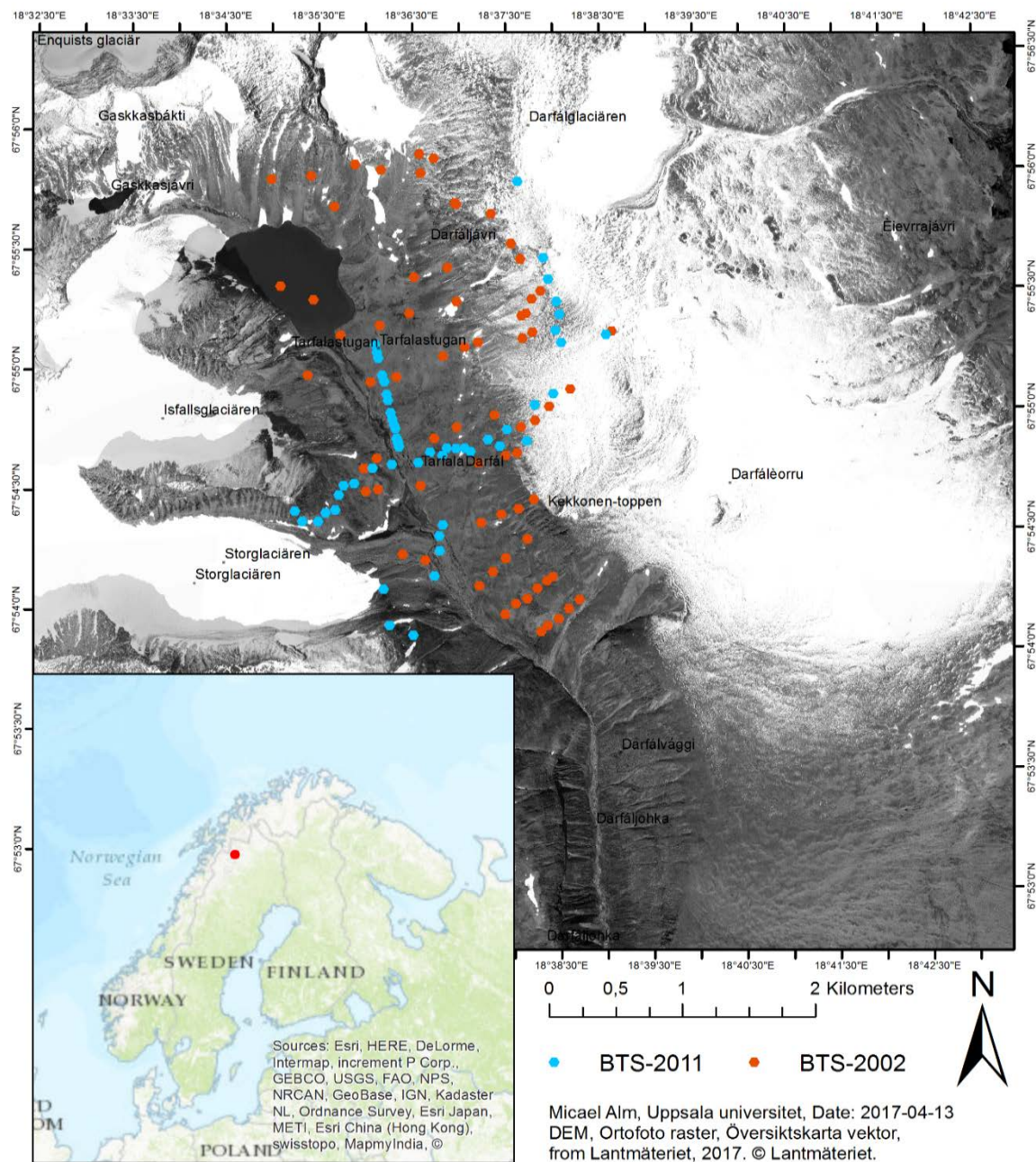
Figure 1. Map over survey area having points where BTS were measured.

1.2 Study Area

Tarfala valley is located in the Kebnekaise massif in north western Sweden. The massif is composed of a few mountains and holds many glaciers. The elevation of the area ranges from approximately 700 to 2100 m a.s.l. Tarfala Research Station is found at around 1100 m a.s.l. The south peak of Kebnekaise is the highest point in the area, and it is covered by a glacier which causes its height to fluctuate annually.

The geology in the area is to a large extent composed of amphibolite, gneiss, and mafic dykes. These three major units have been uplifted through thrusting and are part of the Seve nappes of the Scandinavian Caledonides (Andréasson & Gee 1989). The ground is generally covered by blocky unconsolidated material and sporadic vegetation.

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During a normal winter a thin layer of snow covers the area (Isaksen et al., 2007). The region is affected by a moisture gradient that decreases towards the east as the area is in a climatic transition zone with maritime climate on the western side of the north-south oriented mountain range, and continental climate on the eastern side of the ridge (Liljequist, 1970). A logistic regression model with height as the only independent variable made by Fuchs (2013) concluded that the distribution of alpine permafrost in Tarfala can be recognized as continuous above a height of 1561 m a.s.l. and that discontinuous permafrost is present between 1218 – 1561 m a.s.l. Below the discontinuous zone lies the sporadic permafrost with its base at 875 m a.s.l. The mean annual air temperature or MAAT can be used as a coarse indicator to predict the occurrence of alpine permafrost. Large occurrences of permafrost can be expected in regions with MAAT below -3°C, while regions above -3°C tend to hold less (Haeberlie et al., 2010).

1.3 Background

Permafrost is statistically estimated to cover 24% of the land in the northern hemisphere (Zhang et al., 2003). Some of these places have large occurrences and others do not. The term continuous permafrost is used for areas where most of the ground has a temperature at or below zero, except for locally unfrozen patches caused by e.g. thermal or chemical anomalies. To describe a region where areas of unfrozen ground separate permafrost, the term discontinuous permafrost can be applied. And where only isolated local patches are frozen, permafrost is said to be sporadic (Williams & Smith, 1989).

Alpine permafrost however is distributed where cold, continental climate conditions, are affected by topographic parameters and ground conditions. Generally, areas which have a more humid climate have increased occurrence of glaciers, and thus as a result the amount of space available to permafrost is reduced (Haeberli et al., 2010). Increased snow thickness in regions with moister climate limits the presence of permafrost, especially on gently inclined slopes where snow is easier accumulated (Gruber & Haeberlie, 2009a). This can initially sound confusing as you might think that a thicker snow layer will boost the availability of permafrost, but snow has been found to be a complex influencing factor. For example, a thin cover of snow due to a small amount of precipitation during fall will cool the ground, because the initially warm surface causes the snow to melt and saturates the ground with water. In contrast a thick layer of snow will keep the warmth in the ground, through the snow's insulating effect from the free atmosphere above. Generally, precipitation deposits greater amounts of snow on the lee-side of a dominant wind-direction. And winds may also cause snow to relocate through the processes of saltation and suspension (Lehning et al., 2008). In addition, the snow cover changes the surface's albedo which results in large temperature differences between the ground and the atmosphere (Harris & Corte, 1992).

The earlier mentioned classification of permafrost's distribution, where the distribution of permafrost was continuous in some places and discontinuous or sporadic in other areas is a latitudinal zonation. The same zonation is not suitable for alpine permafrost which mostly depend on topography and for that reason is divided into vertical zones based on height above sea level (King, 1986).

1.4 Properties and conditions at the ground

The temperature of the ground decides whether the ground is frozen or not, this temperature is controlled by the transfer of heat and moisture at the surface-atmosphere boundary (Williams & Smith, 1989). The heat transfer is determined by the net exchange of radiation, the sum of incoming and outgoing radiation. And the magnitude of the sum varies with latitude and over time (Vidstrand, 2003). The conditions and properties at the ground-surface boundary influences the net exchange of radiation (Williams & Smith, 1989).

The surface albedo changes when the snow begins to cover the ground, the albedo determines the magnitude of radiation that gets reflected. The snow cover further influences the heat exchange at the boundary by increasing the amount of moisture, and by isolating the ground from the transfer of sensible heat. The distribution of snow is heterogeneous due to a variable topography, in combination with regional and local differences in atmospheric conditions. Additionally, the snow may be redistributed by e.g. avalanches, creating lateral differences in the thickness of snow. The snow's down-valley displacement in the event of an avalanche causes local thickening of the snow cover, while areas earlier covered by the snow masses become thinner and colder (Hoezle et al., 2001).

The ground itself also contributes to diversity in the ground's temperature. The rate of heat transferring through a medium is referred to as thermal conductivity. How the grounds temperature is affected by its heat conduction is dependent on the mineralogy together with particle sizes and how much water a soil or rock can accommodate. A fine-grained soil can contain more water in contrast to a coarse-grained soil, leading to an increased ability to transfer heat. This is because heat transport is better in water than in air (Côté & Konrad, 2005). Blocky ground coverage is common in cold mountain regions, and has a cooling effect on the ground. During the winter, the snow cover cannot isolate the blocky soil to the same extent as when covering a finer soil. A density contrast develops when the air temperature decreases, and warm air in the large pore spaces is replaced with the cold air from the atmosphere (Gruber & Haeberli, 2009b). High wind speeds may cause snow to penetrate the blocky ground, which prevents vegetation from growing in the summer (Delaloye et al. 2003).

The supply of water in the ground strongly influence the thickness of the active layer, and the thaw or freeze duration (French, 2007). Latent heat is absorbed when water changes state from solid to liquid, and latent heat is released when the reversed action takes place. Freezing or thawing leads to that the temperature of the ground is stable at around freezing-point because the effect of latent heat maintains the temperature, this is called the zero-curtain effect (Outcalt et al., 1990). Less water in the ground results in a thicker active layer, because the heat necessary to thaw or freeze is reduced (Harris & Corte, 1992).

Vegetation affects the conditions at the ground-atmosphere boundary by reducing the surface temperature and increasing the evaporation rate (Yang et al., 2010). The ability of vegetation to grow in alpine areas is governed by the presence or absence of permafrost. The soils hydrological and nutritional status is controlled by if the ground is frozen or not (Christiansen et al., 2004). The nutrients required for vegetation are distributed at the bottom of the active layer, thus the depth holding nutrients fluctuate according to season. Permafrost sometimes prevents surface water from infiltrating and percolating, as the ground there is semi-permeable. The degradation of permafrost forces the active layer to become increasingly thicker; this

alters the conditions in the soils which can have negative impacts on the ecosystems (Yang et al., 2010).

1.5 Bottom temperature of snow cover

The bottom temperature of snow cover (BTS) is a method introduced by Haeberli (1973). This indirect method of measuring is particularly useful to map distribution of permafrost, as the measurements easily can be transformed into a model that describes a phenomenon in the real world. Although the method only predicts the occurrence in one measured point, a stack of measurements can be related to a limited set of parameters using statistical analyses, and ultimately transformed into a model using a geographic information system (GIS) (Lewkowicz et al., 2004).

The principle behind the method is that thick snow covers have low thermal conductivity and functions like a shield that insulates the ground from fluctuations in the atmospheres temperature. The presence or absence of permafrost strongly influences the heat flux from the upper ground layer and controls the temperature at the ground surface, which is the primary factor for the BTS methods functionality (Haeberli, 1985).

Snow has selective absorption that treats incoming radiation different according to their wavelengths. Because of the snows high albedo only a small amount of short-wave solar radiation is absorbed as opposed to the amount that gets reflected. The snows ability to absorb long-wave radiation is greater and furthermore it has high thermal emissivity, which causes radiation with long wavelengths to leave the surface. The removal of energy by reflectivity and emissivity causes the snow to be cold, despite it sometimes being in contact with a positive temperature (Zhang, 2005).

The local characteristics of the snow cover (thickness, density, duration) have an impact on the ground temperature, and the characteristics varies from one year to another (Hoezle et al., 1999).

The density of snow ranges from under 100 kg/m3 to over 600 kg/m3 for fresh and melting snow, respectively. The density of snow is related to how well it thermally insulates the ground. A dense snow pack transfers heat more effectively than uncompressed snow (Zhang, 2005). Snow layers with lower density diminish daily and seasonal variations of the surface temperature to a considerable amount, and the dampening effect decreases with a higher density (Hoezle et al., 1999).

Another factor with significance is the thickness of the snow bed, given that the thickness of the snow layer is 80 cm or more it is thick enough to prevent heat introduced in the summer from escaping, and protects from short term temperature and radiation changes (Vonder Mühll et al., 2002).

The timing and duration of the snow also influences the ground temperature. The duration of the cooling effect caused by a thin layer of snow being deposited on a warm surface in the autumn, is controlled by the rate of snow accumulation. After enough snow has precipitated the snow cover is thick enough to insulate the ground, the insulation effect could last for weeks or months (Zhang, 2005).

When interpreting BTS results one should consider the history of the precipitation of snow, a relatively warm BTS value is expected in respect to early heavy snowfall because of its tendency to preserve energy in the active layer. In contrast a relatively cold BTS is expected in case of having little or no snow at all until late, mid-winter (Vonder Mühll et al., 2002).

1.6 Statistical methods

Permafrost should not be thought of as a substance, but rather a thermal condition of the ground (Lotspiech, 1973). As mentioned earlier the permafrost is controlled by the heat exchange at the surface, which in turn is modified by factors such as snow cover, vegetation cover, and thermal conductivity etc. These small-scale factors however accounts for small-scale variations in the heat transfer process, and to make a model of the distribution of permafrost that cover a larger area, small-scale variations have less relevance (Hoezle et al., 2001). The usage of topo-climatic parameters such as elevation, slope angle, aspect, curvature and solar radiation is a simplification made to limit the number of explanatory variables, and makes empirical-statistical modelling more applicable (Hoezle et al., 2001).

An empirical-statistical model relates an observed occurrence of permafrost, against large scale factors that explain its existence (Riseborough, 2008). The model gives a relationship between the different data that easily can be applied to maps but so far, the models are only valid in local areas (Bonnaventure, 2012). To further simplify the model, permafrost is given a binary value (0, 1) as it either exists or not. This is referred to as a dependent or response variable, in contrast to the explanatory factors height, solar radiation, slope inclination, profile and plan curvature which are independent or predictive variables (Hosmer & Lemeshow, 2000). The occurrence of permafrost is hard to measure directly, and an indirect method of measuring (BTS) can be used. The empirical-statistical model is created using logistic regression and stepwise regression.

1.7 Evaluation of explanatory factors

An earlier study in Tarfala valley made by Marklund (2011) concluded that elevation was the only significant factor that explained the occurrence of frozen ground in Tarfala, this raised some suspicion as it is obvious that the temperature of the ground is influenced by a number of factors. The investigator thought further analysis was needed. Elevation has served as a good substitute variable for MAAT in Norway and has been found to correlate well with permafrost distribution in Norway and Sweden and is therefore included as an independent variable (Isaken et al., 2002; Ridefelt et al., 2008).

The importance of solar radiation as a factor relevant for permafrost is however questionable. In some cases, the solar radiation is considered significant (e.g. Ardelean et al., 2015; Hoezle, 1992), but not as valued in the Swedish latitudes according to studies done by Marklund (2011) and Ridefelt et al (2008). Diffuse radiation is the part of the incoming radiation which is intercepted by clouds. The intercepted radiation is assumed to be isotropic and normally distributed on different slopes by scattering and reflection. Whereas the direct radiation is anisotropic and distributed unevenly (McAneney & Noble, 1976). Shading and reflection of direct radiation in a complex terrain is a function of the slope's character, the solar azimuth and zenith angles that is constantly changing according earth's rotation (Wang et al., 2006). Solar radiation is in theory a relevant parameter to study, but possibly require multiple BTS points on all aspects to be valuable.

The character of slopes has not proven to be relevant to the occurrence of permafrost at all in Sweden (e.g. Marklund, 2011; Ridefelt et al., 2008). Aspect is the direction in which the slope faces given in degrees clockwise from the true north, and should in theory control the amount of incoming direct sunlight. Other characteristics

of slopes are curvature and slope angle. Curvature can either be lateral or vertical, diverging or converging and convex or concave. Curvature and the angles of slopes affect both snow cover thickness and drainage (Quinn, 2013). Concave slopes are for example favourable for accumulation of snow (Ardelean et al., 2015). Gentle inclination of slopes also contributes to accumulation and persistence of the snow, while steeper slopes tend to disfavour snow accumulation (e.g. Gubler et al., 2011; Gruber et al., 2004).

Absence of BTS measurements on different facing slopes is a possible reason why aspect and potential incoming solar radiation is considered insignificant factors (Isaksen et al., 2002). This is a major problem with the BTS method as some slopes simply are too dangerous to visit, or has insufficient amounts of snow due dominant wind exposure. However, the slope angle, aspect, and curvature (plan/profile) were considered potentially significant factors and their relationship with BTS were investigated.

2   Method

Data was collected by doing field work in Tarfala valley for 5 days, at the turn of the month between Mars and April 2017. The equipment used was a probe with a 100 Ohm platinum resistance thermometer attached to one end of a plastic tube. The probe was connected via 3-wire half bridge to a data logger (Campbell Scientific 21X Micro logger) which logged the data. Before collection of data the probe was calibrated in an ice-water bath, to ensure reliable results. To obtain BTS points that cover different aspects and a large span of elevation, several preliminary altitudinal transect were chosen that would cover slopes with as many directions as possible, as well as a large elevation interval. However, restrictions had to be made as some areas were difficult to reach or even dangerous with respect to avalanches.

BTS measurements are influenced by local effects such as snow depth, the evolution of the snow cover, and the quality of the contact between the ground and the temperature sensor (Gruber & Hoezle, 2001). Given that the thickness of the snow layer is 80 cm or more it is thick enough to prevent heat introduced in the summer from escaping, and protect from short term temperature and radiation fluctuations (Vonder Mühll et al., 2002). This is the main reason for restricting measurements taken at places only which has a least thickness of 80 cm (Hoezle, Haeberli & Keller, 1993). The measurements had to be taken in the winter before the snow started to melt, to ensure that the BTS have reached equilibrium (Vonder Mühll et al., 2002). To provide as many measurements as possible in the survey, the restriction on snows thickness was lowered and limited to 60 cm.

The procedure for data collection started with preparing a hole in the snow with an avalanche probe to make sure the tip of the thermometer probe was not damaged. The probe was then held in place until the temperature was stable. The data logger displayed and logged the temperature every 20 seconds and the procedure usually took about 5 minutes. Coordinates, temperature, and snow depth at the point was noted at every location. The height was given first after importing the XY-data onto a DEM.

2.1 GIS-modelling

A high resolution digital elevation model (DEM) has been taken from Lantmäteriet (Lantmäteriet, n.d.). The chosen DEM had 2 m resolution and it was used as a base map in Esri ArcGIS 10.1. The coordinates for each measured point in 2017, 2011, 2002 was then added as XY-data. Usage of the spatial analyst toolbox helped calculating slope angles, aspects, curvature, and solar radiation for the input points in the area of Tarfala. The month July was chosen by it having low snow coverage, thus the amount of radiation that gets reflected by snow is minimized (Hoezle, 1992). A cloud diffusion parameter was set to 0.7 as the normal values point out that mean cloudiness usually is 70% (SMHI, 2017-03-20). Aspects, curvature and angles of the slopes as well as solar radiation were extracted with the sample tool to later be used in the statistical analysis.

2.2 Statistical analysis

Stepwise regression is a statistical method used to investigate if all the independent variables are needed in the final model. It combines forward and backward selection methods, and each step in the procedure examines the possibility to include, exclude or change a variable according to their significance to the response variable. The predictor variables used were elevation, aspect, solar radiation, planar and profile curvature, and slope angle. The variable used as response for the stepwise regression was the BTS which was classified into either 0 or 1 with respect to temperatures being either above or below the limit -2,9°C. The binary data had to be turned into permafrost probability by dividing it with observations per 100 m intervals, this created groups with different statistical probability for permafrost presence. The insignificant variables were removed and not included in the logistic regression model (Blom & Holmquist, 2000). The stepwise selection of the dataset was carried out in a generalized linear regression model with binomially distributed data in Mathworks MATLAB R2017a.

Logistic regression investigated the correlation among the binary response variable and one or more predictor variables. The method demands that the dependent variable is binary, thus no need for the data to be normally distributed. Logistic regression can handle nonlinear relationships between the variables. The method gives a good estimate of the probability of occurrence (Lewkowicz et al., 2004). The response variable being measured BTS, gives the probability of permafrost occurrence against the explanatory factors chosen with stepwise regression. *Equation 1* was used to model the probability in GIS with the raster calculator tool, and the predictive raster outcome of the logistic regression was used as input for reclassification to simplify the model.

$$\ln\left(\frac{p}{1-p}\right) = A + \sum_{n=1}^{k}(B_n X_n)$$

Equation 1. Logistic regression equation

3 Result

The field survey resulted in 36 BTS points that can be seen in *figure 2.* Together with measurements from 2002 and 2011 the sum of the points comes to 156. This is however not enough to do comprehensive statistical analysis on, as some variables from the stepwise regression may be overestimated (Steyerberg, Eijkemans & Habbema, 1999).

A stepwise regression effectively sorted out the irrelevant factors slope angle, curvature, solar radiation and aspect. The data used in the stepwise regression was extracted from the DEM in ArcGIS. All the extractions except for the omitted curvature can be seen in the appendix. The stepwise regression revealed two coefficients needed for the last modeling in GIS. The simplified logistic regression was used to model the permafrost in GIS using *equation 2.*
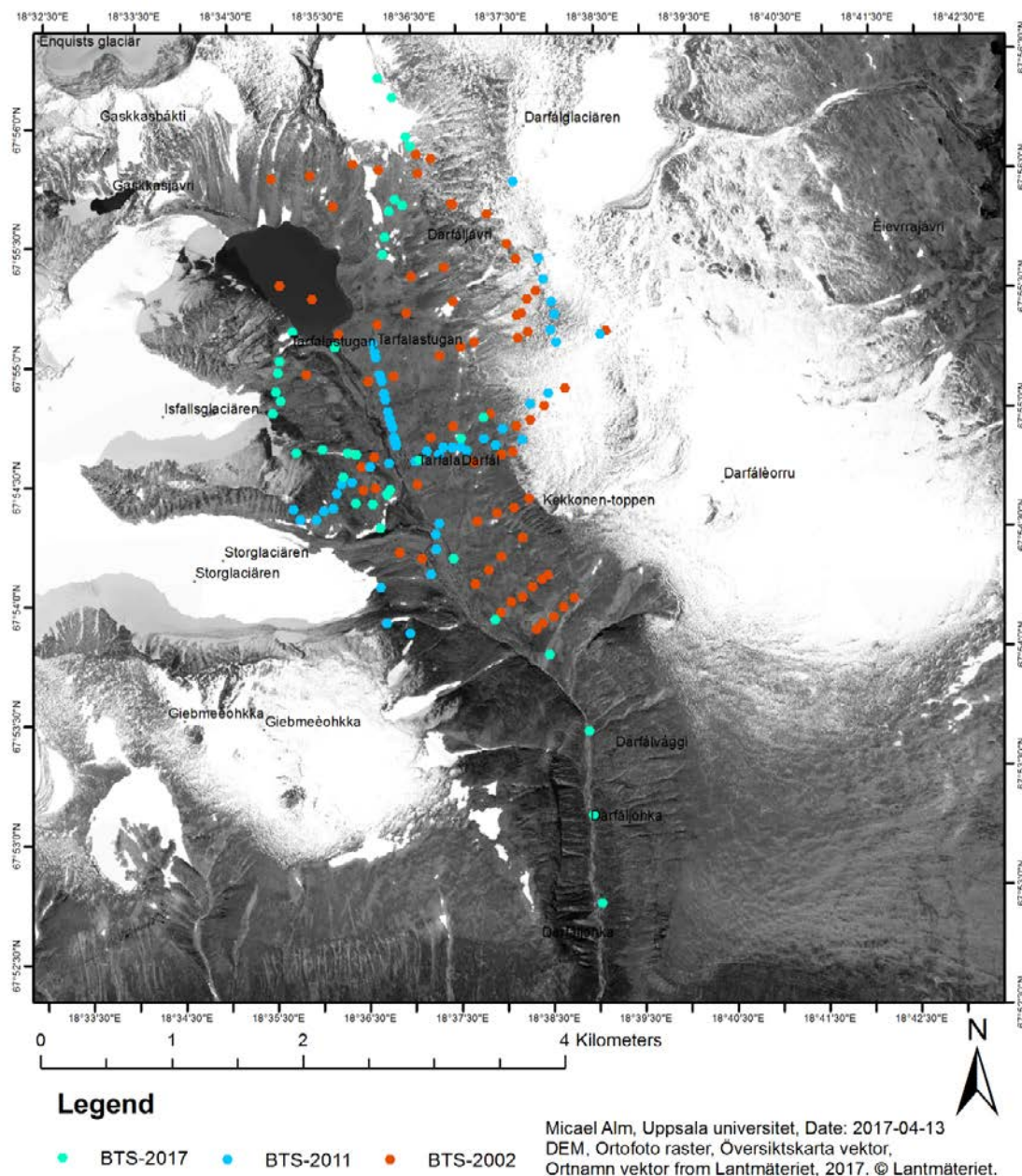
Figure 2. 156 BTS-points collected in surveys 2017, 2011, 2002.

$$p = \frac{1}{1 + e^{-(A+(BX))}}$$

Equation 2. Simplified logistic regression

Out of 156 points measured during the years 2002, 2011 and 2017, 62% suggest that permafrost is probable. Two points were discarded based on insufficient snow thickness. The lowest temperature was found at the lowest elevation, and the highest temperature was found on the highest situated point that was measured. The stepwise regression result is shown in *table 1*, from which the intercept and elevation estimate was acquired and used in the logistic regression. The stepwise regression selected elevation as a single significant factor, the rest is discarded based on having p values above 0.05 due to the default confidence level at 95%.

Table 1. Results from the stepwise regression with probability based on height.

	Estimate	SE	tStat	pValue
Intercept	-3,7087	1,3001	-2,852	0,004338
Elevation	0,003348	0,001054	3,175	0,001499

To finally model the probability of permafrost occurrence in GIS, the intercept estimate and the elevation estimate was treated as constant A and coefficient B in equation 2, and the DEM as the single independent variable x. The raster calculator tool calculated the probability of permafrost on every pixel and the resulted raster shows a probability interval between 0.12 and 0.96. The model was reclassified to show three contrasting areas of likelihood, one zone showing permafrost not probable between 0-50 percent, another illustrating that permafrost is possible between 50-80 % and the last showing that permafrost is probable above 80%. *Figure 3* shows the reclassified probability model, from which height boundaries were obtained. Permafrost is probable at heights above 1523 m a.s.l. and possible in between 1108 and 1523 m a.s.l. and not probable below an elevation of 1108 m a.s.l. Attempts to derive coefficients using other response variables were made, however none of the results agree with figure 3. More details are given in Appendix 1, 2, 7, 8.

Figure 3. Probability zones of permafrost in Kebnekaise massif based on elevation.

4 Discussion

The measurements were mostly taken in local depressions, close to snow free moraines where the snow cover was thicker than 60 cm. Some measurements have not been included in the dataset, because of the uncertainty of a good contact between the ground and the probe. These excluded points were measured where the snow cover had a thickness greater than 250 cm, there the probe was difficult to insert due to several possible ice layers at depth. At some localities, the temperature between two measurements varied approximately 1°C at principally the same location, which led to that more measurements were acquired. The uncertain temperature was attributed to a poor contact with the ground, and was removed when two other or more values were similar.

The data from earlier studies in combination with avalanche danger and snow-free surfaces influenced the selection of transects, the resulted collection expanded the number of points on a few aspects and extended the elevation span. An altitudinal range from 661 m to 1808 m has now been covered during these three surveys in 2002, 2011, 2017. Although the elevation may not be perfectly correct as the handheld GPS accuracy differed depending on the location. With a margin of error between 2-12 m the coordinates could be slightly offset. The extraction of elevation from the DEM using the sample tool in ArcGIS may not have been perfectly accurate. One coordinate yielded a height of 0 m a.s.l., and another coordinate a height of 700 m a.s.l. These points were discovered by them conflicting with the temperature-elevation trend, simply higher equals colder. The same coordinates were checked for inaccuracy and were both wrongly extracted. The points were in fact located at around 1200 m height, this was corrected before the statistical investigation.

The history of the snow layer is of great importance when interpreting BTS data, but with lack of records only speculation is available. And with the series of surveys made in three different years and with each having a unique history it is even more complicated. As mentioned earlier an initially shallow layer of snow acts as a cooler in contrast to a thick initial cover that insulates the ground. A temperature much colder, at the same height of another but different location can therefore be resulted by an initially thin layer. This kind of reasoning can however not be applied to the present study as knowledge of the initial snow layer is lacking.

4.1 Statistical analyses and modelling

The final model only has elevation as a predictive variable, confirming the model previously produced by Marklund (2011). The current study involves his measurements and it is necessary to discuss the differences between previously and present studies. The former student concluded with the help of a logistic regression that the probabilities 0.5 and 0.8 correspond to height boundaries at 1142 and 1190 m. The current study's increased number of observations (n=156 in contrast to n=56) together with the fact that the measurements cover a larger height interval, could explain why the gap between the height boundaries has enlarged and shifted to 1108 and 1523 m a.s.l. The currently presented result lie in the scope of the height interval in which King (1984) concluded discontinuous permafrost to exist within, namely 750 – 1600 m. The permafrost zone of discontinuity could have decreased since 1984, and the decrease could perhaps be supported by a rise in ground temperature at a rate of approximately 0.04-0.07°C yr^{-1}. The rise in the ground temperature has been

investigated by the European Union PACE project in a borehole located in Tarfala (Harris et al., 2009). However, a warming of the ground would also cause the lower boundary of the continuous zone to be higher, and not only the lower boundary of the discontinuous zone.

The BTS were coded into 1 where the temperature was below the temperature limit -2,9°C, and every measurement above that value was given a 0. Probability were then calculated by sorting the dataset by increasing elevation, and dividing the sum of the binary values, with the number of observations per intervals of 100 m. The significance of elevation is possibly influenced by this sorting, thus creation of other probabilities needed to be tested. For example, the dataset was sorted according to increasing aspect, and each 45° constitute one group of observations. The measurements did however not cover enough north aspects and the variable is not to be considered important at this point. The same was done for the rest of the variables. A second model, *appendix 7* was created based on a stepwise regression that revealed significance between BTS and slope angle, the table containing the result from the regression is included as *appendix 1*. The response variable was based on sorting the dataset from least to greatest slope angle, and the observations were divided into groups within an interval of 10°. Observations of BTS below -2,9°C in an interval were divided with the total number of observations within that group. A possible influence on the significance between the temperature and slope angle can be a few measurements, that have been taken on very steep slopes, 56°, 59°. These measurements belong to a previous study, and were possibly incorrectly displayed on the DEM, but are nonetheless included. The second model conflicts with the final model and is therefore left out of the result, based solely on that slope angle had a higher p-value. A model with elevation and slope angle as independent variables could not be made using the coefficients from *appendix 1* and *table 1* because constant A needs to be the same.

Using a binary instead of percental response variable was tested in yet another stepwise regression, the result can be viewed in *appendix 2.* The table shows that all independent variables is significant, apart from the statistically insignificant aspect. Although the curvature variables show significance, their coefficients seem to be under and overestimated. It was decided to exclude curvature in another test of the significance of the variables against BTS. The revised stepwise regression, which result can be viewed in *appendix 3* also had a binary response variable and resulted in selecting the variables elevation, slope angle and elevation*slope angle. The third logistic regression model with coefficients and constant from *appendix 3* together with the slope angle raster (*appendix 6*) and DEM resulted in *appendix 8*. This third model is particularly difficult to interpret, because height and slope angle plus a combination of these are influencing permafrost. From looking at the three-parameter model and comparing it with the single parameter model *figure 3*, it seems that the boundaries for permafrost's zonation has shifted. For instance, the base of the continuous zone is at a lower altitude, making the discontinuous zone smaller. However, it is not possible to delimit a likelihood of permafrost occurrence with only height, because the slope angle is also affecting the distribution. Generally, the lower boundary of the newly created model's continuous zone correlates with a height around 1125 m a.s.l. but in some places, reaches down to 800 m. The angle of the slopes influences the thickness of the snow cover, and where the angle is steep the snows thickness decreases which then might make a steep slope colder. Moreover, a second reason why the slope angle is significant can be caused by that the geothermal heat is affected by the slope angle. A study in Greenland have looked at

the geothermal heat flux with ice penetrating radar, they found that the geothermal heat flux is amplified in troughs leading to increased warmth in the base of valleys. The geothermal heat is also weakened with distance from the troughs, resulting in colder ground at higher elevations. Why this happens is because the heat flux from the ground reacts with the topography, specifically the slope angle and the distance between the sides of the valley (van der Veen, 2007). That slope angle has an influence on the distribution of permafrost in Tarfala can explain the large differences between the models.

From the correlation between snow depth and temperature was not tested. Because their relationship cannot improve the final model as of the difficulty of mapping the snows thickness in a mountain area. Observations in the field point to that the exposed snow cover is strongly redistributed and shaped by the wind, and heterogeneous even at small distances. Simple equations cannot make a good representation of the complex distribution of snow's thickness. In other words, the lack of a raster with snow depth even at a coarse resolution is the reason why snow as a variable is excluded.

From looking at the dataset, specifically the distribution of measurements on different elevations, it is obvious that the number of measurements in one height interval can underestimate or overestimate the probabilities. The dataset contains one measurement in the 1800-1900 m interval, this gave the same interval a likelihood of 100% to hold permafrost. Even if it is possible that all the BTS would have been below -2,9°C above 1800 m, the snow cover could in another location have been thick enough to push the temperature near the limit. Other aspects could have higher temperatures due to increasing amount of sunlight. The dataset further includes a sparse number of measurements below 1000 m, causing the probability to be either 0 or 50%, depending on interval. That height is the single variable permafrost rely on is improbable. However, it is probable that elevation as single independent variable give a coarse estimation of permafrost's spatial distribution.

4.2 Future studies

To get a more certain spatial occurrence, and to be able to differentiate between discontinuous and continuous permafrost in Kebnekaise more BTS need to be collected. The problem with the existing measurements is that only some elevation intervals cover different aspects, improvement of the data could be to cover every aspect with several measurements, or to cover each 100-m height group with a few measurements on different slopes. Although, it is time consuming to measure twice or three times at one location it seems to be necessary to measure at least twice to ensure the contact to the ground is good.

5 Conclusion

The probability of permafrost existence in Tarfala valley have been studied earlier using empirical statistical modelling. This was an attempt to improve the model by expansion of the data collection. The present study involved 100 more BTS points not featured in the study 2011, but the result still points to that elevation is the single significant factor governing permafrost occurrence. Even though the correlation was slightly higher when including more factors, they were not considered significant.

The constructed model shows that the line separating sporadic and discontinuous

permafrost is at a height of 1108 m a.s.l. and that permafrost is continuous above 1523 m. To improve the model, more variables should be proven significant. More BTS-points above 1500 m and below 1100 m, covering more northern aspects are needed. It is important to mention that this result only is true for the area of the Kebnekaise massif.

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8 Appendices

Appendix 1. Result of the second stepwise regression with probability based on slope angle as response variable

	Estimate	SE	tStat	pValue
Intercept	-0,3163	0,3263	-0,9695	0,3322
Slope angle	0,03977	0,015704	2,532	0,01123

Appendix 2. Stepwise regression with binary response variable

	Estimate	SE	tStat	pValue
Intercept	-17.2	5.6699	-3.0335	0.002417
Elevation	0.0035	0.00169	2.0586	0.03953
Profile C	3.15e+06	1.293e+06	2.4386	0.01474
Plan C	-3.15e+06	1.293e+06	-2.4386	0.014746
Curvature	3.15e+06	1.293e+06	2.4386	0.014746
Slope angle	0.6721	0.26043	2.5808	0.0098579
Solar radiation	0.0001	4.166e-05	2.4418	0.014616
Elev:Profile c	-0,0005	0.00017	-3.2213	0.0012761
Slope angle:Sr	-4.63e-06	1.857e-06	-2.4933	0.012657

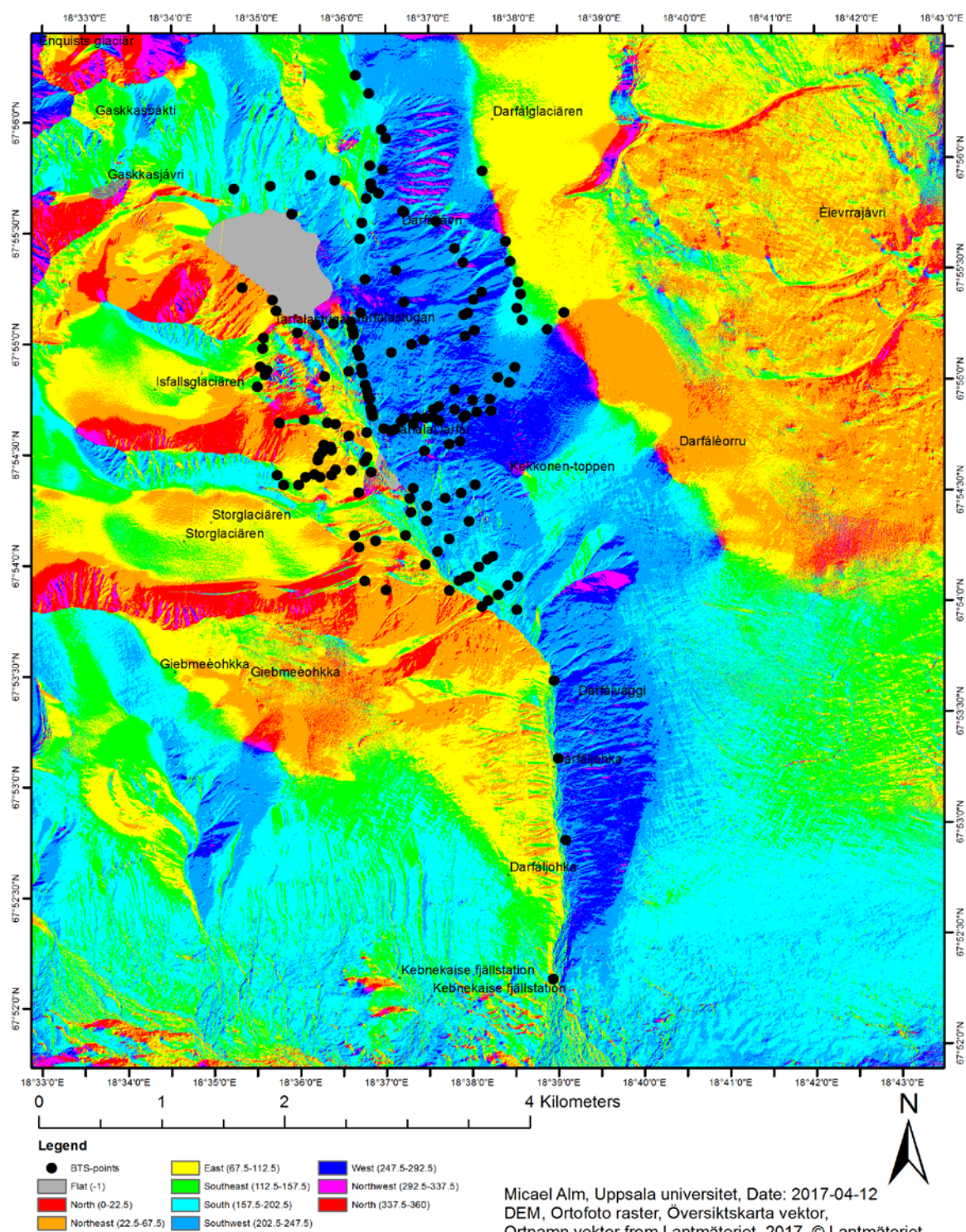**Appendix 3.** Revised stepwise regression with binary response variable

	Estimate	SE	tStat	pValue
Intercept	-10.504	3.4195	-3.0719	0.002127
Elevation	0.00922	0.002869	3.2154	0.001302
Aspect	0.00436	0.002544	-1.7158	0.086202
Slope Angle	0.34601	0.12102	2.8592	0.004247
Elevation*S A	-0.00025	9.2899e-05	-2.7178	0.006571

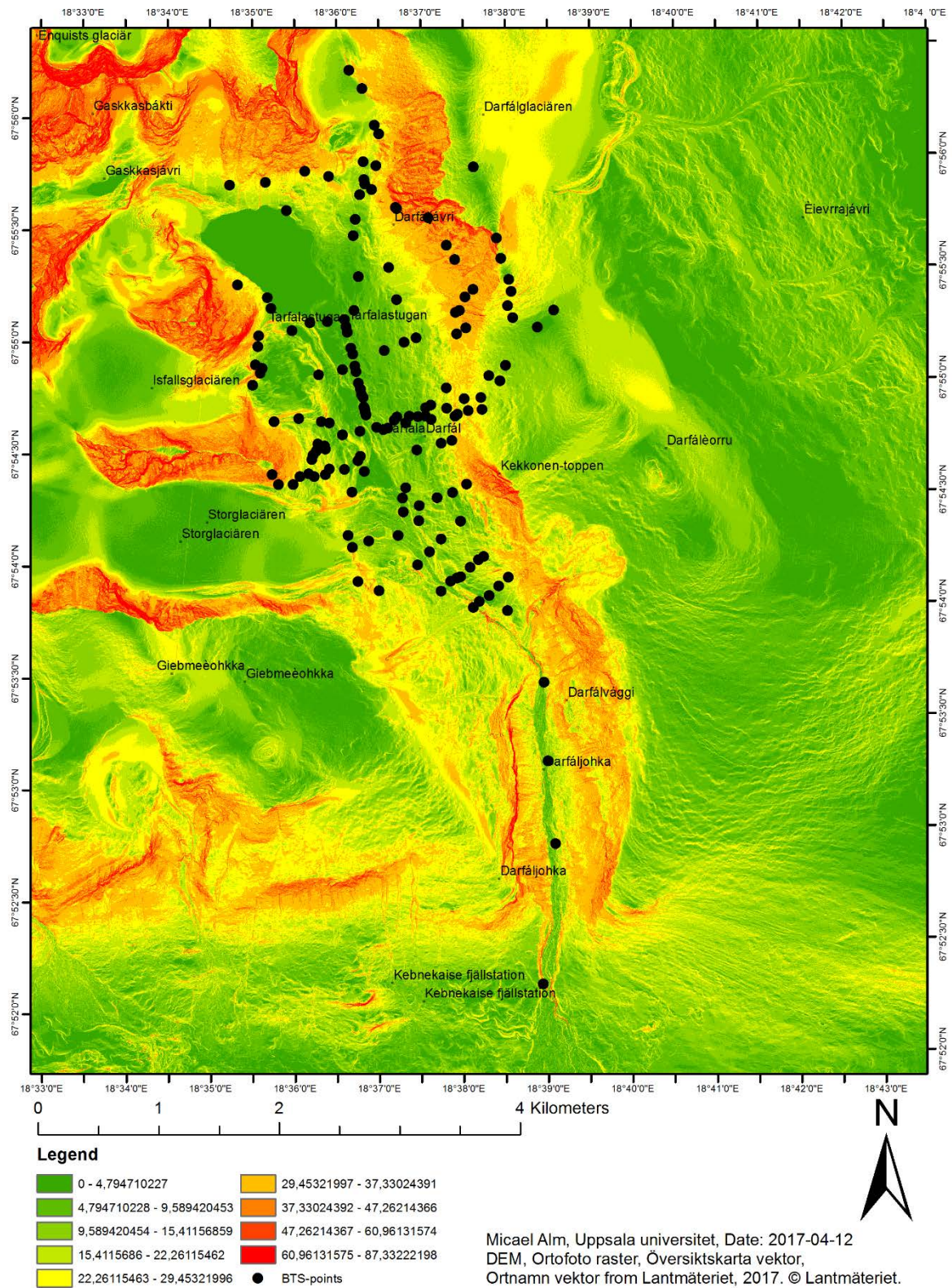**Appendix 4**. Solar radiation in the survey area, based on a tool in ArcGIS.
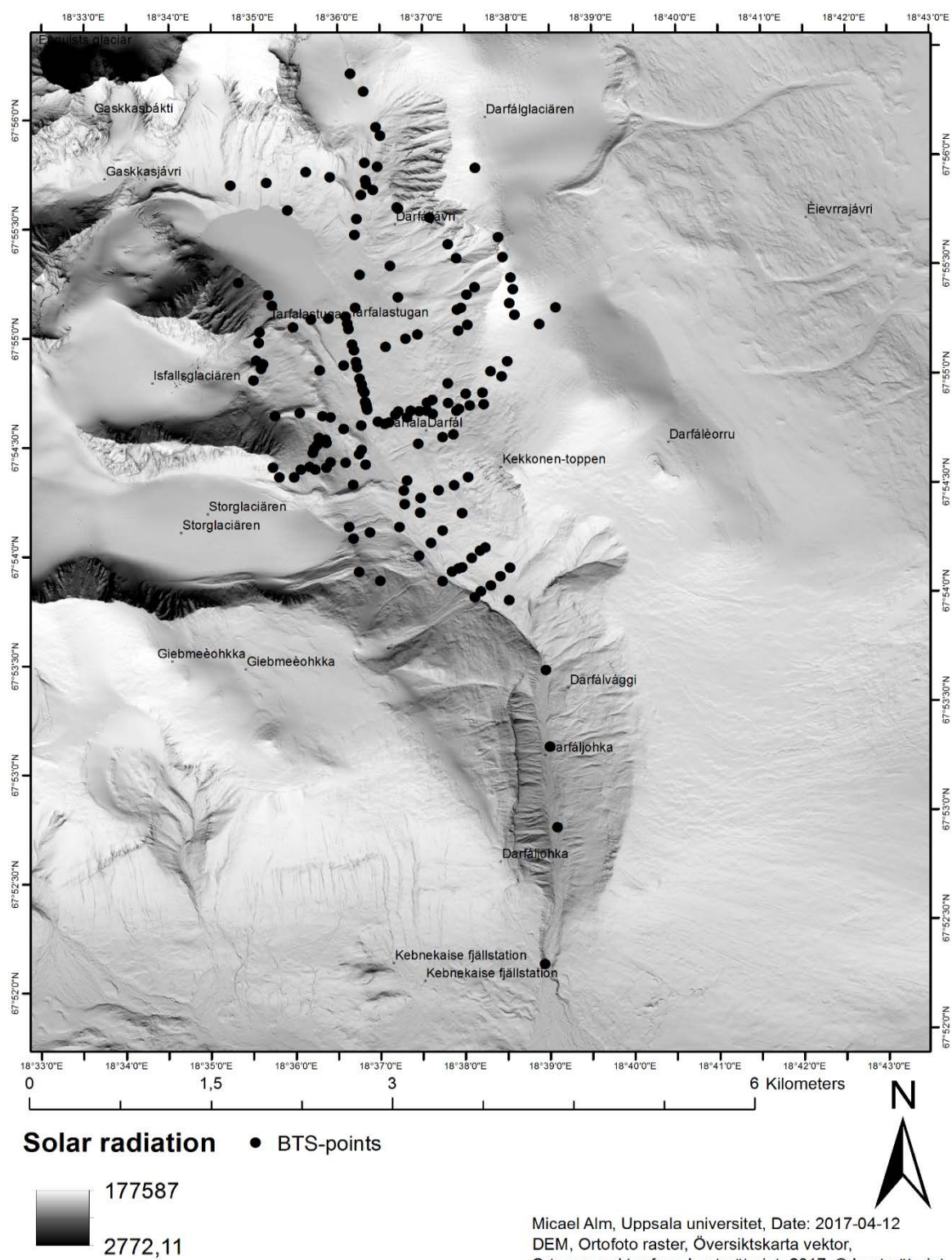
**Appendix 5.** Aspect of the slopes in the survey area, based on a tool in ArcGIS.

Appendix 6. Slope angles in the survey area, based on a tool in ArcGIS.

Legend

0 - 4,794710227	29,45321997 - 37,33024391
4,794710228 - 9,589420453	37,33024392 - 47,26214366
9,589420454 - 15,41156859	47,26214367 - 60,96131574
15,4115686 - 22,26115462	60,96131575 - 87,33222198
22,26115463 - 29,45321996	● BTS-points

Micael Alm, Uppsala universitet, Date: 2017-04-12
DEM, Ortofoto raster, Översiktskarta vektor,
Ortnamn vektor from Lantmäteriet, 2017. © Lantmäteriet.

Appendix 7. Probability of permafrost occurrence based on having only slope angle as an independent variable.
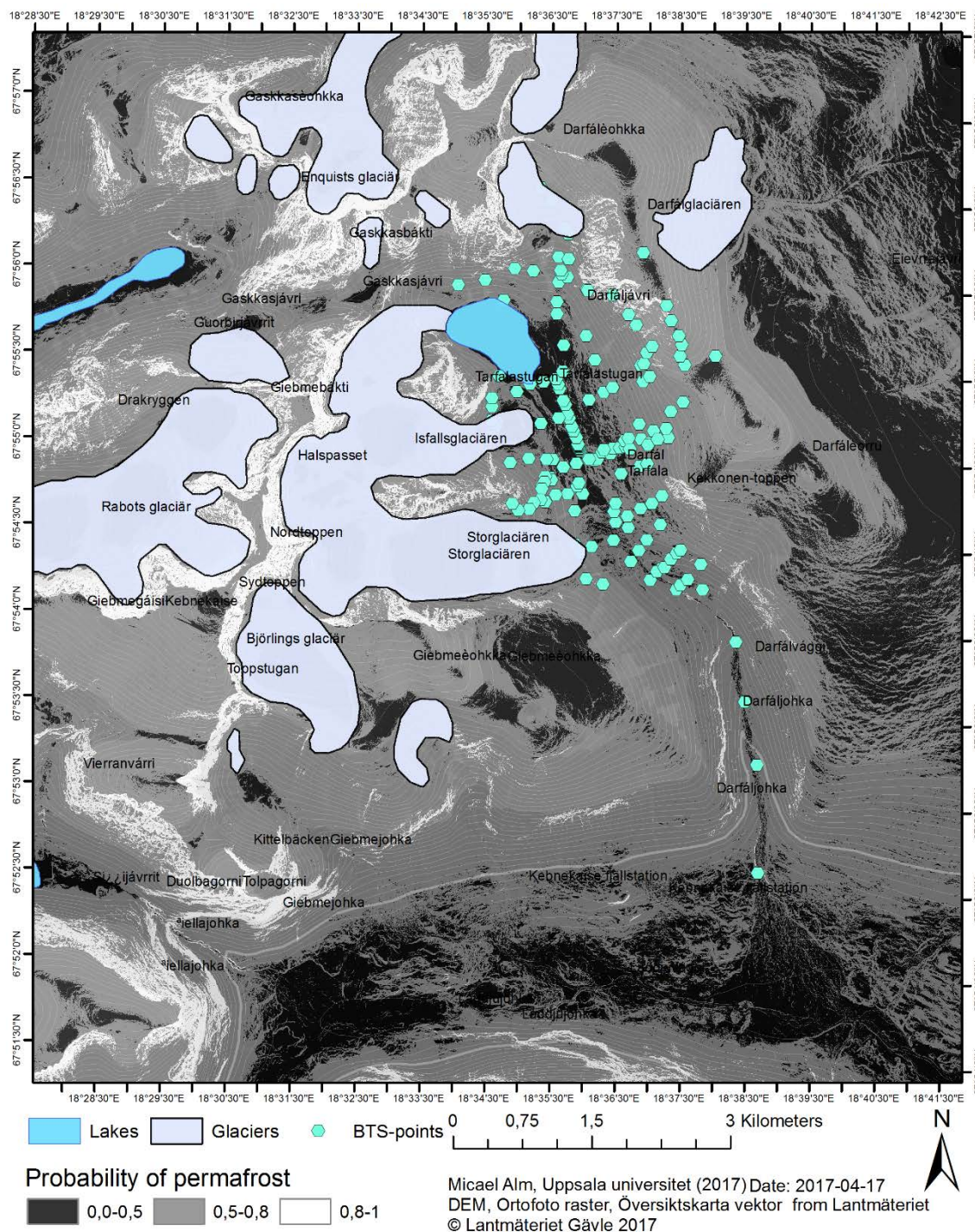
Appendix 8. Logistic regression model over permafrost distribution with elevation, slope angle and a combination of elevation*slope angle as independent variables.