Empirical-Statistical Approach for Modelling of Mountain Permafrost Distribution in the Central Tian Shan Using Detailed Analysis of Mean Annual Ground Surface Temperatures (MAGST)

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Abstract
The distribution and thermal state of permafrost is an important aspect of climate change research in the Central Tian Shan. As data availability is scarce, new approaches are needed to model the permafrost distribution in the region. This paper presents an empirical-statistical model using MAGST (Mean Annual Ground Surface Temperatures) as a proxy for permafrost occurrence. GST (Ground Surface Temperatures) was monitored at an hourly interval at 55 representative locations in the 130 km² Gukur catchment. The model incorporates satellite and DEM (Digital Elevation Model) derived data products like PISR (potential incoming solar radiation), NDVI (Normalized Differential Vegetation Index) and altitude. Model output is the simulated MAGST for the whole research area at a 30 m resolution, which is classified into "permafrost presence" (medium certainty/low certainty) and "permafrost absence" (medium certainty/low certainty). More than 62 % of the variance of MAGST is explained by the model parameters. The resulting map gives a detailed assessment of permafrost distribution in this exemplary subcatchcment of the central Tian Shan.

Introduction
Permafrost is defined as ground where temperatures remain at or below 0 °C for at least two consecutive years (Washburn 1979). Under climate change conditions, the temperature regime and the distribution of mountain permafrost get more and more into the focus of both the public and the scientific community due to its impact on water balance and natural hazards (e.g. Haeberli 2013, Haeberli et al. 2010, Bolch & Marchenko 2006). In contrast to polar lowland permafrost and plateau permafrost (e.g. in Tibet), spatial variability of mountain permafrost is generally very high (Hoelzle et al. 2001). Extensive studies of European mountain permafrost give information on processes like water and air circulation and energy fluxes within the active layer (King 1986, King 2000, Tenthorey 1992, Keller 1994, Hoelzle et al. 1999, Hoelzle et al. 2001, Mittaz 2002). Similar studies have been done in the Tian Shan and other mountain ranges of Central Aisa (Aizen et al. 2002, Gorbunov 2004; Hagg et al. 2007). Within short distances ground temperatures can vary significantly due changes in slope and exposure, subsurface materials, vegetation or snow depth (Gubler et al. 2011, Imbery et al. 2013, Roedder & Kneisel 2012).

In China, research of mountain permafrost got a strong impetus by the international permafrost conference hosted in Beijing in 1993. Later, the construction of the Qinghai-Tibet railway from 2000 to 2006 delivered additional knowledge on permafrost occurrences and dynamics especially of plateau permafrost in Tibet (Wang et al., 2002; Wu et al., 2000, 2004). The "Map of Snow Ice and Frozen Ground in China, 1:4,000,000" (LIGG 1988) and the successive "Map of the Glaciers, Frozen Ground and Desert in China" also in the scale 1 : 4,000,000 (CAREERI 2006) give valuable information on the regional trends concerning glacier and permafrost distribution. A more recent survey is given by Ran et al. (2012). However, the existing small scale maps cannot inform in detail about the large variability of permafrost occurrences that is typical for mountain permafrost. More reliable models are necessary to assess the permafrost distribution for further applications.

Riseborough et al. (2008) give a comprehensive overview of existing permafrost models that have been successfully developed in recent years. While process based models need large amounts of detailed data for computation, statistical models are less demanding. Although giving only an approximate estimate, statistical models are thus more suitable for regional scale modelling and areas where data availability is scarce (Gruber & Hoelzle 2001, Riseborough et al. 2008). This study therefore uses mean annual ground surface temperatures (MAGST) presented by Imbery et al. (2013) to develop an empirical-statistical model for permafrost distribution in the Gukur catchment, Central Tian Shan.

Study Area

Field investigations to monitor GST for two consecutive years were carried out in the 130 km² Gukur catchment (Figure. 1). This subcatchment is a direct tributary to the Aksu River, which contributes more than 70% to the total runoff of the Tarim River. Altitudes range from about 2,000 m a.s.l. up to 5,986 m a.s.l.. The three main glaciers are known as No. 72, No. 74 and No. 76 according to the Glacier Inventory of China (LIGG 1987). During the Little Ice Age (LIA), glaciers in the region advanced by about 300 – 500 m forming one to four end moraines (Zhao et al. 2010). While being very distinctive at slopes below present hanging glaciers and cirques, LIA end moraines are poorly preserved at the larger valley glaciers (Zhao et al. 2009). The periglacial area therefore consists of steep rock surfaces, exposed blocky moraine deposits of the LIA and widespread grass covered valleys. The large amount of debris on top and surrounding the glaciers - a typical feature for the entire region (Wang et al. 2011) – in combination with a highly continental and arid climate, leads to a close interaction of the glacial and permafrost environment (Harris & Murton. 2005). As a result, glaciers in the study area are surrounded by vast ice-cored moraines and rock glaciers are abundant on slopes exposed to the north. Overall it is hence expected, that a high amount of ice is preserved by permafrost in the Gukur catchment.

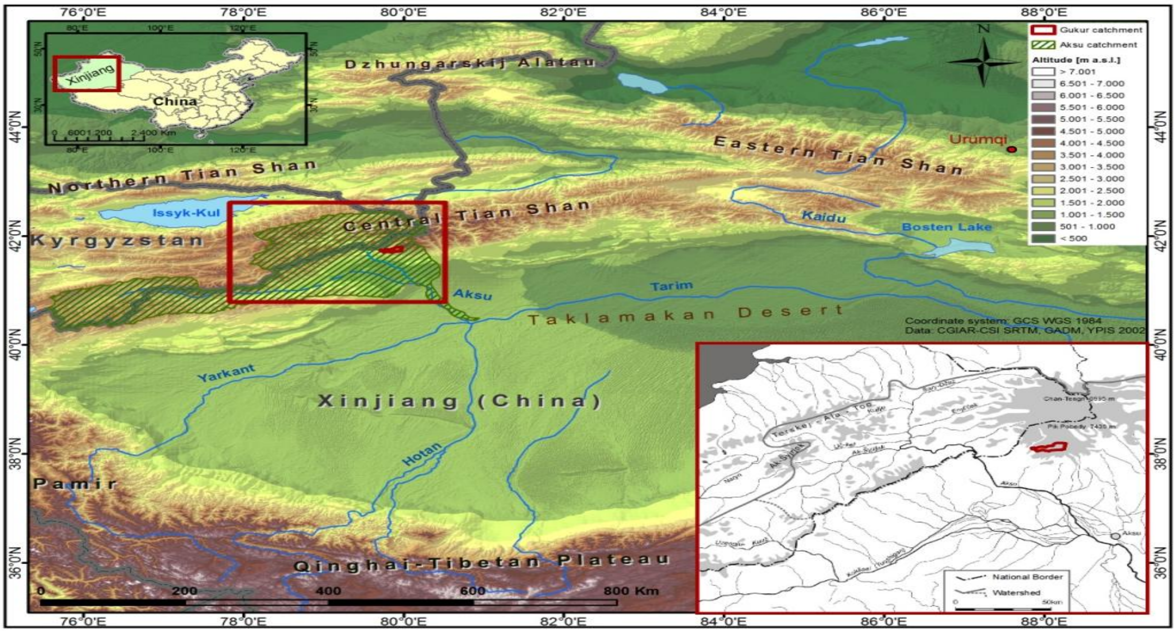

Figure 1: Regional overview and location of the research area (Gukur catchment) within the Aksu catchment, Central Tian Shan.

Model Design

The statistical modelling of permafrost is based on mean annual ground surface temperatures (MAGST) and identification of relevant field parameters presented by Imbery et al. (2013) in the Gukur catchment. Furthermore remotely sensed and GIS derived parameters from Digital elevation models are tested and incorporated in the model. Each relevant parameter tested for the model will be described briefly.

Mean Annual Ground Surface Temperatures (MAGST)

Depending on the accessibility of the terrain, subsurface material and depth of the active layer (ground on top of permafrost, that thaws during summer) direct investigation on permafrost distribution is time consuming and difficult to manage over larger areas. Therefore a proxy for permafrost evidence is needed, that can be extrapolated. Bottom temperature of the winter snow cover (BTS) and MAGST are common indicators for subsurface thermal conditions (e.g. Guadong & Dramis 1992, Gruber & Hoelzle 2001, Cremonese et al. 2011). Making use of the insulating effect of a substantial winter snow cover, BTS is generally used to map the area into zones of "likely permafrost", "possible permafrost" and "no permafrost" (Haeberli 1973, Hoelzle et al. 1993, Gruber & Hoelzle 2001, Brenning et al. 2005). To obtain representative BTS temperatures, remaining constant during midwinter, a continuous snow cover of at least 80 cm is necessary to represent subsurface temperature regimes. In the Central Tian Shan however, drift snow is an important and common factor that results in a thicker snow cover at foot slopes, small depressions and lee positions, while wind exposed locations stay snow free most of the winter (Imbery et al. 2013). Therefore BTS is difficult to use here as an indicator for permafrost in the study area.

MAGST on the other hand is not dependable on a homogenous snow cover. Continuous temperature measurements at an hourly interval secure highly reliable results. Permafrost occurrence is then classified according to Cremonese et al. (2011) by mean annual ground surface temperatures in four categories (permafrost presence: MAGST < −2 °C medium certainty; −2 °C < MAGST < 0 °C low certainty; permafrost absence: 0 °C < MAGST < 2 °C low certainty; MAGST > 2 °C medium certainty).

For continuous simulation of MAGST, a large amount of temperature loggers need to be installed in the catchment to represent the local conditions like altitude, aspect, slope, vegetation and subsurface material. Regression and correlation analysis presented in this paper are based on 55 temperature loggers, recording ground surface temperatures (GST) at an hourly interval from August 16th 2011 to August 15th 2012. A detailed report on experiment design and a description M-Log5W wireless mini data loggers used (GeoPrecision, www.geoprecision.com) is given in Imbery et al. (2013).

Altitude

Ground surface temperatures are generally most dominantly influenced by air temperatures. In mountainous regions this factor is expressed less by latitudinal changes as in lowland periglacial areas, but by altitude. Mean annual air temperature (MAAT) decreases by 0.6 °C per 100 m increase in elevation in the region (Zhou et al. 2009). In this study, considerable variations in MAAT can thus be expected at the selected locations due to the altitudinal differences of more than 1,600 m (between 2,476 m and 4,129 m a.s.l.). Therefore, altitude is identified as the site specific factor having the most significant influence on MAGST, with a coefficient of correlation of $r = -0.76$ ($p < 0.001$, $n = 55$). For adequate representation of the elevation in the Gukur catchment a DEM is used with a 30 m grid size, obtained from ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer).

Potential Incoming Solar Radiation (PISR)

Besides air temperature, solar radiation significantly influences ground surface temperatures. Based on the 30 m ASTER DEM, potential incoming solar radiation is calculated in ArcGIS for the whole year. A wide range of parameters for the computation can be modified to fit the local conditions. While most parameters were left with standard values, parameters like azimuth divisions were adjusted to give credit to the steep and therefore often shaded terrain in mountainous areas.

An attempt to enhance the results by calculating net shortwave radiation was made by Gruber & Hoelzle et al. (2001) by incorporating a summer albedo map. However, the net shortwave radiation model was later on discarded, as no benefit was detectable as compared to the standard model. A summer albedo map is just a snapshot of conditions and does not give credit to the temporal variability of soil moisture or most importantly the snow cover. Due to the importance and high variability of snow distribution and duration in the Gukur catchment as a result of drift snow (Imbery et al. 2013), the integration of an albedo map for correction of the PISR data product was omitted in this study.

Remote Sensing Data Products

To further improve the permafrost distribution model, an attempt is made to incorporate the ground cover. Vegetation cover can significantly influence ground surface temperatures and the thermal regime of the subsurface (e.g. Hoelzle 1994). To implement vegetation cover, a quantitative area wide parameter is needed. Therefore multispectral satellite data is used to calculate the normalized differential vegetation index (NDVI). The formula takes advantage of the high spectral reflectance of vegetation in the near-infrared wavelength (NIR) in contrast to a low spectral reflectance in the visible red wavelength (VIS):

$$NDVI = \frac{NIR - VIS}{NIR + VIS}$$

With grassland being the only abundant vegetation in the relevant altitudinal level, NDVI is a simple but highly suitable quantitative indicator for in the entire research area.

Landsat ETM+ not only has the necessary spectral bands (NIR and VIS) but also an adequate resolution of 30 m, fitting perfectly to the 30 m resolution of ASTER DEM and PISR data products. For best representation of the vegetation and the least presence of snow, an image in late summer was chosen. The selected cloud-free scene was taken on the 5th of October 2002 (with ETM+ scan line corrector still functional). Correlation between MAGST and NDVI is very high and significant ($r = 0.45$, $p < 0.001$).

Furthermore duration and thickness of a snow cover is an important factor for the thermal regime of the subsurface (e.g. Bartlett et al. 2004, 2012 Imbery et al. 2013, Roedder & Kneisel). To assess the duration of snow cover area-wide, high temporal resolution of the satellite data is indispensible. MODIS (Moderate-resolution Imaging Spectroradiometer) provides a very high temporal resolution and its bands can be used to detect snow cover very reliable. However, the spatial resolution of 500 m is not suitable for the application in this study, where MAGST can vary within short distances. For this study a spatial resolution of at least 30 m is desirable. Hence, the addition of snow is omitted in this permafrost distribution model due to scale issues, but highly recommended for larger areas like the entire Central Tian Shan.

Model Results

Applying multiple linear regression analysis, the coefficients obtained predicting MAGST including the parameters altitude, PISR and NDVI are as follows:

$$MAGST = -0.005909 * altitude + 9.065E-07 * PISR + 0.02787 * NDVI + 18.33$$

The resulting multiple coefficient of determination is 0.642. Taking the number of variables and the number of observations and the associated chance into account, the adjusted coefficient of determination (R^2) is 0.621.

Testing the model without NDVI, multiple linear regression analysis produces following formula:

$$MAGST = -0.006227 * altitude + 9.418E-07 * PISR + 19.23$$

The calculated multiple $R^2 = 0.6369$ is marginally lower than in the first model, while the adjusted $R^2 = 0.6229$ is slightly higher. Despite the high coefficient of correlation between NDVI and MAGST, variance explained by NDVI is neglectable and insignificant. The reason is shown in Table 1. A high degree of inter-correlation between NDVI and altitude is detected. Thus, no additional input is given by NDVI as it rather resembles the input already apparent in the model through altitude. Vegetation is bound to climate and therefore decreases with altitude. This relationship is furthermore enhanced, as old fine grained moraine deposits give way to less favourable younger and coarse debris in higher altitudes in the Gukur catchment. As a result, the second and simpler model is chosen, omitting the insignificant parameter NDVI due to its high inter-correlation with altitude and in accordance with previous studies on permafrost distribution modelling in the European Alps (Hoelzle 1994, Gruber & Hoelzle 2001).

Table 1: The table presents the coefficients of correlation for the monitored temperatures (MAGST) and the variables altitude, PISR and NDVI. Note the high correlation between NDVI and altitude, while PISR shows no signs of inter-correlation with altitude.

	MAGST	Altitude	PISR
Altitude	-0.76		
PISR	0.20	0.07	
NDVI	0.45	-0.47	0.08

Permafrost distribution and discussion

The statistical-empirical model simulating continuous MAGST is applied for the whole Gukur catchment research area and categorised into a permafrost distribution map. Figure 2 is a detailed map of the focus area, while Figure 3 gives an overview of the whole catchment and surrounding areas. Monitored MAGST at the individual logger positions indicate the high quality of the model. With an adjusted coefficient of determination of R^2 = 0.62 the explained variation of MAGST is very high and significant. Taking into account the resolution of 30 m for the input parameters and the high variability of MAGST within very short distances (Gubler et al. 2011, Imbery et al. 2013), the deviation of just one category is within a tolerable range. For further justification of the permafrost distribution model, the mapped ice-cored moraines and rock glaciers in the Gukur catchment are taken as permafrost indicators. A detailed description of the features is given by Imbery (2011). Rock glaciers and ice cored moraines are important and safe indicators for permafrost in mountainous areas (e.g. King 2000, Haeberli 1985).

The presented permafrost distribution map is a valuable contribution to the overall research effort on permafrost in the Central Tian Shan.

Existing maps (CAREERI 2006, LIGG 1988) give helpful information on the general permafrost environment at a 1:4,000,000 scale. However, to assess the thermal state of the permafrost on a local to regional scale, higher resolution maps are essential. The 30 m resolution map presented in this study is hence indispensable for the assessment of thermal conditions and the stability of ice preserved within the permafrost environment (ice-cored moraines, rock glaciers and ground ice). Considering the rising demand for water in the surrounding arid lowlands, strongly depending on the runoff generated from the cryosphere (glaciers, permafrost and snow) in the Central Tian Shan, this is one of the greatest challenges in the region under climate change conditions.

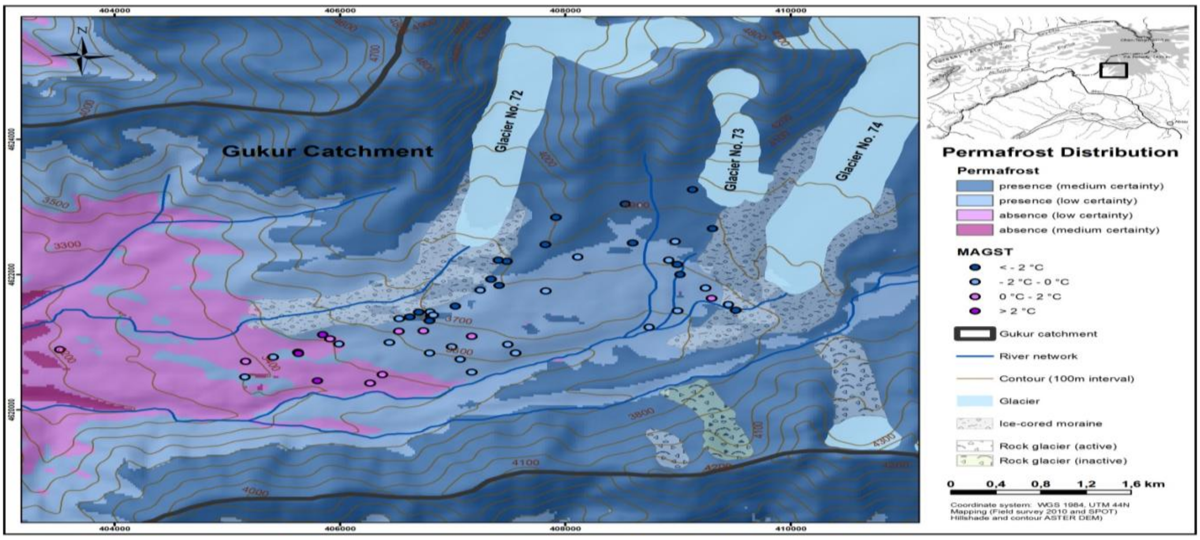

Figure 2: Permafrost distribution map for the focus area, using continuous modelled MAGST as a means of classification into four categories (permafrost presence: MAGST < −2 °C medium certainty; −2 °C < MAGST < 0 °C low certainty; permafrost absence: 0 °C < MAGST < 2 °C low certainty; MAGST > 2 °C medium certainty). Monitored MAGST are included for reference.

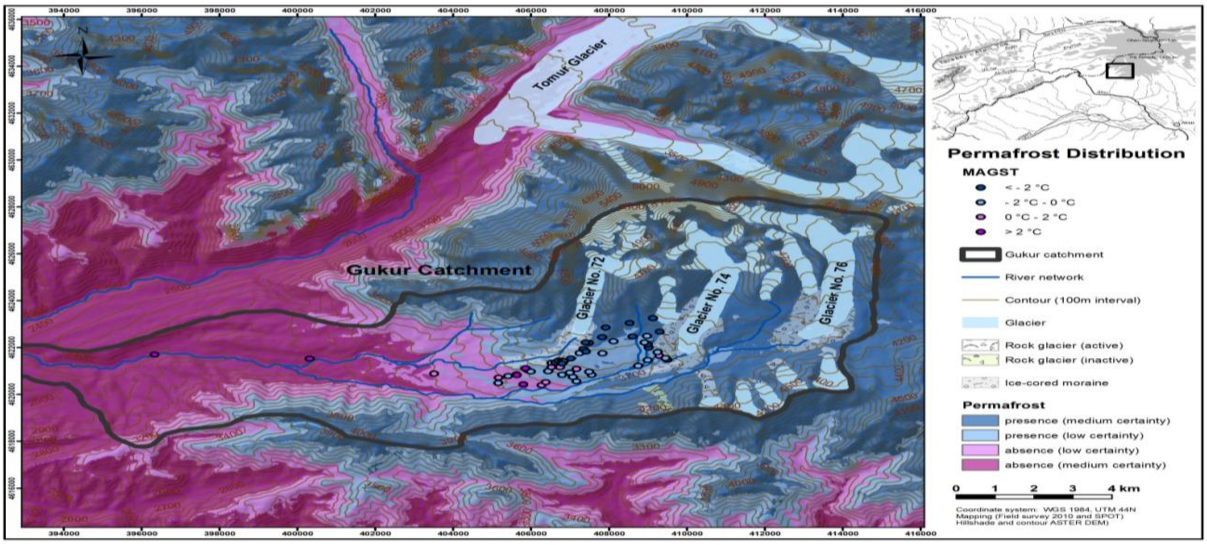

Figure 3: Permafrost distribution map of the Gukur research area, using continuous modelled MAGST as a means of classification into four categories (permafrost presence: MAGST < −2 °C medium certainty; −2 °C < MAGST < 0 °C low certainty; permafrost absence: 0 °C < MAGST < 2 °C low certainty; MAGST > 2 °C medium certainty).

Outlook:

Parameters used in the presented model explain more than 62% of the variance of MAGST. Therefore, the empirical-statistical approach proved to be very effective and highly accurate for the regional scale. Attempts have been made to improve the model by incorporating additional parameters (e.g. NDVI). However, parameters in a statistical model are often compound parameters and already include parameters that correlate with it (e.g. altitude and vegetation). Therefore the parameters should be regarded as a complex system.

Within climatically and geological similar conditions, the model can be used for permafrost distribution modelling in the Central Tian Shan. Nonetheless, further validation of the model, using additional measurements of ground surface temperatures for cross-validation and direct identification of permafrost presence or absence in the field are necessary.

Depending on the scale of application, further changes could be made to the model. For a more detailed analysis of e.g. singular slopes, a higher resolution DEM could improve the accuracy of the model as it would take small scale effects into account that are also important for the calculation of PISR (slope, shielding etc.). For application of the model to a larger scale, where resolution is less important, the authors would recommend to incorporate the factor snow cover into the model (e.g. MODIS at a 500 m grid resolution).

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